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Tooth Length Measurement Accuracy and Reliability with Cone-Beam CT and Panoramic Radiography

by

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Dedication

To my family: for their love, support, encouragement, inspiration, patience and wisdom. You gave me the tools to persevere down my long and sometimes arduous academic path in my pursuit of professional excellence. My successes to date and dreams for the future are a product of your devotion for which I am eternally grateful. It is with the highest moral code and class that I strive to continue to show my sincerest appreciation for your enduring generosity.

Abstract

This study assessed the accuracy and reliability of tooth length measurements through axial, coronal and sagittal serial slices of CBCT volumes; conventional panoramic radiographs; and CBCT panoramic reconstructions to that of a digital caliper gold standard. Samples consisted of maxillary premolars collected from patients requiring extractions for routine orthodontic treatment. Extracted teeth were measured directly with digital calipers and images were digitally measured in Dolphin 3D software. Analysis of CBCT serial slices resulted in highly accurate and reliable tooth length measurements for all slice orientations compared to the gold standard. Conventional panoramic radiographs were relatively inaccurate, overestimating tooth lengths by 29%, while CBCT panoramic reconstructions underestimated lengths by 4%. CBCT serial slice volume analysis provides clinicians with greater measurement confidence, while panoramic radiographs, produced either by conventional means or reconstructed from 3-D volumes should be considered less accurate and reliable for the detection of mild root resorption.

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Thank you to those who made this process so rewarding. To my friends and colleagues whose guidance, support, humour and commiseration made the program memorable and entertaining. To my committee for their feedback and perspective; and especially to my supervisor, Carlos, they say that you never forget your first…well, it's been my privilege. Thanks to your tutelage and research prowess, this thesis stands as a source of great pride for me.

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Chapter 1: Introduction and Literature Review

1.1 Introduction and Statement of Problem

The introduction of computed tomography (CT) offered the medical and dental community great opportunity to improve diagnosis and treatment planning through non-invasive three-dimensional imaging technologies. Initially high radiation exposure to patients, high equipment costs and complexity in image capture and interpretation limited the use of helical CT's to medical and surgical applications. The advent of cone-beam CT (CBCT) technology in the late 1990's removed many of the hurdles dentistry faced and in the last 10 years. General dental practitioners and specialist alike have eagerly invested in in-office CBCT imagers for many reasons not the least of which includes: decreased equipment size and cost; reduced radiation exposure for patients; improved, user-friendly software for image reconstruction and interpretation; more powerful personal computers; and reduced dependency on radiologists for routine image interpretation.

Although it provides far more diagnostic information, adoption of CBCT imaging has been tempered by clinicians concerns over the increased radiation exposure to patients compared to conventional extra-oral radiography and the additional medico-legal responsibility of interpreting the additional information captured by these scans. In order to justify the additional x-ray exposure, researchers and clinicians must adopt guidelines for its application. These protocols require scientific evidence to outline when the diagnostic benefits to the patient outweigh the risk of the associated additional radiation exposure.

CBCT technology offers the opportunity to view maxillofacial structures in three dimensions at a resolution and accuracy far beyond what is available with conventional two dimensional (2-D) panoramic and cephalometric radiographs. While for orthodontic purposes linear and angular measurement accuracy has been established for cephalometric analysis, length measurements in the dentoalveolar region to monitor root resorption have not yet been fully investigated. This may have been due in part to orthodontists' treatment planning need to apply the 2-D analyses to the 3-D imaging technology until new standards of 3-D analyses are established, while the historic method of qualitative assessment of root resorption has been considered adequate.

1.2 Significance of Study

By establishing the accuracy and reliability of tooth size measurements of dental structures from CBCT volumes, clinicians could more confidently use these images to identify and monitor changes in root length and morphology during orthodontic treatment. Increased confidence in dimensional accuracy of root surfaces will also improve estimations of force and biomechanical systems related to orthodontic appliances. This will enable clinicians to better adapt treatment plans and progression to minimize the negative effects of severe root resorption.

1.3 Research Questions

1) Are tooth length measurements determined through landmarks identified from CBCT volume serial slices accurate and reliable?
2) Are tooth length measurements determined through landmarks identified from panoramic reconstructions of CBCT volumes accurate and reliable?

1.4 Null Hypotheses

The hypotheses of interest involved the accuracy and reliability of directly generated CBCT images, and panoramic radiographic images derived from conventional and CBCT generated methods; compared to direct measurement by a digital caliper gold standard, namely:

H_o: There is no difference between the tooth length measured from CBCT axial serial slices and the digital caliper.

H_o: There is no difference between the tooth length measured from CBCT sagittal serial slices and the digital caliper.

H_o: There is no difference between the tooth length measured from CBCT coronal serial slices and the digital caliper.

H_o: There is no difference between the tooth length measured from CBCT panoramic reconstruction and the digital caliper.

H_o: There is no difference between the tooth length measured from conventional panoramic radiographs and the digital caliper.

1.5 Literature Review

1.5.1 Root Resorption

1.5.1.1 Diagnosis

There are almost as many definitions of root resorption as there are methods for detecting it. Diagnosing root resorption on extracted teeth has been quantified by histological[1], microscopic and radiographic techniques. Scanning electron microscopy[2] and micro-computed tomography[3,4] offer the highest resolution of root surfaces contours and have been very sensitive technologies for identifying very small resorption craters. The nature of the techniques, size of the machines and amount of radiation used have limited these technologies to *ex vivo* analyses only and as such limited their clinical potential. With these restrictions notwithstanding, micro-CT scans has identified root resorption on both orthodontically treated and untreated teeth. While the amount of resorption as a percentage of the tooth's overall volume was low, there was a significantly greater amount of resorption following 1 year of treatment[5]. The evidence gained from micro-CT studies confirmed the presence of mild resorption observed by other techniques[6], and calls to the importance of higher resolution three dimensional alternatives to improve clinical care.

The identification of morphologic changes *in vivo* were limited to two dimensional radiographic procedures, such as periapical, panoramic and lateral cephalograms until the advent of three-dimensional spiral and cone beam computed tomography. Due to the inherent lack of precision of 2-D radiographic imaging, researchers have typically resorted to a qualitative approach to describe the amount of root shortening. A typical 5 point grading system would describe the absence of resorption as grade zero; mild resorption creating irregular root surfaces as grade one; moderate resorption in which small areas of detectable root loss and apical blunting as grade two; root shortening up to 1/3 of the root length as severe and grade three; and finally extreme resorption as any resorptive process in which more than 1/3 of the root length was lost as grade four[7,8]. Other investigators have used a 4 point grading system differing only in moderate resorption (grade 2) which was considered any apical root shortening beyond root blunting, up to 1/4 of the root length, and severe resorption (grade 3) which entailed root loss greater than 1/4 of the root[9]. Only a few studies have attempted to quantify apical root resorption in terms of linear measurements[10].

1.5.1.2 Physiology

Resorption of dental tissues is a progressive process that can be arrested by removal of the clastic stimulus. Infective and/or physical agents that degrade the organic cementoid surface layer of the root surface allow the same multinucleated clastic cells that resorb bone the opportunity to resorb cementum and dentin[11]. In orthodontic terms, the resorptive progresses only as long as the mechanical stimulation of the macrophages and osteoclasts are present[11]. By physical removal of the cementoid layer, Tronstad noted that almost 29% of orthodontically treated incisors show some degree of apical root resorption; significantly more than the 3.4% of control group samples[11].

In addition to treatment duration, the magnitude of applied force has also been directly associated with the severity of resorptive pits on root surfaces. Chan *et al.* demonstrated that a heavy force of 225 grams applied for 28 days resulted in many times more root resorption than a light force of 25 grams on the compression side of the root surface[12]. The resorptive pits on the surfaces of teeth exposed to the light forces were in turn many times greater than that of untreated control teeth[13]. Unlike dentin, cementum has regenerative properties which restore the protective layer following termination of the applied forces. This makes early detection vital to minimizing the irreversible loss of root structure by suspending applied forces long enough to allow cementum healing to occur or discontinuing orthodontic treatment indefinitely.

1.5.1.3 Associated Risks

While the severity of root resorption is linked to the magnitude of force applied to the teeth during orthodontic treatment, Wierzbinki noted researchers have found that detectable amounts of apical resorption occurred with forces as light as 50 g[5]. Longitudinal studies have largely been comprised of comparing pre and post orthodontic periapical radiographs. Due to the inherent inaccuracy of the technique, severity was limited to a four or five-stage scale ranging from the absence of apical to substantial root resorption in which more than one third of the root was lost[7,14]. Lupi *et al.* found the frequency of root resorption increased from 15% of incisors pre-treatment to 73% following orthodontic treatment. While moderate and severe levels of root resorption also increased, 69% of the occurrences were in 23% of the patients[7]. The multifactorial risk profile for those patients that will experience more severe resorption means that clinicians must still rely on radiographic screening before and during treatment. Apical root blunting, while common following orthodontic treatment, does not pose long term morbidity to patients. It is the subset of patients that experience moderate to severe levels of resorption that compel researchers to improve diagnostic tests to identify progressive root resorption early in order to make treatment modifications. Kaley *et al.* discovered an even greater percentage of incisors with moderate to severe resorption in an adolescent population that were treated for 34 months compared to Lupi's 20 months[9]. Taken together Lupi's and Kaley's studies offer support to the progressive nature of this destructive process and its association with treatment length in addition to the magnitude of applied orthodontic forces.

1.5.2 *In* vivo Radiographic Root Imaging Techniques

1.5.2.1 Digital Imaging Advantages

Developments in digital imaging have offered clinicians the opportunity to capture radiographic images with comparable or superior resolution with decreased patient exposure compared to their traditional film-based counterparts. In spite of these advantages, CCD (charged couple device) sensors and image plate systems have met the same limitations as film based radiographs in their poor sensitivity for identifying simulated root defects[15]. It has also been found that the defects created artificially have margins that are sharper and more easily identified versus naturally created lesions[16]. This emphasizes the need to exercise caution when attempting to extrapolate the conclusions of *in vitro* studies for clinical applications.

1.5.2.2 Periapical Radiography

Traditionally, periapical radiography has been considered the most reliable *in vivo* method to detect changes to root morphology during the course of orthodontic treatment[17-20]. This was on account of lower levels of magnification and distortion compared to other conventional techniques, such as panoramic radiography[21]. Measurement errors due to root angulation changes and magnification during orthodontic treatment when assessed by 2-D radiographs have led to erroneous reports of tooth elongation in non-growing patients[22,23]. Mathematical algorithms to account for the tooth angulation and film position have been only partially successful in accounting for the variability seen in serial periapical images and as such limited the strength of the studies attempting to quantify resorptive changes in teeth undergoing orthodontic movement[22]. Additionally, other factors could be calculated into formulae for serial periapicals, such as variability in tooth-film distance, affecting magnification; bending of the film; or crown-root dilacerations[24]. Even the landmarks chosen to standardize crown size in order to account for root length changes due to tooth angulation variations were affected by location. Their unreliability became accentuated by greater degrees of angular change between images[24].

1.5.2.3 Panoramic Radiography

Panoramic radiographs are a type of tomography in that a shallow section of the body is kept in focus in order to view it more clearly compared to its surrounding anatomy. The structures outside of the focal trough are blurred and appear as shadows and artifacts. In order to better maintain the elliptical shape of dental structures within the focal trough, panoramic devices have a centre of rotation that changes throughout the scan. The rotational patterns developed by the manufacturers of these devices, which are predetermined and not modifiable, vary widely making the resulting images unique to the developer and model[25].

Many reports have noted that panoramic radiographs do not accurately represent tooth positions requiring the clinician to supplement his/her findings with a clinical assessment. Distortions in root angulation vary in direction and magnitude throughout the image[26].

As reviewed by Van Elslande *et al.* panoramic radiographs are fraught with inconsistent levels of magnification and distortion errors[27]. Some reports found vertical measurements were +/- 10% different from direct measurements of dried skulls[28], while other groups found the difference to be as high as 18-21%[29]. Differences in magnification have been found to vary throughout panoramic images, disparity existed between devices tested, and the majority of manufacturers' documentation did not accurately correspond with calculated magnification in various regions of the panoramic images[27,30]. These distortions pose an unacceptable level of unreliability for all types of measurements, whether they be angular or linear; ratios or direct. Turp *et al.*'s analysis of vertical measurements of ramus and condylar heights concurred with Kjellberg's finding that there was a very low correlation between the lengths recorded on the panoramic images and direct physical measurements[31].

In controlled experimental conditions, Yitschaky recently attempted to quantify the amount of distortion inherent in vertical measurements of tooth length and found that the panorex images magnified the dental structures by approximately 26% in the maxilla and 10-14% in the mandible[32]. They also noted that this level of precision was accomplished by very standardized conditions of imaging equipment, beam angulation and patient head position. The authors warned against applying the calculations for measuring tooth length to other research and clinical scenarios as the results were very equipment and technique specific.

In the dentoalveolar region of the mandible, alveolar bone heights were also not reliable as head position and mandibular body angulation varied through +/- 20^{o} of horizontal which resulted in significantly different image lengths[33]. Using metal bars and markers for reference, some studies have found that measurements with certain devices follow manufacturers' reported magnification in the mandible as long as they don't cross the midline[34], while other studies have found differences in the accuracy of horizontal versus vertical measurements[29,35].

Larheim *et al.* studied dental[36] and mandibular landmark[29] measurements of panoramic radiographs. Their research determined that while vertical measurements were more accurate than horizontal, they were magnified by 18-21%[29]. The repeatability evaluation of tooth length met complications as many teeth (14-17%), especially those in the mandibular anterior region (57%), were not clear enough to locate root apices and up to 7.5% of the teeth were more than 2 mm different in repeated exposures, to which Larheim attributed misidentification of the landmarks of interest[36]. Removal of these outliers improved tooth length measurement precision to within 0.5 mm, or approximately 2% of the radiographic tooth length. While Larheim's study was able to show relatively repeatable measurements when the dental landmarks could be identified, the *in vivo* nature of the study precluded the ability to assess the accuracy of the radiographic measurements with the true lengths of the teeth. Additionally, since the clinically practical application of comparing tooth lengths would be during orthodontic treatment in which dental image elongation and/or foreshortening correspondent to tooth torquing would occur, the error level in the repeatability of the tooth length measurements would likely be overshadowed by the optical errors introduced in the 2-D image[36].

Schulze attributed the statistically greater reliability of the horizontal measurements in digital panorex images of dried skulls to systematic errors in measurement technique, which could be reduced by averaging repeated measurements[35]. He deemed the increased reliability to not be of clinical significance, however. The decreased reliability of the linear measurements with increased magnification of the digital images was another provocative finding[35]. Schulze attributed this counter-intuitive finding to the phenomenon that at greater magnification, landmarks that were represented by one image pixel became divided over many, increasing the opportunity for selecting incorrect locations[35].

Positional variation of patients due to operator error also has significant effects on panoramic imaging accuracy, not only in angulation along the long axis, but in vertical and horizontal translation as well as axial rotation. Laster *et al.* found dimensional inaccuracies developed in both horizontal and vertical directions by skull displacements as little as 7 mm and 10 degrees[37]. Vertical angulation changes resulted in mesiodistal axial tooth inclinations variation as well, with more dramatic effects seen with posterior teeth[38]. Many studies determined that even angular measurements of dental tissues were not represented accurately in panoramic radiographs and have emphasized caution in trusting the accuracy of tooth angulations for clinical evaluation of treatment quality[26,39-41]. Angulations of teeth were under and overestimated on the radiographs depending on tooth location as well as actual root angulation[39]. Owens *et al.*

found that the radiographic images represented dental angulations so poorly that a 22^{o} range existed for the 95% confidence interval[39].

As Van Elslande's review pointed out, conventional film and digital panoramic radiographic units vary between manufacturers with respect to the dimensions of their focal trough and centre of rotation[27]. Attempts to adjust for magnification and distortion variations between images becomes exceedingly difficult and considering the introduction of variable distortion arising from positional errors of the patient, realistically impossible.

1.5.2.4 Volumetric Panoramic Radiography

Volumetric tomography may emerge as a bridge technology between conventional panoramic radiography and CBCT. By combining panoramic radiographs with up to 11 additional extraoral images, centered on an anatomical area of interest, limited 3-D volumes were created[42]. While patient exposure was reduced to only a few times that of a conventional panorex, the image resolution was markedly lower than that of current CBCT devices.

