Accuracy of alveolar bone measurements using cone beam computed tomography compared with direct *in vivo* measurements

Vanessa N Browne, DDS

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Orthodontics

Oregon Health & Science University
Portland, Oregon

December, 2014

Accuracy of alveolar bone measurements using cone beam computed tomography compared with direct *in vivo* measurements

A thesis presented by Vanessa N. Browne, DDS

In partial fulfillment for the degree of Master of Science in Orthodontics

December 2014

[redacted] 12-19-2014

David A. Covell Jr. PhD, DDS

Associate Professor and Chairman

Department of Orthodontics

[redacted]

Larry Doyle, DDS

Assistant Professor and Director

Department of Orthodontics

[redacted]

Winthrop B. Carter, DDS

Associate Professor and Director

Department of Periodontology

Acknowledgements

I would like to thank the members of my thesis committee, Dr. Dave Covell, Dr. Larry Doyle, and Dr. Winthrop Carter, for providing ideas, guidance, and support throughout this process. I would also like to thank Drs. Megan Miller, Adam Timock, and Lane Cook for paving the way for this thesis project from their work on previous research projects involving the accuracy of Cone-Beam Computed Tomography.

I would like to thank Amberena Fairlee for her assistance in obtaining CBCT measurements and Mansen Wang for his tremendous statistical support. I would also like to thank the OHSU Departments of Periodontics, Oral and Maxillofacial Surgery, and Radiology for their assistance.

Finally, thank you to my fiancé, Andrew, for his love, patience, and support during this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Accuracy of alveolar bone measurements using cone beam computed tomography compared with direct *in vivo* measurements

Vanessa N Browne, D.D.S.[a]
Megan E Miller, D.D.S., M.S.[b]
Mansen Wang, Ph.D., M.S.[c]
Winthrop B Carter, D.D.S.[d]
Larry Doyle, D.D.S.[e]
Amberena Fairlee[f]
David A Covell, Jr., D.D.S., Ph.D.[g*]

[a]Resident, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, Portland, Oregon
[b]Orthodontist in Private Practice, Portland, OR
[c]Biostatistician, Medical Data Research Center, Providence Health & Services, Portland, Oregon
[d]Associate Professor and Director, Department of Periodontology School of Dentistry, Oregon Health & Science University, Portland, Oregon
[e]Assistant Professor and Director, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, Portland, Oregon
[f]Dental Student, School of Dentistry, Oregon Health & Science University, Portland, Oregon
[g]Assistant Professor and Chair, Department of Orthodontics, School of Dentistry, Oregon Health & Science University, Portland, Oregon

*Corresponding author
Oregon Health & Science University
Department of Orthodontics, SD 24
2730 SW Moody Ave.
Portland, OR 97239-3097
P: 503 494-6155 F: 503 494-5777
covelljr@ohsu.edu

Abstract

Introduction: Cone beam computed tomography (CBCT) imaging has broadened the clinician's opportunity to examine hard and soft tissue of the craniofacial complex, but limitations of the technology have yet to be fully defined. The purpose of this study was to investigate the accuracy and reliability of CBCT measurements compared to direct measurements *in vivo* of facial alveolar bone height (FBH), and in detecting the presence or absence of naturally occurring dehiscences and fenestrations. **Methods**: FBH measurements and the diagnosis of a dehiscence or fenestration were recorded from CBCT images (i-CAT ® 17-19 unit; Imaging Sciences International, Hatfield, Pennsylvania) acquired using 0.3mm voxel size, 5mA, 120kVp and viewed in standardized 0.5mm radiographic slices. Measurements were recorded using Dolphin 3D Imaging ® (Dolphin Imaging Systems, Chatsworth, CA) software after adjusting for optimal viewing image contrast. All measurements were repeated three times by two blinded independent raters. These measurements were compared to observations made at the time of surgical procedures involving a full thickness mucoperiosteal flap, where FBH and the presence or absence of a facial bone dehiscence or fenestration were also recorded by two independent raters. **Results:** For CBCT FBH measurements, intrarater reliability was high (PCC, CCC, and ICC≥0.98), as was interrater reliability (PCC and CCC≥0.97). The mean absolute difference between mean CBCT measurements for the first and second raters was 0.64±0.77mm. Interrater reliability for direct FBH measurements was high (PCC and ICC both ≥ 0.98). The mean absolute difference between raters for clinical FBH measurements was 0.46±0.35mm. CBCT measurements differed significantly from direct measurements, with a pattern of overestimation for CBCT measurements, which correlates to the appearance of decreased facial alveolar bone levels. The mean absolute differences were 2.49±2.61mm for facial bone height with 95% limits of agreement of -7.76 to 3.20mm. A PCC of 0.81 and CCC of 0.64 for facial bone height were found. The interrater reliability for detection of dehiscences and fenestrations was good (Cohen's kappa 0.65 ±0.11 with 95% CI 0.44 to 0.87). For each rater, in comparing the direct measurements to CBCT measurements for detecting dehiscences and fenestrations, Cohen's kappa was high (0.76 ±.11 with 95% CI 0.54 to 0.98) and moderate (0.50±.13 with 95% CI 0.26 to 0.75). Overall, 71% of dehiscences and fenestrations were detected on the CBCT images. **Conclusions:** For the protocol used in this study, facial alveolar bone height levels were often underestimated in CBCT images, especially in areas where alveolar bone is thin. Similarly, a number of the alveolar bone defects were not detectable in CBCT images.

Introduction

Several methods for non-extraction orthodontic treatment, including expansion and incisor proclination, are associated with the potential for moving teeth beyond the boundary of the alveolar bone, and can be accompanied by a loss of periodontal support as shown by various animal and human studies[1-12]. Loss of periodontal support includes bony dehiscence or fenestration, decreased alveolar bone height or thickness, and gingival recession. In the past, diagnosis of alveolar bone changes has been limited to conventional radiography techniques (e.g., bitewing, periapical, and panoramic radiography) and clinical examination[13-15]. Interproximal bone changes could be detected with conventional two-dimension radiographs, but facial and lingual alveolar bone changes could not be diagnosed due to the superimposition of cortical bony or dental structures[16-18]. Additionally, deterioration of underlying periodontal structures might not be reflected in the clinical appearance of the dentition and soft tissue[19].

The introduction of a three-dimensional medical imaging system, Computed Tomography (CT), in 1972, allowed the facial and lingual bone plates to be visualized radiographically, but the large size of the machine, as well as the high cost and high radiation dose of CT, limited its use in the dental field[20]. In 1998, cone-beam computed tomography (CBCT) was developed[21]. With the advent of this relatively smaller size, lower radiation dose, shorter acquisition time, and lower cost technology, clinicians in the dental field have been able to better visualize and measure their patients' anatomy in three planes of space, including analyzing the tooth position within the alveolar cortical bone plates. CBCT has many advantages over traditional 2-D radiography in that it does not have the distortion, asymmetry, superimposition, or magnification issues[22-24]. The improved diagnostic accuracy of CBCT over two-dimensional imaging for periodontal lesions has been confirmed,[25,26] and in orthodontics, the ability to use CBCT to visualize pre-treatment and post-treatment alveolar bone morphology would be of value in determining boundaries of tooth movement.

As the popularity of CBCT usage for various diagnostic, surgical, and operative applications continues to grow, it is important to critically evaluate the accuracy and validity of this imaging modality. Several studies have verified the accuracy of CBCT linear measurements of teeth, skull, and jaw bones[27-32]. This accuracy allows clinicians to justify the use of CBCT scans for studying implant sites[33-35], palatal thickness[36], and cephalometrics[37]. An important consideration, however, is that these studies have been completed using measurements spanning dimensions up to several centimeters, whereas changes in alveolar bone height and thickness, as well as detection of dehiscences and fenestrations, involve smaller dimensions. Studies on the accuracy of the linear measurements of alveolar bone height derived from CBCT images compared with direct measurements have used phantom modules[38], porcine maxillae[39] and mandibles[18,40], bovine ribs[41], dry human skulls[38,42-46], and formalin-fixed human specimens[18,47-53], and have found inaccuracies in dimensions less than one millimeter.

The accuracy of detecting dehiscences and fenestrations derived from CBCT images compared with direct measurements using cadaver skulls has also been investigated and has shown inconsistent results[18,42,47,52-55]. In orthodontics, certain treatment changes can cause the alveolar bone thickness to further decrease to a near voxel dimension. These thin areas of bone are more subject to artifacts related to CBCT imaging, where the alveolar bone can become indistinguishable from adjacent structures such as the tooth cementum and enamel, resulting in underestimation of alveolar bone height measurements and potentially in an incorrect diagnosis regarding bone changes[22,56].

In vivo studies involving direct measurements of alveolar bone are challenging to perform as soft tissue reflection is impractical to conduct on a frequent basis and has side effects. To our knowledge, there are only five randomly controlled studies and one case report that have been completed comparing alveolar bone measurements on CBCT to direct physical measurements on patients[57-62]. In four of the reports, differences to sub-millimeter accuracy were not assessed, and the other two reports focused on detection of furcation involvement. Although these studies give an important glimpse into comparing CBCT to *in vivo* measurements, the limits of accuracy of CBCT remains, especially in the mandibular anterior region where alveolar bone is often thin.

It is well documented that different areas of the maxilla and mandible have varying alveolar bone thicknesses and that certain teeth are more susceptible to alveolar defects. Previous studies have shown that fenestrations are more commonly associated with anterior teeth than posterior teeth, and dehiscences are most commonly associated with maxillary first molars, maxillary or mandibular canines, and mandibular lateral incisors[63-65]. Furthermore, studies have found that the facial bone plate is thinner in the areas of the maxillary first molars, maxillary canines, and mandibular incisors[5].

The hypothesis for this study is that CBCT measurements around teeth with thin facial alveolar bone will have decreased accuracy compared to CBCT measurements around teeth with thick alveolar bone. We also hypothesize that teeth known to have thin cortical bone plates will have less accuracy in the detection of alveolar defects. Therefore, the purpose of this study is to investigate the accuracy and reliability of CBCT measurements compared to direct measurements *in vivo* of facial alveolar bone height (FBH) of maxillary and mandibular teeth, and in detecting the presence or absence of naturally occurring dehiscences and fenestrations.

Materials and Methods

Following the approval of the study protocol by the Oregon Health & Science University (OHSU) Institutional Review Board (IRB#00008873), study participants were recruited through the OHSU clinics of Periodontics and Oral and Maxillofacial Surgery (Portland, OR). 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 18 months at the start of the study, participants had a CBCT scan taken as part of his or her dental treatment.

(3) Participants needed a surgical procedure requiring a full thickness mucoperiosteal flap as part of his or her dental treatment (Table 1).

(4) Teeth in the area of the surgery had virgin tooth structure or only small composite restorations

(5) The surgery region was free from pathology.

The following exclusion criteria were applied:

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

(2) Additional surgery (i.e., adjacent bone graft, sinus lift, tooth extraction) had been performed after the CBCT image had been taken, but before the tooth in question was measured

Participants were screened from September 6, 2012 to July 3, 2014. During this period, 173 CBCT images were screened. A total of 38 CBCT images met our initial inclusion criteria. The other 135 CBCT images were eliminated for the following reasons: duplicate CBCT image on the same patient, patient undergoing orthodontic treatment, CBCT image taken for private office referral, patient did not require a surgical procedure involving a full thickness mucoperiosteal flap, or patient did not have intact tooth structure in the surgical area. Of the 38 individuals identified with CBCT images meeting our inclusion criteria, 12 were scheduled for surgery during our measurement period (February 1, 2014 to November 7, 2014). Data from four additional individuals were pooled with this study from a pilot study that occurred October through December 2013 using a similar protocol, for a total participation of 16 individuals (Fig. 1). Of these 16 individuals, 10 participants were female and 6 were male with various ethnicities and an average age of 64 years (range 43-81 years). Thirty-one teeth were examined among the 16 participants (Tables 2, 3).

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 or oral surgeon ordering the scan (Table 3). Images were acquired in a single 360-degree rotation around the head of the patient and then stored in DICOM (Digital Imaging Communications in Medicine) file format.

CBCT Measurements

The CBCT scan DICOM file was imported into Dolphin 3D Imaging® (Dolphin Imaging Systems, Chatsworth, CA) for analysis. CBCT images were constructed using the default software setup and displayed on a 17-inch computer screen (Dell E171FPb Computer Monitor Flat Panel LCD, Round Rock, TX) with a resolution of 1280 x1024 pixels (32-bit). Two calibrated investigators (V.B. and A. F.) independently measured alveolar facial bone height (FBH) on the CBCT images. No time restriction was placed on the investigators. FBH was measured with a linear measurement tool to the nearest 0.1mm after the operator manually adjusted for optimal image contrast and enlargement for the area of interest. The FBH measurements were repeated 3 times with a minimum interval of 3 days between each CBCT assessment and 1 day between acquiring the CBCT and direct measurements. Both investigators were blinded to the participant's identity and direct clinical recordings during CBCT measuring.

The measurements were made using sectional slices of 0.5 mm thickness following a standardized orientation protocol, as established by Timock et al. (Fig. 2)[49]. Briefly, 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 root apices were ignored. Using the coronal view for posterior teeth and the sagittal view for anterior teeth, FBH was measured from the most incisal (or occlusal) and facial aspects of the tooth to the most coronal aspect of the facial alveolar bone crest, centered along the tooth's long axis.

