Title
Comparison of Panoramic and Cone Beam CT Radiography in the Assessment of Root Angulation

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Comparison of Panoramic and Cone Beam CT Radiography in the Assessment of Root Angulation

by

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

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in the

GRADUATE DIVISION

of the

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DEDICATION

I would like to dedicate this thesis to my parents, Kim and Duc Huynh. Thank you for all of your sacrifices to provide a better life for your children, and your unwavering love and support.

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I would like to thank my committee for their continued mentorship and support:

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Comparison of Panoramic and Cone Beam CT Radiography in the Assessment of Root Angulation

Linda U. Huynh, D.D.S.

ABSTRACT

Objective: Traditionally, panoramic radiographs have been used to evaluate mesiodistal tooth angulation; however, with the development of 3-D CBCT technology, perhaps a better measurement of tooth angulation can be obtained. The purposes of this study were to: 1). Compare the mesiodistal tooth angulations determined from a typodont (gold standard) with measurements of tooth angulations from panoramic and CBCT radiographs. 2). Compare the differences in the quantity, location, and direction of mesiodistal bracket repositioning by CBCT and panoramic assessment by the *same* orthodontic examiner and between *different* examiners. 3). Assess which method of root assessment (CBCT or panoramic) examiners felt more confident using to diagnose root position.

Methods: A typodont with radiographic markings of each tooth's long axis was used as the gold standard. The root angulation measurements were compared to measurements from panoramic and CBCT images. Twenty-five consecutive subjects had a panoramic radiograph and CBCT scan taken on the same day. All 56 images (panoramic or CBCT) were randomized and evaluated by ten orthodontic examiners to identity each tooth they felt needed to be repositioned in order to obtain parallel roots. A questionnaire was given at the end of the study to rate their confidence level in using each method to assess root positioning.

Results: Compared to the typodont gold standard, the CBCT produced more accurate measurements of root angulation than the panoramic image ($P<0.05$). The two different radiographic methods provided a different assessment in the quantity, location, and direction of bracket repositioning. The teeth with the most disagreement between the two methods were the maxillary second premolar, canine, lateral incisor, and the mandibular first premolar. The panoramic image tends to over-report the maxillary lateral incisors and canines to need distal root tip, and under-report the maxillary premolars and mandibular 1st premolars to need distal root tip. In general, examiners felt more confident using CBCT to diagnose root position.

Conclusion: The CBCT data provided a more accurate representation of mesiodistal tooth angulation when compared to the panoramic radiograph. Using a panoramic radiograph to evaluate root position is inaccurate and will cause the examiner to reposition the wrong teeth.

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INTRODUCTION

Clinical Significance

One of the most important objectives of orthodontic treatment is proper mesiodistal tooth angulation to produce a functional and stable occlusion. Andrew's extensive study revealed that normal occlusion is dependent upon six major keys – one being the correct mesiodistal inclination of the teeth (Andrews 1972). Furthermore, other studies have found that the axial inclination of the teeth and related root parallelism are critical to produce proper occlusal and incisal function, distribution of occlusal forces, and to maintain a stable result (Dewel 1949; Balut, Klapper et al. 1992). Close convergence of the root apices may not allow the crowns of the teeth to touch (Figure 1, (Hatasaka 1976). In addition, the root portion of the tooth after treatment will not change. This is especially important in cases in which extractions were performed and the spaces were closed by orthodontic means, to verify that excessive tipping was avoided (Graber 1966; Graber 1967).

Figure 1. Post-treatment radiograph showing convergent roots and spaces between the crowns

Root Proximity and Convergence

Meyer and Nelson (Meyer and Nelson 1978) noted that the limited space between adjacent roots allows a very small margin of error for root placement. A main objective of orthodontic treatment is to ensure equal bone thickness on either side of parallel roots. Roots that are properly angulated permit the presence of sufficient bone between adjacent roots, which is especially important in patients susceptible to periodontal disease. Periodontal problems can be exacerbated when roots of teeth are too close together. Trossello and Gianelly used the term “root proximity” to describe situations in which the roots of adjacent teeth are 1.0-mm or less apart (Vermylen, De Quincey et al. 2005). In these situations, infectious processes can destroy the overly thin interdental cancellous bone which breaks down readily leaving the buccal and lingual plates of compact bone intact. Pocket formation can result due to the radiating effect of the irritant. Instrumentation to remove the irritants can also be more difficult when roots approximate one another (Hatasaka 1976). Patients with multiple sites with root proximity have a higher chance to be affected with extensive periodontal disease. Vermylen *et al.* found that a subject with bilateral root proximity has 3.6 times higher chance of having periodontitis. Therefore, root proximity must be taken into consideration as a risk marker for periodontal disease (Vermylen, De Quincey et al. 2005).

The clinical relevance of root parallelism in post-extraction cases has been an important topic in orthodontic literature. Jarabak (Jarabak 1972) believed that if roots were not parallel on either side of the extraction site, the distribution of the occlusal loads upon those teeth would exert a tipping and rotational force which could cause the posterior teeth to tip and rotate mesially and the canines to tip and rotate distally. Graber

(Graber 1966) observed that extraction sites may reopen if the roots of the adjacent teeth have not remained parallel. A study by Hatasaka (Hatasaka 1976) took 28 orthodontic cases treated with bicuspid extractions and examined their casts and x-rays taken during retention and post-retention from 1 to 13 years. Roots that were "over-paralleled" to the extent that the apices touched did not relapse to the desired upright positions. He reasoned that close convergence of the root apices may not allow the crowns of the teeth to touch, leaving a space between the crowns. Since the supra-alveolar fibers of the periodontal ligaments did not have the ability to pull the crowns together, the root apices remained in the same convergent position, and spaces in the coronal areas remained opened. Bone or tissue in the apical areas did not appear to have the ability to push the apices apart. Roots that were "over-paralleled," with apices that did not touch tended to upright, some leaving space between the crowns. His findings indicate that the most favorable post-retention results were in instances in which the orthodontic treatment was completed with roots that were parallel, upright, and with equal amounts of supporting bone between all roots.

Bracket Positioning

Properties of a well-finished case include level marginal ridges and the proper alignment of crowns and roots. Orthodontists strive for accurate bracket positioning to facilitate the ease in which an excellent occlusion is achieved with minimal wire bending. Bracket placement has a definite impact on the expressed first, second, and third order movements of the tooth (Sondhi 2003). Where a bracket is placed on the crown will affect the tooth's mesiodistal, buccolingual, occlusogingival, and rotational position –

resulting in the tooth's final tip, torque, height, and rotation (Carlson and Johnson 2001). A malpositioned bracket will move the tooth unfavorably. Meyer and Nelson showed that a three degree error in the tip of a bracket will result in a 0.68-mm deflection at the root tip (Figure 2, (Meyer and Nelson 1978). They noted that a three degree tipping error is relatively easy to make – especially on premolars, maxillary lateral incisors, and mandibular incisors. It is not uncommon to cause six to ten degrees of tipping error. With the development of pre-adjusted appliances, in which the bracket design incorporates customized tip, torque, rotation, and differences in base thickness, accurate placement of the bracket is essential to permit full expression of the prescription, allowing the teeth to be positioned in their correct position with a straight wire and reducing the need for wire bending adjustments (Balut, Klapper et al. 1992).

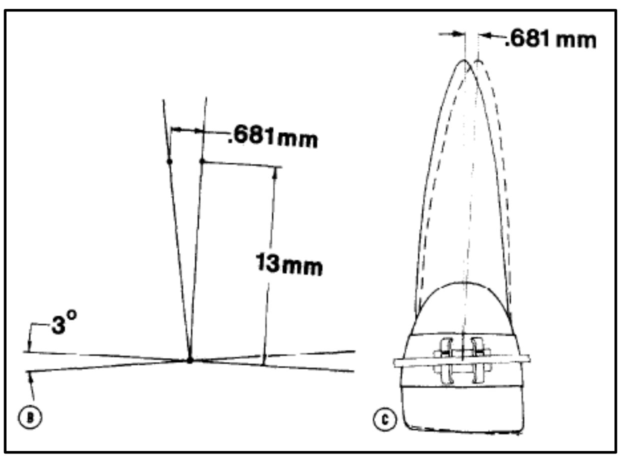


Figure 2. A three degree error in bracket placement will result in a 0.68mm deflection in the root tip; errors of 6-10 degrees in bracket placement is not uncommon.

Pioneers in orthodontics have published different techniques regarding ideal appliance placement. Angle advocated placing the bracket at the center of the labial surface of tooth, Ricketts suggested using the marginal ridges as guidelines for positioning, and Andrews recommended using the long axis and midpoint of the clinical crown (Andrews 1972; Balut, Klapper et al. 1992). But despite the improved "straight wire" (pre-adjusted) appliance and recommendations on ideal appliance placement, most clinicians recognize the difficulty of attaining perfect bracket placement at initial bonding.

Armstrong *et al.* (Armstrong, Shen et al. 2007) compared the accuracy of bracket positioning between two commonly-used techniques: localizing the center of the clinical crown and measuring the distance from the incisal edge. Nineteen experienced orthodontists bonded brackets with both methods on typodont models. They found that there was no significant difference in bracket accuracy between the two techniques ($P<0.05$) and concluded that archwire bending or bracket repositioning was still necessary to compensate for the inaccuracies with both techniques. Variations in tooth morphology (including incisal wear), malocclusions, and operator error all contribute to incorrect bracket placement (Creekmore and Kunik 1993). In a study by Balut *et al.* (Balut, Klapper et al. 1992), ten orthodontists bonded pre-adjusted orthodontic appliances on five models with various malocclusions. The results showed that error in placement was most related to the skill of the operator, tooth structure, size of the clinical crown, and malposition of the tooth in the dental arch. Crowding that resulted in limited access of the tooth surface to bonding also significantly compromised ideal bracket placement. The upper anterior teeth, and the upper and lower canines showed the most angular discrepancy (mean = $5.54° \pm 4.32°$), suggesting that the operators had difficulty in judging root angulation of these teeth by looking only at the crowns.

It has often been suggested that indirect bonding methods in which brackets are first positioned and bonded on a patient's dental cast and then transferred to the mouth, may assist orthodontists in accurate bracket placement. Many proponents believe it is easier to place brackets on models than directly on the patient's teeth due to better visualization and access (especially in the posterior areas), and less chairside working time (Thomas 1979; Hickham 1993). However, studies have shown that while there may be advantages to indirect bonding, more accurate bracket placement has not always been evident (Hodge, Dhopatkar et al. 2004). Koo *et al.* (Koo, Chung et al. 1999) had nine faculty members from the University of Pennsylvania place the brackets on a mannequin (direct bonding method) and on a set of dental models (indirect bonding method), and compared it to each bracket's ideal position on the tooth. Although indirect bonding showed better bracket placement in bracket height, there was no statistically significant differences found between the two methods regarding the angulation and mesiodistal position. Variation in angulation illustrated that the long axis of the tooth was difficult to visualize, especially for those teeth with irregular shapes. Their data clearly showed that both techniques failed to perform ideal bracket placement, and that the examiners made the same mistakes with either direct or indirect bonding.

Bracket Repositioning

To correct improperly placed brackets, a practitioner must either make adjustments in the archwires to move the tooth and its root into the correct position or reposition the bracket. In the past, wire bending adjustments were standard protocol to compensate for this problem. However, bending wires can be a difficult and tedious task, and can produce unwanted side effects on adjacent teeth. It also can increase treatment time, as only incremental adjustments in the wire can be made to allow engagement in the bracket, with varying accuracy. A more efficient alternative was described by Carlson and Johnson (Carlson and Johnson 2001). After initial alignment of the teeth with fixed appliances (which often reveals some bracket-positioning errors), both clinical and radiographic examinations were used to assess the position of the teeth. This was a result of their discovering it was very difficult to judge root parallelism by merely looking at the crowns. If needed, brackets were then repositioned to a more ideal location before resuming treatment. Ideal bracket placement becomes easier to accomplish because after initial leveling and aligning, the tooth-to-tooth relationships have significantly improved, increasing the crown's visibility and access. Correction early in the treatment process enhances efficiency in treatment time and provides a more reliable result in root position. Skidmore *et al.* (Skidmore, Brook et al. 2006) identified and quantified the effect of factors that influence orthodontic treatment time of 366 orthodontic patients from one clinician. They found that having three or more brackets repositioned for positional reasons was associated with an additional 2.5 months of treatment time.

Orthodontists who wish to receive certification as a Diplomat of the American Board of Orthodontics (ABO) must submit a number of clinical case reports that exemplify their high standard of care. One of the ABO's eight Objective Grading System criteria is proper root angulation, used to assess how well the roots of the teeth have been positioned parallel to one another and oriented perpendicular to the occlusal plane. If deviation of the apex is 1-mm or less from the adjacent root, then no points are subtracted from the score. A panoramic radiograph is currently the method used to score root angulation. However, the ABO recognizes that "although the panoramic radiograph is not the perfect record for evaluating root angulation, it is probably the best means possible for making this assessment." Using this system in past field tests, mistakes in root angulation most commonly occurred in the maxillary lateral incisors, canines, and second premolars, and the mandibular first premolars (Casko, Vaden et al. 1998).

Diagnostic Tool – Panoramic Radiograph

Traditionally, planar two-dimensional (2D) panoramic radiographs have been used by orthodontists to assess the mesiodistal root position of the teeth. In a 2002 *Journal of Clinical Orthodontics* (JCO) survey of orthodontic diagnosis and treatment procedures of American orthodontists, 57.9% of the respondents reported taking progress panoramic radiographs (Keim, Gottlieb et al. 2002). However, these panoramic images possess distortion and magnification. A panoramic image is made by generating an image layer or a focal trough in a standard jaw form and size. Any deviation from this standard form will result in an object that is not centered in the image layer and will cause distortion related to the size, location, and form of the image created (Quintero, Trosien et al. 1999; Garcia-Figueroa, Raboud et al. 2008). Scarfe *et al.* (Scarfe, Nummikoski et al. 1993) measured how far various panoramic machines' projection angles of the central beam deviated from the optimal angulation to open interproximal contacts. He found that there were large discrepancies, especially in the premolar area, and concluded that the ideal beam projection angle required to provide open contacts between teeth changed along the arch. Thus, an x-ray beam that is not horizontally perpendicular to the jaw surface can create linear and angular distortion, especially concentrated at the curvature of the dentition in the jaws in the canine-premolar region. Samawi and Burke (Samawi and Burke 1984) confirmed this by using a wire-mesh frame shaped to represent the curvature of jaws, and lead shot to represent the long axes of the teeth, to investigate the magnitude and distribution of angular distortion on the panoramic image. The canine-premolar region of both arches expressed the greatest amount of angular distortion and variability.

In other studies, adjacent teeth that possess differences in buccolingual angulations (torque) were found to create a false perception that the root was misaligned in a mesiodistal direction (tip) since distortion can be affected by changes in the object's depth in the focal trough. Investigating this theory in 2008, Garcia-Figueroa *et al.* (Garcia-Figueroa, Raboud et al. 2008) took panoramic images of a skull-typodont device in which they varied the buccolingual orientation of teeth but maintained the mesiodistal orientation in order to evaluate its effect on the perception of root parallelism. They found the greatest root parallelism difference for adjacent teeth occurred between the maxillary canine and first premolar, and secondly, between the mandibular canine and first premolar regions. These deviations were statistically and clinically significant. In these regions, roots that had a more lingual orientation were projected more mesially on the panoramic image, and roots buccally positioned were projected more distally. They concluded that the clinical usefulness of panoramic radiography to assess root parallelism should be approached with much caution. If there are significant bucco-lingual orientation discrepancies between adjacent teeth, the panoramic image expression might indicate nonexistent root convergence or divergence.