1.5.2.5 Computed Tomography (CT):

In 1967, Sir Godfrey Hounsfield developed the first computed tomography (CT) devices for medical use[43]. For the next three decades advances in the technology improved scan speed and resolution but had only minimally reduced patient exposure, while during the same time developments in conventional radiology improved image quality and reduced the radiation required[43]. Cone beam CT (CBCT), developed in the 1990's was first used in the United States in 2000. It differed from medical CT by producing a cone-shaped x-ray beam allowing 3-D image generation by combining 2-D images taken from 360 degrees in one pass of the device[43,44]. This allowed faster data acquisition at lower overall patient exposure compared to the fan-shaped x-ray beams of medical CT. The decreased patient exposure by CBCT devices came at a trade-off in which higher noise levels limited low contrast resolution. While this affected soft tissue detail, bony and dental structures were largely unaffected[45]. The reduced size, cost, complexity and radiation exposure to patients has fueled the development of CBCT devices for orthodontic use.

1.5.2.6 Medical CT:

Medical CT scanners consist of an x-ray emitter and a series of detectors on the opposite side which rotate around the patient's body capturing 2-D images at many angles. They are designed to emit a thin fan-shaped beam of x-rays which produce axial slices as the scanner moves axially down the length of the subject's body. The raw data may be in the form of a series of stacked 2-D axial slices or continuous spiral that must then be processed into a 3-D reconstruction. Image information in a 2-D digital radiograph is represented by pixels whose varying brightness creates the resulting picture. In 3-D radiographic images, three dimensional pixels, called voxels, represent the radiographic density of its corresponding anatomical structure[46]. The contrast range and number of shades of gray are described in terms of bits[47]. For example a 12-bit apparatus is able to produce 2^{12} = 4096 shades of gray. How the computer software renders the raw data can have a dramatic effect on the resulting 3-D image. Orthographic versus perspective projection type, determination of visible surfaces, and surface texture created by shading and lighting direction are all important in creating a rendering that replicates the original anatomy. The rendering of the 3-D images also requires complex algorithms to determine the appropriate thresholds for voxel density, and changes in density compared to surrounding voxels, to accurately differentiate various soft and hard tissues from air spaces[46].

1.5.2.7 Cone Beam CT (CBCT):

Cone-beam CT scanners consist of an x-ray emitter and a larger detector surface more similar to that used for cephalometric projections, than the small sensors of the medical CT's. The pulsed radiation source decreases the patient's radiation exposure to a fraction of the total scan time, whereas the unpulsed medical CT results in patient exposure times equaling the full scan duration. The large sensor allows the entire image to be obtained in a single pass[44]. The CBCT sensors use an image intensifier which may be a source of noise and increased scattered radiation yielding the decreased image resolution compared to the conventional helical CT devices[48], but also allows improves sensor sensitivity enabling decreased patient exposure.

NewTom 9000 (Quantitative Radiology, Italy) was the first CBCT system designed for dentomaxillofacial imaging[45]. The cone shaped x-ray beam exposed the patient to 360 exposures, for a total exposure time of 18 seconds, during the 70 second scan time. Measurements of simulated osseous structures in phantom heads set in line and at 30 degrees from the primary axial reconstruction found mean width measurements to be accurate to within 0.8-1% of true values and height measurements to an accuracy of 2.2%[45]. The accuracy differences with respect to orientation were not investigated further; however they may have been a result of non-cuboidal voxels and/or a reconstructed slice thickness that was greater than the volume's voxel size. Current CBCT devices are able to produce cubic voxels and reconstruction software allows processing of the volumes without diminishing resolution. These advances contribute to improved accuracy regardless of direction or reconstruction orientation. In terms of absorbed radiation, this early study of the NewTom determined that a 6-fold decrease could be achieved when compared to traditional CT scans, such as with the Siemens Somatom Plus 4 device[45]. Mah attributed the accuracy of CBCT images to a combination of an orthogonal projection in which the x-ray beams are nearly parallel and data correction made in the imaging software[43].

The accuracy of the measurements of dentoalveolar structures has proved useful in other disciplines. Quantification of osseous defects has allowed periodontists to better assess severity of periodontal bone loss and to tailor more appropriate therapies[49]. Periodontal defect heights and widths were measured consistently among trained examiners and accurate visualization and analysis of defects on all root surfaces compared to digital calipers as a gold standard[50]. Virtual implant placement procedures in epoxy mandibles demonstrated significantly improved entrance and apex location using guides produced from CBCT scans versus conventional surgical guides[51].

1.5.2.8 Large vs Small Field of View CBCT

With a voxel size of 0.136 mm, Arai *et al*. have developed other CBCT devices (3DX) claimed to have higher resolution than conventional CT's for smaller regions of the dentoalveolar process[52]. The limited scan size of 32x38 mm limited patients' skin exposure to 0.62 mGy for the 17 second exposure, approximating the exposure received from a panoramic radiograph[52]. The quality of the 3DX images for dental and periodontal structures was also considered far superior to the multidetector conventional CT[53,54]. With skin radiation exposures approximately 130-fold less than the 160 mSv per helical CT's, and 400-fold less than multidetector CT's, the superior images came with the only disadvantage being the relatively small sensor size limiting their field of view to only one or two teeth per scan[53,54]. By comparison, NewTom QR 9000 imagers had a 13x13 cm field of view with a resolution limit of 0.26 mm voxels[47]. Many of the CBCT's on the market have the ability to produce higher resolution images when device settings are changed to smaller scans. This is a matter of the same number of voxels used to produce images regardless of their field of view[48].

CBCT imagers with the larger field of view (FOV) have lower contrast and noise-to-signal ratios compared to the higher resolution but more limited small FOV devices. The large FOV devices are typically used in orthodontics though, as they offer the opportunity to make full craniofacial evaluations from all perspectives, but reduced fine detail quality make differentiating dental tissues from their surrounding anatomy more difficult. Liu *et al.* found that error in volumetric calculations of extracted teeth scanned with i-CAT and CB MercuRay imagers and reconstructed in Amira 4.0 arose from the subjectivity of image segmentation by the operator and the level of surface smoothing by the software[55]. The accuracy of the image segmentation was based on a multitude of factors that affected captured image quality. These variables included device settings, patient positioning and cooperation, reconstruction of the image, and the exported data format, such as DICOM (Digital Imaging and Communications in Medicine)[55]. Similarity in tissue density surrounding the dental tissues of interest also complicated the clinician's ability to accurately segment the dental structures from the surrounding hard and soft tissues. Segmentation errors were on the order of -4 to 7%[55]. The second source of discrepancy between the radiographic and direct measures of tooth volume, surface smoothing, resulted in reductions in reconstructed volumes of 3-12%[55]. Taken together, large FOV volumes have a significant degree of error that cannot be easily adjusted for.

1.5.2.9 CBCT Panoramic Reconstruction

Complex computer algorithms are required to convert 3-D medical and cone beam CT volumes to images that simulate 2-D panoramic radiographs. By removing all voxel information that lies outside the specified focal trough however, the panoramic reconstruction from the CT data improves image clarity by reducing geometric distortions, blurring and artifacts from superimpositions[25].

Ludlow *et al.* scanned dried skulls with the NewTom 9000 at a resolution of 0.5 mm slice thickness to determine vertical and horizontal length accuracy when reconstructed into panoramic projections[56]. While intraobserver reliability was very high at approximately 0.1 mm, identification of the landmarks between observers was significantly different at almost 0.9 mm. Researchers used metal wires of known length laid along the buccal surface of the ramus and mandibular body as reference knowing that while they likely did not lie in the exact plane of the panoramic reconstruction, as long as they were within 18^o of the plane, the foreshortening effect was less than 5%[56]. Conversely, the panoramic reconstruction followed the curvature of the mandible resulting in linear measurements on the image to be overestimated. While operator expertise was considered an important factor in measurement accuracy, the lengths recorded in the 3-D volumes by landmark identification in serial axial slices expressed levels of error in the range of 0.19 to 0.37 mm, or 0.6 to 1.7% of the measured lengths. These values were 1.5-2.5 times lower than the panoramic reconstructions of the same volumes[56].

Echoing the limitations of conventional panoramic projections, the variability and poor representation of mesiodistal angulations of dental structures was also present in the panoramic reconstructions from the 3-D CBCT volumes as well[41].

1.5.2.10 CBCT Lateral Cephalogram Reconstruction

It is interesting to note that CBCT devices set to make single exposures that mimic traditional lateral cephalogram projections produced images that were comparably accurate to the full volume images that used the ray-sum reconstructions to reproduce the 2-D view[57]. The single projection produced an image with a fraction of the radiation required to record the more than 300 exposures that make up the CBCT volume, and the reconstruction software corrected for the relatively short source-object and long object-sensor distances[57]. The single lateral cephalogram projection, produced either from a single CBCT scout view or single-frame basis image, had a similar accuracy to the more common ray-sum reconstruction and most measurements were not significantly different from caliper measurements on the dry skulls[57]. While Moshiri *et al.* found these results impressive; they also noted that the single projection technique carried all of the limitations and inaccuracies inherent with the traditional 2-D lateral cephalogram technique.

1.5.2.11 CBCT Superimposition

Using automated transformations to overlay and align serial CBCT volumes captured with the i-CAT device, Chen *et al.* were able to measure the magnitude and direction of simulated orthodontic tooth movements[58]. The source of error in the measurements was cited as the difficulty in separating the dental structures from the surrounding tissues for accurate isosurface representation and positional comparison by the software. Confounding factors for this technique included the presence of metal introducing imaging artifacts and the presence of growth making superimposition more difficult as no real frame of reference could be established[58]. While translational errors were on the order of 0.37 mm, or 18% of the prescribed movements, repeated measurements improved the diagnostic accuracy of the superimpositions reducing the error to only 4%. Chen concluded that with improved scan resolution, the lower error levels would be achievable without repeated scans[58].

1.5.3 Comparisons of Image Quality

1.5.3.1 Medical CT vs CBCT

Holberg *et al*. compared image quality of dental tissue for the NewTom 9000 CBCT (QR, Verona, Italy) set to a slice thickness of 0.3mm with a 76 sec scan, with the Light Speed Ultra (General Electric, Fairfield, CT, USA) with a spiral slice thickness of 0.6 mm[44]. Detailed dental structures were defined more clearly in conventional CT's in axial slices as they produced images with better contrast and decreased blurring. Holberg noted that reformatted slices in directions perpendicular to the axial slices result in reduced image quality, and as such weren't tested. Conventional CT's experience far greater quality degradation compared to relatively minimal clarity differences with CBCT volume reformatting[48]. This is due to the form in which the data is captured and processed. Raw CBCT images are comprised of cubic-shaped voxels which store the radiopacity for each 3-D location of the image[47]. The viewing software is then able to reformat the entire volume to allow observation from any angle without degradation[47]. Movement artifacts due to the longer acquisition time and complex reconstruction algorithms were believed to be the causative agents for CBCT's decreased contrast and increased likelihood of movement artifacts compared to the conventional CT axial slices[44]. Conspicuously absent from this study's discussion was the effect of the amount of radiation used on the images' clarity; as improved contrast and resolution is directly linked to longer exposures and thinner slice thicknesses for both spiral and cone beam CT technologies. CBCT scans displayed a clear advantage over conventional CT's when metal fillings were present. CBCT images are almost imperceptibly affected while entire sections of conventional CT images become unreadable[44]. Once again, this dramatic difference is a consequence of the way x-ray radiation is scattered by metallic objects and the way in which the volumetric data is captured. Medical CT's reconstruct their images from a series of thin slices taken from only one direction for any given layer. Therefore, all anatomy behind the metal object is not able to be resolved. Although the conventional CT volumes capture their image from all sides of the subject, the volume is actually reconstructed from a series of image slices where each layer is captured from only one direction. CBCT volumes, on the other hand, are reconstructed from a collection of voxels which represent radiographic density information calculated from radiation sources that encompass the subject. While the spiral CT anatomical information is lost due to the x-ray scatter produced by metal objects in the field when the layer is captured from only one side, the CBCT overcomes these artifacts by assigning radiodensity values to all voxels, calculated from data acquired from all directions. As all surrounding anatomical structures are captured beyond the shadow of the metal object, the processing software is able to produce images with minimal scatter artifacts.

1.5.3.2 CBCT vs Conventional Panoramic Radiography

Although definitive results were clouded by methodological complications, Hutchinson attempted to compare angular measurements from traditional panoramic radiographs to CBCT panoramic reconstructions[59]. While the arch width failed to correlate with radiographic widths of measured teeth, arch depth was statistically correlated with radiographic molar size on one side. The author felt this erroneous result could have been due to improper head positioning in the panoramic unit[59]. The panoramic reconstructions from the NewTom 9000, on the other hand, were dimensionally accurate to the patient's dental models. The greatest differences between the film and reconstructions existed in the maxillary canine-premolar region and the mandibular posterior regions[59]. This study exemplified the superiority of CBCT for dimensional accuracy even when used to reconstruct traditional 2-D projections. As head position can be standardized after patient scans are complete and focal trough can be customized based on tooth position and angulation, the reconstructed images can remove many of the distortion variables inherent in the traditional panoramic images.

1.5.3.3 CBCT vs Conventional Lateral Cephalogram

In order for 3-D radiographic techniques to become accepted as the orthodontic standard of care, traditional 2-D analyses must be confidently translated to the newer records. Researchers are making this transition by recreating 2-D projections from the 3-D volumes. Several studies have assessed the accuracy of 2-D reconstruction of CBCT volumes. Kumar *et al.* assessed NewTom 3G's ability to produce lateral cephalograms from dry skulls that were geometrically accurate to the conventional film images[60]. Lamichane *et al.* created lateral cephalograms from i-CAT scans of acrylic plates to simulate skull phantoms and compared them with standard conventional lateral cephalograms[61].

Dolphin 3D offers two methods of reconstruction to allow simulate the magnification error inherent in the conventional images: the orthogonal setting with 0% magnification and the perspective setting with approximately 10% of magnification. The Dolphin 3D orthogonal cephalograms produced images that had very high accuracy for the direct measurements on the phantom and the perspective cephalograms accurate reproduced the magnification of traditional films[61]. The measurements of the landmarks were also very highly reproducible both over time and between examiners[61]. Clinically, lateral cephalograms produced from CBCT images exhibit highly repeatable angular measurements consistent with those achieved by traditional imaging[62]. By using the Bjork analysis, the researchers were able to minimize the effect of magnification and distortion errors between the 2-D and 3-D images, leaving this comparison to other studies[62].

A systematic review of landmark and linear measurement accuracy by CBCT lateral cephalogram reconstructions illustrated the high variability between studies[63]. Methodological differences likely played a significant role in the inconsistency in the literature. Some landmarks were identified from dry skull images as they would have been done clinically, while other studies used metal balls and rods in an attempt to improve identification by increasing the landmark contrast with the skeletal background. The linear and angular measurements also varied between studies, however consensus was difficult to achieve due to the variability in CBCT device used and method of reporting error, as shorter linear measurements and smaller angular measurements would be reported as larger percentage errors. Finally, the dry skulls provided an ideal environment to optimize landmark identification as surrounding soft tissues would result in decreased radiographic contrast for surface locations. In any case, Lou concluded that the under these *in vitro* conditions, measurement accuracy to within 0.5 mm was typically achieved[63].

1.5.3.4 CBCT vs Digital Caliper

Berco *et al.* imaged dried skulls marked with stainless steel balls to represent cephalometric landmarks with a 12-bit i-CAT set to 0.4 mm voxel resolution. Repeated measurements of a single skull scanned in 2 different head positions by two trained clinicians provided excellent measurement accuracy and repeatability when the DICOM volumes were reconstructed and assessed with Dolphin 3D imaging software[64]. Skull position had no influence on accuracy of the linear measurements as the reconstructed volumes were repositioned during analysis and serial slices were assessed in axial, sagittal and coronal directions to verify landmark locations[64]. The level of accuracy achieved by the 0.4 mm scans was determined to be less than one voxel in magnitude resulting in statistically and clinically insignificant differences in linear measurements of CBCT volumes, compared to the direct caliper measurements for cephalometric analyses[64]. This equated to a percentage error for the CBCT measurements ranging from -1.1 to 0.89%[64]. An earlier study comparing CBCT volumes from the NewTom 3G to a coordinate measuring machine (CMM) gold standard found only slightly greater error rates[65]. The 0.6 mm disparity for linear measurements translated to a 2% error approximately[65].