Assessment of the presence or absence of a dehiscence or fenestration was also recorded, when assessing FBH. An alveolar defect was determined to be present when cortical bone could not be observed adjacent to the root surface in three consecutive slices. If the alveolar bone margin was more than 3.0 mm from the cementoenamel junction, it was classified as a dehiscence (Fig. 3)[66]. If the defect did not involve the alveolar margin, it was classified as a fenestration (Fig. 4)[66]. The presence or absence was determined by the majority of the 3 recordings for each examiner.

Direct measurements

During the surgical intervention, a mucoperiosteal flap was reflected and the FBH of each tooth qualifying for the study within the flapped area was measured with a reading to the nearest 0.01mm using a protocol modeled after that by Timock et al[49]. Two changes were made to the Timock et al protocol. To help achieve as large a sample size as possible, teeth that had only one adjacent tooth were included in the present study, whereas these were excluded in the method by Timock et al. To measure the FBH of such 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 FBH (Fig 5, D). The second change to the protocol involved the measuring device. To increase the maneuverability intraorally and improve infection control procedures, a two-point 6" bow compass caliper (Quint Graphics, Columbus, NJ), rather than a digital sliding caliper, was used to measure the FBH from the incisal edge or the facial cusp tip to the center of the root surface at the height of the alveolar facial bone plate along the tooth's long axis, centered mesiodistally(Fig 6). If wear was present on the facial cusp tip, the most coronal point of the tooth centered mesiodistally and along the long axis of the tooth was used. The points of this caliper were then marked on a sheet of white computer weight paper, and a digital caliper (General Tools, New York, NY) was used to measure the distance of the points to the nearest hundredth.

Twenty clinical FBH measurements were randomly selected and were remeasured twice with a minimum one day interval between measurements to test the validity of the protocol change from the digital sliding caliper to the point caliper. The presence or absence of a periodontal dehiscence or fenestration was also recorded. A dehiscence was recorded if the alveolar bone was more than 3 mm from the cementoenamel junction and a fenestration was recorded if there was an alveolar defect present where the root was denuded of alveolar bone, but the defect did not involve the alveolar crest[67]. These measurements were completed independently by the primary investigator (VB) and one of the surgeons performing the flapped procedure. All surgeons were calibrated prior to the study. A photograph was made of the area with the flap reflected, including all of the measured teeth and associated alveolar bone (Fig. 7).

Statistical Analysis

A power analysis determined that a sample size of 14 alveolar bone measurement sites would be sufficient to detect a difference of 0.3mm at α=.05 for a power of 0.80. Our actual sample size of 31 alveolar bone measurements yielded a power of 0.99.

R software (version 3.1.2) (R Foundation for Statistical Computing, Vienna, Austria) was used for statistical analysis, and Excel® was used to create the Bland-Altman Plot. Intrarater and interrater reliability of FBH measurements made directly and from CBCT images were calculated using concordance correlation coefficients (CCC), Pearson correlation coefficients (PCC), and Intraclass correlation coefficients (ICC). Data from repeated measurements were pooled to calculate mean differences and mean absolute differences.

Comparisons of means, mean differences, and mean absolute differences between measurements from the direct and CBCT measurements were made using 2-tailed paired t-tests (p value set to $\leq$0.05). Agreement between measurements made directly and from CBCT images was assessed with Bland-Altman plots using 95% limits of agreement (LOA; -7.76,3.20)

When determining the validity of dehiscence and fenestration detection on CBCT images, Cohen's Kappa Coefficient with a 95% Confidence Interval was used to assess interrater agreement for dehiscence and fenestration between clinical measurements and each CBCT rater, as well as between CBCT raters.

Results

FBH Measurements

Repeated measurements of the 2-point bow compass caliper marks with a digital sliding caliper showed a mean absolute difference of 0.18mm. Interrater agreement values for the direct and CBCT-derived alveolar FBH measurements are shown in Table 5. For direct measurements, interrater agreement was high with CCC and PCC for both ≥0.98. The mean absolute differences and standard deviations between the two raters' of 0.46±0.35mm. Because of the high agreement, the direct measurements from the two raters were averaged and used for comparison with the CBCT-derived measurements.

For CBCT-derived measurements, intrarater and interrater agreement values were high with CCC and PCC ≥0.98 and ≥0.97, respectfully. The mean absolute difference for pooled CBCT measurements between the first rater and second rater was 0.64±0.77mm.

Comparison of Direct and CBCT FBH Measurements

Compared with direct measurements, measurements from the CBCT images showed larger values. When positive and negative signs were ignored, the mean absolute difference was 2.49±2.61mm ($p<0.0001$). Agreement between CBCT and direct measurements was moderate, with CCC of 0.64 (95% CL 0.45 to 0.77) and PCC of 0.81. The Bland-Altman 95% LOA was -7.76 to 3.20 (Fig 9). Overall, 45% of the CBCT measurements confirmed the direct FBH findings to within 1mm, while 29% of the CBCT measurements confirmed the direct FBH findings to within 0.5mm.

Direct Dehiscence and Fenestration Measurements

Dehiscence and fenestration findings are shown in Tables 8 and 9. Clinically, 58% of teeth were found to have an alveolar bone defect. 89% of these defects were dehiscences and 11% were fenestrations. There was 100% agreement between raters clinically for the detection of dehiscences and fenestrations. Of the 31 teeth examined, for two teeth, one rater did not detect the presence of an alveolar defect on the CBCT. There was also one instance where a fenestration detected clinically was identified as a dehiscence on the CBCT by both raters (due to the fact that the bone coronal to the fenestration was too thin to be detected on the CBCT), and another instance where a dehiscence detected clinically was identified as a fenestration on the CBCT by one rater and as no defect by the other rater. Of the 62 CBCT findings by the two raters combined, there were also five false positives for dehiscences and three false positives for fenestrations.

CBCT Dehiscence and Fenestration Measurements

Interrater reliability for detection of dehiscence and fenestrations was good with Cohen's kappa of 0.653±0.11 (95% CI 0.44 to 0.87). There was agreement between raters 81% of the time.

Comparison of Direct and CBCT Dehiscence and Fenestration Measurements

For each rater, in comparing the direct measurements to CBCT measurements for detecting dehiscences and fenestrations, Cohen's kappa was high (0.76 ±.11 with 95% CI 0.54 to 0.98) and moderate (0.50±.13 with 95% CI 0.26 to 0.75). Overall, CBCT data confirmed direct findings 71% of the time. There was no difference in ability to detect alveolar defects on the CBCT between different tooth types. 100% of the alveolar defects that were not detected on the CBCT were associated with mandibular teeth.

Discussion

This study investigated the accuracy and reliability of measuring FBH made from CBCT images compared to direct measurements taken clinically during surgical procedures involving a mucoperiosteal flaps. Assessment of overall FBH measurement accuracy in this study showed a mean absolute difference between direct clinical and CBCT measurements of 2.49±2.61mm ($p \leq 0.0001$), with a pattern of overestimating the linear distances on CBCT images. In other words, the alveolar bone levels were consistently found to be more apical on the CBCT images. The mean difference and standard deviation are higher than in previously reported studies.

The CCC of 0.64 and PCC of 0.81 for FBH indicated moderate agreement between direct and CBCT measurements. Studies using CBCT scans to measure linear distances in the maxillomandibular region have demonstrated moderate to high accuracy. Comparing physical to CBCT measurements of linear distances on skulls using artificial markers as landmarks, previous studies show a mean difference of 0.0-0.29mm[28,38,48, 85,86]. A study by Lascala et al found mean differences of 1.64-6.59mm over large distances between sites labeled with 2mm diameter pellets when comparing measurements from CBCT images to those made on a dry human skull [27]. However, the only differences that were statistically significant were measurements around the skull base[27]. Overall, these studies tend to support the accuracy of CBCT for linear measurements; however, all were completed over large distances on dry skulls with radiopaque markers to aid in landmark identification. The accuracy of these studies might be overestimated compared to clinical settings because artificial landmarks such as metal spheres or gutta percha points improve visualization during measurements, and because small measurement errors have less of a damaging effect on the accuracy and reliability of measurements over large distances compared to smaller distances. Without radiopaque landmarks, Baumgaertel et al found mean differences in dental linear measurements ranging from 0.01 to 0.89mm, when comparing CBCT to direct measurements[32].

CBCT studies evaluating the accuracy of smaller distances, such as linear measurements of alveolar bone, tend to show more variable results. Using measurements between artificial landmarks on dry skulls or cadaver heads with soft tissue, studies have reported mean measurement errors of 0.22-0.69mm[18,44,45,52,53]. When investigating facial, lingual, and interproximal bone height measurements of simulated osseous defects with gutta percha landmarks on dry skulls, Misch et al demonstrated a mean difference of 0.41±1.19mm[47]. In a similar study using radiopaque markers, Mol and Balasundarum found a mean absolute difference of 1.27±1.43mm between FBH on CBCT images compared to those measured on dry skulls[43]. The current study did not use artificial markers to identify landmarks on the CBCT images, thus a larger mean difference for FBH measurements derived from CBCT images is to be expected.

A number of studies have measured alveolar bone height without artificial landmarks *ex vivo* with varied results. Using traditional CT to assess interproximal bone levels on dry skulls, Fuhrmann found a 0.2mm mean systemic difference in bone height compared to direct measurements[91]. Looking at facial, lingual, and interproximal bone levels on dry skulls and on CBCT images, Fleiner et al found deviations ranging from 0.29mm to 0.46mm[45]. Looking at the FBH of all teeth, Timock et al and Cook et al found mean absolute differences of 0.30±0.27 and 0.41±0.32[49,50]. Sun et al measured alveolar bone height around maxillary molars and found differences of 0.9 to 1.2mm when the bone thickness was near the 0.4mm voxel size[39]. Looking at the FBH of mandibular anterior teeth on cadavers with soft tissue, Patcas et al found mean differences of 0.13mm but the limits of agreement showed discrepancies up to 2.1mm[51]. Wood et al studied FBH of molars on porcine cadavers and found differences near zero[40]. Leung found a difference of 0.6±0.8mm when measuring FBH cusp tip to bone margin on CBCT images and dry skulls[42]. Lund evaluating facial, lingual, and interproximal bone levels on dry skulls found a bone height difference of 0.04±0.54mm[88]. Overall, these studies had smaller mean differences then the 2.49±2.61mm mean difference that the current study found. An important consideration to take into account is that many of these studies grouped facial, lingual, and interproximal alveolar bone measurements together. Because the ability to accurately measure interproximal bone levels may be different than the ability to measure facial or lingual alveolar bone measurements, these mean differences may not be representative of the accuracy of FBH. Additionally, certain factors are introduced when studying live patients that can increase sources of error or diagnostic difficulty, and artificial radiopaque landmarks, which improve visualization, are not found in clinical settings.

There have been very few studies completed *in vivo* comparing the accuracy of FBH from direct measurements to measurements from CBCT images. Naito et al. conducted an *in vivo* study measuring sites of periodontal breakdown with a periodontal probe to the CEJ after flap surgery and compared these to CT measurements[89]. The results showed that the mean difference between CT and the true bone level was 0.41±2.53 mm with a correlation of 0.75. Pistorius et al conducted a similar study, without a flap reflected, comparing sites of periodontal breakdown using a periodontal probe to measure from alveolar bone to the CEJ in comparison to measurements derived from a CT image[61]. They found the clinical mean probing depths to have a mean value of 2.6±2.0mm while the CT measurements exhibited a mean value of 4.2±2.3mm. The study also demonstrated high variability, with 49.5% of the sites having a difference greater than 2mm with greatest differences found on the facial and lingual sites (P=0.0004)[61]. Feijo studying the FBH of molars and Grimard studying interproximal bone levels, reported standard errors of 0.58±0.39mm and 0.9±0.8mm respectively when comparing direct measurements to those from CBCT images[57,58]. These studies generally show increased variability compared to *ex* vivo studies, and have results closer to the results of the current study. However, in all these studies clinical measurements using a periodontal probe were rounded to the nearest millimeter. Periodontal probes are known to show greater variability at increased depths and at different angles, and have been shown to be reliable to ±1mm[82]. Therefore, these studies reported submillimeter accuracies with clinical measurements that were accurate to only ±1mm. The current study used a two point 6'' bow compass caliper to be able to measure the direct FBH to submillimeter accuracy as shown by our repeat measurement error analysis showing 0.18mm.

When defining accuracy in terms of clinical measurement, a certain discrepancy between actual bone level and estimated bone level on radiographs has to be considered as clinically acceptable. Considering that a 0.5-1mm discrepancy in bone height can be seen clinically[13], this level of accuracy could be considered acceptable radiographically. In another approach, Waitzmann et al studied conventional CT accuracy and indicated that measurement error in craniofacial imaging within 5% is clinically acceptable[87]. In this study, a 20% measurement error was found when comparing clinical measurements to the mean difference in FBH between CBCT and clinical measurements. Overall, 45% of the CBCT measurements confirmed the direct FBH findings to within 1mm and 29% of the CBCT measurements confirmed the direct FBH findings to within 0.5mm. Thus, a 0.5-1mm level of accuracy was not obtained, nor was a 5% level of error achieved for a majority of measurements in this study, suggesting caution should be used when interpreting CBCT measurements for FBH.