Various other factors including aberrant head positioning (McKee, Glover et al. 2001; Stramotas, Geenty et al. 2002), cant of the occlusal plane (Philipp and Hurst 1978), and geometry of the patient can produce effects with the panoramic machine that do not accurately represent the patient , and is a two-dimensional representation of a three-dimensional structure (Harrell, Hatcher et al. 2002). McKee *et al.* (McKee, Glover et al. 2001) constructed a typodont testing device within a human skull to examine the effect of various patient positioning errors in panoramic radiography on imaged mesiodistal tooth angulations and compared these results with the imaged mesiodistal tooth angulations present at an idealized head position. The typodont was positioned at an ideal head position, 5° right, 5° left, 5° up, and 5° down. Results showed that the majority of image angles derived from the deviant head positions were statistically significantly different than the image angle from the idealized head position (Figure 3,(McKee, Glover et al. 2001). For example, maxillary teeth were more sensitive to up/down head rotation (5° up caused a more mesial root projection, and 5° down caused a more distal root projection); whereas mandibular teeth were more sensitive to right/left head rotation (angular differences ranged from 4°-22.3°).

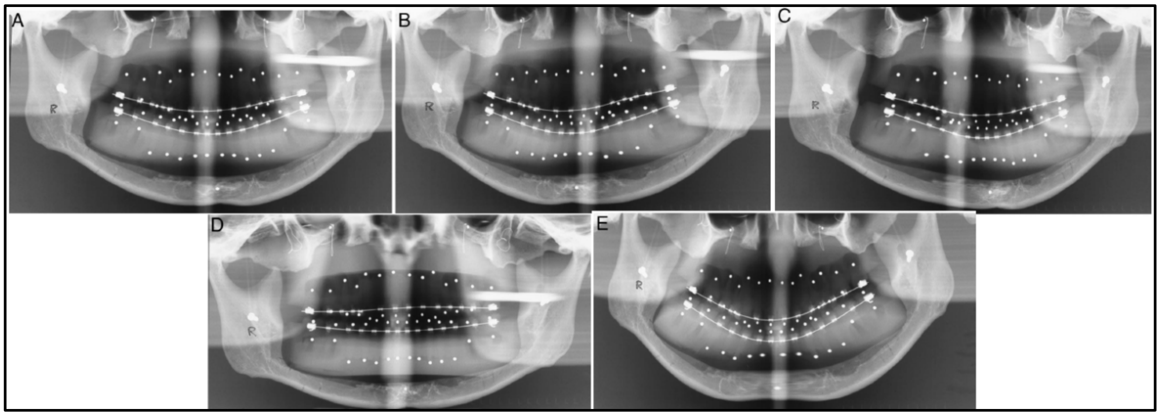


Figure 3. Panoramic images of typodont with head held at different positions: A = ideal, B = 5 degrees right, C = 5 degrees left, D = 5 degrees upward, E = 5 degrees downward.

In another study by McKee *et al.* (McKee, Williamson et al. 2002), a similar typodont within a skull was constructed, this time investigating the accuracy of four different panoramic machines in determining the projection of mesiodistal tooth angulations. Similar results were found, in which the majority of image angles from the four different units were statistically significantly different from the true angle measurements. Definite trends included findings in the maxillary arch, where the images projected the anterior roots more mesially and the posterior roots more distally, creating the appearance of exaggerated root divergence between the canine and first premolar. In the mandibular arch, the images projected almost all roots more mesial than they really were, with the canine and first premolar the most severely affected. The largest angular error between adjacent teeth occurred between the mandibular lateral incisor and the canine, with actual root parallelism projected as root convergence on the panoramic film.

Diagnostic Tool – Cone-beam Computed Tomography (CBCT)

Three-dimensional (3-D) imaging of hard tissues has been an important diagnostic tool in the medical field since the 1970s. However, the medical helical and spiral CT (3D-CT) has certain limitations that are drawbacks for use in the dental field: much higher radiation dose, access of the modality, a higher financial cost, and low image resolution (Tantanapornkul, Okouchi et al. 2007). Conventional medical CT devices image patients with a high output rotating anode generator in a series of axial plane slices that are captured either as stacked slices or from a continuous spiral motion over the axial plane using a fan-shaped x-ray beam (Hounsfield 1973).

With the recent development of Cone-beam Computed Tomography in the late 1990s (Mozzo, Procacci et al. 1998; Arai, Tammisalo et al. 1999), which was specifically designed for craniofacial imaging, clinicians in the dental field have been using it as a valuable diagnostic tool. Machines such as the Hitachi MercuRay (Hitachi Medical Technology, Tokyo, Japan) uses a low energy fixed anode tube which produces a cone-shaped x-ray beam, and captures the image with a special image intensifier, a solid state sensor or an amorphous silicon plate. The CBCT requires only a single 360-degree rotation sweep of the patient, similar to the path of panoramic radiography. Image data can be collected for either an entire maxillofacial volume or focused on a specific region of interest (Yamamoto, Ueno et al. 2003). This alternative to traditional medical 3D-CT possesses a reduction in radiation dosage, cost, size, and image artifacts (Holberg, Steinhauser et al. 2005; Scarfe, Farman et al. 2006; Cha, Mah et al. 2007).

The rendered three-dimensional information has been used to diagnose and treatment plan numerous dental procedures such as canine impactions and their subsequent surgical exposure (Walker, Enciso et al. 2005), orthognathic surgery (Cevidanes, Bailey et al. 2005), temporomandibular joint (TMJ) disorders (Hintze, Wiese et al. 2007), implant placement, and airway (Aboudara, Nielsen et al. 2009). In addition, incidental findings in the airway and TMJ, and the presence of endodontic lesions, could be found with CBCT examination (Cha, Mah et al. 2007). Recent studies have assessed the use of three-dimensional (3-D) cone-beam CT for orthodontic treatment and diagnosis (Huang, Bumann et al. 2005). Specifically, cone-beam CT was shown to be more accurate in measuring root angulation than panoramic images (Peck, Sameshima et al. 2007).

Previous Root Angulation Studies

Previous studies have evaluated the accuracy of mesiodistal root angulation on panoramic film. Lucchesi *et al.* (Lucchesi, Wood et al. 1988) used a mandibular Plexiglass model to investigate the suitability of panoramic radiograph for assessment of the mesiodistal angulation of teeth in the buccal segments of the mandible. Steel pins were placed in the model at known angulation, and were then radiographed with both panoramic and plane-film techniques. These measurements were compared to the actual angulation. They found that the degree of deviation from normality was greater with the panoramic technique; this difference was accentuated with increased lingual inclination of the steel pins. In addition, the group concluded that root parallelism interpretation from radiographs is a subjective assessment; the degree of disagreement between either radiographic technique from the actual situation may be of limited importance. Perhaps the degree of error associated with the use of panoramic radiographs is within the range of error of perception of the practitioner. They suggested further research directed toward the practitioner's ability to discriminate different degrees of root angulation (and parallelism).

A similar study was conducted by Owens and Johal.(Owens and Johal 2008) They compared the mesiodistal root angulation measured on a panoramic radiograph to the actual mesiodistal root angulation of teeth in a typodont set-up. Their results revealed that only 26.7% of the panoramic radiographic root angulations were within the clinically acceptable angular variation range of ±2.5°. The greatest variation in the upper arch occurred in the canine-premolar area where the roots were projected as being more divergent; and in the lower arch, it was between the lateral incisor and canine region where these roots were projected as being more convergent. These results were similar to the results from the previous mentioned study by McKee *et al.*(McKee, Williamson et al. 2002).

Recently, a study by Peck *et al.* (Peck, Sameshima et al. 2007) investigated whether the panoramic projection can accurately determine mesiodistal root angulations. Five subjects' plaster study models were used to fabricate radiographic stents that marked the approximate root angulation of various teeth throughout the dental arch. The subjects then had panoramic and CBCT scans taken with the stent seated on the dentition, and root angulations for each of the radiographic images were measured and compared to the plaster model (used as a gold standard). Results showed the CBCT scan produced very accurate measurements of root angulation, while the panoramic projections did not provide reliable data on root angulation. More specifically, with the panoramic measurements, the maxillary anterior roots were over-inclined in a mesial direction, and posterior roots were over-inclined in a distal direction compared to CBCT measurements. Mandibular roots generally showed excessive mesial angulation. They also found that the largest deviation on the panoramic image was between maxillary canines and first premolars, where average angular differences were ten degrees. This creates an illusion that there is an exaggerated root divergence between these teeth. If one were to rely on this image to reposition the brackets and tip the teeth until the roots appeared parallel on the panoramic image, it would actually create excessive convergence of the canine and first premolar roots. While this study confirms that there are differences between panoramic and CBCT root angulation, it lacks the investigation of detecting a *clinical* significance. Would clinicians actually choose to reposition the tooth to obtain parallel roots by looking at patients' panoramic and CBCT images?

Rationale and Significance

Cognizant about the inherent distortion of traditional panoramic radiographs, orthodontic clinicians may not have sufficiently accurate information to detect root position errors in order to decide which brackets will require repositioning to achieve parallel roots. This could lead to difficulty in achieving alignment of the teeth, level marginal ridges, and possibly a compromised finished occlusion. In addition, efficiency is reduced as more time is required during the finishing stage of treatment to make adjustments in the archwire with detailing bends. Past studies have shown that 3-D CBCT is more accurate at measuring mesio-distal root angulation than traditional 2-D panoramic radiography. This study will first attempt to verify this claim, and subsequently, determine if practitioners are able to discriminate a clinically significant difference in root angulation within a given sample of subjects (indicated by a clinician's decision to reposition a tooth) when viewing 3-D CBCT images and 2-D panoramic radiographs.

Overall Objective

The broad scope of this study is to compare the diagnostic value of 3-D cone beam computed tomography against traditional 2-D panoramic radiographs in evaluating the mesiodistal root angulation of teeth.

Specific Aim #1:

To compare the actual mesiodistal root angulation of teeth on a typodont model to the mesiodistal root angulation as measured on the panoramic radiograph and 3-D CBCT, and to verify that 3-D CBCT is more accurate.

Specific Aim #2:

To compare the perceived diagnostic differences in the quantity, location, and direction of necessary root repositioning identified by independent 3-D CBCT and panoramic assessment by the same orthodontic examiner.

Specific Aim #3:

To compare the perceived differences in the quantity, location, and direction of necessary root repositioning identified by 3-D CBCT and panoramic assessment between different orthodontic examiners.

Specific Aim #4:

To evaluate which radiographic method (CBCT or panoramic) clinicians felt more confident using to diagnose root position.

Specific Aim #5:

To assess whether a clinician's comfort level with using CBCT influenced their confidence in using this method to diagnose root positioning.

MATERIALS AND METHODS

PART 1: Testing the Accuracy of Root Angulation Measurement using Panoramic vs. CBCT Images

Typodont Model – Establishing the Gold Standard

A plastic typodont with direct visualization of both the crowns and roots of the dentition from second molar to second molar was used as the gold standard with which to compare root angulation in panoramic and CBCT images (Figure 4). The crown tip and root apex (or furcation, if posterior tooth) of each tooth was marked with 2-mm metal ball bearing (St. John Companies, Inc., Santa Clarita, CA), serving as radiographic markers. A line joining the two balls represented the long axis of the tooth. A 0.0175 x 0.0175 inch stainless steel archwire was secured on both upper and lower arches across the center of the facial surfaces of each tooth to create a horizontal reference planes from which to measure relative root angulation.

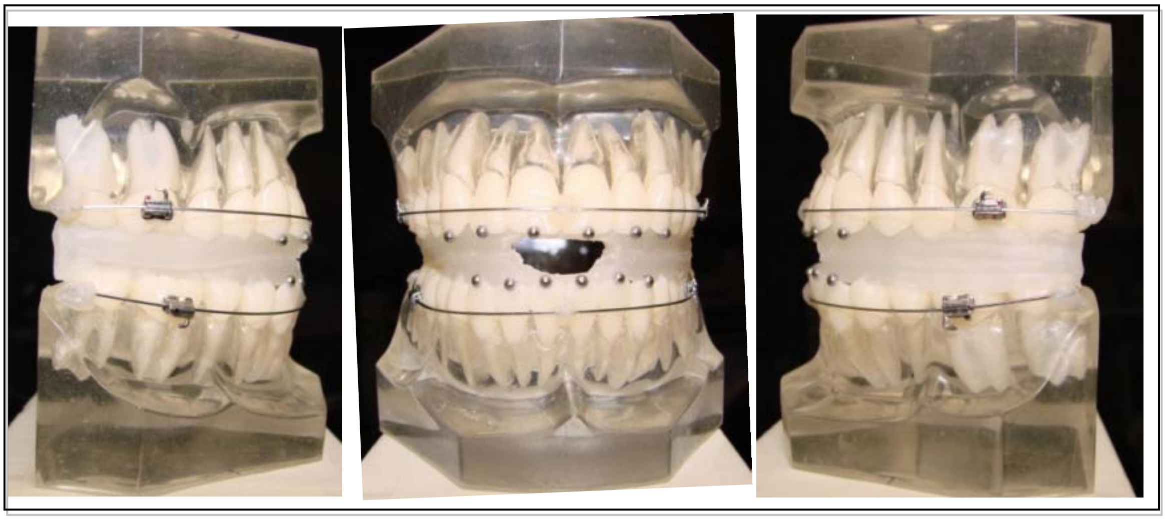


Figure 4. Pictures of the typodont model used as the Gold Standard.

A traditional two-dimensional panoramic radiograph (Planmeca ProMax, Planmeca USA, Roselle, IL; Figure 5) and a cone-beam computerized tomography (CBCT) data scan in DICOM format (Hitachi MercuRay, Hitachi Medical Technology, Tokyo, Japan; Figure 6) were taken of this typodont. The Hitachi MercuRay charge-coupled sensor device with a rotating source gantry captured an image of the model, a process similar to panoramic radiography. A 10-second scan acquired 288 primary images in a 12" diameter spherical volume field of view with 0.376 mm^3 voxel and 12 bit (2^{12} = 4096 shades of gray) resolution. The x-ray source was generated with a voltage of 120-kV and a current of 15-mA for each scan. The position of the model was measured and marked within each radiographic unit to allow accurate repositioning within each machine on different occasions (repeated three weeks later). All images and measurements were taken by the same certified radiologic technologist.