Using acrylic and chromium metal markers, Ballrick *et al.* tested several imaging settings of the i-CAT to determine the device's level of image distortion and spatial resolution[66]. The study determined that all image settings, dimensions and regions were equivalent with respect to landmark accuracy. All CBCT linear measurements were within 0.1 mm of caliper measures and considered clinically insignificant, however Ballrick noted that the CBCT lengths were consistently lower than the direct measurements thus raising a concern for additive inaccuracies with applications involving the summation of several lengths, such as for measuring tooth width – arch length discrepancies[66]. Longer scan times and smaller voxel setting on the i-CAT generally increased image resolution, however software processing to improve the signal to noise ratio by merging adjacent pixels on the detector ameliorated some of the gains[66]. While the i-CAT was able to produce images that were spatially accurate to within 0.1 mm of direct caliper measurements, a minimum spatial resolution of 0.86 mm may make differentiation of fine dental tissues *in vivo* more difficult and as such make the identification of landmarks less precise[66].

To test the accuracy of linear measurements in the dentoalveolar region of CBCT scans made with the Hitachi CB MercuRay device, Baumgaertel *et al.* used digital calipers to assess the imaged skulls as a gold standard[67]. Both measurement methods provided a very high level of reliability when repeated by the same examiner. While all CBCT measurements were not significantly different than that of the direct method, slight underestimation of distances became cumulative to significant levels when many tooth width measurements were added to assess tooth size-arch perimeter discrepancies[67]. Baumgaertel hypothesized that the systematic error observed in the CBCT measurements may have been due to the imaging software determining distances to the midpoint of the voxels resulting in half a voxel width not being included in the length measurement on each side. By adding an extra voxel width to each measurement, the resultant CBCT measurements were all insignificantly different than the caliper lengths[67]. Baumgaertel's alternative explanation involves the averaging of voxels along the borders of two zones of different radiopacity and depending on the density threshold level set by the imaging software, these voxels of diminished density could be excluded from the tooth structure, also resulting in an underestimation of the tooth sizes[67].

1.5.4 *In vivo* Diagnosis of Root Resorption

1.5.4.1 2-D vs 3-D Radiography

Root resorption is classified by its cervical or apical root location, and the surface affected, being internal or external. The process is infrequently serious and is unpredictable, but in those few cases carries a high morbidity, thus it requires vigilant monitoring in all patients[68]. Orthodontic treatment has been identified as a predisposing factor for external cervical resorption of maxillary incisors and canines, and mandibular molars with a stronger association than trauma and intracoronal bleaching[69]. The effects of the root changes remained identifiable even long after the removal of the appliances (1.5-33 years)[69] indicating that once established, the destructive process can be arrested but not reversed.

The ability to radiographically image the third dimension and then accurately represent it through multiplanar reformatting for accurate reproduction of patients' true anatomical and spatial relationships became within the dental clinicians' reach with the introduction of the NewTom QR 9000 (Verona, Italy)[47]. Three dimensional radiographs offer the greatest advantage over traditional two dimensional imaging techniques in the identification of root resorption on the buccal and lingual surfaces of teeth. This is a product of the difficulty in resolving small density changes against the radiopaque background of the root body in traditional methods. The additional sensitivity and specificity of the records must always be weighed against the increased x-ray exposure for the patient. Increased CBCT resolution with smaller voxel sizes require longer scans resulting in greater patient exposure. However these increases may be justified if they improve the ability for clinicians to identify root changes at earlier stages and modify treatment to minimize its progression and thus long-term health risks to affected teeth. Liedke *et al* evaluated the ability of trained radiologists to identify small root pits drilled into the buccal surface of extracted teeth that were radiographed by CBCT at several typical resolutions[70]. The buccal surface of the teeth was selected as it highlighted the benefit of 3-D imaging over the traditional 2-D images. The 2-D radiographs are poorest at differentiating root changes against the radiopaque body of the root in the path of the x-ray beam and when anatomic structures overlap the region of interest[71]. These would include the buccal and lingual root surfaces. Liedke *et al* found that root pits down to 0.6mm in diameter and 0.3mm in depth were reliably identified in all thirds and at all the resolutions tested, although the mid-voxel size of 0.3mm offered the highest identification while at a resolution that required lower radiation exposure to patients[70].

While conventional radiographic studies found no difference in identification sensitivity[72], traditional multi-slice CT imaging techniques have had greater difficulty identifying simulated resorptive pits in the apical third of the root[71]. Attributed to anatomical differences in the different regions of the root, da Silveria noted that the smaller root diameter might have masked the resorptive pits. Analyzed axial slices images were taken every 1 mm which resulted in significantly fewer positive identifications of the smaller (0.6 mm diameter) cavities compared to larger 1.2 and 1.8 mm pits, especially in the apical third of the root[71]. While not quantifying the radiological dose to patients, da Silveria echoed concerns to the routine use of multi-slice CT imaging as a replacement to conventional imaging until advancements in technology reduced patient exposure.

1.5.4.2 Periapical Radiography

Most 2-D radiographic studies to date described apical root resorption in terms of qualitative severity. This was a result of the many methodological and anatomical limitations that reduced investigators' ability to achieve accurate and reliable linear measurements from the conventional radiographs. In addition to interfering anatomic structures, identification of resorption by 2-D imaging was confounded by bone trabeculation and variable angulation of the central x-ray beam[72]. This made smaller lesions more difficult to identify even in controlled lab conditions where overlapping anatomy was removed. Andreasen extrapolated the findings of an earlier study in which a 7% change in mineralization was required to identify the lesion radiographically[72,73]. Chapnick's follow up study also supported Andreasen's conclusions that conventional radiographs were inadequate for reliable detection of small resorptive defects[74].

Mohandesan *et al.* used the long cone paralleling technique to quantitatively describe root shortening during one year of orthodontic treatment[10]. Image distortion was accounted for by applying a multiplier based on the difference in crown lengths. The appropriate use of the correction factor must assume however that the elongation/foreshortening changes between the serial images were constant throughout the film and that there was no deflection of the film against the patients' palate. Root length decreases that exceeded 1 mm during the 12 months of treatment were considered clinically significant[10]. All central and lateral incisors showed similar level of root resorption in the study, and with average root lengths of 17.1 and 15.5 mm respectively, the 1.67 and 1.8 mm of root loss constituted a shortening of 9.8 and 11.5% respectively[10]. Mohandesan also found that the amount of apical root loss positively correlated with increased treatment duration and distance teeth travelled, such as those cases involving premolar extractions. To improve the sensitivity of detecting root changes in serial periapical radiographs, mathematical computer-based reconstructions have been used to compare pre and post-treatment images[75]. The method is time consuming however, limiting the technique's adoption in the clinical setting[76].

The ability of periapical radiographs to detect orthodontically induced apical root resorption was evaluated following 8 weeks of tooth movement and compared to micro-CT scans as a gold standard[3]. While significantly more teeth were identified as having root resorption following the orthodontic forces compared to control teeth (55% vs 5%), these values were substantially lower than the number of teeth with resorption observed by micro-CT following their extraction[3]. With 86% of treated and 21% of control teeth identified as having apical resorption by micro-CT imaging, the traditional periapical radiographic technique was modestly specific (78%) but had only a fair sensitivity (44%). With less than half of the actual teeth with apical root loss being identified, it is likely that many of the earlier studies that relied on this technique to evaluate for root resorption would have achieved results that greatly underestimate its prevalence.

1.5.4.3 Panoramic Radiography

Like many clinicians, Kaley *et al.* assessed root resorption by comparing pre and post orthodontic treatment panoramic radiographs[9]. The study concluded that a disproportionate number patients starting with class III malocclusions and patients with treatment progression that positioned maxillary incisor roots in close proximity to the lingual cortical plate had severe root loss[9]. While this conclusion may be partially correct, the lack of standardization of patient position and technique protocols may have also contributed to the results. Proclination of incisors to compensate for a class III malocclusion would have resulted in foreshortening in the panoramic images exaggerating apical resorption. By the same logic class II division 1 patients would have underestimated root loss and it begs the question why treatment resulting in root proximity to the buccal cortical plate does not have the same destructive effects on the roots.

1.5.4.4 Periapical vs Panoramic Radiography

While not even attempting to quantify the amount of apical root resorption, Sameshima *et al.* compared the ability to detect root resorption before and after orthodontic treatment by panoramic radiographs and full mouth series (FMS)[77]. His findings showed that while panoramic images were less likely to be able to identify root morphological anomalies and dilacerations, they likely overestimated the frequency of apical resorption by as much as 20% or more[77]. Since the most dramatic differences were found in the mandibular incisor region, the differences were attributed to the location of the focal trough and position of the lower incisors with respect to the occlusal plane. The posturing of the mandible forward into the bite block for imaging was thought to exaggerate malpositions in the lower incisor region[77]. Micro-CT studies have supported the conclusions that periapical radiographs are a technique with low sensitivity for identifying apical root resorption[78]. Following orthodontic tooth movement, 86% of the subsequently extracted premolars had evidence of root resorption by micro-CT compared to only 55% of the teeth identified by periapical radiography[78].

1.5.4.5 CBCT vs Panoramic Radiography

Comparing panoramic radiographs with CBCT imaging, Dudic found significantly higher prevalence and severity of apical root resorption in CBCT slices. Examiners diagnosed 69% of orthodontically treated teeth as having some level of apical root resorption, while only 44% of teeth were identified in panoramic radiographs[8]. CBCT images showed the greatest increase in sensitivity for identifying the root surfaces experiencing mild levels of resorption in which normal lengths were maintained but had become roughened and irregular[8]. The ability to view serial slices through the roots from many directions contributed to CBCT's superior visualization.

1.5.5 Radiation Exposure

1.5.5.1 ALARA

The concern for adhering to the ALARA principle (As Low As Reasonable Achievable) for x-ray exposure has prompted much research to determine comparative levels of radiation dosage for the various imaging techniques used in orthodontics. It is generally accepted that CBCT imaging requires greater levels of patient exposure compared to panoramic radiographs and cephalograms, and far lower doses compared to medical CT images. Quantitative comparisons become less definitive however as there is significant variability in the patient exposure depending on the equipment design, scan size and device settings[79].

1.5.5.2 Equivalent Dose vs Effective Dose

As a point of clarification, units of micrograys (μGy) measure the "mean tissue absorbed dose", whereas units of microsieverts (μSv) additionally account for the percentage of the body exposed in a measurement referred to as the "equivalent dose"[43]. It is this "equivalent dose" that also accounts for the different types of radiation on tissues[43]. The "effective dose", as defined by the International Commission on Radiological Protection (ICRP), also measured in microsieverts factors in the type, quantity, sensitivity and carcinogenic potential of the tissues and organs[80].

Danforth *et* al. noted that panoramic radiography was developed and used clinically since the late 1940's by Paatero and Hudson[81]. Efforts have been made in the ensuing decades to reduce patient exposure, however studies to quantify these advances has been complicated by inconsistent methods. Danforth *et al*. attempted to standardize the exposure measurements by using the ICRP definition of effective dose in 2000[81].

1.5.5.3 Radiation Exposure to Patients

The common arguments against the routine use of CBCT imaging for orthodontics are 2-fold: the radiation dose compared to traditional 2-D radiographic series, and the placement of responsibility on clinicians to identify and diagnose lesions beyond their region of specialty and/or focus. In terms of x-ray dosage, the level of patient exposure is hardware dependent[82].

At 56.2 and 61.1 μGy effective doses for the NewTom 9000 and i-CAT devices respectively, patient exposure was 5.5-6 times greater than the 10.4 μGy received by conventional panorex and lateral cephalograms[83]. This in turn is approximately 2 times greater than the same images captured with digital sensors[84]. Medical CT's on the other hand exposed patients to 7-8 times more radiation registering effective doses as high as 429.7 μGy[83].

A standard series of conventional extraoral 2-D imaging, such as panoramic, modified Waters, orbital and postero-anterior views, exposed various oromaxillofacial structures to radiation doses in the range of 1-3 mGy, which was equivalent to the Siremobil Iso-C^{3D} (18 sec exposure) CBCT[82]. Conversely, the same tissues registered 2-3x higher dosages with the NewTom 9000 CBCT (76 sec exposure)[82]. By comparison, multi-slice CT units (Volume Zoom and Sensation 16) resulted in 4-8x greater exposure compared to the conventional series[82]. A 2005 report found effective patient exposure varied widely between 45 and 650 μSv[85]. Mah's study in 2003 reported the NewTom 9000 imager produced an effective dose of 50.3 μSv[80]. For comparison, Kau *et al*. reported an exposure of 150 μSv for film-based full mouth series and 54 μSv for a film-based panoramic radiograph[85]; whereas Mah cited exposure ranges of 2.9 to 9.6 μSv for panoramic images; and 33-84 μSv and 14-100 μSv for full mouth series depending on the film speed, technique and device used[80]. Mah reported medical CT devices produced effective dose range of 142.5 and 907.2 μSv when maxillary and mandibular scans were added together[80]. Ngan *et al*. reported full head CT scans producing effective doses of 2000 μSv of exposure[86]. Variations in anatomical field scanned, device design and manufacturer, scanner settings, type of phantom used, and tissues evaluated result in the great range of exposure levels reported in the literature[80].

1.6 Conclusion

A sizable body of evidence is growing to support CBCT's ability to provide accurate landmark identification as well as angular and length measurements for cephalometric analysis. Orthogonal settings in reconstruction software recreate geometrically accurate anatomical measurements, while perspective settings introduce levels of magnification reliably reproducing traditional cephalograms. The limitations of conventional 2-D radiography for assessing root size, morphology and resorption has also been well documented. Variable magnification, distortion, superimpositions, and image artifacts combine with technique and equipment inconsistencies to make analysis of periapical and panoramic radiographs highly unreliable.

These imaging complexities have led to relatively little attention being paid to the radiography accuracy of quantitative dental tissue measurements and the ability to identify resorptive root changes. Although CBCT offers a quantum leap in diagnostic accuracy and resolution over the traditional 2-D radiographic records, research is needed to justify its routine use for all orthodontic patients. Especially in light of the additional radiation dosage orthodontic patients would be exposed to in comparison to traditional 2-D radiographic records such as panoramic and periapical radiographs, and lateral cephalograms. An increased array of diagnostic applications and confidence in imaging accuracy will help orthodontists embrace the transition to 3-D CBCT imaging and better justify the increased x-ray exposure to patients.

1.7 References

1. Kurol J, Owman-Moll P, Lundgren D. Time-related root resorption after application of a controlled continuous orthodontic force. American Journal of Orthodontics & Dentofacial Orthopedics 1996;110:303-310.

2. Chan EKM, Darendeliler MA, Petocz P, Jones AS. A new method for volumetric measurement of orthodontically induced root resorption craters. European Journal of Oral Sciences 2004;112:134-139.

3. Dudic A, Giannopoulou C, Martinez M, Montet X, Kiliaridis S. Diagnostic accuracy of digitized periapical radiographs validated against micro-computed tomography scanning in evaluating orthodontically induced apical root resorption. European Journal of Oral Sciences 2008;116:467-472.

4. Harris DA, Jones AS, Darendeliler MA. Physical properties of root cementum: part 8. Volumetric analysis of root resorption craters after application of controlled intrusive light and heavy orthodontic forces: a microcomputed tomography scan study. American Journal of Orthodontics & Dentofacial Orthopedics 2006;130:639-647.

5. Wierzbicki T, El-Bialy T, Aldaghreer S, Li G, Doschak M. Analysis of orthodontically induced root resorption using micro-computed tomography (Micro-CT). Angle Orthodontist 2009;79:91-96.

6. Jimenez-Pellegrin C, Arana-Chavez VE. Root resorption in human mandibular first premolars after rotation as detected by scanning electron microscopy. American Journal of Orthodontics & Dentofacial Orthopedics 2004;126:178-184; discussion 184-175.

7. Lupi JE, Handelman CS, Sadowsky C. Prevalence and severity of apical root resorption and alveolar bone loss in orthodontically treated adults. American Journal of Orthodontics & Dentofacial Orthopedics 1996;109:28-37.

8. Dudic A, Giannopoulou C, Leuzinger M, Kiliaridis S. Detection of apical root resorption after orthodontic treatment by using panoramic radiography and cone-beam computed tomography of super-high resolution. American Journal of Orthodontics & Dentofacial Orthopedics 2009;135:434-437.