Several studies have noted a pattern of over- or underestimation of bone loss by the CBCT images compared to direct measurements. When comparing over- or underestimation results from different studies, it is important to pay attention to the measurement methodology. For example, CBCT linear measurements that show an overerestimation in distance compared to the direct measurements could show an over- or underestimation of alveolar bone depending on how the measurements were taken. Underestimation of the real anatomic truth of alveolar bone by the CBCT has been shown in studies by Lascala et al[27], Baumgaertel et al[32], Pinsky et al[38], Sun et al[39], Leung et al[42], Patcas et al[51], Grimard et al[58], Stratemann et al[86], and Fuhrmann et al[91]. These underestimations of the actual bone level range from 0.2-1.2mm. An overestimation of bone levels from the CBCT has been shown much less frequently[43,44,47], and show a smaller range of 0.23-0.41mm. The results of the current study agreed with the results from the majority of previous studies, showing a consistent underestimation of bone levels by the CBCT by an average of around 2.5mm. It should also be noted that some studies did not find a pattern of over or underestimation[28,40,48, 49, 52,91].

The results from this study confirmed our hypothesis that CBCT measurements associated with specific teeth with thin facial alveolar bone would have decreased accuracy compared to direct measurements. The current study showed mandibular anterior teeth to have the least accurate FBH measurements with a mean error of 3.8±2.2mm for mandibular incisors and 2.9±3.7mm for mandibular canines, relative to the overall mean error of 2.49±2.61mm for the FBH of all teeth (Table 10). Results from previous studies are consistent with these findings. Wood et al found that the accuracy of measurements facial to the maxillary molars, where cortical bone is known to be thinner, was inferior to those made facial to the mandibular molars, where the cortical bone is known to be thicker[40]. Mol and Balasundarum's study found a statistically significant decrease in accuracy for FBH measurements of mandibular anterior teeth[43]. Patcas et al found limits of agreement of 2.1mm for the FBH in the mandibular incisor region, indicating variability in accuracy[51].

Because direct *in vivo* measurements were used as the standard from which to evaluate overall CBCT accuracy and reliability, it was important to have high confidence in the direct measurement values. The mean absolute differences and standard deviations between the 2 raters' direct FBH measurements was 0.46±0.35mm, with PCC and ICC both > 0.98. These indices showed very high interrater agreement and support the appropriateness of the direct measurement technique used, creating a reliable standard from which to evaluate the CBCT measurements. High correlation coefficients using this protocol have previously been demonstrated, further justifying our use of the direct measurements as a control[49,50].

Repeated CBCT and direct measurements by 2 investigators allowed assessment of both intrarater and interrater reliabilities, minimized possible biases associated with specific investigators, and allowed for better precision and accuracy of the measurements by minimizing reproducibility errors. Previous studies have reported high intrarater reliability, with ICC ranging from 0.75 to nearly 1 for linear measurements derived from CBCT images[32,38,42,49,50,55], and 0.89-0.99 for direct linear measurements on fresh porcine[39], fresh cadaver[50,52], or dry human skulls[42]. The results from the current study are similar, having an ICC of ≥0.98 for both direct FBH measurements and CBCT FBH measurements. For interrater reliability, our CBCT values showed an average absolute difference of 0.64±0.77mm for FBH. This difference is equivalent to two voxels, as used in the scan settings. Several studies have used multiple examiners to analyze interrater reliability with direct and CBCT measurements, finding an ICC range of 0.95-0.99[40,49] and 0.73 to 0.999 respectively[39,47,49,50,55,64]. In this study, we showed comparable, high interrater reliability with a CCC of ≥0.98 and ≥0.97 for facial bone height measured directly and on CBCT images respectively.

A number of studies have investigated the interexaminer differences for clinical periodontal measurements, such as probing depths and attachment loss, and mean differences of 0.2-1.0mm have been found[68-83]. The mean differences between raters for both clinical and CBCT measurements in this study are larger than those reported by Timock et al and Cook et al[49.50]. The small amount of mean difference, 0.46mm and 0.64mm, found between raters within this study for direct measurements and CBCT measurements respectively, is attributable mainly to human error. For direct measurements, this may be due to maneuverability of the measuring device in patients with a shallow vestibule, strong oro-facial musculature, or limited mandibular opening, ability to distinguish the alveolar bone when bleeding is present, and identifying the mesiodistal center of the cusp tip or incisal edge of the tooth measured. The thinner 6" bow compass caliper, compared to the bulkier digital caliper used in previous studies, was selected to improve the measurement accuracy in *in vivo* conditions[49,50,93]. In CBCT images, the ability to distinguish the very thin bone and the root of the tooth can be difficult. Voxel size and bone quality play smaller roles as well[22].

A secondary aim of this study was to evaluate CBCT accuracy in detecting facial alveolar dehiscences and fenestrations. There have only been a few studies that have evaluated the ability of CBCT images to detect alveolar dehiscences and fenestrations around teeth, and most have been performed on dry porcine and human skulls. The results from these studies have been variable. Mengel et al created dehiscences and fenestrations of standardized size on dry porcine and human skulls, and reported that 100% of alveolar defects were identifiable on the CBCT[18]. However, this study used gutta percha markers to aid visualization and the defects were artificially created with sharp bone boundaries that could have improved the detection of the defects on CBCT compared to if they had contoured the defects to mimic the gradual thinning of bone found in naturally occurring dehiscences and fenestrations. Misch et al also looked at artificial dehiscences on dry human skulls and also reported that all defects were identifiable on CBCT images[47]. Similarly, Pinsky et al identified bony defects and cavitations on dry human mandibles and acrylic blocks, but again, these were artificially created[38]. Leung et al looked at over 300 teeth to determine CBCT imaging accuracy and reliability in diagnosing naturally occurring fenestrations and dehiscences. They found that three times more fenestrations were detected on the CBCT than were actually present on the skulls. Furthermore, more than half of the dehiscences present clinically were not detected on the CBCT[42]. Kamburoğlu et al created artificial periodontal defects of standardized sizes in dry mandible skulls around premolars and molars and found an interobserver kappa of 0.189-1 among 6 observers with an overall 42% chance of detecting a periodontal defect[55]. In a study of labial-lingual bony dimensions by Fuhrmann, 80% of the dehiscences were identified in the area of the mandibular incisors. [87]. Fuhrmann et al also conducted a series of studies using 33 CT scans to study dehiscences, labial-lingual bone width, and orthodontic treatment effects. Seventy percent of the 60 artificially made dehiscences could be identified on the scans using the multiplanar sections[91]. Overall, depending on the study methodology, 42-100% of dehiscences and fenestrations have been detectable on CT or CBCT. In this study, CBCT confirmed 71% of the direct clinical findings. With regard to our hypothesis on the ability to detect alveolar defects around teeth with varying thicknesses of alveolar bone, this study did not find a pattern of decreased ability to detect a dehiscence or fenestration in specific areas of the mouth. Thus this hypothesis was rejected. This study found detection issues associated with all tooth types where an alveolar defect noted clinically was not identified on the CBCT image. However, due to the small sample size for various teeth, further clinical investigation with more teeth in each tooth category are needed to confirm these results.CBCT imaging provides for the use of isotrophic voxels ranging from 0.07 to 0.4mm, allowing the practitioner to visualize and measure the craniofacial complex in great detail[22]. It has been common practice for clinicians to assume the high definition images produced by the CBCT are inherently accurate to the submillimeter voxel size used. Although Bryant et al found the i-CAT CBCT machine to have an accuracy of ±1 voxel[92], according to Molen, this is not actually the case. Molen states that it is important to also consider spatial resolution, noise, artifacts, and partial volume averaging, which combined make accuracy to the voxel size impossible[56]. Sun et al, Wood et al, and Cook et al found that decreasing the CBCT voxel size could improve the accuracy of alveolar bone linear measurement from CBCT images[39,40,50]. However, it is also important to consider other technical parameters when comparing CBCT studies, as well as the risk-benefit relationship of increased radiation dosage to the patient with decreased voxel size.

Measuring alveolar bone height and identifying alveolar defects requires identification of selected landmarks on the CBCT image. Most studies have measured between the alveolar bone margin (ABM) and CEJ. The CEJ is the intersection of two different structures, enamel and cementum, with two different densities. On the CBCT, this landmark can be difficult to identify, evidenced by the many studies that have attempted to increase the accuracy of the study by placing a radiopaque fiducial landmark at the CEJ[43,47]. Clinically, patients do not have a radiopaque landmark at the CEJ; thus use of artificial landmarks was avoided in the current study. The second landmark identified is the ABM. This landmark has an even lower difference in contrast between two materials: bone and cementum. The similarity in radiographic density is due to the similar hydroxyapatite content of bone and cementum. Cementum has 45-50% hydroxyapatite, and bone has 65%[66]. This low contrast similarity can lead to the partial volume averaging effect, which is an artifact that occurs when a voxel lies on 2 objects of different densities causing the voxel on CBCT images to reflect the average density of both objects rather than the true value of either object. Because of the partial volume averaging effect, a thin layer of alveolar bone with a thickness near or below the voxel size of the CBCT images can become indistinguishable from the adjacent periodontal ligament and fail to be visualized as bone when taking alveolar bone-height measurements[56]. A few studies, including the current study, measured from the cusp tip or incisal edge of the tooth to the ABM. Locating the cusp tip rather than the CEJ allows a landmark to be identified in a high contrast setting because air and tooth enamel have vastly different densities. On the other hand, the bone margin remains a difficult landmark to accurately detect. Not only is the ABM a low contrast area, but it can also have a broad thickness that makes selecting the landmark difficult.

Contrast resolution determines the ability to distinguish between 2 objects of similar densities and in close proximity[22]. Using a high-contrast line-pair phantom, Ballrick et al examined this aspect of the iCAT system and found that a minimum distance of 0.86mm is required for clear distinction between 2 metal plates of the same density[94]. Anatomically, the alveolar bone is separated from the cementum by the .05mm thick periodontal ligament, which is smaller than this minimum distance requirement, suggesting that the alveolar bone is likely to become indistinguishable from the cementum. Leung et al and Fuhrmann et al also examined the ability to distinguish alveolar bone from cementum and found that areas with bone less than 0.6mm and 0.5mm thick, respectively, were invisible on CBCT images[42,87].

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 controls the amount of x-rays that will be produced at a target area, which in turn, controls the density or darkness of the image[96]. The effect of mA on image quality has been studied extensively. When a lower mA setting is used, there is a loss of contrast resolution. Misch et al and Pinsky et al reported that all operator created dehiscences and fenestrations were detectable using 47.7 mA, 120 kVp, 20 second and 98 mA, 120 kVp, and 20 second scanning parameters respectively[47,38]. Lascala et al 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[27].The scanning parameters used in this study were 5 mA and 120 kVp,which is less than the mA values used by Misch et al, Pinsky et al, and Lascala et al. Interestingly, the CBCT FBH measurements in the current study were more variable and 71% of alveolar defects were detected, compared to 100% by Misch et al and Pinsky et al . Leung et al reported less accuracy in detecting bony dehiscences and fenestrations then the current study, and used scan setting of 110 kVp, 2 mA, 9.6 s, 12 in FOV, and 0.38 mm voxel[42].

With the examination of live individuals, the effect of cell water content must be taken into account when assessing the accuracy of the CBCT images. The addition of water, compared to a dry human skull, increases the tissue attenuation of the X-ray photons[93]. CBCT image quality on live patients is further decreased by the presence of soft tissue, which creates a range of contrast that can make landmark identification difficult, and possible patient movement during scanning. An *in vivo* study is an improvement to past studies assessing the accuracy and reliability of CBCT imaging for measuring alveolar bone, but there are limitations. In this study, CBCT raters were allowed to adjust for density and contrast before measuring, as most practitioners in a clinical setting would do. Ising et al evaluated this factor by measuring bone levels on dehiscences at different density values and found no difference between raters[52]; thus this protocol used in our study was justified. A second factor is that we pooled our sample with a pilot study done by Miller for a larger sample size[93]. All protocols were the same, except that Miller et al used a digital sliding caliper rather than a 6'' bow caliper compass to measure the teeth intraorally. Thus, eleven measurements included in this study were measured using a digital sliding caliper where the other twenty measurements were measured using a 6'' bow compass caliper. Specifications for the digital sliding caliper indicate that it is accurate to 0.1mm and repeated measurements done to assess the validity of the 6'' bow compass caliper found a mean difference of 0.18mm. Both of these devices have levels of error less than the 0.3mm voxel size used, thus they can be considered accurate for this study. A third limiting factor is the expertise of the CBCT raters. Although both raters had been calibrated on the measurement protocol, the investigators had limited training working with CBCT images. It would be interesting to see if studies using experienced radiographers completing the same measurements would find different results. A fourth point is that our patient population was older and periodontally compromised. Although this was beneficial to studying thin facial bone and alveolar defects for this study, and although previous studies have shown that there is no difference in age for the prevalence of dehiscences and fenestrations in a population[64,65], caution should be used when interpreting this data across different populations, such as adolescent orthodontic patients. Finally, a potential issue in this study was the difficulty in differentiating alveolar dehiscences from horizontal bone loss. Our protocol stated that if the facial alveolar bone margin was greater than 3mm from the CEJ in three consecutive CBCT slices, there was a dehiscence. This protocol was derived from several studies that have previously studied the presence or absence of a dehiscence[54,91].