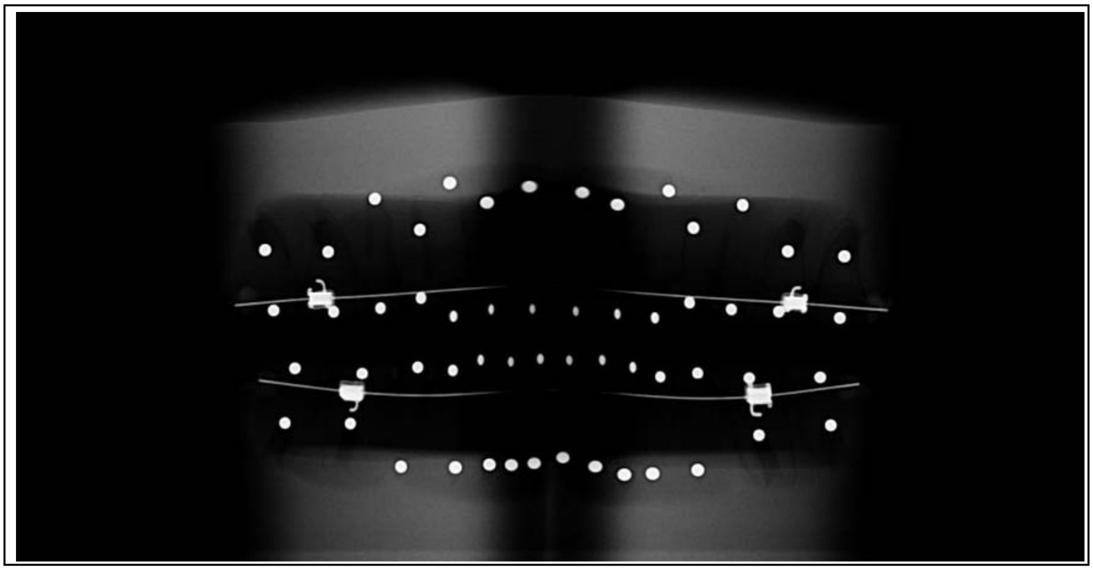


Figure 5. Panoramic radiograph of typodont model. A line connecting the opaque circles at the tip and apical base of each tooth define the long axis of each tooth.

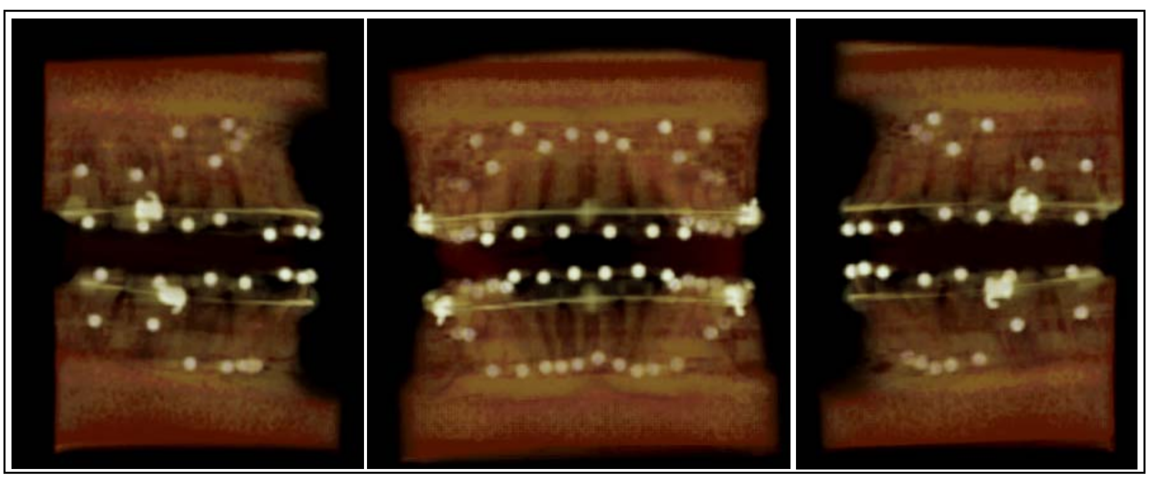
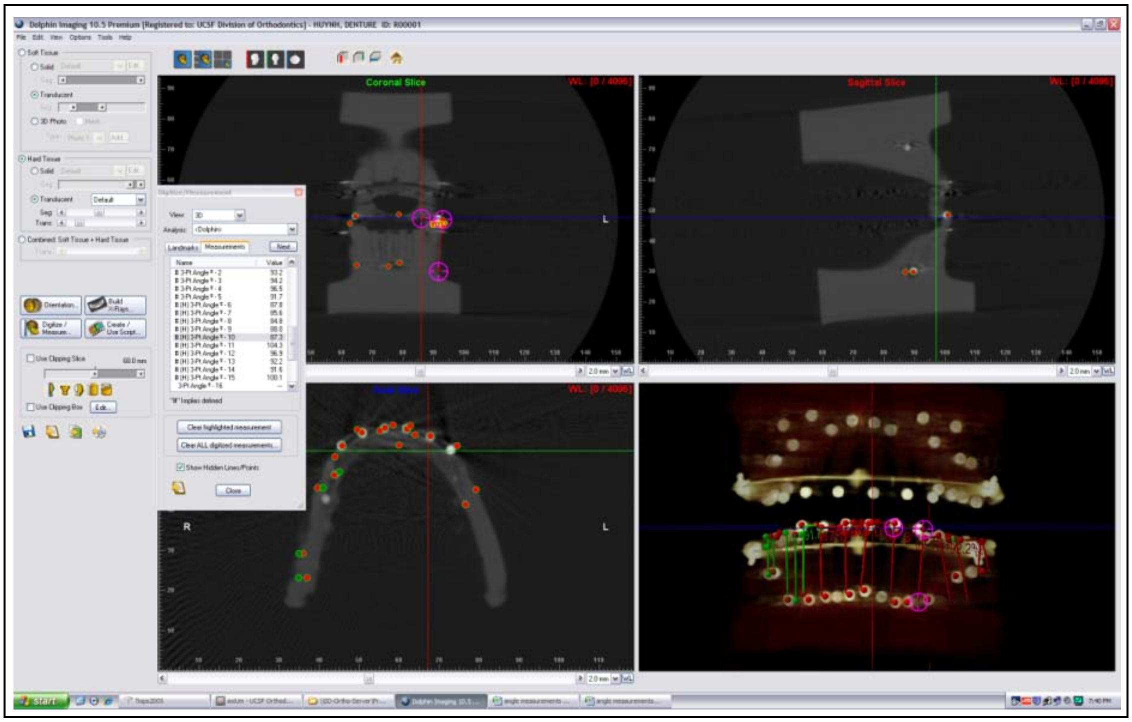
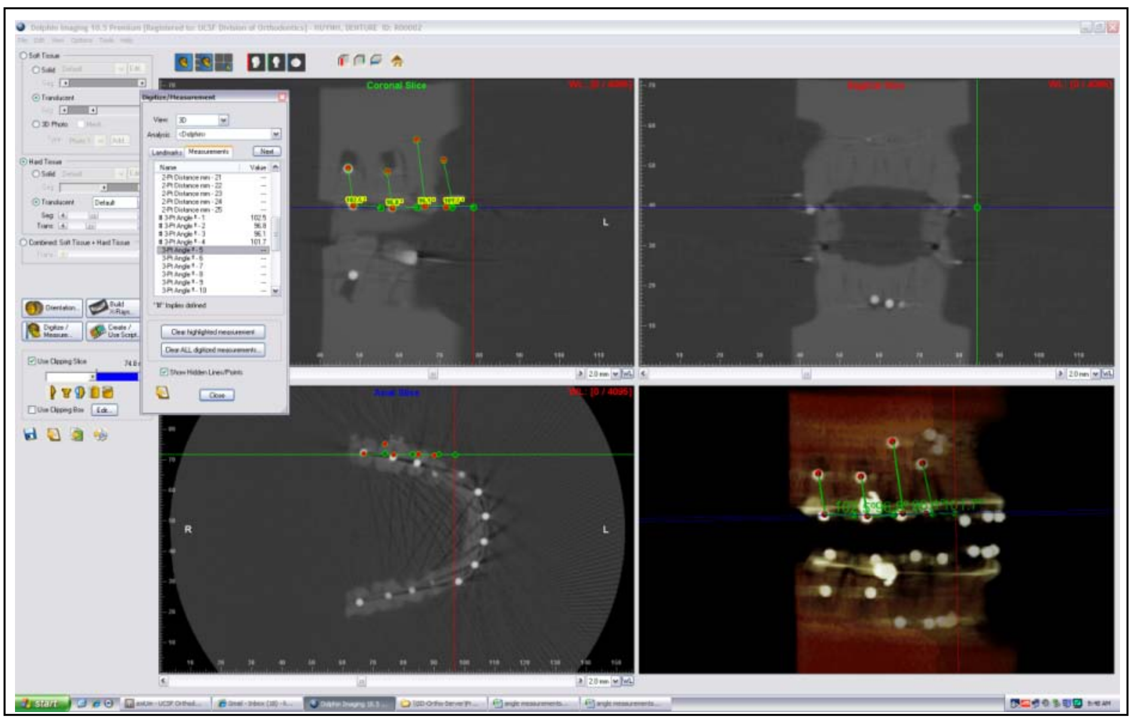


Figure 6. CBCT volumetric images of typodont model, viewed using Dolphin Imaging software.

The root angulation was measured for each tooth (third molars excluded) on the typodont, panoramic images, and CBCT images. The root angulation was measured as the angle formed from the intersection of the long axis of the tooth (line connecting the apical and incisal metal marker) to the horizontal reference plane (stainless steel archwire) in the respective arch. The panoramic images were printed on photo paper (Epson Premium Photo Paper – Glossy) using a photo-quality inkjet printer (Epson Stylus Photo R800). Root angulation was measured on the two-dimensional flat paper. The CBCT DICOM data was loaded into 3-D Dolphin (Dolphin Imaging software program version 10.1, Chatsworth, CA). Using all of the four available views (sagittal, transverse, vertical, and volumetric), each metal marker was identified as a landmark with a numerical X-Y-Z coordinate (Figures 7 and 8). The angular measurement tool in 3-D Dolphin was used to calculate the angle formed by the long axis of the tooth (defined by the apical & incisal/occlusal 3-D landmarks) and the horizontal reference plane. The angulations of each tooth to the archwire were measured twice, 1 week apart, for each image. This was to assess repeatability of measurement technique.





Figures 7 and 8. Root angulation measured with 3-D Dolphin. Frontal view (top), lateral view (bottom).

PART 2: Clinical Application

Subjects

Forty-four consecutive subjects scheduled for their routine bracket repositioning appointment were identified in the Orthodontic Clinic at the University of California at San Francisco (UCSF). The subjects ranged in age from 12 years 3 months to 26 years 1 month (mean = 16 years 2 months ± 3 years 11 months) with 12 male and 13 female. All identifying patient information was removed, including name, sex, age, and race. For each subject, both a traditional two-dimensional panoramic radiograph and a cone beam computerized tomography (CBCT) data scan in DICOM form were obtained, using the same x-ray machines and methods as used for the typodont.

This study was approved by the UCSF Institutional Review Board, the Committee on Human Research. Informed consent to participate in this study was obtained from each subject or, in the case of minors, their parent or guardian.

Radiographic Images

All panoramic and CBCT images were screened for exclusion criteria including: poor quality of x-rays, obvious identifiers of the subject (i.e., implants, multiple missing teeth), or potential confusion in identifying teeth (i.e. transposed teeth, one missing lower incisor). After careful evaluation, twenty-five subjects were used in this study; the remaining subjects were removed based on the exclusion criteria listed above. Three subjects were randomly chosen for repeating evaluation to test for intra-examiner reliability.

Evaluation Criteria

Before beginning, each examiner was given a demonstration/tutorial on 3-D Dolphin on how to manipulate the image (moving/rotating the image, slicing the image, and changing the contrast of tooth and bone) as part of the calibration process. Instructions given to the examiners are provided in Appendix A.

The criterion for repositioning was based on the American Board of Orthodontics (ABO) standards of a 1-mm or less deviation of the root apex between adjacent teeth. A data collection worksheet was developed that asked examiners to identify every tooth they felt needed to be repositioned in order to obtain parallel roots, and which direction the tooth needed to be moved (mesial or distal). This worksheet was generated for each subject’s panoramic and CBCT image. At the conclusion of the data input session, a questionnaire (Appendix B) was given to each examiner to evaluate their diagnostic confidence in using panoramic and CBCT images to assess root positioning. A scale of 1-10 (1 being least confident, 10 being most confident) was used.

The presentation order of the subjects’ panoramic and CBCT images was randomly produced with a random number generator (www.randomizer.org). Twenty-five subjects, with 3 repeated, produced a total of 56 images (28 panoramic and 28 CBCT images) to be evaluated. Five orthodontic faculty members and five 2nd-year orthodontic residents at the UCSF orthodontic program participated in the study. Three of the faculty members had more than 10 years of clinical orthodontic experience, while two had less than ten years of clinical experience. Each faculty member and resident routinely incorporated bracket repositioning as part of his/her treatment protocol, and, thus, was familiar with the progress repositioning procedure. All 56 images were evaluated in one sitting by each examiner. The time to evaluate all images ranged from 45 minutes to 6 hours.

A pilot study was performed with four 3rd-year UCSF orthodontic residents. The aim of the pilot study was to validate and refine the study protocol and questionnaire. Five subjects (with one repeated) were evaluated. Based on the feedback from the examiners, the study was refined. The length of time to load the DICOM data for each CBCT image was the rate-limiting step in the pilot study. Thus, examiners in the actual study used two computers (with identical physical hardware and monitor type) to view the data (the DICOM data for one subject would be loading on one computer while the examiner viewed images on the second computer). If a subject was missing teeth (*i.e.*, in extraction cases), the tooth number was crossed off of the worksheet to make it less confusing for the examiner. Lastly, the criteria to evaluate which teeth should be adjusted to achieve root parallelism needed to be defined. Without a clear definition, the pilot examiners found themselves selecting teeth based on clinical experience. Therefore, to minimize subjectivity, ABO grading standards were used in which root parallelism was considered a deviation of the apex from the adjacent root of 1-mm or less (Casko, Vaden et al. 1998).

RESULTS

PART 1: Accuracy of Measuring Root Angulation on Panoramic and CBCT Images Compared to the Gold Standard

The typodont angulation measurements with metal markings identifying the long axis of each tooth served as the Gold Standard with which to compare the panoramic and CBCT angular measurements. Measurements on the typodont were taken two times, one week apart, and then averaged. Measurements on the panoramic and CBCT images were taken four times each (the typodont was imaged two times, and each image was measured twice), and then averaged. Raw angular measurements using all three methods are provided in Appendix C. Figures 9 and 10 compare the raw angular measurements using all three methods. In general, the CBCT measurements more closely resemble the actual measurements than the panoramic measurements do.