9. Kaley J, Phillips C. Factors related to root resorption in edgewise practice. Angle Orthodontist 1991;61:125-132.

10. Mohandesan H, Ravanmehr H, Valaei N. A radiographic analysis of external apical root resorption of maxillary incisors during active orthodontic treatment. European Journal of Orthodontics 2007;29:134-139.

11. Tronstad L. Root resorption--etiology, terminology and clinical manifestations. Endodontics & Dental Traumatology 1988;4:241-252.

12. Chan E, Darendeliler MA. Physical properties of root cementum: part 7. Extent of root resorption under areas of compression and tension. American Journal of Orthodontics & Dentofacial Orthopedics 2006;129:504-510.

13. Chan E, Darendeliler MA. Physical properties of root cementum: Part 5. Volumetric analysis of root resorption craters after application of light and heavy orthodontic forces. American Journal of Orthodontics & Dentofacial Orthopedics 2005;127:186-195.

14. Sharpe W, Reed B, Subtelny JD, Polson A. Orthodontic relapse, apical root resorption, and crestal alveolar bone levels. American Journal of Orthodontics & Dentofacial Orthopedics 1987;91:252-258.

15. Borg E, Kallqvist A, Grondahl K, Grondahl HG. Film and digital radiography for detection of simulated root resorption cavities. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 1998;86:110-114.

16. Kang BC, Farman AG, Scarfe WC, Goldsmith LJ. Mechanical defects in dental enamel vs. natural dental caries: observer differentiation using Ektaspeed Plus film. Caries Research 1996;30:156-162.

17. Levander E, Bajka R, Malmgren O. Early radiographic diagnosis of apical root resorption during orthodontic treatment: a study of maxillary incisors. European Journal of Orthodontics 1998;20:57-63.

18. de Freitas MR, Beltrao RTS, Janson G, Henriques JFC, Chiqueto K. Evaluation of root resorption after open bite treatment with and without extractions. American Journal of Orthodontics & Dentofacial Orthopedics 2007;132:143.e115-122.

19. Levander E, Malmgren O, Eliasson S. Evaluation of root resorption in relation to two orthodontic treatment regimes. A clinical experimental study. European Journal of Orthodontics 1994;16:223-228.

20. Remington DN, Joondeph DR, Artun J, Riedel RA, Chapko MK. Long-term evaluation of root resorption occurring during orthodontic treatment. American Journal of Orthodontics & Dentofacial Orthopedics 1989;96:43-46.

21. Taylor NG, Jones AG. Are anterior occlusal radiographs indicated to supplement panoramic radiography during an orthodontic assessment? British Dental Journal 1995;179:377-381.

22. Baumrind S, Korn EL, Boyd RL. Apical root resorption in orthodontically treated adults. American Journal of Orthodontics & Dentofacial Orthopedics 1996;110:311-320.

23. Mirabella AD, Artun J. Prevalence and severity of apical root resorption of maxillary anterior teeth in adult orthodontic patients. European Journal of Orthodontics 1995;17:93-99.

24. Brezniak N, Goren S, Zoizner R, Dinbar A, Arad A, Wasserstein A et al. A comparison of three methods to accurately measure root length. Angle Orthodontist 2004;74:786-791.

25. Tohnak S, Mehnert A, Crozier S, Mahoney M. Synthesizing panoramic radiographs by unwrapping dental CT data. Conference Proceedings: ... Annual International Conference of the IEEE Engineering in Medicine & Biology Society 2006;1:3329-3332.

26. McKee IW, Williamson PC, Lam EW, Heo G, Glover KE, Major PW. The accuracy of 4 panoramic units in the projection of mesiodistal tooth angulations. American Journal of Orthodontics & Dentofacial Orthopedics 2002;121:166-175; quiz 192.

27. Van Elslande DC, Russett SJ, Major PW, Flores-Mir C. Mandibular asymmetry diagnosis with panoramic imaging. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:183-192.

28. Tronje G, Eliasson S, Julin P, Welander U. Image distortion in rotational panoramic radiography. II. Vertical distances. Acta Radiologica: Diagnosis 1981;22:449-455.

29. Larheim TA, Svanaes DB. Reproducibility of rotational panoramic radiography: mandibular linear dimensions and angles. American Journal of Orthodontics & Dentofacial Orthopedics 1986;90:45-51.

30. Kjellberg H, Ekestubbe A, Kiliaridis S, Thilander B. Condylar height on panoramic radiographs. A methodologic study with a clinical application. Acta Odontologica Scandinavica 1994;52:43-50.

31. Turp JC, Vach W, Harbich K, Alt KW, Strub JR. Determining mandibular condyle and ramus height with the help of an Orthopantomogram--a valid method? Journal of Oral Rehabilitation 1996;23:395-400.

32. Yitschaky M, Haviv Y, Aframian DJ, Abed Y, Redlich M. Prediction of premolar tooth lengths based on their panoramic radiographic lengths. Dento-Maxillo-Facial Radiology 2004;33:370-372.

33. Batenburg RH, Stellingsma K, Raghoebar GM, Vissink A. Bone height measurements on panoramic radiographs: the effect of shape and position of edentulous mandibles. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 1997;84:430-435.

34. Catic A, Celebic A, Valentic-Peruzovic M, Catovic A, Jerolimov V, Muretic I. Evaluation of the precision of dimensional measurements of the mandible on panoramic radiographs. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 1998;86:242-248.

35. Schulze R, Krummenauer F, Schalldach F, d'Hoedt B. Precision and accuracy of measurements in digital panoramic radiography. Dento-Maxillo-Facial Radiology 2000;29:52-56.

36. Larheim TA, Svanaes DB, Johannessen S. Reproducibility of radiographs with the orthopantomograph 5: tooth-length assessment. Oral Surgery, Oral Medicine, Oral Pathology 1984;58:736-741.

37. Laster WS, Ludlow JB, Bailey LJ, Hershey HG. Accuracy of measurements of mandibular anatomy and prediction of asymmetry in panoramic radiographic images. Dento-Maxillo-Facial Radiology 2005;34:343-349.

38. Hardy TC, Suri L, Stark P. Influence of patient head positioning on measured axial tooth inclination in panoramic radiography. Journal of Orthodontics 2009;36:103-110.

39. Owens AM, Johal A. Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. Angle Orthodontist 2008;78:475-481.

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

41. Van Elslande DC, Heo G, Flores-Mir C, Carey J, Lam EW, Major PW. The accuracy of mesiodistal root angulation projected by the CBCT panoramic-like image. American Journal of Orthodontics & Dentofacial Orthopedics 2009;Accepted for Publication.

42. Cederlund A, Kalke M, Welander U. Volumetric tomography - a new tomographic technique for panoramic units. Dento-Maxillo-Facial Radiology 2009;38:104-111.

43. Mah J, Hatcher D. Three-dimensional craniofacial imaging. American Journal of Orthodontics & Dentofacial Orthopedics 2004;126:308-309.

44. Holberg C, Steinhauser S, Geis P, Rudzki-Janson I. Cone-beam computed tomography in orthodontics: benefits and limitations. Journal of Orofacial Orthopedics 2005;66:434-444.

45. 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. European Radiology 1998;8:1558-1564.

46. Halazonetis DJ. From 2-dimensional cephalograms to 3-dimensional computed tomography scans. American Journal of Orthodontics & Dentofacial Orthopedics 2005;127:627-637.

47. Hatcher DC, Aboudara CL. Diagnosis goes digital. American Journal of Orthodontics & Dentofacial Orthopedics 2004;125:512-515.

48. Araki K, Maki K, Seki K, Sakamaki K, Harata Y, Sakaino R et al. Characteristics of a newly developed dentomaxillofacial X-ray cone beam CT scanner (CB MercuRay): system configuration and physical properties. Dento-Maxillo-Facial Radiology 2004;33:51-59.

49. Walter C, Kaner D, Berndt DC, Weiger R, Zitzmann NU. Three-dimensional imaging as a pre-operative tool in decision making for furcation surgery. Journal of Clinical Periodontology 2009;36:250-257.

50. Misch KA, Yi ES, Sarment DP. Accuracy of cone beam computed tomography for periodontal defect measurements. Journal of Periodontology 2006;77:1261-1266.

51. Sukovic P. Cone beam computed tomography in craniofacial imaging. Orthodontics & Craniofacial Research 2003;6 Suppl 1:31-36; discussion 179-182.

52. Arai Y, Tammisalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. Dento-Maxillo-Facial Radiology 1999;28:245-248.

53. Hashimoto K, Arai Y, Iwai K, Araki M, Kawashima S, Terakado M. A comparison of a new limited cone beam computed tomography machine for dental use with a multidetector row helical CT machine. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2003;95:371-377.

54. Hashimoto K, Kawashima S, Araki M, Iwai K, Sawada K, Akiyama Y. Comparison of image performance between cone-beam computed tomography for dental use and four-row multidetector helical CT. Journal of Oral Science 2006;48:27-34.

55. Liu Y, Olszewski R, Alexandroni E, Enciso R, Xu T, Mah J. The validity of in vivo tooth volume determinations from cone-beam computed tomography. Angle Orthodontist 2010;80:160-166.

56. Ludlow JB, Laster WS, See M, Bailey LTJ, Hershey HG. Accuracy of measurements of mandibular anatomy in cone beam computed tomography images. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2007;103:534-542.

57. 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. American Journal of Orthodontics & Dentofacial Orthopedics 2007;132:550-560.

58. Chen J, Li S, Fang S. Quantification of tooth displacement from cone-beam computed tomography images. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:393-400.

59. Hutchinson SY. Cone beam computed tomography panoramic images vs. traditional panoramic radiographs. American Journal of Orthodontics & Dentofacial Orthopedics 2005;128:550.

60. Kumar V, Ludlow JB, Mol A, Cevidanes L. Comparison of conventional and cone beam CT synthesized cephalograms. Dento-Maxillo-Facial Radiology 2007;36:263-269.

61. Lamichane M, Anderson NK, Rigali PH, Seldin EB, Will LA. Accuracy of reconstructed images from cone-beam computed tomography scans. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:156.e151-156; discussion 156-157.

62. Cattaneo PM, Bloch CB, Calmar D, Hjortshoj M, Melsen B. Comparison between conventional and cone-beam computed tomography-generated cephalograms. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:798-802.

63. Lou L, Lagravere MO, Compton S, Major PW, Flores-Mir C. Accuracy of measurements and reliability of landmark identification with computed tomography (CT) techniques in the maxillofacial area: a systematic review. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2007;104:402-411.

64. Berco M, Rigali PH, Jr., 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. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:17.e11-19; discussion 17-18.

65. Lagravere MO, Carey J, Toogood RW, Major PW. Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:112-116.

66. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:573-582.

67. Baumgaertel S, Palomo JM, Palomo L, Hans MG. Reliability and accuracy of cone-beam computed tomography dental measurements. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:19-25; discussion 25-18.

68. Patel S, Kanagasingam S, Pitt Ford T. External cervical resorption: a review. Journal of Endodontics 2009;35:616-625.

69. Heithersay GS. Invasive cervical resorption: an analysis of potential predisposing factors. Quintessence International 1999;30:83-95.

70. Liedke GS, da Silveira HED, da Silveira HLD, Dutra V, de Figueiredo JAP. Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. Journal of Endodontics 2009;35:233-235.

71. da Silveira HLD, Silveira HED, Liedke GS, Lermen CA, Dos Santos RB, de Figueiredo JAP. Diagnostic ability of computed tomography to evaluate external root resorption in vitro. Dento-Maxillo-Facial Radiology 2007;36:393-396.

72. Andreasen FM, Sewerin I, Mandel U, Andreasen JO. Radiographic assessment of simulated root resorption cavities. Endodontics & Dental Traumatology 1987;3:21-27.

73. Bender IB. Factors influencing the radiographic appearance of bony lesions. Journal of Endodontics 1982;8:161-170.

74. Chapnick L. External root resorption: an experimental radiographic evaluation. Oral Surgery, Oral Medicine, Oral Pathology 1989;67:578-582.

75. Reukers E, Sanderink G, Kuijpers-Jagtman AM, van't Hof M. Assessment of apical root resorption using digital reconstruction. Dento-Maxillo-Facial Radiology 1998;27:25-29.

76. Versteeg CH, Sanderink GC, van der Stelt PF. Efficacy of digital intra-oral radiography in clinical dentistry. Journal of Dentistry 1997;25:215-224.

77. Sameshima GT, Asgarifar KO. Assessment of root resorption and root shape: periapical vs panoramic films. Angle Orthodontist 2001;71:185-189.

78. Giannopoulou C, Dudic A, Montet X, Kiliaridis S, Mombelli A. Periodontal parameters and cervical root resorption during orthodontic tooth movement. Journal of Clinical Periodontology 2008;35:501-506.

79. Kwong JC, Palomo JM, Landers MA, Figueroa A, Hans MG. Image quality produced by different cone-beam computed tomography settings. American Journal of Orthodontics & Dentofacial Orthopedics 2008;133:317-327.

80. Mah JK, Danforth RA, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2003;96:508-513.

81. Danforth RA, Clark DE. Effective dose from radiation absorbed during a panoramic examination with a new generation machine. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2000;89:236-243.

82. Schulze D, Heiland M, Thurmann H, Adam G. Radiation exposure during midfacial imaging using 4- and 16-slice computed tomography, cone beam computed tomography systems and conventional radiography. Dento-Maxillo-Facial Radiology 2004;33:83-86.

83. Silva MAG, Wolf U, Heinicke F, Bumann A, Visser H, Hirsch E. Cone-beam computed tomography for routine orthodontic treatment planning: a radiation dose evaluation. American Journal of Orthodontics & Dentofacial Orthopedics 2008;133:640.e641-645.

84. Visser H, Rodig T, Hermann KP. Dose reduction by direct-digital cephalometric radiography. Angle Orthodontist 2001;71:159-163.

85. Kau CH, Richmond S, Palomo JM, Hans MG. Three-dimensional cone beam computerized tomography in orthodontics. Journal of Orthodontics 2005;32:282-293.

86. Ngan DCS, Kharbanda OP, Geenty JP, Darendeliler MA. Comparison of radiation levels from computed tomography and conventional dental radiographs. Australian Orthodontic Journal 2003;19:67-75.

Chapter 2: Measurement Accuracy and Precision of Tooth Length with CBCT Axial, Sagittal and Coronal Serial Slices

2.1 Introduction

In 1967, Sir Godfrey Hounsfield developed the first computed tomography (CT) devices for medical use[1]. For the next three decades advances in the technology improved scan speed and resolution but had only minimally reduced patient exposure, while during the same time developments in conventional radiology improved image quality and reduced the radiation required[1]. Cone beam CT (CBCT), developed in the 1990's was first used in the United States in 2000. It differed from medical CT by producing a cone-shaped x-ray beam allowing 3-D image generation by combining 2-D images taken from 360 degrees in one pass of the device[1,2]. This allowed faster data acquisition at lower overall patient exposure compared to the fan-shaped x-ray beams of medical CT. Cone-beam CT scanners consist of an x-ray emitter and a larger detector surface more similar to that used for cephalometric projections, than the small sensors of the medical CT's. The pulsed radiation source decreases the patient's radiation exposure to a fraction of the total scan time, whereas the unpulsed medical CT results in patient exposure times equaling the full scan duration. The large sensor allows the entire image to be obtained in a single pass[2]. The CBCT sensors use an image intensifier which may be a source of noise and increased scattered radiation yielding the decreased image resolution compared to the conventional helical CT devices[3], but also allows improves sensor sensitivity enabling decreased patient exposure.

In orthodontics, 3-D imaging offers diagnosis and treatment planning advantages over conventional 2-D radiographs for unerupted teeth with respect to their position and orientation without the confounding factors such as anatomical overlap, image distortion or operator[4]. Another proposed advantage to 3-D radiographic records includes the diagnosis and monitoring of root resorption prior to and throughout treatment[5]. The 3-D imaging equipment comes at increased cost however, in terms of hardware, software, training, image evaluation and radiation exposure. It is thus worthwhile to evaluate 3-D imaging technology to determine if it is currently worth the monetary and time investment for the practitioner, and increased radiation exposure for the patient.