Nevertheless, it is possible that for some dehiscences detected on the CBCT, the defect could be related to horizontal bone loss.

This study found that it is important to exercise caution when using the CBCT images to interpret facial alveolar bone measurements as the technology tends to underestimate the height of the bone. Although obtaining scans with higher resolution using a smaller voxel size would give a more accurate depiction of the facial alveolar bone[50], it is important for clinicians to weigh the balance between diagnostic need and radiation exposure in order to optimize imaging strategies for specific assessments. In consideration of the ALARA principle, perhaps through use of highly reduced fields of view, future studies should be conducted to determine the value of more ideal CBCT exposure settings aimed at optimizing assessments of periodontal defects.

Conclusions

For the protocol used in this study:

1. Facial alveolar bone height levels were underestimated in CBCT images, especially in areas where alveolar bone is known to be thin.
2. Approximately 30% of alveolar defects involving dihescences and fenestrations were not detected in CBCT images.

References

1. Zachrisson BU, Alnaes L. Periodontal condition in orthodontically treated and untreated individuals. II . Alveolar bone loss: radiographic findings. Angle Orthod 1974;44:48-55.
2. Wehrbein H, Bauer W, Diedrich P. Mandibular incisors, alveolar bone, and symphysis after orthodontic treatment. A retrospective study. Am J Orthod Dentofacial Orthop 1996;110:239-46.
3. Karring T, Nyman S, Thilander B, Magnusson I. Bone regeneration in orthodontically produced alveolar bone dehiscences. J Periodontal Res 1982;17:309-15.
4. Wainwright WM. Faciolingual tooth movement: its influence on the root and cortical plate. Am J Orthod 1973;64:278-302.
5. Garib DG, Henriques JF, Janson G, de Freitas MR, Fernandes AY. Periodontal effects of rapid maxillary expansion with tooth-tissue-borne and tooth-borne expanders: a computed tomography evaluation. Am J Orthod Dentofacial Orthop 2006;129:749-58.
6. Sarikaya S, Haydar B, Ciger S, Ariyurek M. Changes in alveolar bone thickness due to retraction of anterior teeth. Am J Orthod Dentofacial Orthop 2002;122:15-26.
7. Ericsson I, Thilander B, Lindhe J, Okamoto H. The effect of orthodontic tilting movements on the periodontal tissues of infected and non-infected dentitions in dogs. J Clin Periodontol 1977;4:278-93.
8. Rungcharassaeng K, Caruso JM, Kan JYK, Taylor G. Factors affecting buccal bone changes of maxillary posterior teeth after rapid maxillary expansion. Am J Orthod Dentofacial Orthop 2007; 132:428.e1-428.e8.

9. Steiner GG, Pearson JK, Ainamo J. Changes of the marginal periodontium as a result of labial tooth movement in monkeys. J. Periodontol. 1981;52:314-320.
10. Handelman CS. The anterior alveolus: its importance in limiting orthodontic treatment and its influence on the occurrence of iatrogenic sequelae. Angle Orthod. 1996;66:95-109; discussion 109-110.
11. Allais D, Melsen B. Does labial movement of lower incisors influence the level of the gingival margin? A case-control study of adult orthodontic patients. Eur J Orthod 2003;25:434-52.
12. Karring T, Nyman S, Thilander B, Magnuisson I. Bone regeneration in orthodontically produced alveolar bone dehiscences. J Periodontal Res 1982;17:309-15.
13. Mol A. Imaging methods in periodontology. Periodontal 2000; 34:34-48.
14. Akesson L, Håkansson J, Rohlin M Comparison of panoramic and intraoral radiography and pocket probing for the measurement of the marginal bone level. J Clin Periodontol 1992;19:326–332.
15. Jeffcoat MK, Wang IC, Reddy MS. Radiographic diagnosis in periodontics. Periodontol 2000. 1995;7:54-68.
16. Lang NP, Hill RW. Radiographs in periodontics. J Clin Periodontol 1977;4:16-28.
17. Rees TD, Biggs NL , Collings CK. Radiographic interpretation of periodontal osseous lesions. Oral Surg Oral Med Oral Pathol 971;32:141-53.
18. Mengel R, Candir M, Shiratori K, Flores-de-Jacoby L. Digital colume tomography in the diagnosis of periodontal defects: An in vitro study on native pig and human mandibles. J Periodontal Res 1991; 26:527-529.

19. Löst C. Depth of alveolar bone dehiscences in relation to gingival recessions. J. Clin. Periodontol. 1984;11:583-589.

20. Kalender W. X-ray computed tomography. Phys Med Biol 2006; R29-R43.
21. Mozzo P, Procacci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. Eur Radiol 1998;8:1558-64.
22. Scarfe WC, Farman AG. What is cone-beam CT and how does it work? Dent Clin North Am 2008;52:707-30.
23. Adams GL, Gansky SA, Miller AJ, Harrell WE, Hatcher DC. Comparison between traditional 2-dimensional cephalometry and a 3-dimensional approach on human dry skulls. Am J Orthod Dentofacial Orthop 2004;126:397-409.
24. Gribel BF, Gribel MN, Frazão DC, McNamara JA, Manzi FR. Accuracy and reliability of craniometric measurements on lateral cephalometry and 3D measurements on CBCT scans. Angle Orthod. 2011;81:26-35.
25. Braun X, Riter L, Jervøe-Storm PM, Frentzen M. Diagnostic accuracy of CBCT for periodontal lesions. Clin Oral Invest. 2014;18:1229-1236.
26. de Faria Vasconcelos K, Evangelista KM, Rodrigues CD, Estrela C, de Sousa TO, Silva MAG. Detection of periodontal bone loss using cone beam CT and intraoral radiography. Dentomaxillofacial Radiology. 2012;41:64-69.
27. Lascala CA, Panella J, Marques MM. Analysis of the accuracy of linear measurements obtained by cone beam computed tomography (CBCT-NewTom). Dentomaxillofacial Radiol 2004; 33:291-294.

28. Berco M, Rigali, Jr. PH, Miner RM, DeLuca S, Anderson NK, Will LA. Accuracy and reliability of linear cephalometric measurements from cone-beam computed tomography scans of a dry human skull. Am J Orthod Dentofacial Orthop 2009; 136:17.e1-17.e9.

29. Hilgers ML, Scarfe WC, Scheetz JP, Farman AG. Accuracy of linear temporomandibular joint measurements with cone beam computed tomography and digital cephalometric radiography. Am J Orthod Dentofacial Orthop 2005; 128:803–811.

30. Moshiri M, Scarfe WC, Hilgers ML, Scheetz JP, Silveira AM, Farman AG. Accuracy of linear measurements from imaging plate and lateral cephalometric images derived from cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2007; 132:550–560.

31. Benninger B, Peterson A, Cook V. Assessing validity of actual tooth height and width from cone beam images of cadavers with subsequent dissection to aid oral surgery. J Oral Maxillofac Surg. 2012;70:302-306.

32. Baumgaertel S, Paloma JM, Paloma L, Hans MG. Reliability and accuracy of cone-beam computed tomography dental measurements. Am J Orthod Dentofacial Orthop 2009; 136:19-28.

33. Cortes ARG, de Arruda Monteiro Gomes AF, Pereira de Sousa e Tuncunduva MOA, Arita ES. Evaluation of linear tomography and cone beam computed tomography accuracy in measuring ridge bone width for planning implant placement. Braz J Oral Sci. 2012;11(2):116-119.

34. Chen LC, Lundgren T, Hallström H, Cherel F. Comparison of different methods of assessing alveolar ridge dimensions prior to dental implant placement. J Periodontol 2008;79:401-5.

35. Moshfeghi M, Tavakoli MA, Hosseini ET, Hosseini AT, Hosseini IT. Analysis of linear measurement accuracy obtained by cone beam computed tomography (CBCT-NewTom VG). Dent Res J. 2012;9(Suppl 1):S57-S62.
36. Gracco A, Lombardo L, Cozzani M, Siciliani G. Quantitative cone-beam computed tomography evaluation of palatal bone thickness for orthodontic miniscrew placement. Am J Orthod Dentofacial Orthop 2008;134:361-9.
37. Chien P, Parks E, Eraso F, Hartsfield J, Roberts W, Ofner S. Comparison of reliability in anatomical landmark identification using two-dimensional digital cephalometrics and three-dimensional cone beam computed tomography in vivo. Dentomaxillofac Radiol 2009;38:262-73
38. Pinsky HM, Dyda S, Pinsky RW, Misch KA, Sarment DP.Accuracy of three-dimensional measurements using cone-beam CT. Dentomaxillofac Radiol 2006;35:410-6.
39. Sun Z, Smith T, Kortam S, Kim DG, Tee BC, Fields H. Effect of bone thickness on alveolar bone-height measurements from cone-beam computed tomography images. Am J Orthod Dentofacial Orthop 2011;139:e117-e127.
40. Wood R, Sun Z, Chaudhry J, Tee BC, Kim D, Leblebicioglu B, England G. Factors affecting the accuracy of buccal alveolar bone height measurements from cone-beam computed tomography images. Am J Orthod Dentofacial Orthop 2013;143:353-63.
41. Razavi T, Palmer RM, Davies J, Wilson R, Palmer PJ. Accuracy of measuring the cortical bone thickness adjacent to dental implants using cone beam computed tomography. Clin Oral Impl Res 2010;21:718-725.
42. Leung CC, Palomo L, Griffith R, Hans MG. Accuracy and reliability of cone-beam computed tomography for measuring alveolar bone height and detecting bony

dehiscences and fenestrations. Am J Orthod Dentofacial Orthop 2010;137(Suppl):S109-19.

43. Mol A, BalasundaramA. In vitro cone beam computed tomography imaging of periodontal bone. Dentomaxillofac Radiol 2008;37:319-24.
44. Vandenberghe B, Jacobs R, Yang J. Detection of periodontal bone loss using digital intraoral and cone beam computed tomography images: an in vitro assessment of bony and/or infrabony defects. Dentomaxillofac Radiol 2008;37:252-60.
45. Fleiner J, Hannig C, Schulze D, Stricker A, Jacobs R. Digital method for quantification of circumferential bone level using cone beam CT. Clin Oral Invest 2013;17:389-396.
46. Fang D, Jiang H, Lin Z. Evaluation of the accuracy of alveolar bone height measurement in vitro by cone beam computed tomography. Hua Xi Kou Qiang Yi Xue Za Zhi. 2012;30(6):603-6.
47. Misch KA, Yi ES, Sarment DP. Accuracy of Cone Beam Computed Tomography for Periodontal Defect Measurements. J Periodontology July 2006;77:1261-1266.
48. Loubele M, Guerrero M, Jacobs R, Suetens P, van Steenberghe D. A comparison of jaw dimensional and quality assessments of bone characteristics with cone-beam CT, spiral tomography, and multi-slice spiral CT. Int J Oral Maxillofac Implants 2007;22:446-54.
49. Timock A, Cook VC, McDonald T, Leo MC, Crowe J, Major PW. Accuracy and reliability of buccal bone height and thickness measurements from cone-beam computed tomography imaging. Am J Orthod Dentofacial Orthop 2011;140:734-44.
50. Cook VC. Accuracy of alveolar bone measurements from cone beam computed tomography at multiple parameters. Master's thesis, Oregon Health & Science University 2011.

51. Patcas R, Müller L, Ullrich O, Peltomäld T. Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth. Am J Orthod Dentofacial Orthop 2012;141:41-50.
52. Ising N, Kim KB, Araujo E, Buschang P. Evaluation of dehiscences using cone beam computed tomography. Angle Orthod. 2012;82:122-130.
53. Kobayashi K, Shimoda S, Nakagawa Y, Yamamoto A. Accuracy of distance using limited cone-beam computerized tomography. Int J Oral Maxillofac Implants 2004; 19:228-231.
54. Mostafa YA, El Sharaby FA, El Beialy AR. Do alveolar bone defects merit orthodontists' respect? World J Orthod 2009;10:16-20.
55. Kamburoğlu K, Kiliç C, Özen T, Yüksel SP. Measurements of mandibular canal region obtained by cone-beam computed tomography: a cadaveric study. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009;107:e34-42.
56. Molen AD. Considerations in the use of cone-beam computed tomography for buccal bone measurements. Am J Orthod Dentofacial Orthop 2010;137:S130-5.
57. Feijó CV, Feitosa de Lucena JG, Kurita LM, Pereira SLDS. Evaluation of conebeam computed tomography in the detection of horizontal periodontal bone defects: an in vivo study. Int J Periodontics Restorative Dent 2012;32:e162-e168.
58. Grimard BA, Hoidal MJ, Mills MP, Mellonig JT, Nummikoski PV, Mealey BL. Comparison of clinical, periapical radiograph, and cone-beam volume tomography for assessing bone level changes following regenerative periodontal therapy. J Periodontol 2009; 80:48-55.