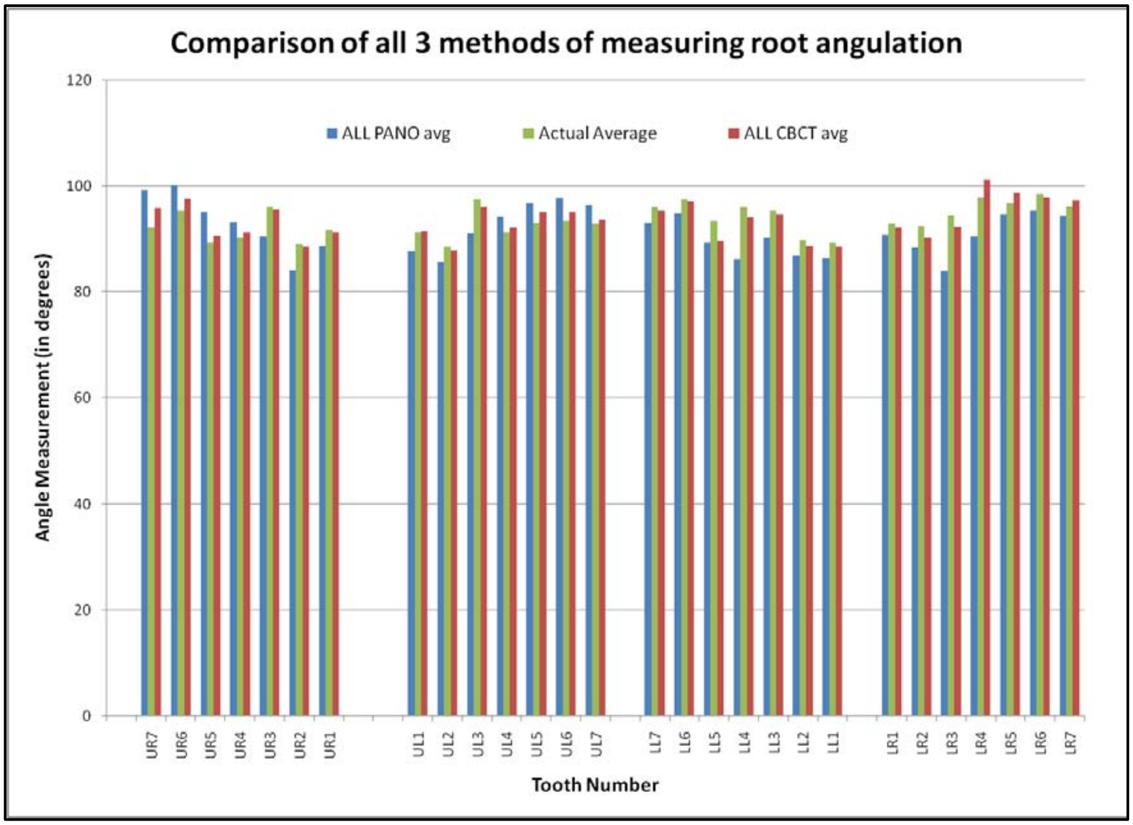


Figure 9. Bar graph comparing the angular measurements from the panoramic (blue) and CBCT (red) images to the actual measurements on the typodont (green).

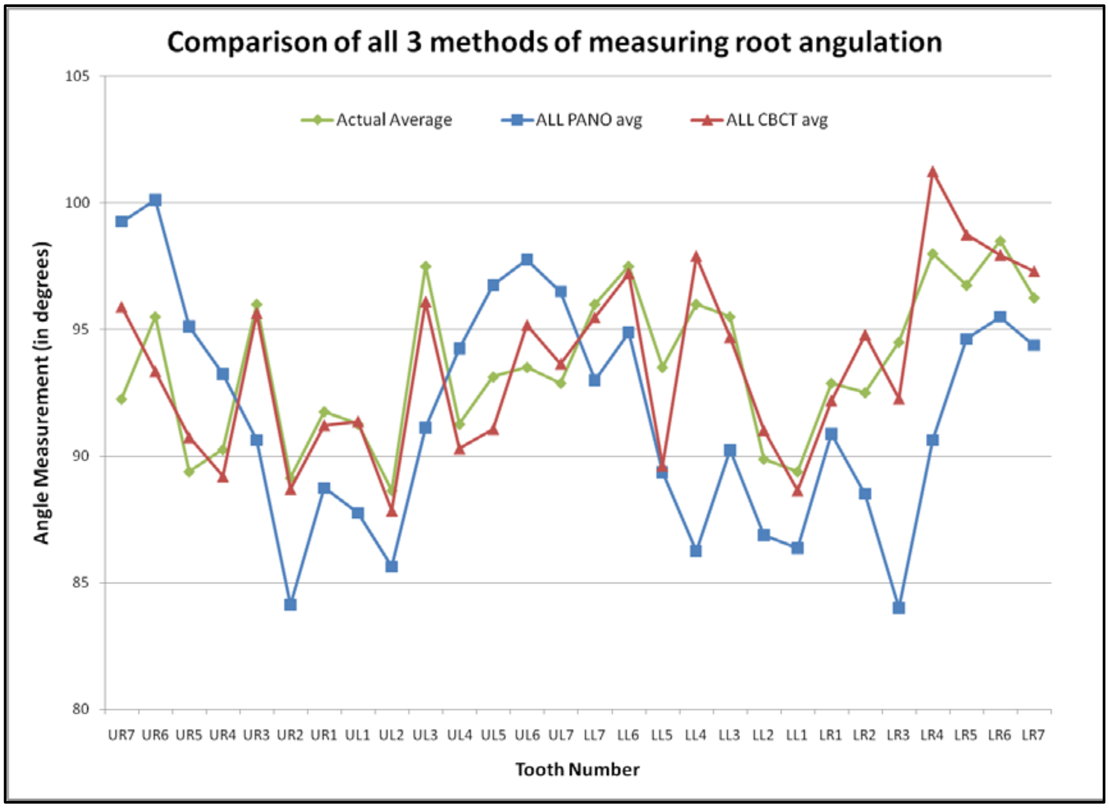
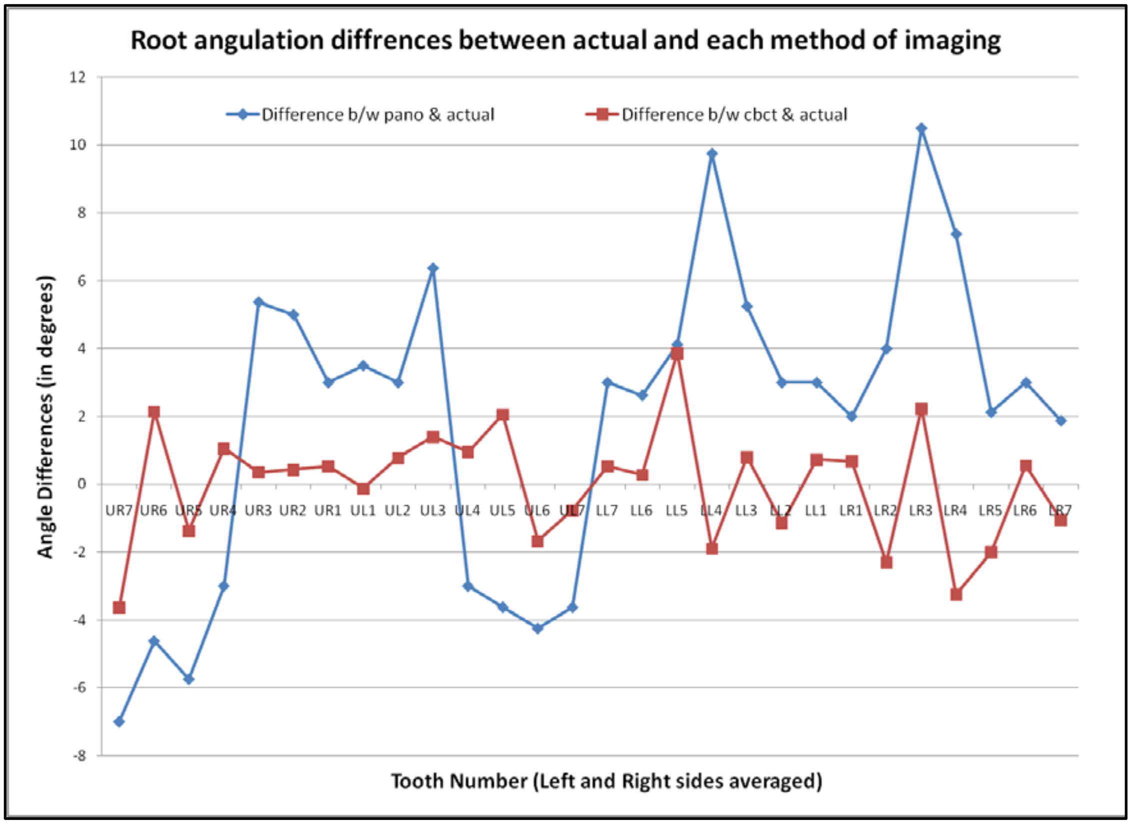
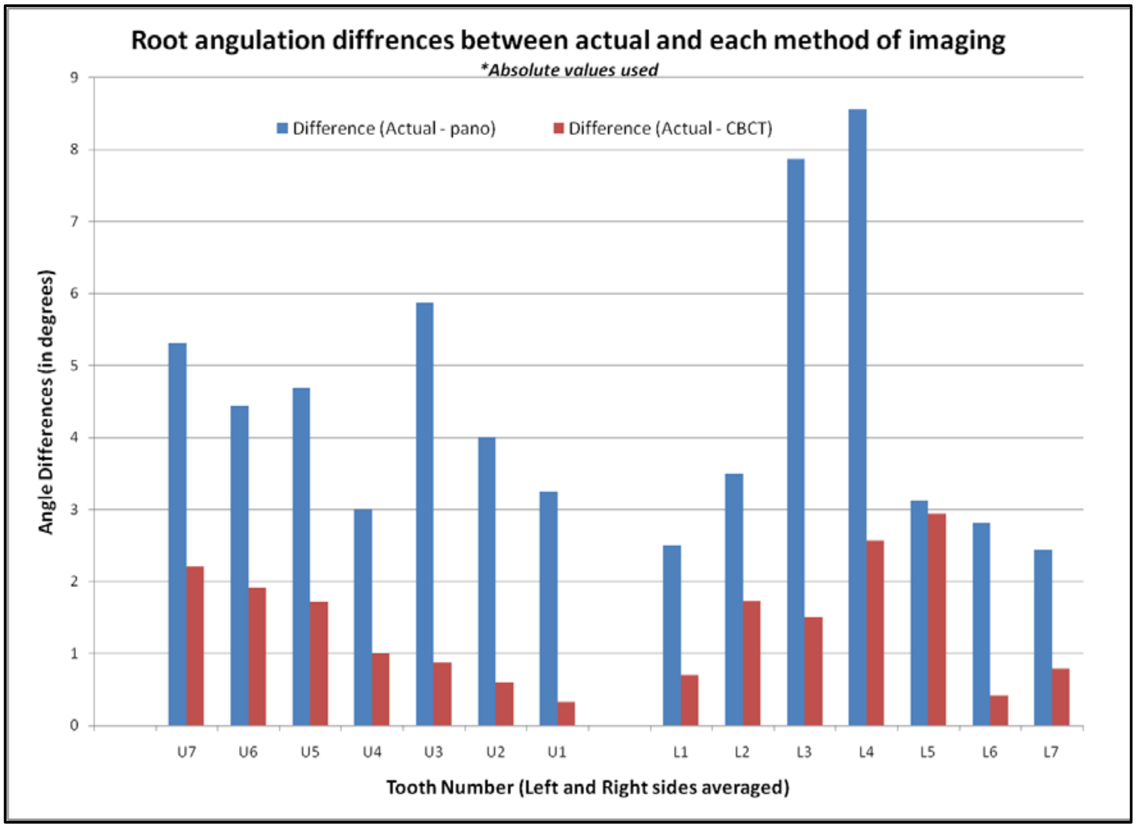


Figure 10. Line graph comparing the angular measurements from the panoramic (blue) and CBCT (red) images to the actual measurements on the typodont (green).

The difference between the actual measurements and each of the two radiographic methods (panoramic and CBCT) was calculated to represent the amount of disagreement between the two measures, also known as the "bias." The raw data of the differences is provided in Appendix D. The right and left side angular measurements of the same type of tooth (*i.e.* maxillary left and right second premolars) were shown to have no statistically significant difference (two-tailed paired t-test, $P<0.05$), and thus they were combined for graphic simplicity. Figure 11 is a line plot comparing the raw angular differences between the actual versus each method of imaging, whereas Figure 12 is a bar graph showing the *absolute value* differences between the two methods. Paired t-test calculations reveal that there is a statistically significant difference between the actual and panoramic differences versus the actual and CBCT differences (P=0.0515).



Figures 11. The raw angular differences between actual angulation and each method of imaging (panoramic or CBCT), measured in degrees. The right and left sides of the same tooth were combined and averaged.



Figures 12. The absolute differences between actual angulation and each method of imaging (panoramic or CBCT), measured in degrees. The right and left sides of the same tooth were combined and averaged.

The difference between actual measurements and measurements on the panoramic image for each tooth ranged from -7° to +10.5°, and the mean difference was 1.85° (± 4.58°). The absolute difference was 4.38° ± 2.17°. The 95% confidence interval (mean ± 1.96 StD), representing the limits of agreement, was -7.32° to +11.02°. The difference between actual measurements and measurements on the CBCT image for each tooth ranged from -3.65° to +3.875°, and the average difference was 0.003° (± 1.698°). The absolute difference was 1.38° ± 1.01°. The 95% confidence interval was -3.399° to +3.393°. The mandibular canine and first premolar panoramic angular measurements exhibited the greatest deviation from the actual angular measurements.

A Bland-Altman analysis, which plots the average actual measurements against the difference between the two methods, was used to assess the level of agreement between the imaged measurements and the established gold standard (Figures 12 and 13). The resulting scatter plot serves as a visual judgment of how well each of the two methods of imaging agrees with the gold standard. The location of each type of tooth – maxillary posterior, maxillary anterior, mandibular posterior, mandibular anterior – was color-coded to show any trends in angular differences.

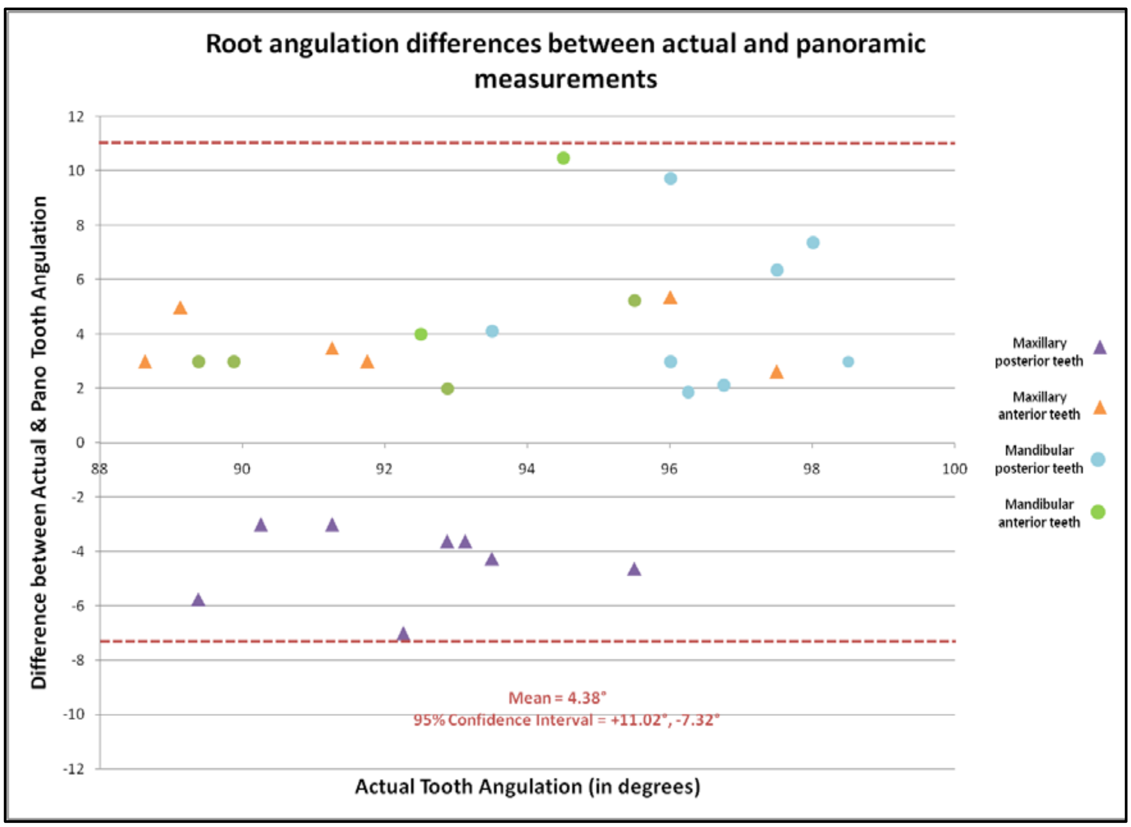


Figure 13. Bland-Altman Analysis of root angulation differences between the actual and panoramic measurements, with 95% confidence interval.