While histological studies have found a high incidence of apical root resorption, radiographic analyses have been less conclusive as variations in technique and study protocol have made results comparisons more difficult[6,7]. Many etiological factors may predispose a patient to root resorption due to orthodontic tooth movement, however it was felt that pre-treatment radiographic evidence was the best diagnostic aid to predict its occurrence (or continuation)[8]. To date, quantitative measurement accuracy of CBCT images have been limited to *in vitro* measurements of artificial acrylic blocks[9], and linear measurements of skull and cranial base landmarks in dry skulls[10]. Lou *et al.'s* systematic review of landmark and linear measurement accuracy by CBCT lateral cephalogram reconstructions illustrated the high variability between studies[10]. Methodological differences likely played a significant role in the inconsistency in the literature, however under the idealized *in vitro* conditions; measurement accuracy to within 0.5 mm was typically achieved.

Many CBCT imaging studies have achieved very high levels of reliability and accuracy for the identification of cephalometric landmarks with linear measurement errors of less than 2%[11-13]. Only one other study has tested the accuracy of linear measurements in the dentoalveolar region of CBCT scans and used digital calipers to assess the imaged skulls as a gold standard[14]. Both measurement methods provided a very high level of reliability when repeated by the same examiner. While all CBCT measurements were not significantly different than that of the direct method, slight underestimation of distances became cumulative to significant levels when many tooth width measurements were added to assess tooth size-arch perimeter discrepancies[14].

Three dimensional radiographs offer the greatest advantage over traditional two dimensional imaging techniques in the identification of root resorption on the buccal and lingual surfaces of teeth. This is a product of the difficulty in resolving small density changes against the radiopaque background of the root body in traditional methods. The additional sensitivity and specificity of the records must always be weighed against the increased x-ray exposure for the patient. Increased CBCT resolution with smaller voxel sizes require longer scans resulting in greater patient exposure. However these increases may be justified if they improve the ability for clinicians to identify root changes at earlier stages and modify treatment to minimize its progression and thus long-term health risks to affected teeth. Liedke *et al* evaluated the ability of trained radiologists to identify small root pits drilled into the buccal surface of extracted teeth that were radiographed by CBCT at several typical resolutions[15]. The buccal surface of the teeth was selected as it highlighted the benefit of 3-D imaging over the traditional 2-D images. The 2-D radiographs are poorest at differentiating root changes against the radiopaque body of the root in the path of the x-ray beam and when anatomic structures overlap the region of interest[16]. These would include the buccal and lingual root surfaces. Liedke *et al* found that root pits down to 0.6 mm in diameter and 0.3 mm in depth were reliably identified in all thirds and at all the resolutions tested, although the mid-voxel size of 0.3 mm offered the highest identification while at a resolution that required lower radiation exposure to patients[15].

Resorption of dental tissues is a progressive process that can be arrested by removal of the clastic stimulus. Infective and/or physical agents that degrade the organic cementoid surface layer of the root surface allow the same multinucleated clastic cells that resorb bone the opportunity to resorb cementum and dentin[17]. In orthodontic terms, the resorptive progresses only as long as the mechanical stimulation of the macrophages and osteoclasts are present[17]. While the severity of root resorption is linked to the magnitude of force applied to the teeth during orthodontic treatment, Wierzbinki noted researchers have found that detectable amounts of apical resorption occurred with forces as light as 50 g[18]. Longitudinal studies have largely been comprised of comparing pre and post orthodontic periapical radiographs. Apical root blunting, while common following orthodontic treatment, does not pose long term morbidity to patients. It is the subset of patients that experience moderate to severe levels of resorption that compel researchers to improve diagnostic tests to identify progressive root resorption early in order to make treatment modifications.

By addressing the accuracy and reliability of CBCT image reconstructions to measure root length, this study aims to increase clinicians' confidence in using 3-D imaging software to improve diagnosis, treatment planning and assess treatment progression with respect to root resorption.

2.2 Materials and Methods

This study was conducted under the approval of the Health Research Ethics Board (HREB) at the University of Alberta (Appendix A).

Study subjects were selected from the University of Alberta graduate orthodontic clinic that required maxillary premolar extractions to complete their regular orthodontic treatment goals. Consent forms were explained and signed by all subjects prior to their inclusion in the study (Appendix B).

CBCT images were taken with the 12-bit i-CAT (Imaging Sciences International, Hatfield, Penn) set to a 40-second scan allowing image reconstruction with a voxel size of 0.25 mm. Standard clinical protocols were used for patient positioning and a cotton roll between incisor teeth was used to stably hold the occlusion apart to improve cusp tip identification. Images were saved as DICOM files and were reconstructed in Dolphin Imaging 10.5 Premium software (Dolphin Imaging Sciences, Chatsworth, Calif). Head positions in the reconstructed images were standardized anteroposteriorly by Frankfort Horizontal (Fig 2-1), and sagittally for maximal overlap of bilateral structures in the maxilla, ramus and body of the mandible (Figs 2-1 and 2-2).

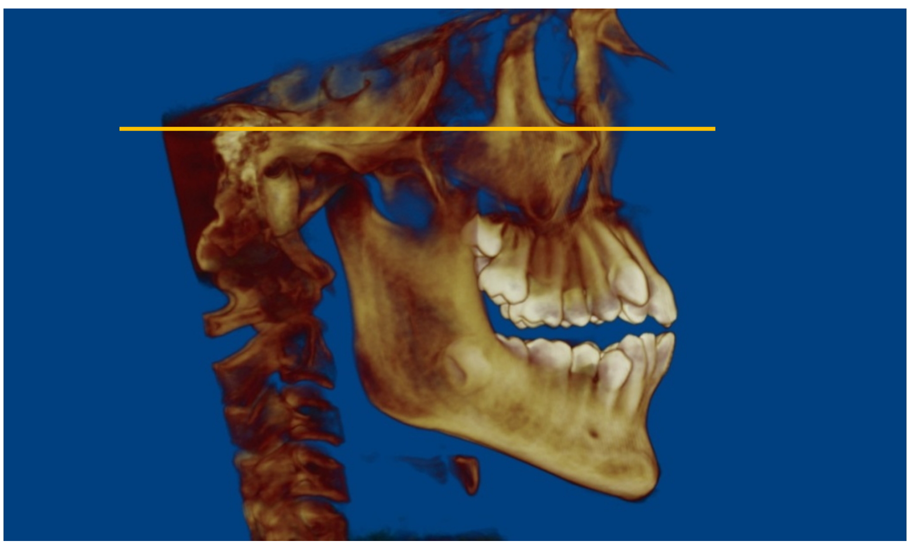

Figure 2-1: Standardized Volume Orientation - Sagittal view

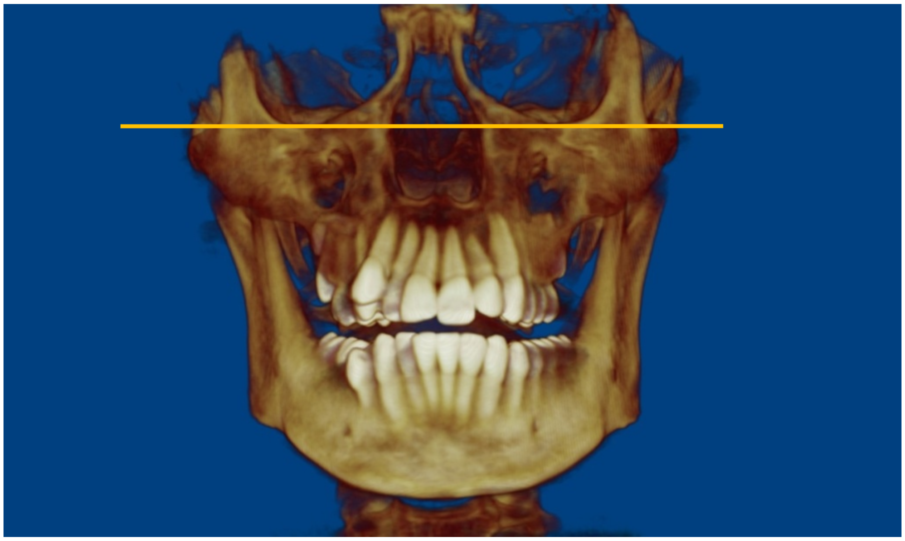

Figure 2-2: Standardized Volume Orientation – Frontal View

Tooth lengths were later measured by determining the apex and occlusal tips independently from serial axial (Fig 2-3), coronal (Fig 2-4) and sagittal (Fig 2-5) 2-D slices of voxel (0.25 mm) thickness using the built-in digital ruler in the Dolphin 3D software. For each of the 3 slice orientations tested, the landmarks used to measure tooth length were identified only through evaluation of the serial slices for that single orientation. Alternate serial slice views were not used in attempt to improve landmark localization.

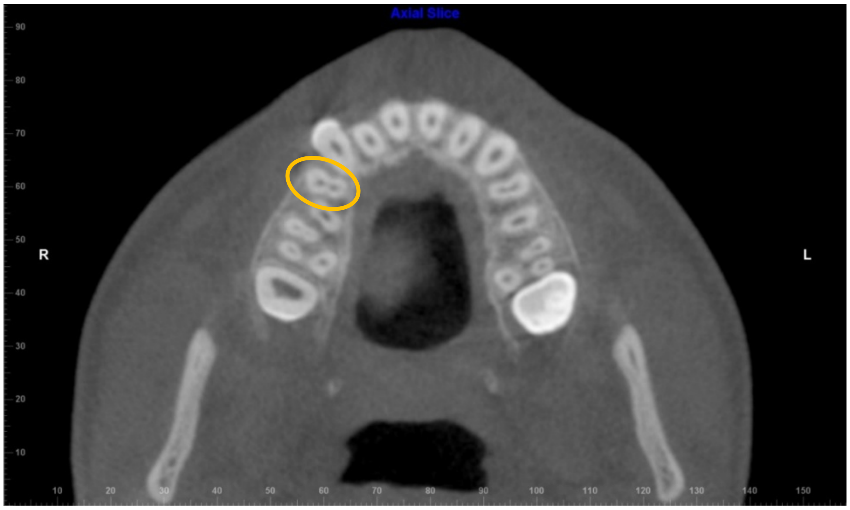

Figure 2-3: CBCT Axial Serial Slice

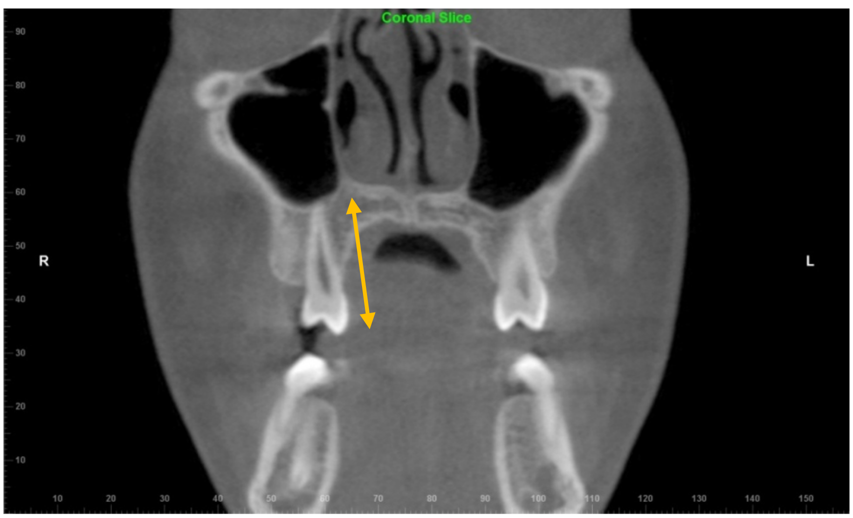

Figure 2-4: CBCT Coronal Serial Slice

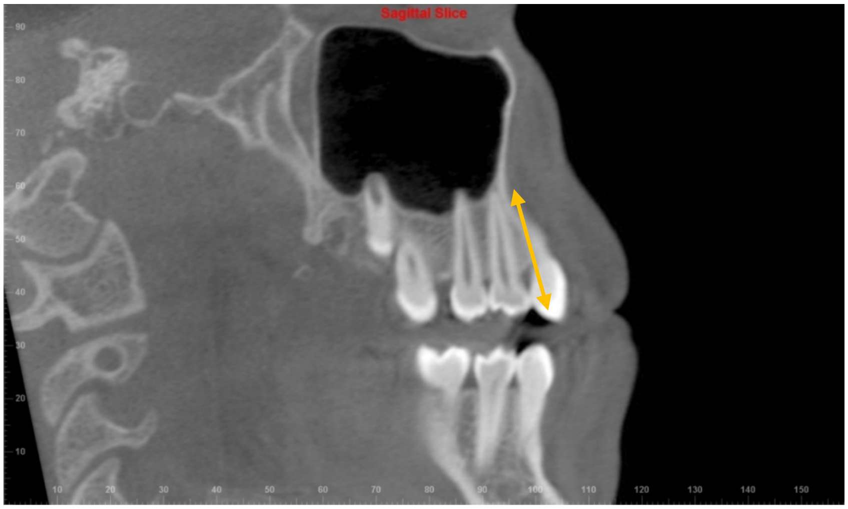

Figure 2-5: CBCT Sagittal Serial Slice

Following imaging, one or two maxillary 1st or 2nd premolar teeth were extracted as per the patient's orthodontic treatment plan and stored in 95% ethanol. Minimum sample size to achieve a significance level of $\alpha = 0.05$ with a study power ($1-\beta$) of 0.90 was determined to be 58 based on an *in vitro* pilot study in which previously extracted teeth were imaged and measured following the same measurement protocols as described above[19]. For this *ex vivo* study, the 58 premolars, collected from 32 subjects, were then measured directly with a digital caliper (OrthoPli, Philadelphia, Penn) following extraction. The minimum caliper reading was 0.013 mm and its measurement accuracy was 0.025 mm as reported by the manufacturer.

The entire tooth length was measured at its longest point from the buccal cusp tip to the root apex. In cases of multiple roots, the buccal root was used unless it had fractured during extraction in which case measurements were made to the intact lingual root apex. These exceptions were noted so the corresponding measurements were made in the CBCT serial slices. For CBCT image analysis, correct root and cusp identification was determined based on confirmation of the landmark position from other slice orientations and the identification of adjacent teeth. These alternate views were not used to confirm the accuracy of the landmark chosen, however, only to verify that the appropriate cusp tip and root apex was selected. All measurements were recorded to the nearest tenth of a millimeter. The raw data is summarized in Appendix E.

Ten of the 58 samples were randomly selected and measured in triplicate, in random order, with at least one week between each measurement, in order to assess intra-rater reliability. Each of the slice orientations and digital caliper measurements were repeated three times for the 10 samples for the reliability assessment.

Accuracy of tooth length measurements made by the CBCT serial slices were compared to the digital caliper gold standard by repeated measures one-way ANOVA with Bonferroni correction and by single measures intraclass correlation coefficient using SPSS version 16.0 software (SPSS, Chicago, Ill). Statistical analysis of intra-rater reliability of the triplicate measurements were assessed by single measures intraclass correlation coefficient (ICC) in SPSS.

The statistical analyses for the reliability and accuracy assessments were repeated following the removal of all outlying data points. Since they were determined to have no significant effect on the results, all data points were maintained for the reporting and analyses in this study. Clinically significant changes in root length were considered to be values of 1.0 mm and greater, consistent with those studies by Copeland[20] and Mohandesan[21].

The minimum sample size was then recalculated treating this study as a pilot to provide future research with a guide with which to achieve adequate power to distinguish clinically significant tooth length changes in the *in vivo* CBCT images, where surrounding hard and soft tissues diminish landmark localization compared to the *in vitro* study of previously extracted teeth.

Several known sources of measurement error in this study were identified. Sources such as landmark identification, voxel size resolution limitations, and standardization of the digital and software generated calipers were addressed and quantified by repeated sample measurements and an *in vitro* pilot study of 10 previously extracted teeth. Others, such as volume segmentation, were avoided altogether by analyzing serial slices of the CBCT volumes instead of relying on the computer-assisted removal of voxels falling below an arbitrary density threshold. Sources of error that were not addressed in this study, however, included the reliability of standardizing the volume position with the imaging software prior to serial slicing and the resolution loss accompanying the smoothing, compression and reconstruction algorithms that the Dolphin 3D imaging software used to store and manipulate the large datasets.