59. Walter C, Kaner D, Berndt DC, Weiger R, Zitzmann NU. Three-dimensional imaging as a pre-operative tool in decision making for furcation surgery. J Clin Periodontol 2009;36:250-257.

60. Mohan R, Mark R, Sing I, Jain A. Diagnostic accuracy of CBCT for aggressive periodontitis. J Clin Imag Sci. 2014;4(2):1-5.

61. Pistorius A, Patrosio C, Willershausen B, Mildenberger P, Rippen G. Periodontal probing in comparison to diagnosis by CT-scan. Int Dent J. 2001;51:339-347.

62. Qiao J, Wang S, Duan J, Zhang Y, Qiu Y, Sun C, Liu D. The accuracy of cone-beam computed tomography in assessing maxillary molar furcation involvement. J Clin Periodontol. 2014;41:269-274.

63. Elliott GM, Bowers GM. Alveolar dehiscences and fenestrations. Periodontics 1963:1:245-248.

64. Larato DC. Alveolar plate fenestration and dehiscences of the human skull. Oral Surg Oral Med Oral Pathol. 1970;29(6):816-9.

65. Edel A. Alveolar bone fenestrations and dehiscences in dry Bedouin Jaws. J Clin Periodontol 1981:8:491-499.

66. Enhos S, Uysai T, Yagci A, Veli I, Ucar FI, Ozer T. Dehiscence and fenestration in patients with different vertical growth patterns assessed with cone beam computed tomography. Angle Orthod. 2012;82(5):868-74.

67. Carranza. The tooth-supporting structures. Clinical periodontology. 9th ed. Philadelphia: W.B. Saunders; 2002.

68. Suomalainen A, Vehmas T, Kortesniemi M, Robinson S, Peltola J. Accuracy of linear

measurements using dental cone beam and conventional multislice computed tomography. Dentomaxillofac Radiol 2008;37:10–7.

69. Hassell TM, Germann MA, Saxer UP. Periodontal probing: Interinvestigator discrepancies and correlations between probing force and recorded depth. Helv Odontol Acta. 1973;17:38-42.
70. van der Velden U, de Vries IH. Introduction of a new periodontal probe: The pressure probe. J Clin Periodontol 1978;5:188-197.
71. van der Velden U, de Vries IH. The influence of probing force on the reproducibility of pocket depth measurments. J Clin Periodontol. 1980;7:414-420.
72. Watts TLP. Constant force probing with and without a stent in untreated periodontal disease: The clinical reproducibility problem and possible sources of error. J Clin Periodontol. 1987;14:407-411.
73. Watts TLP. Probing site configuration in patients with untreated periodontitis. J Clin Periodontol. 1989; 16:529-533.
74. McCulloch CAG, Birek P, Hardy V. Comparison of gingival attachment level measurements with an automated periodontal probe and a pressure-sensitive probe. J Periodont Res. 1987;22:348-352.
75. Gibbs CH, Hirschfeld IW, Lee JG, Low SB, Magnusson I, Thousand RR, et al. Description and clinical evaluation of a new computerized periodontal probe-the Florida Probe. J Clin Periodontol. 1988;15:137-144.
76. Goodson IM, Kondon N. Periodontal pocket depth measurements by fiber optic technology. J Clin Dent. 1988;1:35-38.

77. Magnusson I, Fuller WW, Heins PJ, Rau CF, Gibbs CH, Marks RG, et al. Correlation between electronic and visual readings of pocket depths with a newly developed constant force probe. J Clin Periodontol. 1988a; 1 5:180-184.

78. Magnusson I, Clark WB, Marks RG, Gibbs CH, Manouchehr-Pour M, Low SB. Attachment level measurements with a constant force electronic probe. J Clin Periodontol. 1988a;15:185-188.

79. Osborn JB, Stoltenberg IL, Huso BA, Aeppli DM, Pihlstrom BL. Comparison of measurement variability using a standard and constant force periodontal probe. J Periodontol. 1990;61:497-503.

80. Osborn IB, Stoltenberg IL, Huso BA, Aeppli DM, Pihlstrom BL. Comparison of measurement variability in subjects with moderate periodontitis using a conventional and constant force periodontal probe. J Periodontol. 1992;63:283-289.

81. Becherer CF, Rateitschak KH, Hefti AF. Vergleichende Sondierung mit einer elektronischen und einer manuellen Parodontalsonde. Schweiz Monatsschr Zahnmed. 1993;103:715-721.

82. Tupta-Veselicky L, Famili P, Ceravolo Fl, Zullo T. A clinical study of an electronic constant force periodontal probe. J Periodontol. 1994;65:616-622.

83. Wang SF, Leknes KN, Zimmerman GJ, Sigurdsson TJ, Wikesjö UM, Selvig KA. Reproducibility of periodontal probing using a conventional manual and an automated force-controlled electronic probe. J Periodontol 1995; 66:38-46.

84. Mayfield L, Bratthall G, Attstrom R. Periodontal probe precision using 4 different periodontal probes. J Clin Periodontol. 1996;23:76-82.

85. Mischkowski RA , Pulsfort R, Ritter L, Neugebauer J, Brochhagen HG, Keeve E, et al

Geometric accuracy of a newly developed cone-beam device for maxillofacial imaging. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2007;104:551-9.

86. Stratemann SA, Huang JC, Maki K, Miller AJ, Hatcher DC. Comparison of cone beam computed tomography imaging with physical measures. Dentomaxillofac Radiol 2008;37:80-93.

87. Fuhrmann R. Three-dimensional interpretation of labiolingual bone width of the lower incisors. Part II. J Orofac Orthop. 1996;57:168-185.

88. Lund H, Gröndahl K, Gröndahl HG. Cone beam computed tomography for assessment of root length and marginal bone level during orthodontic treatment. Angle Orthod. 2010;80:466-473.

89. Naito T, Hosokawa R, Yokota M. Three-dimensional alveolar bone morphology analysis using computed tomography. J. Periodontol. 1998;69:584-589

90. Waitzman A, Posnick J, Armstrong D, Pron G. Craniofacial skeletal measuremens based on computed tomography: part I. accuracy and reproducibility. Cleft Palate-Craniofacial Journal.1992;29(2):112-7.

91. Fuhrmann R. Three-dimensional interpretation of alveolar bone dehiscences. An anatomical-radiological study--Part I. J Orofac Orthop. 1996;57:62-74.

92. Bryant JA, Drage NA, Richmond S. Study of the scan uniformity from an i-CAT cone beam computed tomography dental imaging system. Dentomaxillofac Radiol. 2008;37:365-374.

93. Miller M. Accuracy of cone beam computed tomography in measuring alveolar bone height and detecting dehiscences and fenestrations in patients undergoing periodontal surgery. Master's thesis, Oregon Health & Science University 2011.

94. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available conebeam computed tomography machine. Am J Orthod Dentofacial Orthop 2008;134:573-82
95. Fosbinder Robert and Orth Denise. Essentials of Radiologic Science. Wolters Kluwer /Lippincott Williams & Wilkins; 2012.

Figure Legends

Figure 1. Participant Screening Protocol

Figure 2. Illustration of the 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 facial bone height (green arrow) will be made in the sagittal plane from the incisal edge (or the facial cusp tip) to the alveolar bone crest[49]”

Figure 3. Dehiscence detection protocol: “at least three sequential views (A indicates cement-enamel junction; B, bone level)[97]”

Figure 4. Fenestration detection protocol: “at least three sequential views (A indicates bone; B fenestration area/cement of the root)[97]”

Figure 5. Illustrations of the direct measurement protocol: **A** and **B**, facial bone height (green arrow) measured from the incisal edge or the facial cusp tip to the alveolar crest following the long axis of the tooth; **C**, when a tooth is rotated, the mesiodistal locations for facial bone height and facial 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)[49]”; **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).

Figure 1.

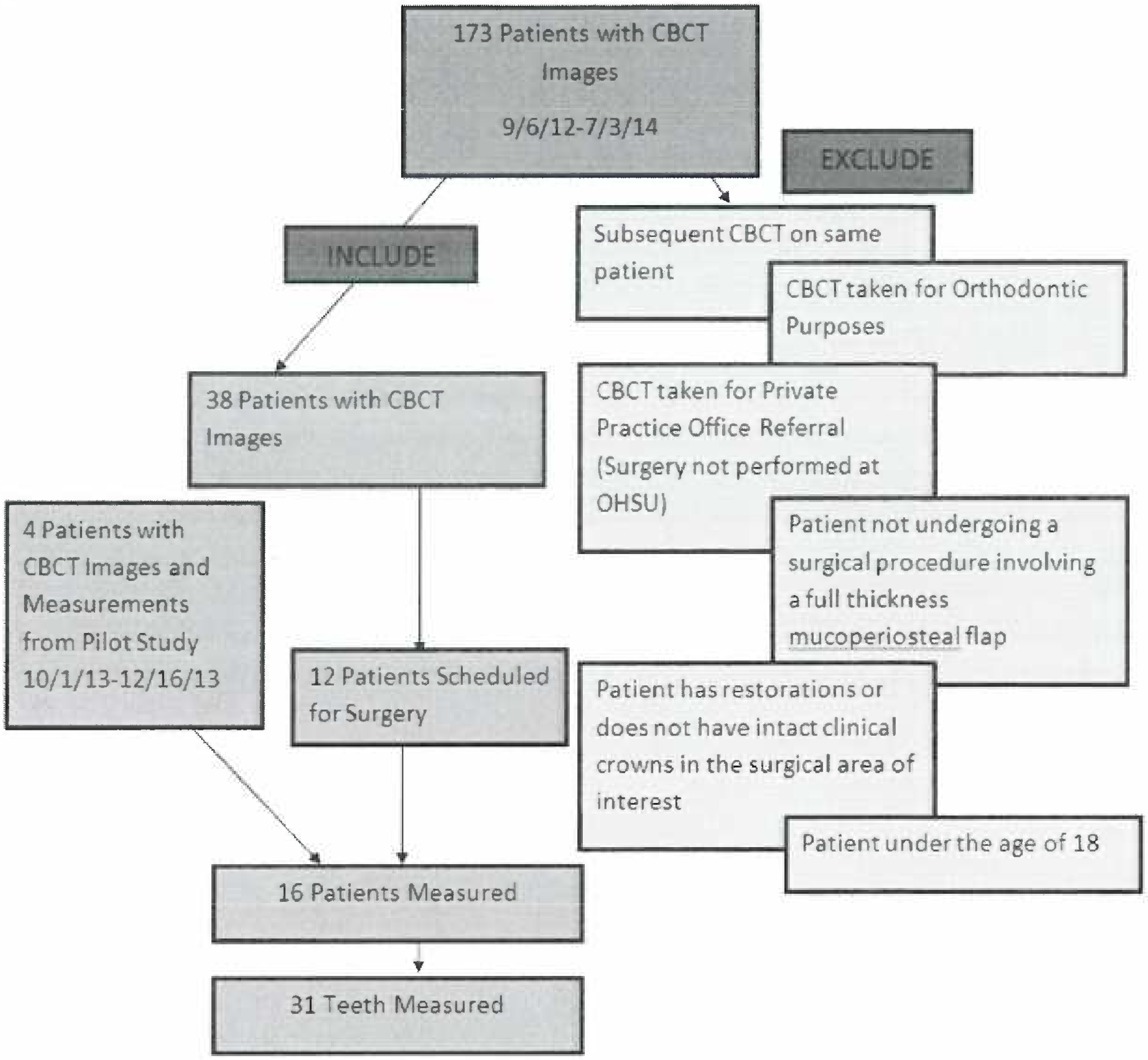
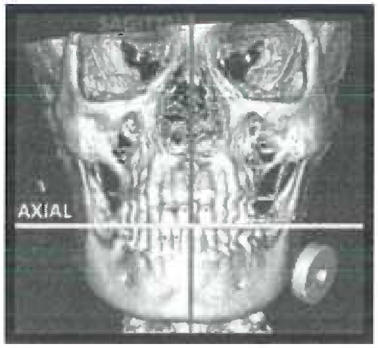
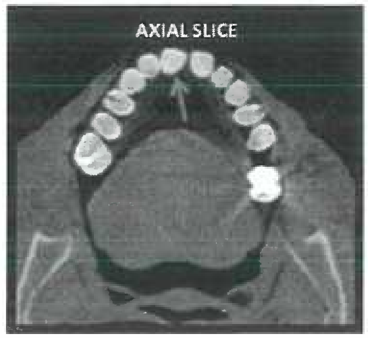
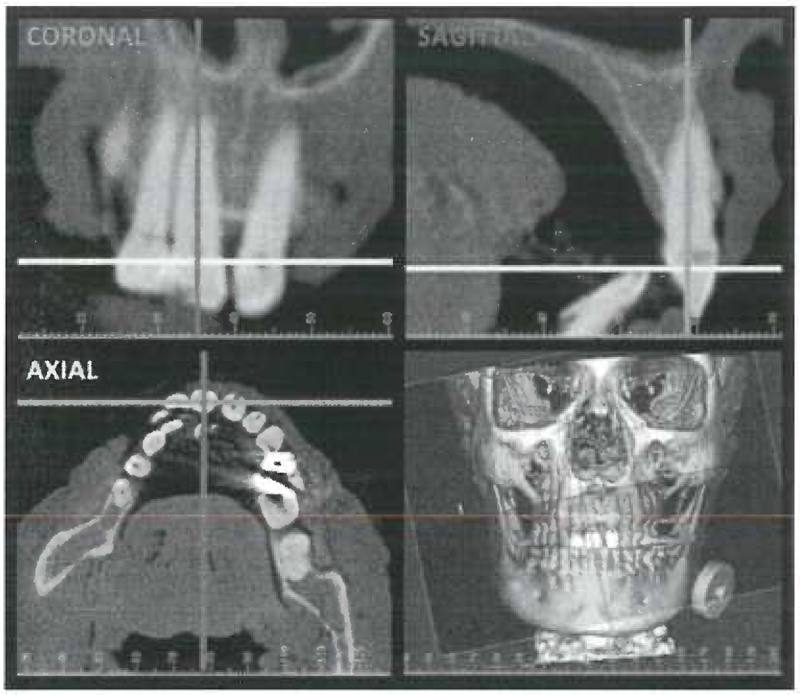