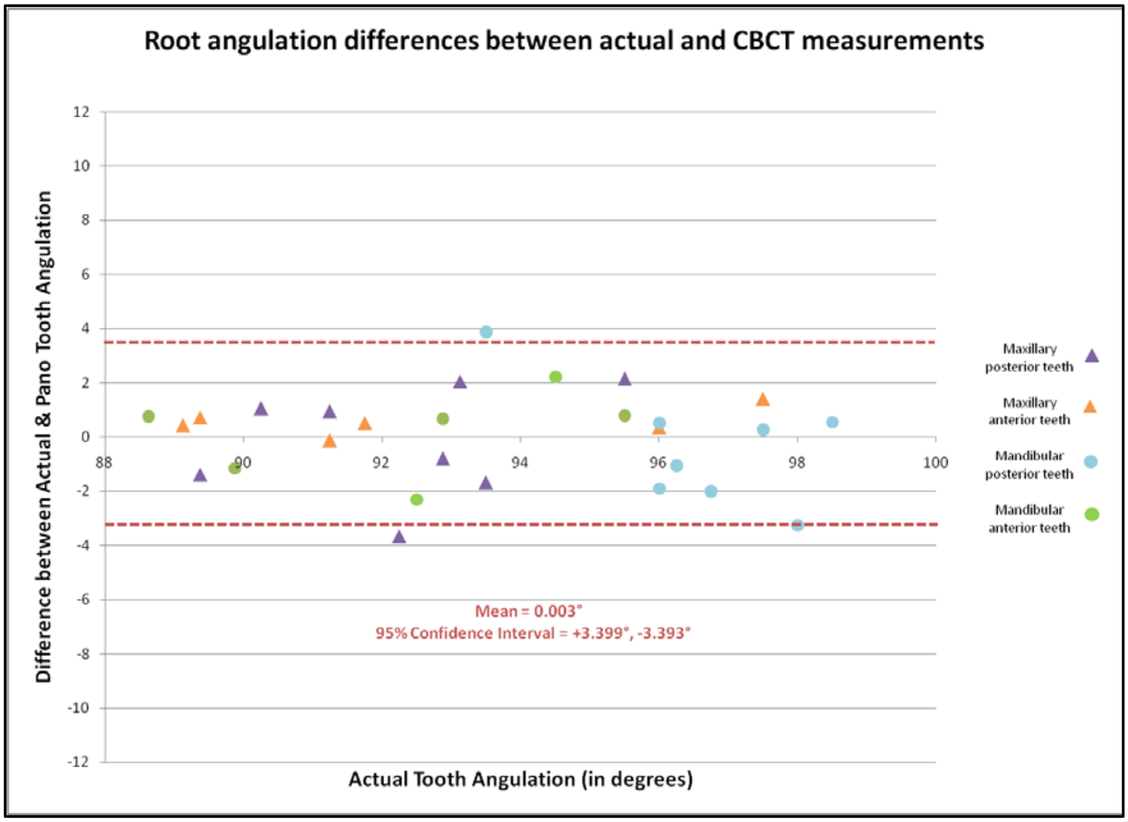


Figure 14. Bland-Altman depiction of root angulation differences between the actual and CBCT measurements, with 95% confidence interval.

From the calculations and representative figures, the CBCT angular measurements more closely matched the actual measurements than the panoramic measurements (P<.05). The panoramic angular measurement of each tooth showed much more deviation from the gold standard measured directly from the typodont.

PART 2: Clinical Application

Intra-examiner Repeatability

Three subjects were analyzed twice by the judges in the study to test for intra-examiner repeatability (Figure 15). The average percent error/disagreement for each examiner looking at the repeated panoramic images was 6.19% ± 2.5%, with a range of 2.98% to 10.12%. The average percent error/disagreement for each examiner looking at the repeated CBCT images was 6.31% ± 1.32%, with a range of 4.76% to 8.33%. This reveals that the percent of error was similar between both methods. Because the error was 10.12% or less, this shows the examiners are generally consistent with their repositioning decisions, regardless of the type of image media they evaluated. A two-tailed paired t-test reveals that there was no statistically significant difference between the percent error with the panoramic radiograph and the CBCT (P=0.896).

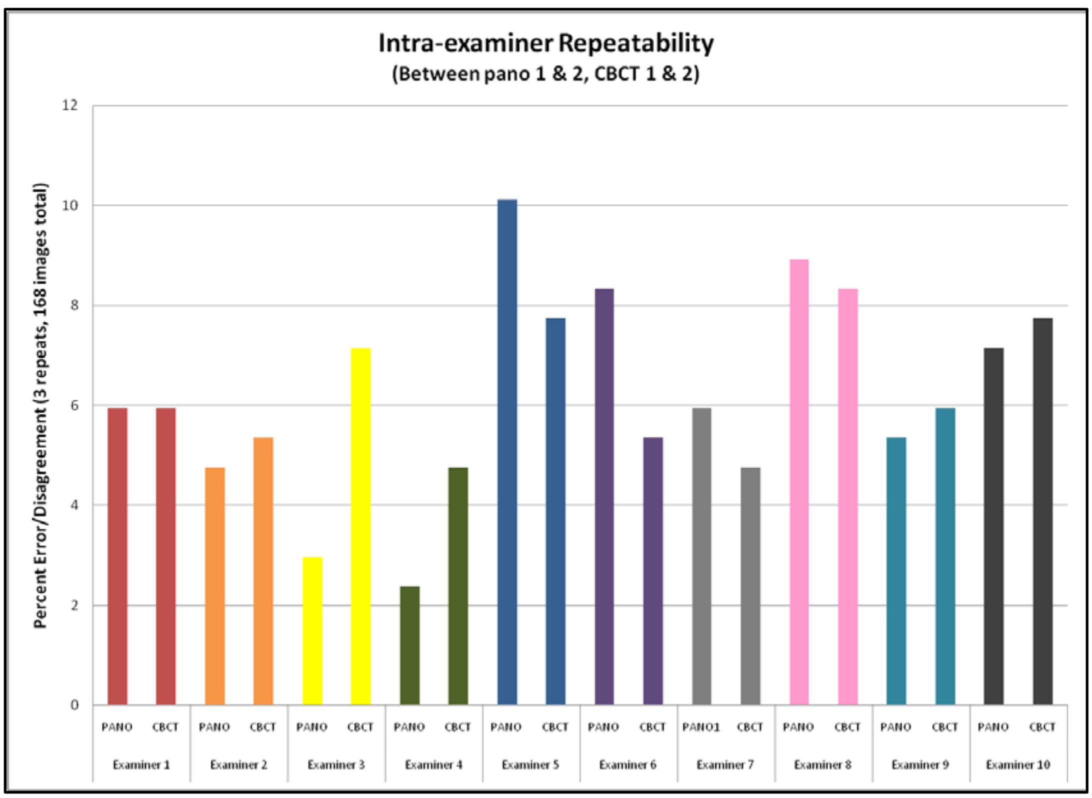


Figure 15. Intra-examiner repeatability based on 3 repeat subjects. Disagreement was measured as percent error.

Distribution of Data

Variation in detection existed between all of the teeth being evaluated for root repositioning (Figure 16). We first used a paired t-test to compare the same tooth between the sides of the arch and found no difference; thus we were able to combine the left and right side data to increase the sample size during comparisons of groups ($p = 0.934$ in upper arch, $p=0.403$ in lower arch). The number of times a tooth was chosen to be repositioned ranged from 72 to 294 times. Some teeth were chosen more often than others to be repositioned. The most commonly repositioned teeth, whether it was from the panoramic image, the CBCT volume, or both, were the mandibular first premolar (297 times, 29.7%), the maxillary lateral incisor (294 times, 29.4%), and the maxillary second premolar (214 times, 21.4%). The raw data can be viewed in Appendix E.

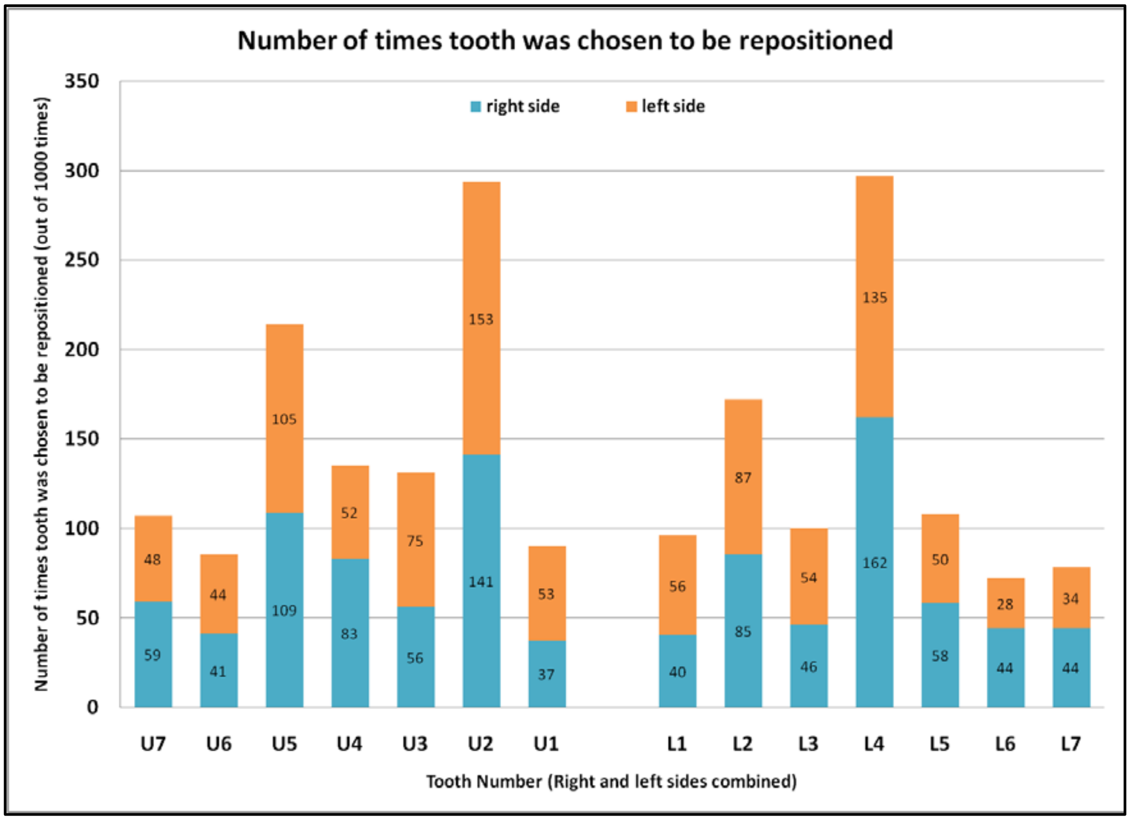


Figure 16. The total number of times an examiner decided to reposition the root (either by the panoramic image, CBCT, or both) is shown for each tooth. Left and right sides of the same tooth were combined.

Agreement and Disagreement Between the Two Methods of Diagnosis

Each examiner looked at 25 subjects' panoramic and CBCT images (50 images total) in a random order to identify which teeth they would reposition to obtain more parallel roots. The results looking at the same examiner evaluating at the same patient, between the two methods, was compared. The number of times in which an examiner decided to reposition a tooth when looking at both the panoramic and CBCT images was tallied. This represented an agreement despite the two different methods of diagnosis (Figure 17).

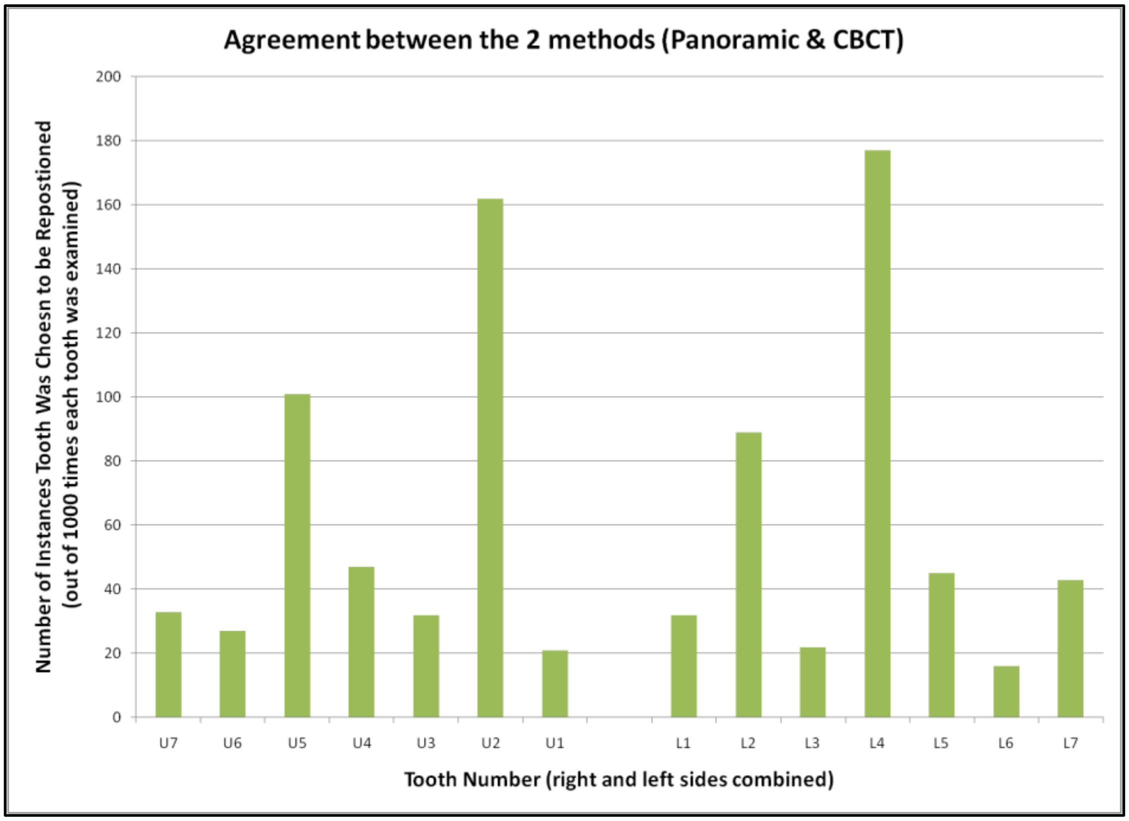


Figure 17. The total number of times in which an examiner decided to reposition a tooth when looking at both the panoramic and CBCT images.