2.3 Results

2.3.1 Reliability

Triplicate measurements for 10 samples were extremely consistent for all measurement methods tested. Repeated measures with digital calipers achieved the highest measurement reliability with a single measures intraclass correlation coefficient value of 1.000 (95% CI: 0.999, 1.000). The CBCT serial slice measurements were also highly repeatable. Of these reconstructions the axial slice orientation resulted in tooth length measurements that were the most reliable with an ICC of 0.991 (95% CI: 0.976, 0.998), followed very closely by coronal serial slices with an ICC of 0.987 (95% CI: 0.964, 0.996) and sagittal slices at 0.985 (95% CI: 0.958, 0.996). Compared to the caliper gold standard, axial slice tooth measurements were on average 0.02 mm (SD = 0.6 mm) shorter, coronal slice tooth measurements were an average of 0.1 mm (SD = 0.6 mm) shorter, and sagittal slice tooth measurements were an average of 0.04 mm (SD = 0.6 mm) shorter. As another measure of reliability, the mean and standard deviation for the differences between the average gold standard tooth length measurements and each corresponding axial, coronal and sagittal serial slice measurement are summarized in Appendix C.

2.3.2 Accuracy

Comparison of tooth lengths of 58 maxillary premolars measured by Dolphin 3D reconstructions of i-CAT CBCT images resulted in insignificant differences regardless of slice orientation. Due to the individual variability of teeth used in this study and the opportunity to measure the same teeth by multiple techniques, the repeated measures ANOVA (RM-ANOVA) method of analysis the most appropriate means of comparison for the differences in group averages. This parametric statistical test was deemed acceptable as the model assumptions for its use, including normally distributed data sets with similar variances that were obtained by independent sampling, were adequately met. When comparing the different slice orientations to each other, teeth measured by serial slicing in axial, coronal and sagittal directions resulted in lengths that were within 0.6 mm of each other (Fig 2-6) which was considered not significantly different, as determined by a $p>0.05$ for repeated measures ANOVA analysis with Bonferroni correction (Table 2-1). Regardless of the slice orientation, all CBCT image measurements were significantly lower than that achieved by direct measurement of the extracted teeth by digital calipers ($p<0.001$) (Table 2-1). The calipers, considered in this study as the gold standard for tooth length, resulted in measurements that ranged from 1.0 mm shorter to 2.5 mm longer compared to the reconstructed DICOMs (Fig 2-7).

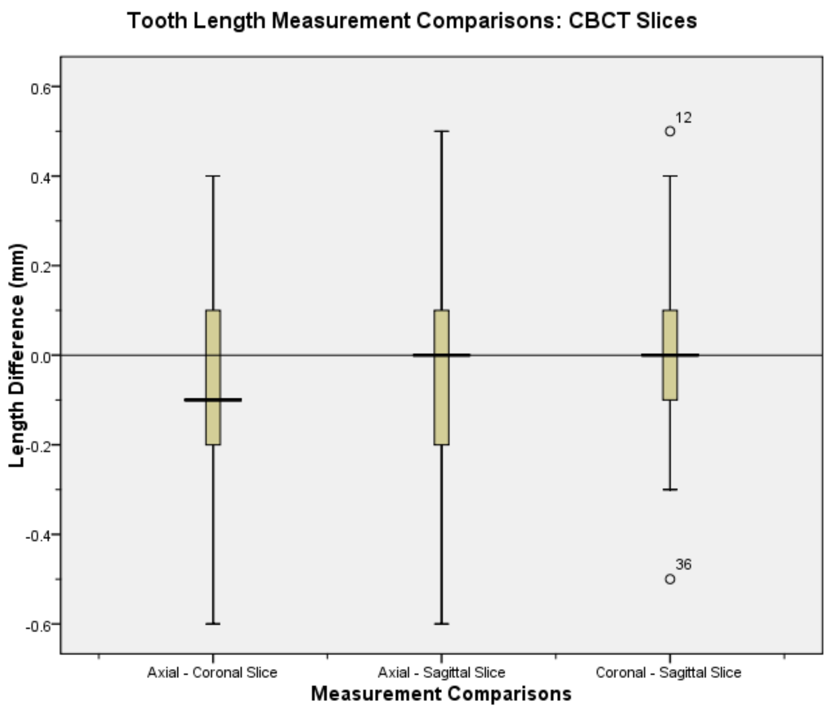

Figure 2-6: Comparison of Tooth Length Measurements by CBCT Slice Orientation

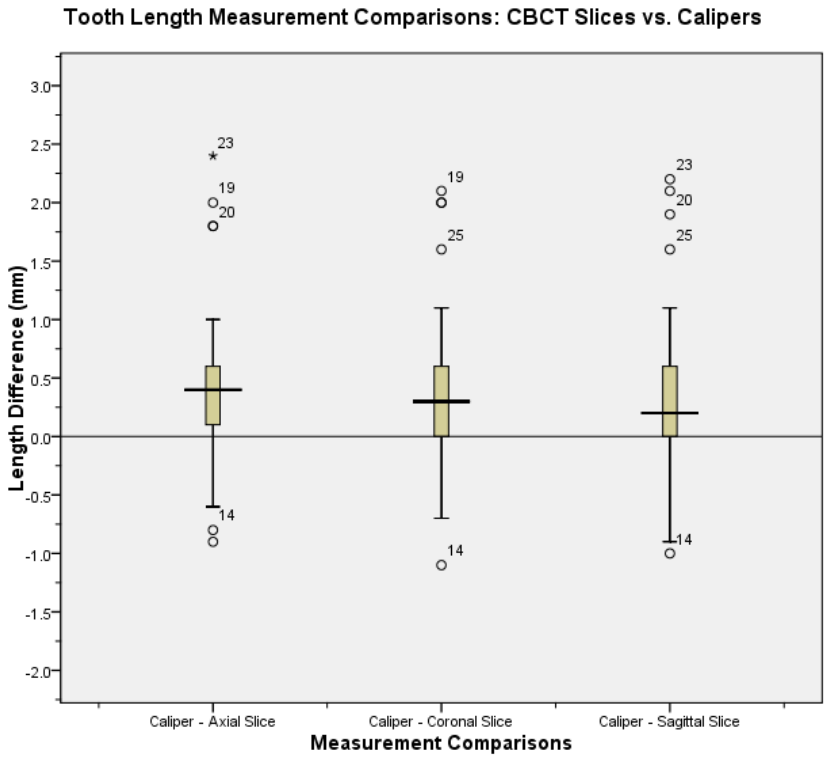

Figure 2-7: Comparison of Tooth Length Measurements for Calipers and CBCT Slice Orientation

These differences were highly significant by repeated measures ANOVA ($p<0.001$) (Table 2-1). While statistically significant, the differences in mean length measurements are around the error expected due to the i-CAT slice thickness of 0.25 mm, which would create an inherent resolution limit of 0.5 mm as the tooth length required identification of 2 points (the crown tip and root apex). The accuracy of the CBCT measurements also was smaller than the set clinically significant level of 1.0 mm.

Orientation (A)	Orientation (B)	Mean Difference (A-B)	Significance p	95% CI for Difference
Caliper	Axial Slice	0.4	<0.001	0.2, 0.6
	Coronal Slice	0.3	<0.001	0.1, 0.6
	Sagittal Slice	0.3	<0.001	0.1, 0.6
Axial	Coronal Slice	0.0	1.000	-0.1, 0.0
	Sagittal Slice	0.0	0.523	-0.1, 0.0
Coronal	Sagittal Slice	0.0	1.000	-0.1, 0.1

Table 2-1: Repeated Measures ANOVA for Measured Tooth Length with Bonferroni Correction

Scatter plots comparing each CBCT slice orientation with the caliper standard reveal a consistent measurement bias representing an underestimation of tooth size regardless of actual tooth length (Fig 2-12 to 2-14). Comparisons between the measurement methods do show a high degree of consistency, however, with ICC values of 0.919 (95% CI: 0.785, 0.962) for caliper and axial slice measurements; 0.925 (95% CI: 0.821, 0.963) for caliper and coronal slice measurements; and 0.926 (95% CI: 0.825, 0.963) for caliper and sagittal slice measurements.

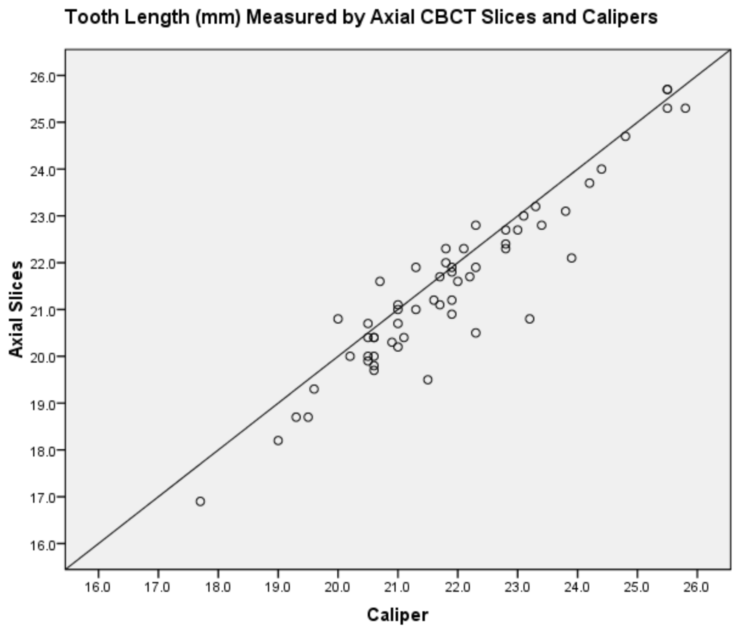

Figure 2-12: Scatter Plot of Tooth Length – Caliper vs. CBCT Axial Slices

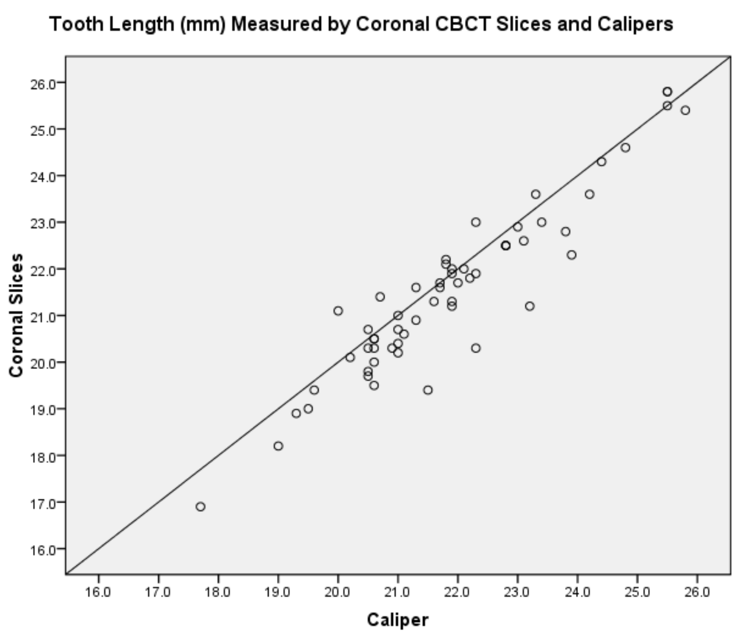

Figure 2-13: Scatter Plot of Tooth Length – Caliper vs. CBCT Coronal Slices

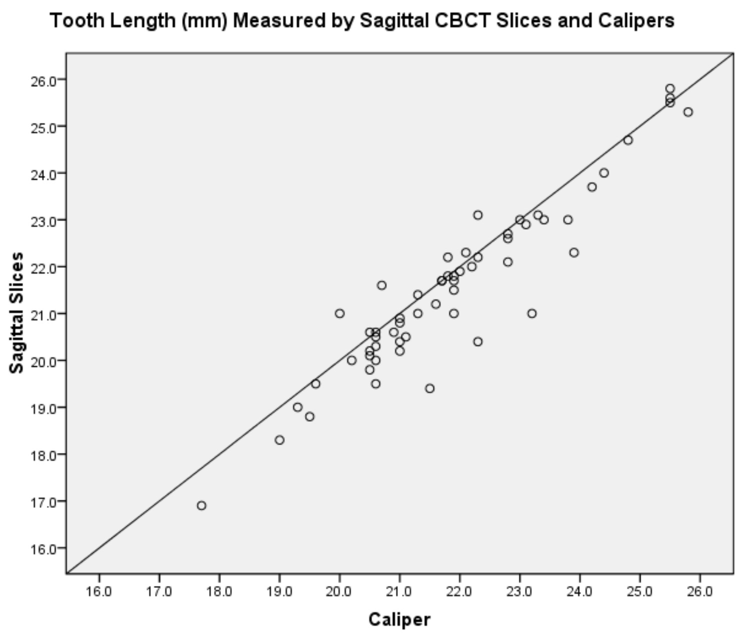

Figure 2-14: Scatter Plot of Tooth Length – Caliper vs. CBCT Sagittal Slices

An alternative analysis of the data using single measures intraclass correlation coefficient was used to determine the reliability between the four measurement techniques for each tooth individually made the same determination. Using an absolute agreement definition, the ICC value of 0.959 (95% CI: 0.929, 0.976) indicated that larger measurements by one technique highly corresponded with larger measurements by the other techniques.

2.3.3 Sample Size Calculation

In order to facilitate future *in vivo* studies, sample sizes calculations were performed based on the variability of the measurement differences between each slice orientation and calipers. Considering the 58 samples as a pilot study, the minimum sample sizes required to identify length differences of 0.5 mm would be 16, and for a 1.0 mm difference, 4 (Table 2-2). The formula used for this calculation was:

$$n \geq \sigma^2 \left[\frac{z_\beta^* + z_{\alpha/2}^*}{\delta}\right]^2$$

Where $\alpha = 0.05 \quad \beta = 0.1 \quad z^*_{\alpha/_2} = 1.96 \quad z_\beta = 1.285$

	Mean Difference	Standard Deviation σ	Detectable Length Difference δ = 0.5 mm	Detectable Length Difference δ = 1.0 mm
Caliper – Axial Slice Difference	0.38	0.61	16	4
Caliper – Coronal Slice Difference	0.34	0.61	16	4
Caliper – Sagittal Slice Difference	0.34	0.60	16	4

Table 2-2: Sample Size Calculation for Future Study based on Caliper and CBCT Slice Measurement Differences

2.4 Discussion

Orthodontically induced root resorption has been so difficult to quantify *in vivo* due to the limitations of the 2-D methods traditionally employed, such as periapical, panoramic and cephalometric radiographs. These images allowed resorption to be identified on tooth surfaces creating outer edges perpendicular to the x-ray beam[22]. Anatomical overlap often obscured the views of these root surfaces and resulted in less consistent readings and underreporting of resorption magnitudes. 3-D imaging technology has provided an ability to view root morphology and detect changes to root structures with higher resolution than conventional radiography can offer[23]. It also reduces ghost images, magnification, distortion and artifacts providing greater accuracy for determination of tooth position and size[24].

This study has demonstrated that CBCT reconstructions can provide reliable accurate tooth length measurements when images are compressed, stored and reconstructed in 3rd party software image management software common to orthodontics, such as Dolphin 3D. While the CBCT measurements were significantly shorter than direct caliper measurements statistically, the average difference of 0.34-0.38 mm is clinically insignificant and represents a dramatic improvement for early detection of root shortening due to iatrogenic and idiopathic resorption. The difference represented an error only slightly greater than one voxel thickness (0.25 mm) and may have been due to the similarity in radiopacity of the fine apical root structures and surrounding bone. This result bested the expected accuracy limit of 0.5 mm representing that the actual anatomical landmark likely fell between image slices.

While voxel size is important to image resolution, the bit rate of the imager has an effect on the image contrast and resolution as well. A higher bit rate allows finer details to be distinguished from one another as they may be assigned a radiopacity within a broader range of gray. The 12-bit i-CAT used in this study was capable of 4096 (2^{12}) levels of radiopacity. If fine root apices terminated partway through a voxel, the imaging software may assign that voxel with a radiopacity that averages the dental and surrounding periodontal ligament tissue and thus register at a lower intensity compared to voxels wholly inside of the dental tissue. As the reduced radiopacity of the voxel approaches that of the surrounding tissue, correctly identifying the voxel as one that should be included by the examiner for the purposes of tooth length become more difficult. It is likely that if more than half of the voxel contains root structure, the averaged radiopacity of the voxel would be more similar to the adjacent dental, versus soft tissue voxels and as such would be included as dental tissue in tooth length measurements. Contrarily, if less than half the voxel contained root structure; its radiopacity would approximate the PDL and thus be excluded from the measurement. Following this logic, one would expect that the CBCT measurements would over and underestimate the tooth length compared to the calipers an equal amount of time.