173 Patients with CBCT Images
9/6/12-7/3/14
EXCLUDE
INCLUDE
Subsequent CBCT on same patient
CBCT taken for Orthodontic Purposes
38 Patients with CBCT Images
CBCT taken for Private Practice Office Referral (Surgery not performed at OHSU)
4 Patients with CBCT Images and Measurements from Pilot Study 10/1/13-12/16/13
Patient not undergoing a surgical procedure involving a full thickness mucoperiosteal flap
12 Patients Scheduled for Surgery
Patient has restorations or does not have intact clinical crowns in the surgical area of interest
Patient under the age of 18
16 Patients Measured
31 Teeth Measured

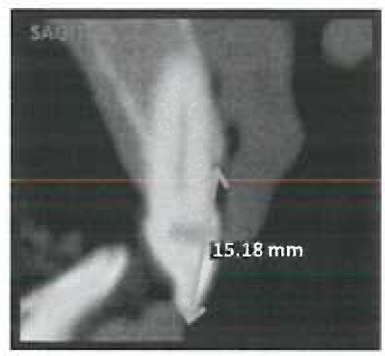
Figure 2.





A. B.

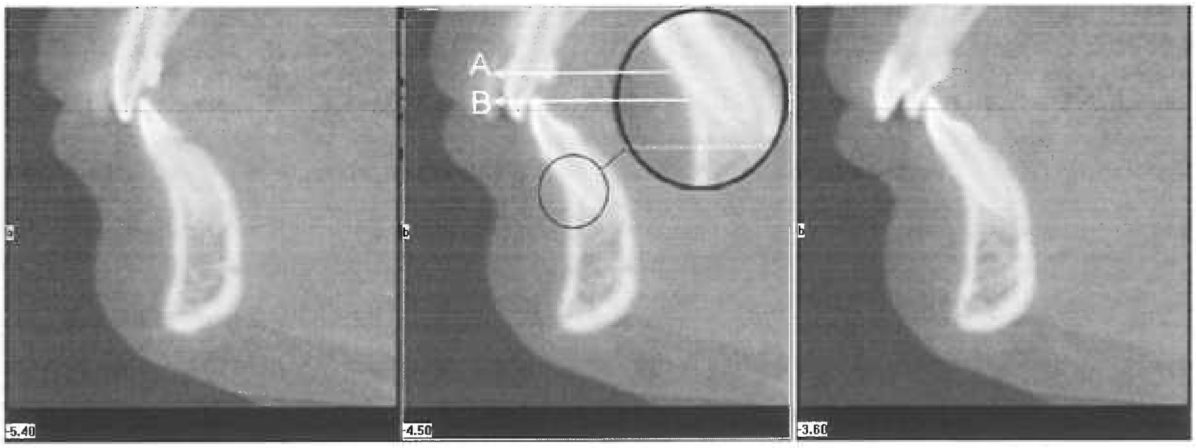




C. D.

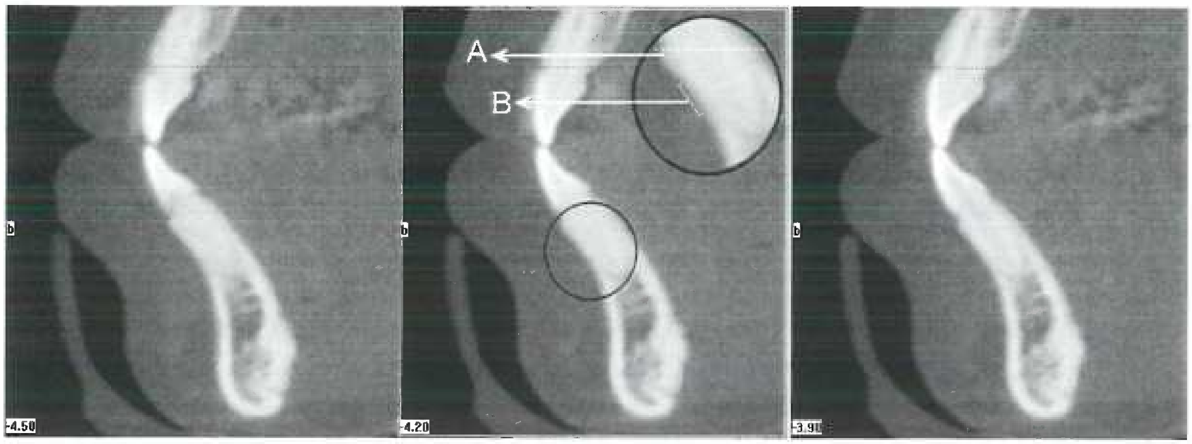
Courtesy of Timock et al 2011

Figure 3.



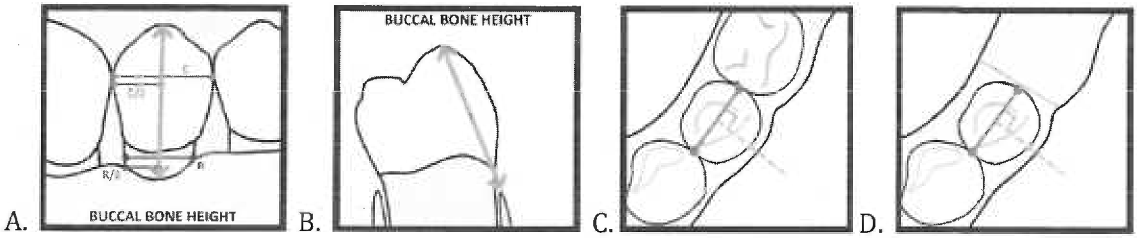
Courtesy of Enhos et al 2012

Figure 4.



Courtesy of Enhos et al 2012

Figure 5.



A-C Courtesy of Timock et al 2011 D Courtesy of Miller et al 2013

Figure 6.

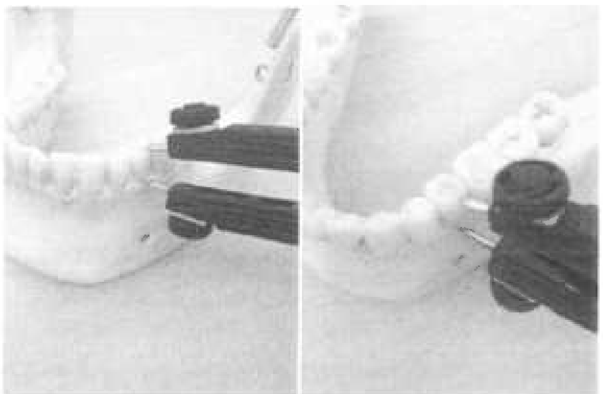


Figure 7.

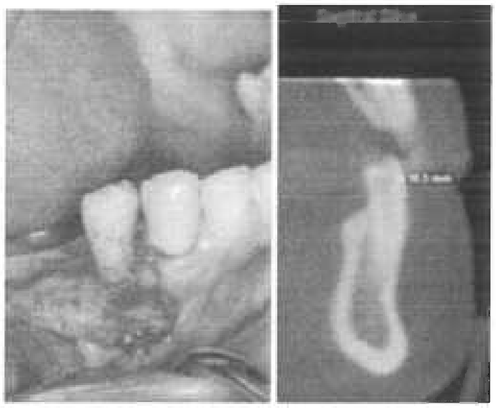


Figure 8.

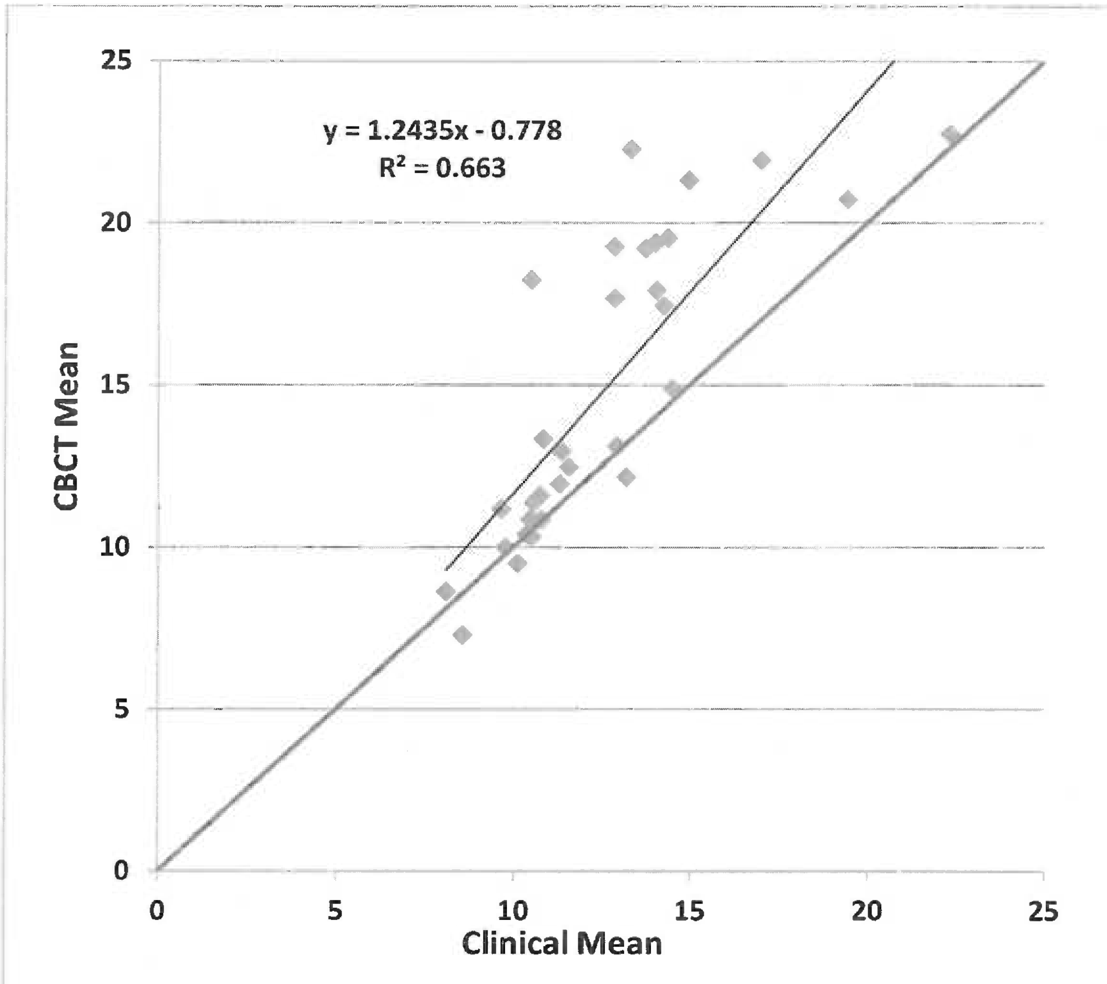

y = 1.2435x - 0.778
R² = 0.663
25
20
15
10
5
0
CBCT Mean
0
5
10
15
20
25
Clinical Mean

Figure 9.