The number of times in which an examiner decided to reposition a tooth based on one image source and not the other (*i.e.* an examiner decided to reposition the maxillary left lateral incisor based on the panoramic image but not on the CBCT image) was tallied. This represents a disagreement between the two methods of diagnosis. The disagreement distribution across all of the teeth examined (28 teeth total) is shown in Figure 18. The most common teeth in which there was a disagreement were the maxillary second premolar, the maxillary lateral incisor, and the mandibular first premolar. In all of these instances, the disagreement surpassed 100 times.

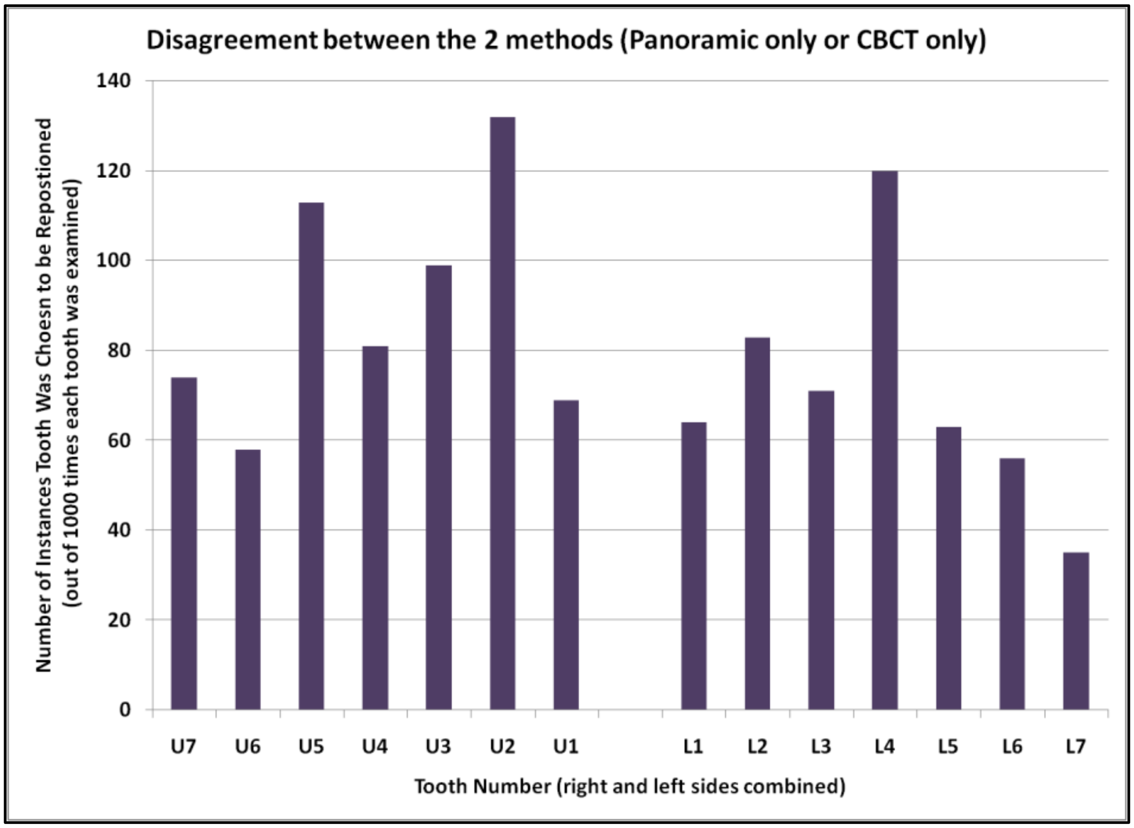
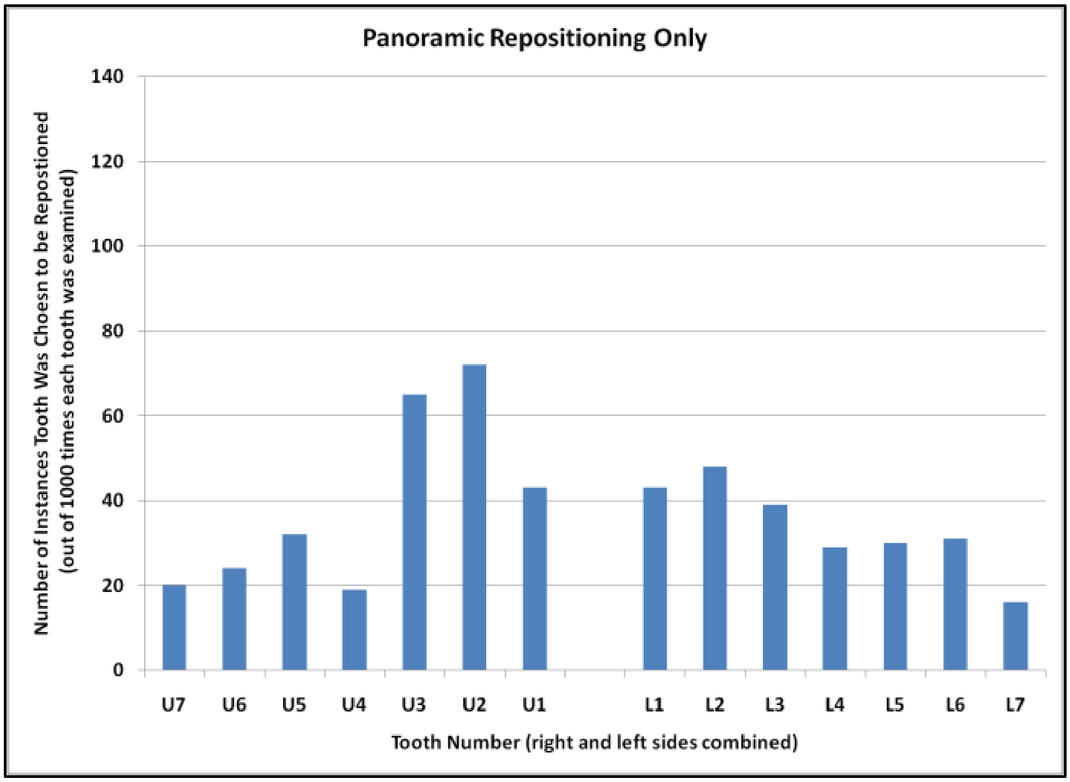
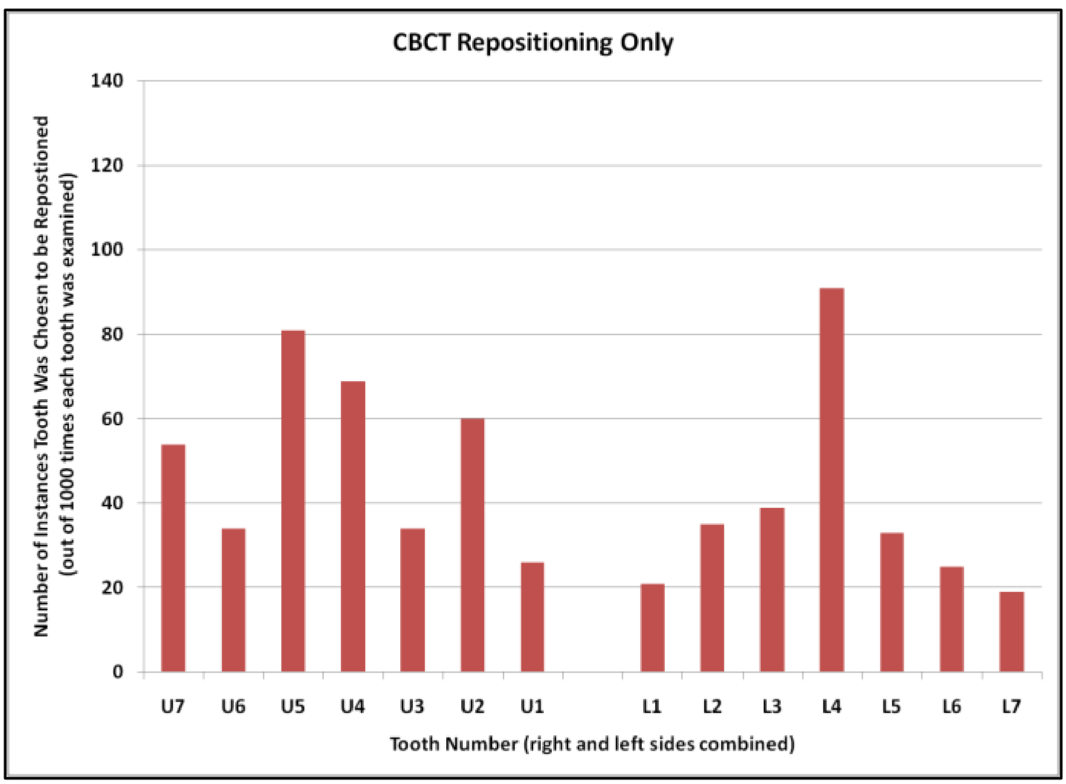


Figure 18. The total number of times in which an examiner decided to reposition a tooth based on one image and not the other.

The number of disagreements can be broken down into instances in which a tooth was chosen to be repositioned when looking at a subject's panoramic image but not their CBCT counterpart (Figure 19), and instances in which a tooth was chosen to be repositioned when looking at a subject's CBCT image but not their panoramic image (Figure 20).





Figures 19 and 20. The total number of times an examiner decided to reposition a tooth based on the panoramic view only (top) or the CBCT view only (bottom).

The most common teeth that were chosen to be repositioned only on the subject's panoramic image only were the maxillary canine and maxillary lateral incisor. The most common teeth that were chosen to be repositioned only on the subject's CBCT image were the maxillary second premolar, and the mandibular first premolar. This data shows that the panoramic views identify different teeth to reposition than the CBCT views.

Specificity and Sensitivity

From Part 1 of the study, it was concluded that the CBCT was more accurate at measuring root angulation than the panoramic image. In a previous published validation article, Stratemann et al. (Stratemann, Huang et al. 2008) used a typodont within a dry skull and metal fiducials to demonstrate that digital CBCT measurements are accurate to 0.01mm. Therefore, we adopted CBCT as the new Gold Standard. Assuming the CBCT is more accurate at measuring root angulation, we can use sensitivity and specificity as statistical measures of the performance of the panoramic radiograph (Table 1).

Specificity measures the proportion of negatives which are correctly identified (*i.e.* percentage of teeth that did not need to be repositioned in the CBCT images and were also not identified as needing repositioning in the panoramic film). The specificity calculations were all above 90%. This suggests that the panoramic radiograph correctly identified over 90% of those teeth that did *not* need to be repositioned.

Sensitivity measures the proportion of actual positives which are correctly identified as such. In this case, instances in which both the panoramic radiograph and the CBCT identified the same tooth to be repositioned were tallied. This would mean that the panoramic diagnosis correctly identified a tooth that needed to be repositioned. The sensitivity calculations varied depending on the specific tooth examined. In 9 out of the 14 teeth, the sensitivity calculation was below 60%. This suggests that the panoramic film correctly diagnosed less than 64.3% of all the teeth that needed to be repositioned.

Tooth	Sensitivity	Specificity
U7	0.38	0.98
U6	0.44	0.97
U5	0.55	0.96
U4	0.41	0.98
U3	0.48	0.93
U2	0.73	0.91
U1	0.45	0.95
L1	0.63	0.98
L2	0.78	0.97
L3	0.40	0.97
L4	0.66	0.96
L5	0.54	0.96
L6	0.31	0.95
L7	0.67	0.95

Table 1. Sensitivity and specificity calculations for using the panoramic images as a diagnostic tool for repositioning. The CBCT served as the gold standard. Calculations below 60% are indicated in red.

Results of the Questionnaire: Confidence Levels

Each examiner was given a questionnaire at the conclusion of this study. This set of questions asked the examiner to rate their confidence level (on a scale of 1-10) using each method as a diagnostic tool to diagnose root repositioning (Figure 21). The average confidence level using the panoramic image was 7.0 and the median was 7 (range of 5 to

10). The average confidence level using the CBCT imaging was 8.5 and the median was 8 (range of 6 to 10).

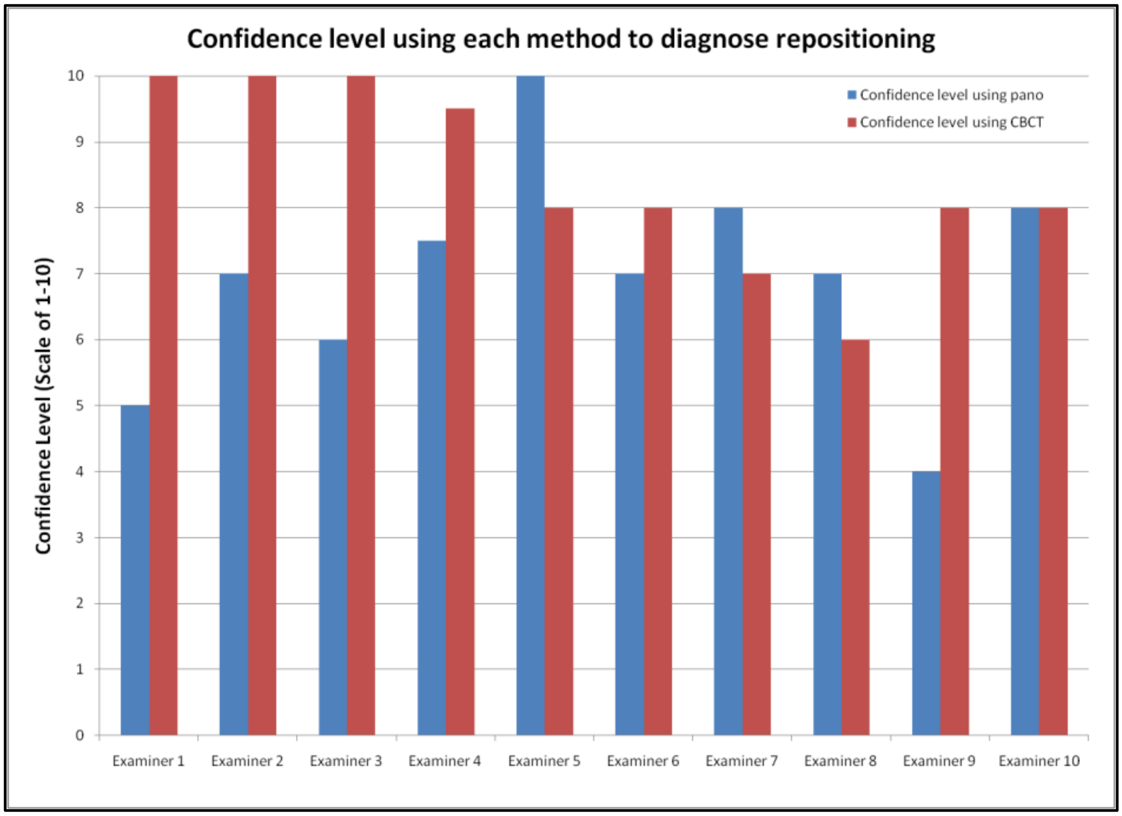


Figure 21. Each examiner's confidence level (1-10, ordinal scale) using panoramic (blue) and CBCT (red) methods to evaluate root positioning.

Each examiner was also asked which radiographic method they felt more confident using to assess which teeth to reposition (Figure 22). Six of the examiners chose the CBCT as the method they felt more confident using to assess root repositioning, whereas four examiners chose the panoramic film. Therefore, examiners felt more confident using the CBCT imaging over the panoramic imaging by a ratio of 3:2.