The regular underestimation of CBCT measurements of the tooth length in this study was consistent with Baumgaertel *et al.*'s findings and could be rationalized in several ways. Firstly, if the tooth tip/apex falling partly within the voxel falls below the density threshold, that slice will not register any tooth structure. Alternately, as root structures become finer, difficulty distinguishing root tips from surrounding cortical bone may have required the apical landmarks to be located further into the root body for increased identification confidence. Finally, the systematic error observed in the CBCT measurements may have been due to the imaging software determining distances to the midpoint of the voxels resulting in half a voxel width not being included in the length measurement on each side. By adding an extra voxel width to each measurement, the resultant CBCT measurements were all insignificantly different than the caliper lengths[14].

Liu's volumetric analysis of dental structures imaged by i-CAT CBCT and reconstructed in Amira Imaging software (Visage Imaging Inc, Carlsbad, Calif) also experienced underestimation of measurements, in that case volume, compared to direct means[25]. Variations in radiodensity throughout teeth, and root density approaching that of the surrounding bone increases the risk of misidentification of the dental landmarks of interest. Additionally, the smoothing algorithms the imaging programs used to reduce noise and improve image clarity decreased anatomical accuracy[25]. These revisions may not only incorrectly identify and remove border voxels that fall below a user-set threshold, but may also combine voxels for data compression in order to improve software performance for viewing and manipulating the volumes[25].

The multi-factorial etiology of root resorption remains elusive and complicated. As imaging software improves, the opportunity to assess quantitatively root length will provide orthodontists with the tools to more precisely monitor the length and surface stability of all roots. The result will be earlier identification of resorptive complications and more responsive treatment progression to minimize tooth loss due to root destruction.

2.5 Conclusions and Recommendations

While slice orientation had no significant impact on tooth length, it is advised that clinicians select multiple angles to best visualize root apices. Tooth position with respect to cortical plates; root angulation with respect to slice orientation; fineness of root tips; thinness of dental follicle; prominence of lamina dura; and the presence of dense bone islands may confound the identification of root apices from a single orientation but not interfere when viewed from other directions. Roots that dilacerate in the plane of the reconstructed slices are more difficult to determine accurate apex location. Dense bone islands and cortical bone has similar radiopacity to fine root structures making them prone to misidentification. Standardized technique and fastidious documentation are required to ensure the same cusp tips and apices are compared in serial images if used to monitor root changes during treatment.

2.6 References

1. Mah J, Hatcher D. Three-dimensional craniofacial imaging. American Journal of Orthodontics & Dentofacial Orthopedics 2004;126:308-309.

2. Holberg C, Steinhauser S, Geis P, Rudzki-Janson I. Cone-beam computed tomography in orthodontics: benefits and limitations. Journal of Orofacial Orthopedics 2005;66:434-444.

3. Araki K, Maki K, Seki K, Sakamaki K, Harata Y, Sakaino R et al. Characteristics of a newly developed dentomaxillofacial X-ray cone beam CT scanner (CB MercuRay): system configuration and physical properties. Dento-Maxillo-Facial Radiology 2004;33:51-59.

4. Leach HA, Ireland AJ, Whaites EJ. Radiographic diagnosis of root resorption in relation to orthodontics. British Dental Journal 2001;190:16-22.

5. Hechler SL. Cone-beam CT: applications in orthodontics. Dental Clinics of North America 2008;52:809-823.

6. Brezniak N, Wasserstein A. Root resorption after orthodontic treatment: Part 1. Literature review. American Journal of Orthodontics & Dentofacial Orthopedics 1993;103:62-66.

7. Mirabella AD, Artun J. Prevalence and severity of apical root resorption of maxillary anterior teeth in adult orthodontic patients. European Journal of Orthodontics 1995;17:93-99.

8. Brezniak N, Wasserstein A. Root resorption after orthodontic treatment: Part 2. Literature review. American Journal of Orthodontics & Dentofacial Orthopedics 1993;103:138-146.

9. Marmulla R, Wortche R, Muhling J, Hassfeld S. Geometric accuracy of the NewTom 9000 Cone Beam CT. Dento-Maxillo-Facial Radiology 2005;34:28-31.

10. Lou L, Lagravere MO, Compton S, Major PW, Flores-Mir C. Accuracy of measurements and reliability of landmark identification with computed tomography (CT) techniques in the maxillofacial area: a systematic review. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2007;104:402-411.

11. Berco M, Rigali PH, Jr., 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. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:17.e11-19; discussion 17-18.

12. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:573-582.

13. Lagravere MO, Carey J, Toogood RW, Major PW. Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:112-116.

14. Baumgaertel S, Palomo JM, Palomo L, Hans MG. Reliability and accuracy of cone-beam computed tomography dental measurements. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:19-25; discussion 25-18.

15. Liedke GS, da Silveira HED, da Silveira HLD, Dutra V, de Figueiredo JAP. Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. Journal of Endodontics 2009;35:233-235.

16. da Silveira HLD, Silveira HED, Liedke GS, Lermen CA, Dos Santos RB, de Figueiredo JAP. Diagnostic ability of computed tomography to evaluate external root resorption in vitro. Dento-Maxillo-Facial Radiology 2007;36:393-396.

17. Tronstad L. Root resorption--etiology, terminology and clinical manifestations. Endodontics & Dental Traumatology 1988;4:241-252.

18. Wierzbicki T, El-Bialy T, Aldaghreer S, Li G, Doschak M. Analysis of orthodontically induced root resorption using micro-computed tomography (Micro-CT). Angle Orthodontist 2009;79:91-96.

19. Warner RM. Applied Statistics - From bivariate through multivariate techniques. Los Angeles: SAGE Publications; 2008;917.

20. Copeland S, Green LJ. Root resorption in maxillary central incisors following active orthodontic treatment. American Journal of Orthodontics 1986;89:51-55.

21. Mohandesan H, Ravanmehr H, Valaei N. A radiographic analysis of external apical root resorption of maxillary incisors during active orthodontic treatment. European Journal of Orthodontics 2007;29:134-139.

22. Chan EKM, Darendeliler MA. Exploring the third dimension in root resorption. Orthodontics & Craniofacial Research 2004;7:64-70.

23. Dudic A, Giannopoulou C, Leuzinger M, Kiliaridis S. Detection of apical root resorption after orthodontic treatment by using panoramic radiography and cone-beam computed tomography of super-high resolution. American Journal of Orthodontics & Dentofacial Orthopedics 2009;135:434-437.

24. Tohnak S, Mehnert A, Crozier S, Mahoney M. Synthesizing panoramic radiographs by unwrapping dental CT data. Conference Proceedings: Annual International Conference of the IEEE Engineering in Medicine & Biology Society 2006;1:3329-3332.

25. Liu Y, Olszewski R, Alexandroni E, Enciso R, Xu T, Mah J. The validity of in vivo tooth volume determinations from cone-beam computed tomography. Angle Orthodontist 2010;80:160-166.

Chapter 3: Measurement Accuracy and Precision of Tooth Length with Conventional and CBCT Reconstructed Panoramic Radiographs

3.1 Introduction

Panoramic radiographs are a type of tomography in that a shallow section of body is kept in focus in order to view it more clearly compared to its surrounding anatomy. The structures outside of the focal trough are blurred and appear as shadows and artifacts. In order to better maintain the elliptical shape of dental structures within the focal trough, panoramic devices have a centre of rotation that changes throughout the scan. The rotational patterns developed by the manufacturers of these devices vary widely making the resulting images unique to the developer and model[1]. Modifications in arc radius and shape as well as static versus variable centres of rotation have been used to better approximate the shape of the maxillomandibular process in order to maintain patients' dentoalveolar structures within the device's focal trough. Even with standardized head positions, the great inconsistency in individual's jaw dimensions and shape make achieving optimized panoramic images unpredictable.

Many reports have noted that panoramic radiographs do not accurately represent tooth positions requiring the clinician to supplement his/her findings with a clinical assessment. As reviewed by Van Elslande *et al.* panoramic radiographs are fraught with inconsistent levels of magnification and distortion errors[2]. Some reports found vertical measurements were +/- 10% different from direct measurements of dried skulls[3], while other groups found the difference to be as high as 18-21%[4]. Differences in magnification have been found to vary throughout panoramic images, disparity existed between devices tested and the majority manufacturers' documentation did not accurately correspond with calculated magnification in various regions of the panoramic images[2,5]. While these distortions may be acceptable for ratio calculations, they pose an unacceptable level of unreliability for linear measurements. Turp *et al.*'s analysis of vertical measurements of ramus and condylar heights concurred with Kjellberg's finding that there was a very low correlation coefficient between the lengths recorded on the panoramic images and direct physical measurements[6].

In controlled experimental conditions, Yitschaky recently attempted to quantify the amount of distortion inherent in vertical measurements of tooth length are and found that the panorex images magnified the dental structures by approximately 26% in the maxilla and 10-14% in the mandible[7]. They also noted that this level of precision was accomplished by very standardized conditions of imaging equipment, beam angulation and patient head position.

In the dentoalveolar region of the mandible, alveolar bone heights were also not reliable as head position and mandibular body angulation varied through +/- 20^{o} of horizontal resulted in significantly different image lengths[8]. Using metal bars and markers for reference, some studies have found that measurements with certain devices follow manufacturers' reported magnification in the mandible as long as they don't cross the midline[9], while others have found that horizontal measurements are more reliable than vertical[10].

Larheim *et al.* studied dental[11] and mandibular landmark[4] measurements of panoramic radiographs. Their research determined that while vertical measurements were more accurate than horizontal, they were magnified by 18-21%[4]. The repeatability evaluation of tooth length met complications as many teeth (14-17%), especially those in the mandibular anterior region (57%), were not clear enough to locate root apices and up to 7.5% of the teeth were more than 2 mm different in repeated exposures, to which Larheim attributed misidentification of the landmarks of interest[11]. Additionally, since the clinically practical application of comparing tooth lengths would be during orthodontic treatment in which dental image elongation and/or foreshortening correspondent to tooth torquing would occur, the error level in the repeatability of the tooth length measurements would likely be overshadowed by the optical errors introduced in the 2-D image[11].

Positional variation of patients due to operator error also has significant effects on panoramic imaging accuracy, not only in angulation along the long axis, but in vertical and horizontal translation as well as axial rotation. Laster *et al.* found dimensional inaccuracies developed in both horizontal and vertical directions by skull displacements as little as 7 mm and 10 degrees[12]. Vertical angulation changes resulted in mesiodistal axial tooth inclinations variation as well, with more dramatic effects seen with posterior teeth[13]. Many studies determined that even angular measurements of dental tissues were not represented accurately in panoramic radiographs and have emphasized caution in trusting the accuracy of tooth angulations for clinical evaluation of treatment quality[14-17]. Angulations of teeth were under and overestimated on the radiographs depending on tooth location as well as actual root angulation[15]. Owens *et al.* found that the radiographic images represented dental angulations so poorly that a 22^{o} range existed for the 95% confidence interval[15].

As Van Elslande's review pointed out, conventional film and digital panoramic radiographic units vary between manufacturers with respect to the dimensions of their focal trough and centre of rotation[2]. Adjusting for magnification and distortion variation between images becomes exceedingly difficult and considering the introduction of variable distortion arising from positional errors of the patient, realistically impossible.

Like many clinicians, Kaley *et al.* assessed root resorption by comparing pre and post orthodontic treatment panoramic radiographs[18]. The study concluded that a disproportionate number patients starting with class III malocclusions and patients with treatment progression that positioned maxillary incisor roots in close proximity to the lingual cortical plate had severe root loss[18]. Proclination of incisors to compensate for a class III malocclusion would have resulted in foreshortening in the panoramic images exaggerating apical resorption. By the same logic class II division 1 patients would have underestimated root loss and it begs the question why treatment resulting in root proximity to the buccal cortical plate does not have the same destructive effects on the roots.

Cone-beam computed tomography (CBCT) has offered clinicians a radiographic technique with a high degree of resolution to identify craniofacial landmarks and a spatially accurate means of analyzing them[19-21]. In order to make the transition from the more familiar analyses of 2-D radiography, researchers have attempted to correlate the 3-D CBCT images with panoramic and cephalometric radiographs. Imaging software now offers the opportunity to reconstruct the 3-D volumes into lateral cephalograms with two types of projections. The orthogonal setting introduces no magnification, thus producing an image with highly accurate linear dimensions. The perspective setting introduces approximately 10% magnification to simulate conventional lateral cephalograms. This setting allows clinicians to compare archived patient data and make direct comparisons to the new images[22-24]. While CBCT software has the ability to produce panoramic reconstructions, the inherent inaccuracies of the conventional image format have prompted only a few studies to compare the accuracy level of these reconstructions not only with conventional images but with the true anatomy by direct measure.

Although definitive results were clouded by methodological complications, Hutchinson attempted to compare angular measurements from traditional panoramic radiographs to CBCT panoramic reconstructions[25]. While the arch width failed to correlate with radiographic widths of measured teeth, arch depth was statistically correlated with radiographic molar size on one side. The author felt this erroneous result could have been due to improper head positioning in the panoramic unit[25]. The panoramic reconstructions from the NewTom 9000, on the other hand, were dimensionally accurate to the patient's dental models. The greatest differences between the film and reconstructions existed in the maxillary canine-premolar region and the mandibular posterior regions[25]. This study exemplified the superiority of CBCT for dimensional accuracy even when used to reconstruct traditional 2-D projections. As head position can be standardized after patient scans are complete and focal trough can be customized based on tooth position and angulation, the reconstructed images can remove many of the distortion variables inherent in the traditional panoramic images.

Complex computer algorithms are required to convert 3-D medical and cone beam CT volumes to images that simulate 2-D panoramic radiographs. By removing all voxel information that lies outside the specified focal trough however, the panoramic reconstruction from the CT data improves image clarity by reducing geometric distortions, blurring and artifacts from superimpositions[1].

Ludlow *et al.* scanned dried skulls with the NewTom 9000 at a resolution of 0.5 mm slice thickness to determine vertical and horizontal length accuracy when reconstructed into panoramic projections[26]. While intraobserver reliability was very high at approximately 0.1 mm, identification of the landmarks between observers was significantly different at almost 0.9 mm. Researchers used metal wires of known length laid along the buccal surface of the ramus and mandibular body as reference knowing that while they likely did not lie in the exact plane of the panoramic reconstruction, as long as they were within 18^{o} of the plane, the foreshortening effect would be less than 5%[26]. Conversely, the panoramic reconstruction followed the curvature of the mandible resulting in linear measurements on the image to be overestimated. While operator expertise was considered an important factor in measurement accuracy, the lengths recorded in the 3-D volumes by landmark identification in serial axial slices expressed levels of error in the range of 0.19 to 0.37 mm, or 0.6 to 1.7% of the measured lengths. These values were 1.5-2.5 times lower than the panoramic reconstructions of the same volumes[26].

This study can be considered an extension of Ludlow *et al.*'s work in that linear measurement accuracy of conventional panoramic images were compared to panoramic reconstructions from CBCT volumes and digital calipers, considered the gold standard. The *in vivo* nature of this study offers orthodontists a clinically realistic result to apply to their diagnosis and treatment planning routines.

3.2 Materials and Methods

This study was conducted under the approval of the Health Research Ethics Board (HREB) at the University of Alberta (Appendix A).

Study subjects were selected from the University of Alberta graduate orthodontic clinic that required maxillary premolar extractions to complete their regular orthodontic treatment goals. Consent forms were explained and signed by all subjects prior to their inclusion in the study (Appendix B). Inclusion criteria for the study required all subjects to have also had conventional panoramic radiographs taken within the previous 24 months. All teeth included in the study were fully erupted maxillary premolars at the time the conventional panorex was taken.

CBCT images were taken with the 12-bit i-CAT (Imaging Sciences International, Hatfield, Penn) set to a 40-second scan allowing image reconstruction with a voxel size of 0.25mm. Standard clinical protocols were used for patient positioning and a cotton roll between incisor teeth was used to stably hold the occlusion apart to improve cusp tip identification. Images were saved as DICOM files and were reconstructed in Dolphin Imaging 10.5 Premium software (Dolphin Imaging Sciences, Chatsworth, Calif). Head positions in the reconstructed images were standardized anteroposteriorly by Frankfort Horizontal (Fig 2-1), and sagittally for maximal overlap of bilateral structures in the maxilla, ramus and body of the mandible (Figs 2-1 and 2-2). Panoramic images were reconstructed from CBCT volumes by selecting a custom focal trough that passed through the lingual cusps of the maxillary teeth and extended posterior to the condyles. Focal trough width was varied to ensure it encompassed the entire length and height of the maxillary dentition. Axial serial slices were reviewed to ensure the focal trough encompassed all teeth regardless of their angulation and with the centre of the custom focal trough bisecting as close to the centre of the long axis of the teeth as possible (Figs 3-1 and 3-1).