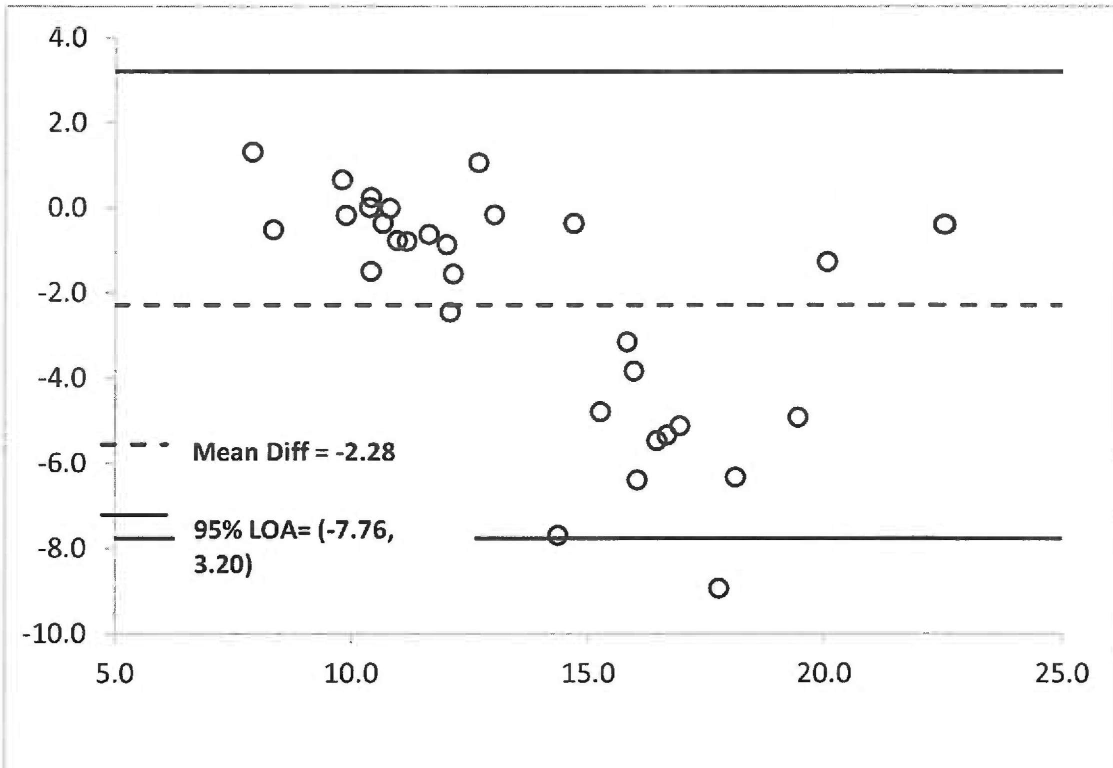

4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
5.0
10.0
15.0
20.0
25.0
Mean Diff = -2.28
95% LOA= (-7.76, 3.20)

Table 1. Surgical Procedures Qualifying For Study
Osteotomy
Bone Graft
Crown Lengthening
Dental Implant
Connective Tissue Graft
Surgical Extraction
Sinus Lift
Stage 2 Implant Procedure (if a full thickness flap was needed)

Table 2. Patient Characteristics				
	Gender	Age	Tooth #	Months between CBCT and Surgery
1	F	68	22	2
2	F	43	22	2
3	F	63	11	2
4	F	68	20, 21,22, 28	1 (20-22) 6 (28)
5	F	48	6	3
6	M	74	11	3
7	M	49	5	3
8	M	73	12	12
9	M	68	29	22
10	M	81	24, 25, 26, 28	3
11	F	58	22	7
12	M	74	22, 23, 24, 25, 26, 27	5
13	F	69	21, 22, 24, 25, 26	5
14	F	69	6	1
15	F	48	28	6
16	M	66	27	2

Table 3. Distribution of teeth examined by tooth type			
Tooth Type	*Maxilla*	*Mandible*	*Total*
Anterior			
Central Incisor	0	6	6
Lateral Incisor	0	5	5
Canine	4	7	11
Anterior total	4	18	22
Posterior			
First Premolar	2	5	7
Second Premolar	0	2	2
Posterior total	2	7	9
Total	6	25	31

Table 4. i-CAT® 17-19† Technical Image Acquisition Parameters and Settings	
Voxel	0.3 mm
Field of View (FOV)	10 cm x10 cm (two arches) or 10 cm x 5 cm (one arch)
kVp	120
mA	5
Exposure Time	4 seconds (s)

†Manufacturer: Imaging Sciences International, Hatfield, PA

Table 5. Intrarater and Interrater Reliability, Direct and CBCT FBH Measurements						
Comparison	**Paired T test P value**	**PCC**	**CCC**	**95% CI of CCC**		**ICC**
Clinical 1 vs. Clinical 2	0.3963	0.9824	0.9819	0.9629	0.9912	
CBCT #1 1 vs. 2	0.4213	0.9939	0.9937	0.987	0.9969	0.994
CBCT #1 1 vs. 3	0.063	0.9963	0.9954	0.9909	0.9977	
CBCT #1 2 vs. 3	0.0309	0.9937	0.9921	0.9841	0.996	
CBCT #2 1 vs. 2	0.9558	0.9936	0.9877	0.9862	0.9966	0.9908
CBCT #2 1 vs. 3	0.9295	0.9868	0.9855	0.9712	0.9927	
CBCT #2 2 vs. 3	0.8604	0.993	0.9927	0.9852	0.9964	
Mean CBCT #1 vs. Mean CBCT #2	0.282	0.9777	0.9765	0.9522	0.9885	
Mean Clinical vs. mean CBCT	0.0001	0.8143	0.6355	0.4487	0.7691	

Table 6. Interrater Reliability, Direct and CBCT FBH Measurements		
	Direct Measurement	**CBCT Measurement**
Mean Diff±SD (mm)	-0.09±0.58	-0.20±0.99
Mean Abs±SD (mm)	0.46±0.35	0.64±0.77
CCC (95% CI)	0.9819 (0.9629, 0.9912)	0.9765 (0.9522, 0.9885)
PCC	0.9824	0.9777

Table 7. Facial Alveolar Bone Height Measurement Results, Direct and CBCT						
	Direct	**CBCT**	**Difference (direct-CBCT)**			
Variable	**Mean±SD (mm)**	**Mean±SD (mm)**	**Mean Diff±SD (mm)**	**Mean Abs±SD (mm)**	**CCC (95% CI)**	**PCC**
FBH	12.56±3.04	14.84±4.65	-2.28±2.80	2.49±2.61	0.6355 (0.4487, 0.7691)	0.8143

Table 8. Dehiscences (D) and Fenestrations (F) detected clinically and in CBCT images from assessments pooled from 2 raters

Mx/Md	Teeth #	Clinical	Pooled CBCT for rater #1	Pooled CBCT for rater #2
Md	22	D	None	F
Md	22	F	D	D
Mx	11	None	None	None
Md	28	None	None	D
Mx	6	None	None	None
Mx	11	None	None	None
Mx	5	D	D	D
Mx	12	D	D	D
Md	29	None	None	None
Md	24	D	D	D
Md	25	None	D	D
Md	26	None	D	D
Md	28	None	None	None
Md	22	None	None	None
Md	22	D	D	D
Md	23	D	D	D
Md	24	D	D	D
Md	25	D	D	D
Md	26	D	D	D
Md	27	D	D	D
Md	21	D	D	D
Md	22	D	D	D
Md	24	D	D	D
Md	25	D	D	D
Md	26	D	D	D
Md	20	None	None	F
Md	21	None	None	F
Md	22	F	F	F
Mx	6	None	None	F
Md	28	D	D	None
Md	27	None	None	None

Table 9. Dehiscences and Fenestrations detected Clinically by Tooth Type				
	Dehiscences	**Fenestrations**	**None**	**Total**
Mandibular Incisors	8	0	2	10
Mandibular Canines	4	2	3	9
Maxillary Canines	0	0	3	3
Mandibular 1st premolars	2	0	3	5
Maxillary 1st premolars	2	0	0	2
Mandibular 2nd premolars	0	0	2	2
Total	16	2	13	31

Table 10. Standard Mean Difference by Tooth Type							
Level	**- Level**	**Score Mean Difference**	**Std Err Dif**	**Z**	**p-Value**	**Lower CL**	**Upper CL**
Md Incisor	Md 2nd premolar	3.90	2.79	1.40	0.162		
Md Incisor	Md Canine	2.59	2.53	1.02	0.307	-2.87	4.98
Md Incisor	Md 1st premolar	2.55	2.45	1.04	0.297	-1.2	4.58
Mx 1st premolar	Md 2nd premolar	0.50	1.29	0.39	0.699		
Mx 1st premolar	Md Canine	0.31	2.39	0.13	0.896		
Mx 1st premolar	Md 1st premolar	0.00	1.81	0.00	1.000		
Md Canine	Md 2nd premolar	-0.31	2.39	-0.13	0.896		
Md Canine	Md 1st premolar	-1.14	2.22	-0.51	0.608	-2.45	6.53
Md 2nd premolar	Md 1st premolar	-1.75	1.81	-0.97	0.333		
Mx Canine	Md Canine	-2.44	2.19	-1.11	0.266	-8.62	0.17
Mx Canine	Md 2nd premolar	-2.63	1.60	-1.64	0.100		
Mx Canine	Mx 1st premolar	-2.63	1.60	-1.64	0.100		
Mx 1st premolar	Md Incisor	-2.70	2.79	-0.97	0.333		
Mx Canine	Md 1st premolar	-4.28	1.83	-2.34	0.019*	-5.45	-0.26
Mx Canine	Md Incisor	-6.83	2.47	-2.76	0.006*	-6.08	-0.64

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).

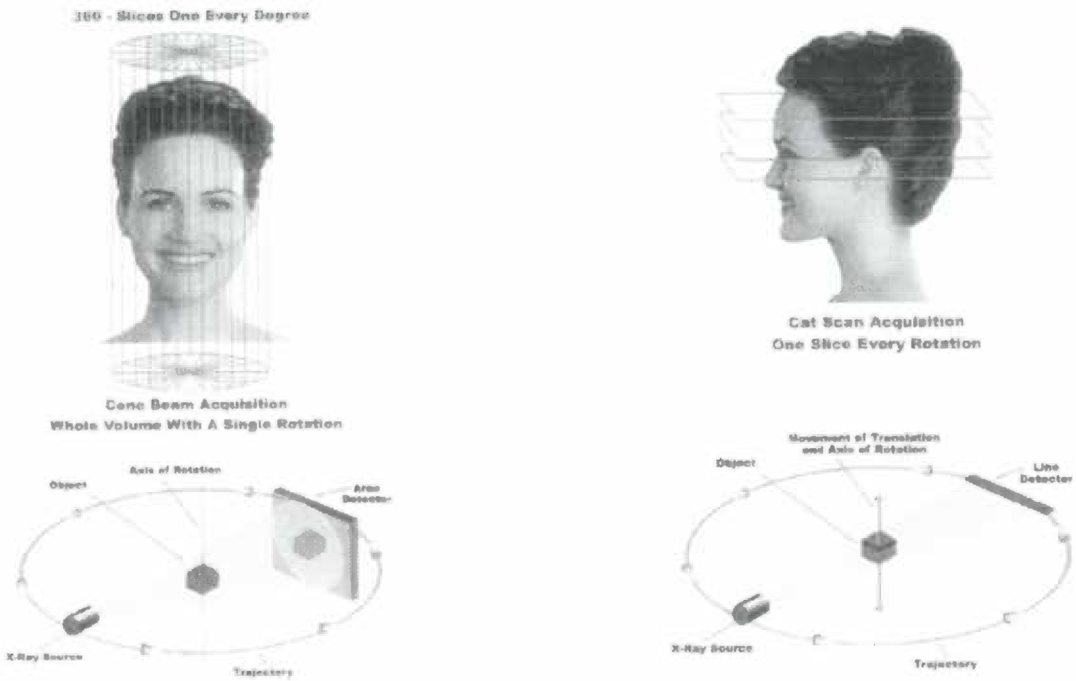


Figure 1. Comparison of fan beam CT and cone beam computed tomography imaging (Mah and Hatcher 2004).

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).

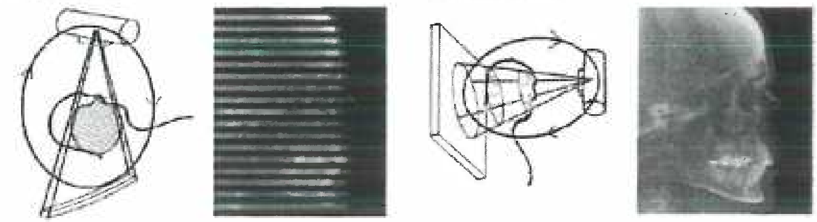


Figure 2. Comparison of fan beam and cone beam computed tomography imaging geometry (Farman and Scarfe 2009)

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.

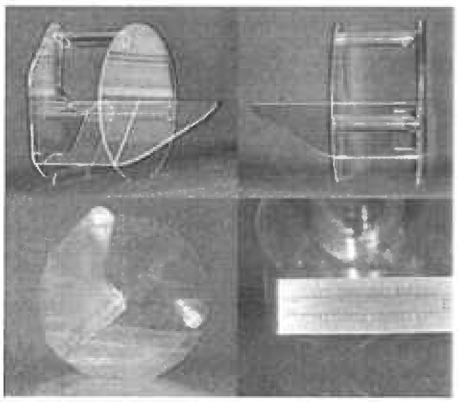


Fig 3. "The CIC phantom viewed at different angles and 0.3-mm spheres compared with a ruler. " (Ballrick et al 2008).

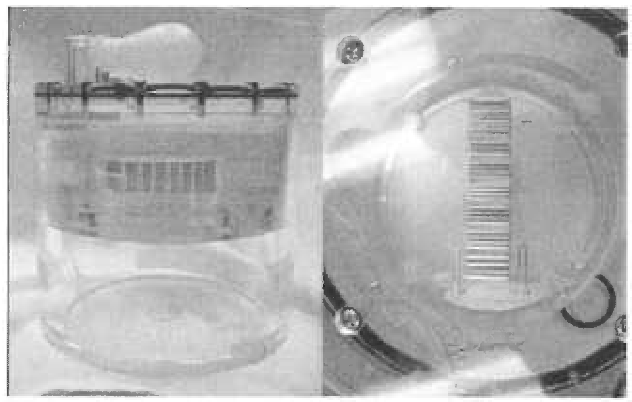


Fig 4. "Full view of the C phantom and a close up view from the top showing the 9 chromium series of metal lines used to assess image resolution" (Ballrick et al 2008).