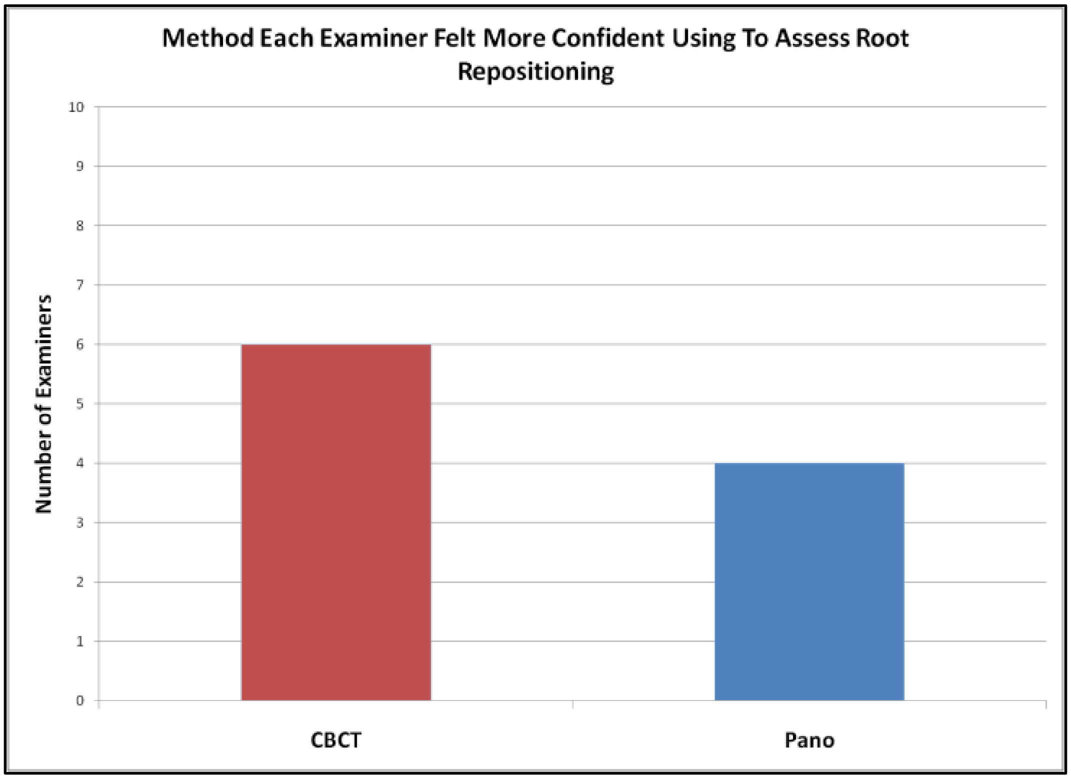


Figure 22. The method of imaging each examiner felt more comfortable using to evaluate root repositioning (CBCT in red, panoramic in blue).

Results of the Questionnaire: Comfort Level Using CBCT

Since CBCT is a relatively new method of imaging and diagnosing in dentistry, the examiners were also asked how comfortable they felt using the CBCT image and software. The average was 8.6 with a median of 9 and range of 5-10 (Figure 23).

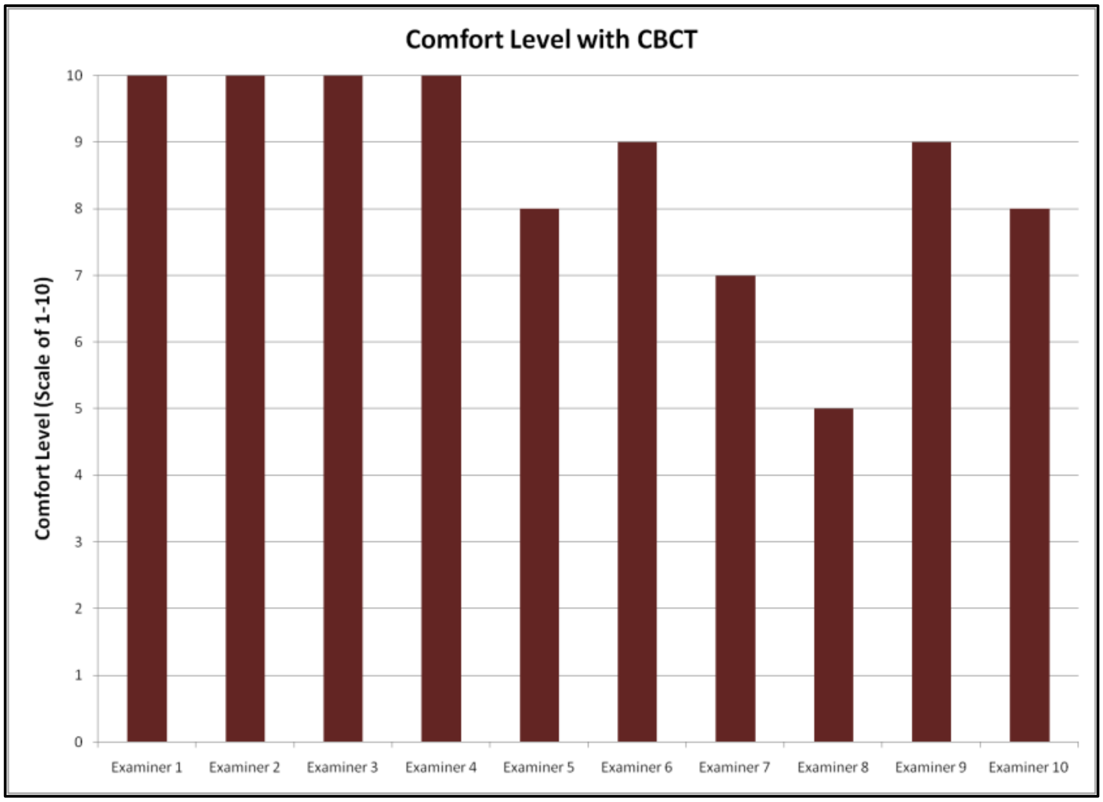


Figure 23. Each examiner's comfort level (1-10, ordinal scale) using the CBCT imaging and software.

Results of the Questionnaire: Relationship Between Comfort and Confidence Levels Using CBCT

The relationship between an examiner's comfort level using the CBCT imaging and software, and whether this was related to his/her confidence level using CBCT to diagnose root repositioning was evaluated using a linear regression analysis. The resultant Figure 24 illustrates the positive correlation (R^2=0.886). Thus, the more comfortable the examiner felt in using the CBCT, the more confident they were in their diagnoses.

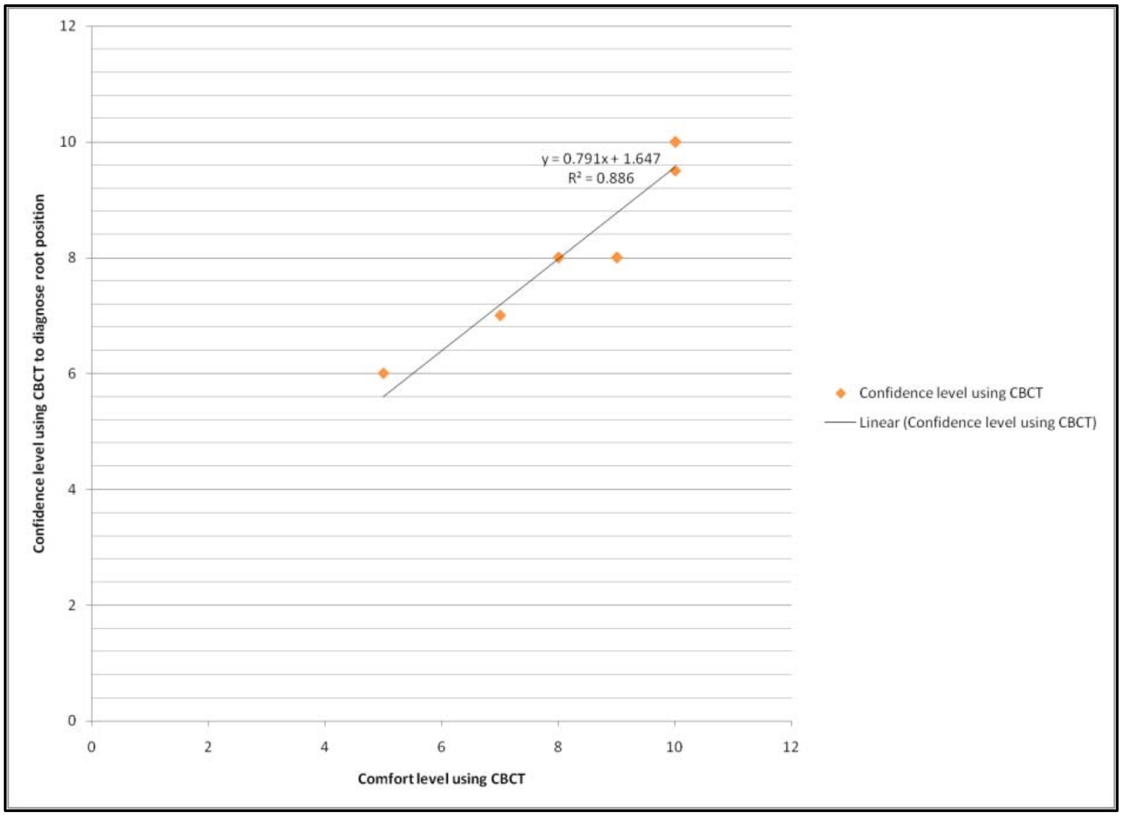


Figure 24. The relationship between each examiner's comfort level using the CBCT imaging software (x-axis) and confidence level (y-axis).

Results of the Questionnaire: Preference in Private Practice

The last question in the study asked examiners to choose which method of imaging they would use for bracket repositioning, assuming both were available. Six examiners chose the CBCT, while four chose the panoramic radiograph. Reasons for choosing CBCT included:

1. The ability to view the image from any angle
2. The ease of use of the Dolphin software
3. Being able to view the roots at a perpendicular angle

4. The more accurate representation of anatomic root structures and less distortion due to the x-ray imaging of the arch/curved structures (i.e. the canine region)
5. The superior precision of the image rendered
6. The increased diagnostic value

Reasons for choosing the panoramic film included:

1. The cost/benefit judgment – does the extra radiation justify the information increase: NO
2. It is less complicated to use
3. It can be used chairside
4. CBCT is cumbersome to manipulate and takes longer
5. The x-ray is used as a quick screening tool; more concern is placed on the angulation of the clinical crown in the mouth
6. The ease of use
7. Less patient radiation

DISCUSSION

An important objective in orthodontic treatment is proper mesiodistal tooth angulation and root parallelism. Orthodontists strive for accurate bracket positioning to facilitate efficient delivery of treatment while minimizing wire bending. Clinical factors such as variations in tooth size and structure, malposition of the tooth in the dental arch, and operator error all lead to brackets that are often placed incorrectly during initial bonding. From past studies, mere visual inspection of the crown is a very unreliable process, and repositioning during treatment may be needed. Using the traditional panoramic radiograph to diagnose root position has its limitations; magnification, distortion, and patient head positioning errors can all contribute to a misleading view of patient's roots. With the advent of 3-D CBCT, it is advantageous to investigate its application and potential accuracy.

Past studies have compared panoramic root angulation to actual root angulations on typodont models and have shown inaccuracies in the panoramic image (Lucchesi, Wood et al. 1988; McKee, Glover et al. 2001; McKee, Williamson et al. 2002; Owens and Johal 2008). In addition, a recent study by Peck et al. in 2007 (Peck, Sameshima et al. 2007) showed that 3-D CBCT was more accurate at measuring mesio-distal root angulation than traditional 2-D panoramic radiography based on a plaster model.

The purpose of this study was two-fold: first, to verify past studies that the 3-D CBCT was more accurate in measuring mesio-distal root angulation than 2-D panoramic radiography based on a typodont model serving as a gold standard; second, to determine if practitioners were able to discriminate a clinically significant difference in root angulation using a sample of twenty-five subjects' panoramic and CBCT images. This investigation is the first study to evaluate the clinical implications of using CBCT images versus panoramic radiography for the diagnosis and treatment planning of root repositioning. Can the practitioner discriminate different degrees of root angulation in patients, and is the degree of error associated with panoramic films clinically significant?

PART 1: Accuracy of Measuring Root Angulation on Panoramic and CBCT Images Compared to the Gold Standard

The angulation of twenty-eight teeth on a typodont model was measured directly (establishing a gold standard) and then compared to measurements taken of the model using panoramic radiography and CBCT. In general, the CBCT measurements more closely resembled the actual measurements than the panoramic measurements did. Further statistical analysis using a Bland-Altman plot assessed the level of agreement between the panoramic or CBCT measurements and the established gold standard.

The average deviation of the panoramic root angulation from the actual measurements was 4.38° (± 2.17°). The 95% confidence interval (mean ± 1.96 StD), representing the limits of agreement, was -7.32° to +11.02°. In comparison, the average deviation of CBCT root angulation from the actual measurements was significantly smaller at 1.38° ± 1.01°. The 95% confidence interval was -3.399° to +3.393°. Not only did the panoramic angular measurement of each tooth show much more deviation from the gold standard, but the distribution of points was more spread out with the panoramic measurements than the CBCT measurements, suggesting less accuracy in measuring the root angulation. A paired t-test confirmed that there was a statistically significant difference between the actual and panoramic differences versus the actual and CBCT differences ($P<.05$).

The angular differences between the actual and CBCT measurements were low and randomly scattered, indicating no specific trend and randomized error. However, there were certain patterns observed with the differences between the actual and panoramic measurements. In the maxillary posterior teeth, the differences were all negative, indicating that the panoramic root position was greater than the actual angulation. This suggests that the panoramic view tends to over exaggerate the root angulation of maxillary posterior teeth as being more distal than they actually are located. In the maxillary anterior teeth, the differences were all positive, suggesting that the panoramic view tends to over exaggerate the root angulation of maxillary anterior teeth as being more mesial than they actually are. In the mandibular arch, the differences for all of the teeth were positive, indicating that the panoramic root angulation was smaller than the actual angulation. This suggests that the panoramic view tends to over exaggerate the root angulation of all mandibular teeth as more mesial than they actually are. The mandibular canine and first premolar panoramic angular measurements exhibited the greatest deviation from the actual angular measurements. The results in both the maxillary and mandibular arches agree with past studies by McKee *et al*. (McKee, Glover et al. 2001; McKee, Williamson et al. 2002), Owens and Johal (Owens and Johal 2008), and Peck *et al*. (Peck, Sameshima et al. 2007). A visual representation of the panoramic discrepancies are featured in Figure 25.

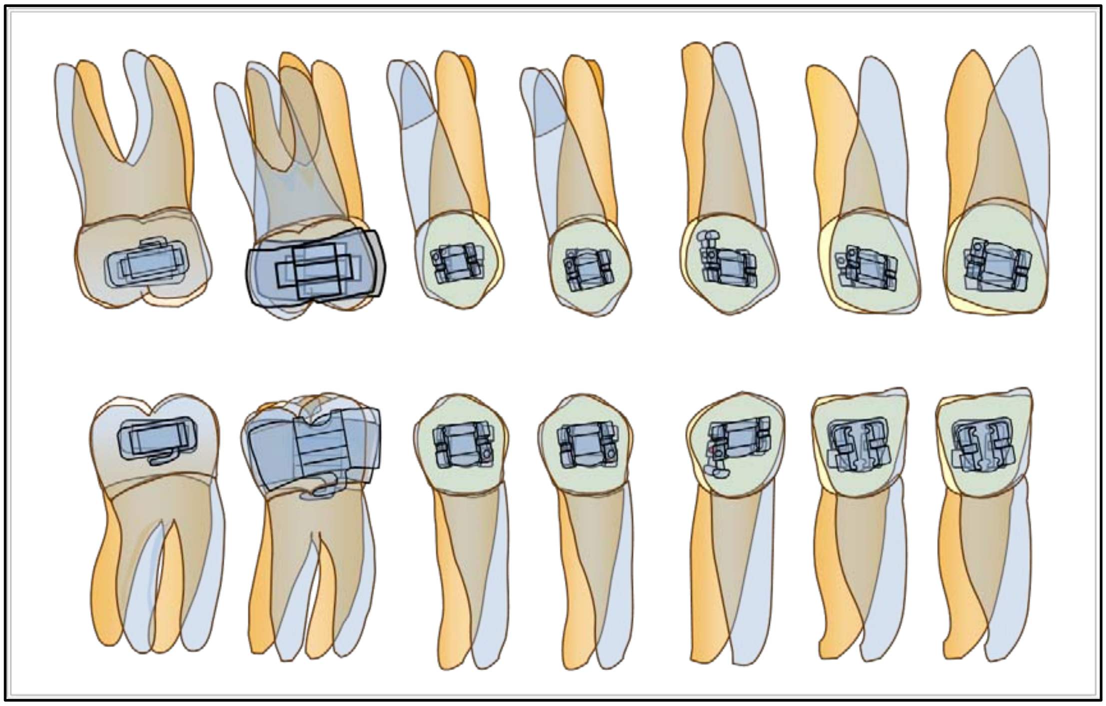


Figure 25. Schematic illustration of the right sided maxillary and mandibular teeth. The beige teeth represent the true angulation of the teeth. The blue teeth represent the perceived angulation of the teeth as seen on a panoramic radiograph. Note, angulation of teeth is not scaled to represent numerical angular differences.

PART 2: Clinical Application

Intra-examiner Repeatability

The average percent error or disagreement for all examiners looking at the three repeated subjects' images was similar between both methods (approximately 6%). A t-test reveals that there was no statistically significant difference between the percent error with the panoramic radiograph and the CBCT (P=0.896). Because the error was almost less than 10% and similar when looking at panoramic and CBCT images, it shows that the examiners are generally consistent in their decision to reposition a tooth, regardless of the imaging method, and that they are equally accurate in root evaluation with both CBCT and panoramic images.

Distribution of Data

A tooth that is difficult to visualize due to its morphology or its malposition in the dental arch may not allow the clinician to perfectly place the bracket in its ideal position. In the pool of subjects from this study, the number of times in which a tooth was chosen to be repositioned whether it was from the panoramic image, the CBCT volumetric image, or both, ranged from 72 to 294 times. This supports past studies regarding the difficulty in achieving accurate bracket placement by using the tooth's clinical crown (Balut, Klapper et al. 1992; Creekmore and Kunik 1993; Armstrong, Shen et al. 2007). Much variation in detection existed between the number and location of teeth needing repositioning. The teeth most often chosen to be repositioned were the mandibular first premolar (29.7%), the maxillary lateral incisor (29.4%), and the maxillary second premolar (21.4%). This agrees with the American Board of Orthodontics observation that the most common mistakes in root angulation in cases submitted for ABO certification occurred in the maxillary lateral incisors, canines, and second premolars, and the mandibular first premolars (Casko, Vaden et al. 1998).

Agreement and Disagreement Between the Two Methods of Diagnosis

The teeth that were chosen to be repositioned can be broken down into instances in which there was an agreement between the two methods (the examiner chose to reposition the same tooth in the panoramic image and the corresponding CBCT) and when there was a disagreement between the two methods the examiner decided to reposition the tooth based on one image and not the other). The most common teeth in which there was a disagreement was the maxillary 2nd premolar, the maxillary lateral incisor, and the mandibular 1st premolar. In all of these instances, the disagreement surpassed 100 times.

The teeth that were most often chosen to be repositioned only on the subject's panoramic image were the maxillary canine and maxillary lateral incisor. This highlights the problem areas on the panoramic image. From the first part of the study, the panoramic image was found to exaggerate the mesial inclination of the maxillary lateral incisor and maxillary canine roots, explaining why examiners would frequently choose to reposition those roots more distally.

The teeth that were most often chosen to be repositioned only on the subject's CBCT image were the maxillary second premolar, and the mandibular first premolar. From the first part of the study the panoramic image was found to exaggerate the distal inclination of the maxillary posterior teeth, explaining why examiners often did not choose to reposition the maxillary second premolar when in actuality, those teeth needed more distal root tip.

The results prove that the panoramic views identify different teeth to reposition than the CBCT views. If we adopt the CBCT view as the new gold standard based on past studies (Stratemann, Huang et al. 2008) and results from the first part of this study, we can make some conclusions about how the panoramic image can mislead the clinician. The panoramic x-ray tends to over-report the maxillary lateral incisors and canines to need distal root tip, and under-report the maxillary premolars and mandibular first premolar to need distal root tip.

Sensitivity and Specificity

The specificity calculations were all above 90%. This suggests that the panoramic radiograph correctly identified over 90% of those teeth that did not need to be repositioned, suggesting its accuracy in ruling out certain teeth to need repositioning. However, the sensitivity calculations varied. In 9 out of the 14 teeth (64.3%), the sensitivity calculation was below 60%. The teeth that fell below 60% were the maxillary canine, premolars, and molars, and the mandibular canine, second premolar, and first molar. This suggests that the panoramic film was not accurate in identifying those teeth to be repositioned.

Clinical Opinions from the Questionnaire

For the ten examiners in the study, the average confidence level (ordinal scale of 1-10) using the panoramic image to diagnose root position was 7.0 whereas for the CBCT it was 8. Six of the ten examiners felt more confident using CBCT imaging to diagnose root repositioning, three examiners felt more confident using the panoramic image to diagnose root repositioning, and one examiner felt equally confident using both methods. Interestingly, the same six examiners chose the CBCT as the method they would use in private practice to assess root position, whereas the remaining four examiners chose the panoramic method. Performing a linear regression analysis reveals a strong correlation (R^2=0.866) between a clinician's comfort level using the CBCT software and their confidence level using it. Thus, a possible explanation as to why some examiners did not choose the CBCT as the method they felt more confident with, and the one they would use in private practice, could be their unfamiliarity with manipulating the software. Other reasons, as listed at the end of the questionnaire, included the CBCT's extra radiation and the extra time to manipulate the patient's dentition. One examiner felt that the radiograph was a supplemental screening tool in the evaluation of root position, and would rely more heavily on clinical evaluation of the crowns of the teeth. However, from past studies (Balut, Klapper et al. 1992; Creekmore and Kunik 1993; Armstrong, Shen et al. 2007) and this study, it is clear that relying on evaluation of the crowns of the teeth is unreliable.

CONCLUSION

- Compared to the gold standard, the CBCT was more accurate than the panoramic x-ray in root angulation measurements.
- Using a panoramic radiograph to evaluate root position can be inaccurate and misleading, causing the examiner to reposition the wrong teeth
    - Most notably, the maxillary lateral incisor and canine were over-reported as to need distal root tip, and the maxillary second premolar and mandibular first premolar were under-reported as to need distal root tip.

- In general, examiners felt more confident using the CBCT to diagnose root position. Those that did not feel more confident using the CBCT also did not feel as comfortable manipulating the software.

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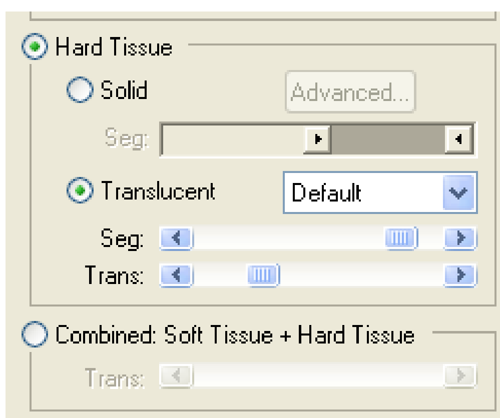
Appendix A

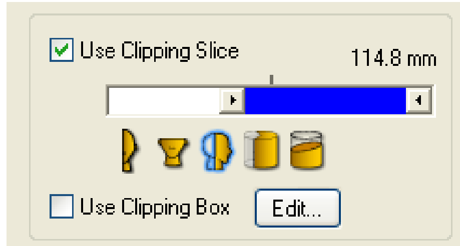
Instructions to Examiner

1. Open Dolphin Imaging software to view CBCT subjects
2. Open "Reset Study Panos" folder to view pano subjects
   - Edits → Linda → Research → RESET STUDY PANOS
3. Proceed in order (RS01-RS56) through each subject's CBCT or pano image
   - CBCT = Purple paper
   - Pano = Blue paper
4. To load a CBCT subject:
   - Enter "RS__" (subject's assigned #) in search window at the top of the "Patient Lookup" screen
   - Highlight the subject of interest on left side of screen
   - Select "OK" on right side of screen
   - Patient will load on screen
   - On left side of screen, select the "3D" icon and highlight "View only…"
   - Patient's 3D image will load (may take a few minutes)
5. Manipulating the 3D image:
   - To magnify the image:
     i. Move rubber scroll button on the mouse up or down, or
     ii. Hold the "Ctrl" button down (on the keyboard) + right button (on mouse) + move mouse up or down
   - To move the entire image on the screen:
     i. Hold the "Shift" button down (on the keyboard) + right button (on mouse) + move mouse around
   - To alter translucency of image:



     i. Make sure "Translucent" is selected under "Hard Tissue" [Left side of screen]
     ii. Move the "Seg" and "Trans" scroll bars left and right to alter the soft tissue and bone surrounding the teeth

- To section the image



    i. Left side of screen has icons that display the direction of the cut/section (Sagittal = left/right, Coronal = front/back, Axial = top/bottom) -- Select the desired cut
    ii. Alter the amount of the cut you want to view by moving the gray scroll bar above the icons
    iii. To restore the entire image, unclick the "Use clipping slice" box above the scroll bar
- To restore the patient's original head position:
    i. Select the icon on the very bottom of the screen 

6. Go through each subject in order (RS01-RS56)
7. Mark on the Reset worksheet which roots need to be repositioned:
    - Circle the tooth number
    - Write "M" (root tip needs to be moved towards the mesial) or "D" (root tip needs to be moved towards the distal)
8. At the end of the study, fill out the Bracket Repositioning Questionnaire
9. Turn in all forms to Linda Huynh

Appendix B

Examiner Questionnaire

1. Which radiographic method did you feel more confident using to assess which teeth to reposition?

    Panoramic x-ray **3-D Conebeam CT**

2. How confident are you of your decision to reposition the selected teeth using the **panoramic image** as the diagnostic tool? Rate on a scale from 1-10 (1 being least confident, 10 being most confident).

    1 2 3 4 5 6 7 8 9 10

3. How confident are you of your decision to reposition the selected teeth using the **3-D Conebeam CT** as the diagnostic tool? Rate on a scale from 1-10 (1 being least confident, 10 being most confident).

    1 2 3 4 5 6 7 8 9 10

4. How comfortable do you feel using 3-D Conebeam CT? Rate on a scale from 1-10 (1 being least comfortable, 10 being most comfortable).

    1 2 3 4 5 6 7 8 9 10

5. In private practice, if both are available, which radiographic method would you use to assess root position?

    Panoramic x-ray **3-D Conebeam CT** **Other:__________________**

    What factors influenced your choice? _________________________________

Appendix C

Part 1: Raw Angular Measurements Using All 3 Methods

Tooth	Actual Average	ALL PANO avg	ALL CBCT avg
UR7	92.25	99.25	95.9
UR6	95.5	100.125	93.35
UR5	89.375	95.125	90.75
UR4	90.25	93.25	89.2
UR3	96	90.625	95.65
UR2	89.125	84.125	88.7
UR1	91.75	88.75	91.225
UL1	91.25	87.75	91.375
UL2	88.625	85.625	87.85
UL3	97.5	91.125	96.1
UL4	91.25	94.25	90.3
UL5	93.125	96.75	91.075
UL6	93.5	97.75	95.175
UL7	92.875	96.5	93.65
LL7	96	93	95.475
LL6	97.5	94.875	97.225
LL5	93.5	89.375	89.625
LL4	96	86.25	97.9
LL3	95.5	90.25	94.7
LL2	89.875	86.875	91.025
LL1	89.375	86.375	88.65
LR1	92.875	90.875	92.2
LR2	92.5	88.5	94.8
LR3	94.5	84	92.275
LR4	98	90.625	101.25
LR5	96.75	94.625	98.75
LR6	98.5	95.5	97.95
LR7	96.25	94.375	97.3

Appendix D

Part 1: Difference Between Actual Angular Measurement and Each Method of Imaging

Tooth	Difference b/w pano & actual	Difference b/w cbct & actual
UR7	-7	-3.650
UR6	-4.625	2.150
UR5	-5.75	-1.375
UR4	-3	1.050
UR3	5.375	0.350
UR2	5	0.425
UR1	3	0.525
UL1	3.5	-0.125
UL2	3	0.775
UL3	6.375	1.400
UL4	-3	0.950
UL5	-3.625	2.050
UL6	-4.25	-1.675
UL7	-3.625	-0.775
LL7	3	0.525
LL6	2.625	0.275
LL5	4.125	3.875
LL4	9.75	-1.900
LL3	5.25	0.800
LL2	3	-1.150
LL1	3	0.725
LR1	2	0.675
LR2	4	-2.300
LR3	10.5	2.225
LR4	7.375	-3.250
LR5	2.125	-2.000
LR6	3	0.550
LR7	1.875	-1.050

Appendix E

Part 2: Summary of Results – All Examiners, All Subjects

	PANO only	CBCT only	BOTH
UR7	14	26	19
UR6	13	18	10
UR5	17	48	44
UR4	11	38	34
UR3	30	13	13
UR2	35	33	73
UR1	17	11	9
UL1	26	15	12
UL2	37	27	89
UL3	35	21	19
UL4	8	31	13
UL5	15	33	57
UL6	11	16	17
UL7	6	28	14
LL7	5	8	21
LL6	10	10	8
LL5	20	9	21
LL4	9	56	70
LL3	17	22	15
LL2	25	16	46
LL1	16	11	29
LR1	27	10	3
LR2	23	19	43
LR3	22	17	7
LR4	20	35	107
LR5	10	24	24
LR6	21	15	8
LR7	11	11	22

	PANO only	CBCT only	BOTH	TOTAL
U7	20	54	33	107
U6	24	34	27	85
U5	32	81	101	214
U4	19	69	47	135
U3	65	34	32	131
U2	72	60	162	294
U1	43	26	21	90
L1	43	21	32	96
L2	48	35	89	172
L3	39	39	22	100
L4	29	91	177	297
L5	30	33	45	108
L6	31	25	16	72
L7	16	19	43	78

	Agreement b/w methods	Disagreement b/w methods
U7	33	74
U6	27	58
U5	101	113
U4	47	81
U3	32	99
U2	162	132
U1	21	69
L1	32	64
L2	89	83
L3	22	71
L4	177	120
L5	45	63
L6	16	56
L7	43	35

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