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

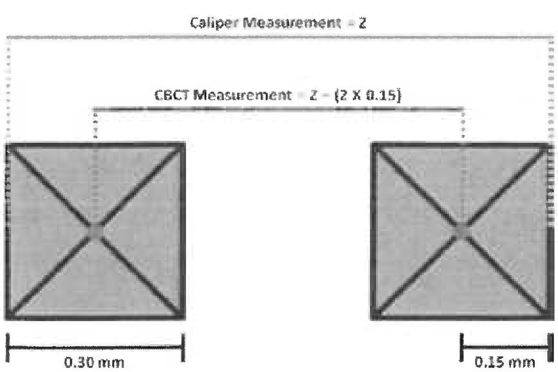


Figure 5. "Description of possible origin of systematic underestimation" (Baumgaertel et al 2009)

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*.

Literature Cited:

Allais D. and Melsen B. Does labial movement of lower incisors influence the level of the gingival margin? A case-control study of adult orthodontic patients. Eur J Orthod 2003;25:1-10.

American Association of Orthodontists. Minutes of Meetings of Council on Scientific Affairs. Conference Call March 16, 2009.

American Association of Orthodontists. Want a beautiful smile? St. Louis: American Association of Orthodontists; 2006. www.webcitation.org/5RDWqElut". Accessed August 29, 2013.

Årtun J, Osterberg SK, Kokich VG. Long-term effect of thin interdental alveolar bone on periodontal health after orthodontic treatment. J Periodontol 1986;57:341-346.

Årtun J and Krogstad O. Periodontal status of mandibular incisors following excessive proclination: a study in adults with surgically treated mandibular prognathism. Am J Orthod Dentofac Orthop 1987;91:225–232.

Ballrick, JW, Palomo, JM, Ruch, E, Amberman, BD, Hans, MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. Amer J Orthod Dentofacial Orthoped 2008;(Oct):573-82.

Baumgaertel S, Paloma JM, Paloma L, Hans MG. Reliability and accuracy of cone-beam computed tomography dental measurements. Am J Orthod Dentofacial Orthop 2009;136:19-28.

Berco M, Rigali, Jr. PH, Miner RM, DeLuca S, Anderson NK, Will LA. Accuracy and reliability of linear cephalometric measurements from cone-beam computed tomography scans of a dry human skull. Am J Orthod Dentofacial Orthop 2009;136:17.e1-17.e9.

Bollen AM, Cunha-Cruz J, Bakko DW, Huang GJ, Hujoel PP. The effects of orthodontic therapy on periodontal health: a systematic review of controlled evidence. J Am Dent Assoc 2008;139:413-422.

Boyd RL. Mucogingival consideration and their relationship to orthodontics. J Periodontol 1978;49:67-76.

Brooks SL. CBCT Dosimetry: orthodontic considerations. Semin Orthod 2009;15:14-18.

Brown AA, Scarfe WC, Scheetz JP, Silveira AM, Farman AG. Linear accuracy of cone beam CT derived 3D images. Angle Orthod 2009 Jan;79(1):150-7.

Carvalho FAR, Cevidanes LHS, Motta A, et al. 3D assessment of mandibular advancement 1 year after surgery. Am J Orthod Dentofac Orthop 2010;137:S53.e1-e12.

Cevidanes LH, Bailey LJ, Tucker GR Jr, Styner MA, Mol A, Phillips CL, Proffitt WR, Turvey T. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. Dentomaxillofac Radiol 2005;34:369-375.

Cevidanes LH, Bailey LJ, Tucker SF, Styner MA, Mol A, Phillips CL, Proffitt WR, Turvey T. Three-dimensional cone-beam computed tomography for assessment of mandibular changes after orthognathic surgery. Am J Orthod Dentofacial Orthop 2007;131:44-50.

Christie KF, Boucher N, Chung CH. Effects of bonded rapid palatal expansion on the transverse dimensions of the maxilla: a cone-beam computed tomography study. Am J Orthod Dentofacial Orthop 2010;137:S79-85.

Claffey N, Shanley D. Relationship of gingival thickness and bleeding to loss of probing attachment in shallow sites following nonsurgical periodontal therapy. J Clin Periodontol 1986;13:654-657.

Cook VC. Accuracy of alveolar bone measurements from cone beam computed tomography at multiple parameters. Masters's thesis, Oregon Health & Science University 2011.

Enhos S, Uysal T, Yagci A, Veli I, Ucar FI, and Ozer T. Dehiscence and fenestration in patients with different vertical growth patterns assessed with cone-beam computed tomography. The Angle Orthodontist: September 2012;82(5):868-874.

Farman AG, Scarfe EC. The business of maxillofacial cone beam computed tomography. Semin Orthod 2009;15: 2-13.

Fuhrmann RA, Bucker A, Diedrich PR. Assessment of alveolar bone loss with high resolution computed tomography. J Periodontal Res 1995;30:258-63.

Geiger AM. Mucogingival problems and the movement of mandibular incisors: a clinical review. Am J Orthod 1980; 8:511-527.

Graber TM, Vanarsdall RL. Orthodontics: current principles and techniques. 4th ed. St. Louis: Mosby;2005:901-36.

Gracco, A, Lombardo L, Cozzani M , and Siciliani G. Quantitative cone-beam computed tomography evaluation of palatal bone thickness for orthodontic miniscrew placement. *Am J Orthod Dentofacial Orthop* 2008;134:361–369.

Grimard BA, Hoidal MJ, Mills MP, Mellonig JT, Nummikoski PV, Mealey BL. Comparison of clinical, periapical radiograph, and cone-beam volume tomography for assessing bone level changes following regenerative periodontal therapy. J Periodontol 2009;80:48-55.

Hamada Y, Kondoh T, Noguchi K, Mitsuyoshi I, Hiroaki I, Mishima A, Kobayashi A, Seto, K. Application of limited cone beam computed tomography to clinical assessment of alveolar bone grafting: A preliminary report. Cleft Palate Craniofacial J 2005;42:128-37.

Hilgers ML, Scarfe WC, Scheetz JP, Farman AG. Accuracy of linear temporomandibular joint measurements with cone beam computed tomography and digital cephalometric radiography. Am J Orthod Dentofacial Orthop 2005; 128:803–811.

Kan JY, Rungcharassaeng K, Lozada JL, Zimmerman G. Facial gingival tissue stability following immediate placement and provisionalization of maxillary anterior single implants: a 2- to 8-year follow-up. Int J Oral Maxillofac Implants 2011. Jan-Feb;26(1):179-87.

Karring T, Nyman S, Thilander B, Magnuisson I. Bone regeneration in orthodontically produced alveolar bone dehiscences. J Periodontal Res 1982;17:309-315.

Kobayashi K, Shimoda S, Nakagawa Y, Yamamoto A. Accuracy of distance using limited cone-beam computerized tomography. Int J Oral Maxillofac Implants 2004;19:228-231.

Lascala CA, Panella J, Marques MM. Analysis of the accuracy of linear measurements obtained by cone beam computed tomography (CBCT-NewTom). Dentomaxillofacial Radiol 2004;33:291-294.

Leuzinger M, Dudic A, Giannopoulou C, Kiliaridis S. Root-contact evaluation by panoramic radiography and cone-beam computed tomography of super-high resolution. Am J Orthod Dentofacial Orthop 2010;137:389-92.

Little RM, Riedel RA. Postretention evaluation of stability and relapse—mandibular arches with generalized spacing. American J Orthod Dentofacial Orthop 1989;95:37-41.

Ludlow JB, Davies-Ludlow LE, Brooks SL. Dosimetry of two extraoral direct imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. Dentomaxillofacial Radiol 2003; 32:229-234.

Ludlow JB, Davies-Ludlow LE, Brooks SL, et al. Dosimetry of 3 CBCT units for oral and maxillofacial radiology: CB Mercuray, NewTom 3G and i-CAT. Dentomaxillofac Radiol 2006;35:219-226.

Ludlow JB, Ivanovic M. Comparison dosimetry of dental CBC devices and 64-slice CT for oral and maxillofacial radiology. Oral Surg Oral Med Oral Pathol Radiol Endod 2008;106:106-114.

Mah J and Hatcher D. Current status and future needs in craniofacial imaging. Orthod Craniofac Res 2003;6(Suppl 1):10-16.

Mah J and Hatcher D. Three-dimensional craniofacial imaging. Am J Orthod Dentofacial Orthop 2004;126:308-309.

Maynard JG. The rationale for mucogingival therapy in the child and adolescent. Int J Periodontics Restorative Dent 1987;7:37-51.

Mengel R, Candir M, Shiratori K, Flores-de-Jacoby L. Digital colume tomography in the diagnosis of periodontal defects: An in vitro study on native pig and human mandibles. J Periodontal Res 1991;26:527-529.

Misch KA, Yi ES, Sarment DP. Accuracy of Cone Beam Computed Tomography for Periodontal Defect Measurements. J Periodontology July 2006;77:1261-1266.

Moshiri M, Scarfe WC, Hilgers ML, Scheetz JP, Silveira AM, Farman AG. Accuracy of linear measurements from imaging plate and lateral cephalometric images derived from cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2007;132:550–560.

Nakajima A, Sameshima GT, Arai Y, Homme Y, Shimizu N, Dougherty H Sr. Two- and three-dimensional orthodontic imaging using limited cone beam-computed tomography. Angle Orthod 2005; 75: 895-903.

Ogawa T, Enciso R, Shintaku WH, Clark GT. Evaluation of cross-section airway configuration of obstructive sleep apnea. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2007;103:102-108.

Ochsenbein C and Ross S. A reevaluation of osseous surgery. Dent Clin North am 1996. Jan;13(1):87-102.

Olsson M, Lindhe J. Periodontal characteristics in individuals with varying form of the upper central incisors. *J Clin Periodontol* 1991;18:78-82.

Olsson M, Lindhe J, Marinello CP. On the relationship between crown form and clinical features of the gingiva in adolescents. *J Clin Periodontol* 1993;20:570-577.

Parel SM, Triplett RG. Interactive imaging for implant planning, placement, and prosthesis construction. J Oral Maxillofac Surg 2004;62(S2):41-7.

Paventy A. Facial alveolar bone evaluation with cone beam computed tomography in non extraction treatment using the Damon system: a prospective clinical trial. Master's thesis, University of Oklahoma 2008.

Peck JL, Sameshima GT, Miller A, Worth P, Hatcher DC. Mesiodistal root angulation using panoramic and cone beam CT. Angle Orthod 2007; 77:206-213.

Persson RE, Hollender LG, Laurell L, Perrson GR. Horizontal alveolar bone loss and vertical bone defects in an adult population. J Periodontol. 1998;69:348-356.

Rychman MS, Harrison S, Oliver D, Sander C, Boryor AA, Hohmann AA. Soft-tissue changes after maxillomandibular advancement surgery assessed with cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2010;137:S86-S93.

Rungcharassaeng K, Caruso JM, Kan JYK, Taylor G. Factors affecting buccal bone changes of maxillary posterior teeth after rapid maxillary expansion. Am J Orthod Dentofacial Orthop 2007;132:428.e1-428.e8.

Scarfe, William C. and Farman, Allan G. What is Cone-Beam CT and How Does it Work?. Dent Clin N Am. 2008;52:707-730.

Seibert JL. Esthetics and periodontal therapy. In: Lindhe J, ed. Textbook of Clinical Periodontology. 2nd edition. Copenhagen: Munksgaard; 1989:477–514.

Sherrard JF, Rossouw PE, Benson BW, Carrillo R, Buschang PH. Accuracy and reliability of tooth and root lengths measured on cone-beam computed tomographs. Am J Orthod Dentofacial Orthop 2010;137: S100–108.

Swan KA. Image quality and radiation dose in cone beam computed tomography for orthodontics. Master's thesis, University of Michigan, 2007.

Ten Hoeve A, Mülie RM. The effect of antero-posterior incisor repositioning on the palatal cortex as studied with laminography. J Clin Orthod 1976; 10:804-822.

Timock A, Cook VC, McDonald T, Leo MC, Crowe J. Accuracy and reliability of buccal bone height and thickness measurements from cone-beam computed tomography imaging. Am J Orthod Dentofac Orthop 2011;140:734-44.

Van Elslande D, Heo G, Flores-Mir C, Carey J, Major PW. Accuracy of mesiodistal root angulation projected by cone-beam computed tomographic panoramic-like images. Am J Orthod Dentofacial Orthop 2010;137: S94–99.

Walker L, Enciso R, Mah J. Three-dimensional localization of maxillary canines with cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2005;128:418-423.

Weisgold, A. (1977) Contours of the full crown restoration. Alpha Omegan 70, 77–89.

Wennström JL, Lindhe J, Sinclair F, Thilander B. Some periodontal tissue reactions to orthodontic tooth movement in monkeys. J Clin Periodontol 1987;14:121-129.

Wennstrom JL. Mucogingival considerations in orthodontic treatment. Semin Orthod 1996;2(1):46-54.