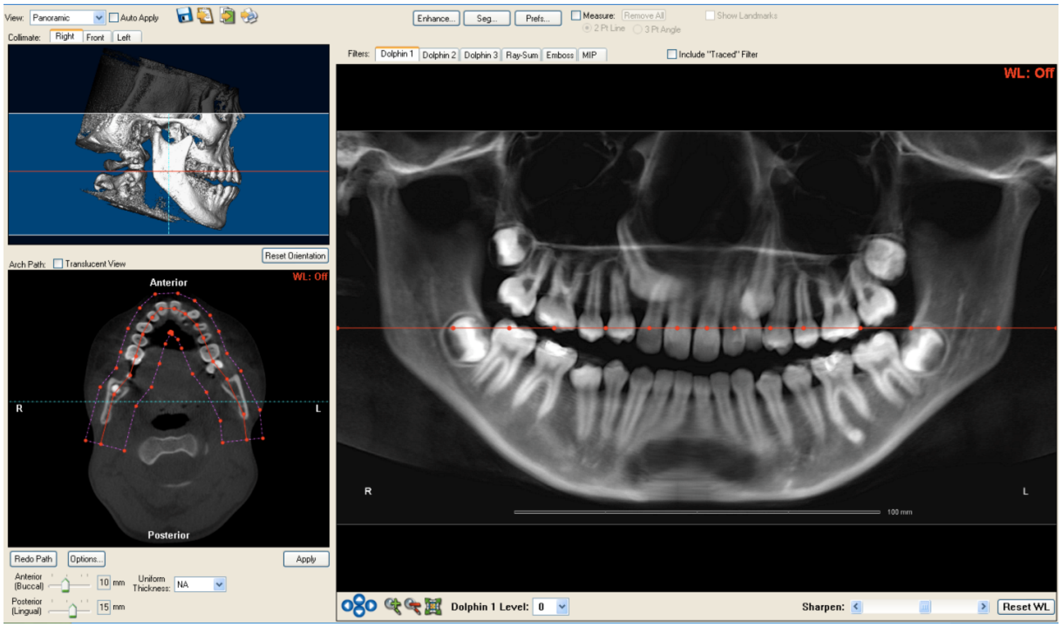

Figure 3-1: Custom Focal Trough Selection for Panoramic Reconstruction from CBCT

Figure 3-2: Panoramic Reconstruction from CBCT

Conventional panoramic radiographs were produced with a 17.6 second duration exposure on automatic settings with an Instrumentarium Orthopantomograph OP100 on Fuji Super HRT30 film and Kodak Lanex Regular Intensity screen. The films were developed in a Kodak M35A processor, scanned with an Epson Perfection 700 photo scanner (Epson, Long Beach, Calif) at 300 dpi and 24-bit colour, and optimized for contrast and brightness with the Epson scanning software. The JPEG images (saved at lowest compression) were imported into Dolphin Imaging for analysis (Fig 3-3).

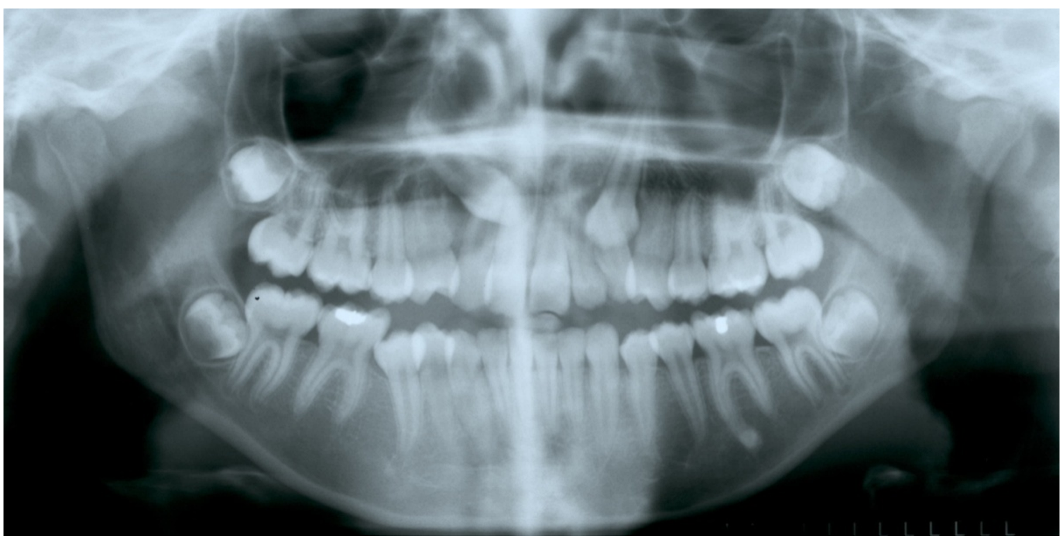

Figure 3-3: Scanned Conventional Panoramic Radiograph

Following imaging, one or two maxillary 1st or 2nd premolar teeth were extracted as per the patient's orthodontic treatment plan were extracted and stored in 95% ethanol. The 48 premolars, collected from 26 subjects, were then measured directly with a digital caliper (OrthoPli, Philadelphia, Penn) following extraction.

The minimum caliper reading was 0.013 mm and its measurement accuracy was 0.025 mm as reported by the manufacturer.

The entire tooth length was measured at its longest point from the buccal cusp tip to the root apex. In cases of multiple roots, the buccal root was used unless it had fractured during extraction in which case measurements were made to the intact lingual root apex. These exceptions were noted so the corresponding measurements were made in the panoramic images. Knowledge of dental anatomy was used to assist in the correct identification of the buccal cusps and roots in the panoramic images. Consultation with the corresponding extracted teeth was occasionally done to improve the likelihood of correct root selection in situations where the appropriate root could not be determined due to the tooth's long axis angulation or rotation. Scanned conventional panoramic radiograph measurements were standardized to measurements made on the physical films with the digital caliper. The CBCT panoramic reconstruction measurements were calibrated to the digital ruler produced by the Dolphin Imaging software from the 3-D volume. All measurements were recorded to the nearest tenth of a millimeter. The raw data is summarized in Appendix F.

Ten of the 48 samples were randomly selected and measured in triplicate, in random order, with at least one week between each measurement, in order to assess intra-rater reliability. Conventional and digital panoramic images and digital caliper measurements were repeated three times for the 10 samples for the reliability assessment.

Accuracy of tooth length measurements made by the CBCT panoramic reconstructions, conventional panoramic radiographs and the digital caliper gold standard were compared to each other by repeated measures one-way ANOVA with Bonferroni correction and by single measures intraclass correlation coefficient using SPSS version 16.0 software (SPSS, Chicago, Ill). Statistical analysis of intra-rater reliability of the triplicate measurements were assessed by single measures intraclass correlation coefficient (ICC) in SPSS.

The statistical analyses for the reliability and accuracy assessments were repeated following the removal of all outlying data points. Since they were determined to have no significant effect on the results, all data points were maintained for the reporting and analyses in this study. Clinically significant changes in root length were considered to be values of 1.0 mm and greater, consistent with those studies by Copeland[27] and Mohandesan[28].

The minimum sample size was then recalculated treating this study as a pilot to provide future research with a guide with which to achieve adequate power to distinguish clinically significant tooth length changes in the *in vivo* conventional and CBCT reconstructed panoramic images.

Several known sources of measurement error in this study were identified. For CBCT panoramic reconstructions, sources such as landmark identification, voxel size resolution limitations, and standardization of the digital and software generated calipers were addressed and quantified by repeated sample measurements. Others, such as patient positioning variations, focal trough compatibility with patient anatomy, and image artifacts and ghosting were avoided altogether by careful volume positioning and focal trough customization. Sources of error that were not addressed in this study, however, included the reliability of standardizing the volume 3-D position and focal trough size/shape with the imaging software prior to producing the panoramic reconstructions; and the resolution loss accompanying the smoothing, compression and reconstruction algorithms that the Dolphin 3D imaging software used to store and manipulate the large datasets.

Similar to the CBCT reconstruction arm of the study, reliability of landmark identification was addressed by repeated measurements. Digital and imager calipers were standardized from landmarks that could be identified on the physical films and scanned images. Aspects of the conventional panoramic radiograph technique that were not addressed in this study included variability in patient head position, imager settings, as well as technician ability and technique as the images were obtained retrospectively from existing patient records. Since these images were taken up to 24 months prior to the CBCT records, variability in patient growth and development was another uncontrollable source of error. Ghost images and artifacts from overlapping anatomy are inherent to the conventional imaging process and are not removable to improve dental landmark identification. Additionally, indeterminate levels of magnification and distortion inherent in the panoramic images were expected to produce measurement errors not easily accounted for. These may have been exacerbated by focal trough sizes and shapes that didn't adequately follow patients' anatomy.

Finally, variations in tooth angulations would result in elongation and foreshortening errors in both conventional and CBCT reconstructed panoramic radiographs that would only be accounted for through customized complex mathematics and were not applied in this study.

3.3 Results

3.3.1 Reliability

Triplicate measurements for 10 samples were extremely consistent for all measurement methods tested. Repeated measures with digital calipers achieved the highest measurement reliability with a single measures intraclass correlation coefficient value of 0.999 (95% CI: 0.998, 1.000). Landmark identification and thus tooth length measurements were also highly repeatable in the conventional panorex images with a single measures ICC of 0.997 (95% CI: 0.993, 0.999) and for the CBCT panoramic reconstructions with a single measures ICC of 0.995 (95% CI: 0.995, 0.999). Compared to the caliper gold standard, tooth measurements made from conventional panoramic radiographs were on average 6.3 mm (SD = 2.0 mm) longer, while tooth measurements from

CBCT panoramic reconstructions were an average of 1.7 mm (SD = 1.2 mm) shorter. As another measure of reliability, the mean and standard deviation for the differences between the average gold standard tooth length measurements and each corresponding conventional and reconstructed panorex measurement are summarized in Appendix F.

3.3.2 Accuracy

Tooth lengths for 48 maxillary premolars measured by the scanned film panorex, and reconstructed CBCT panorex images were significantly different from each other and the direct measurements with calipers. Comparisons of each measurement technique were done by repeated measures ANOVA and intraclass correlation coefficient (ICC) methods. Following design protocols for the study, the measurement techniques were carried out in a random order with examiner blinding. Due to the individual variability of teeth used in this study and the opportunity to measure the same teeth by multiple techniques, the repeated measures ANOVA (RM-ANOVA) method of analysis the most appropriate means of comparison for the differences in group averages. This parametric statistical test was deemed acceptable as the model assumptions for its use, including normally distributed data sets with similar variances that were obtained by independent sampling, were adequately met.

Box plots of tooth length differences between the three measurement techniques are depicted in Figure 3-4. Compared to the caliper gold standard, the conventional panoramic images resulted in tooth measurements that were generally longer and ranged from 1 mm shorter to 9 mm longer. Tooth lengths in the CBCT reconstructions, on the other hand, were generally shorter than the gold standard, with a smaller measurement discrepancy. These measurements ranged from 1 mm longer to 5 mm shorter than that determined by the calipers (Fig 3-4).

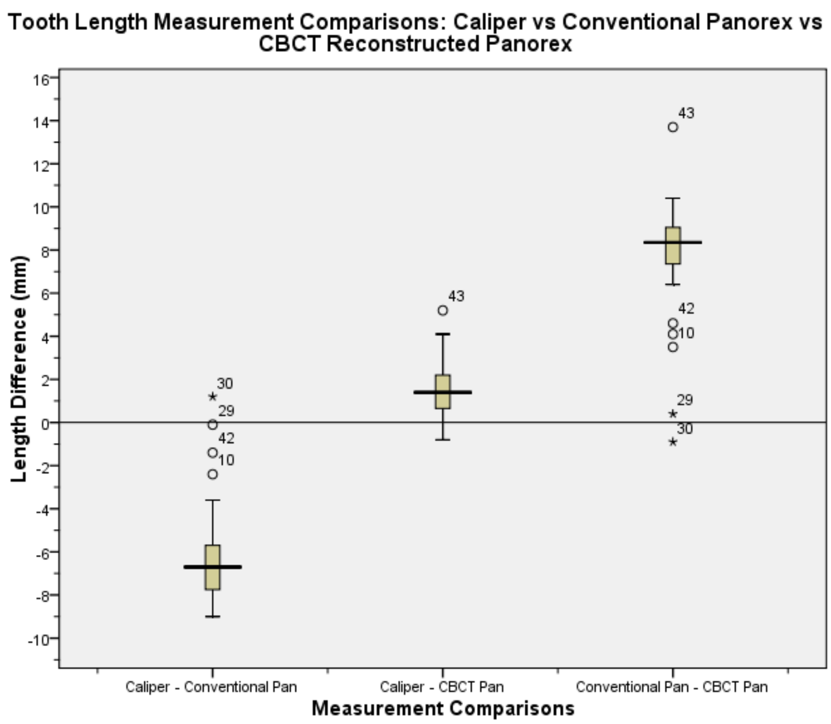

Figure 3-4: Comparison of Tooth Length Measurements for Calipers, Conventional Panoramic Radiographs and CBCT Panoramic Reconstructions

The 3-D CBCT images were standardized for head position sagittally (Fig 2-1) and coronally (Fig 2-2) by the by Frankfort Horizontal, inferior orbital rims, condylar heads and inferior border of the mandible prior to panorex reconstruction. This standardization would have reduced the randomness of elongation and foreshortening distortions compared to the caliper measurements. It would not, however, account for the variability in tooth angulation with respect to the standardized neutral head position. The data distribution revealed in the scatter plots (Figs 3-5 & 3-6) indicated tooth lengths showed relatively good measurement consistency across techniques, regardless of actual tooth size, and a measurement bias that resulted in an overestimation of tooth lengths in conventional panorex images and an underestimation in CBCT panoramic reconstructions. The bias was less distinct for the CBCT reconstructions, however, as the underestimation appeared to increase for longer teeth (Fig 3-6).

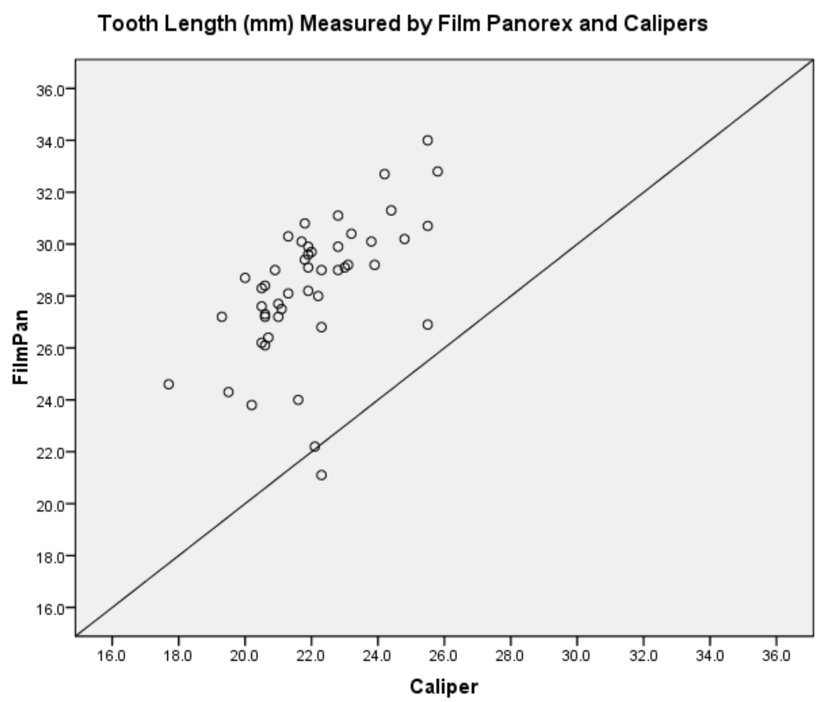

Figure 3-5: Scatter Plot of Tooth Length – Caliper vs. Conventional Panorex

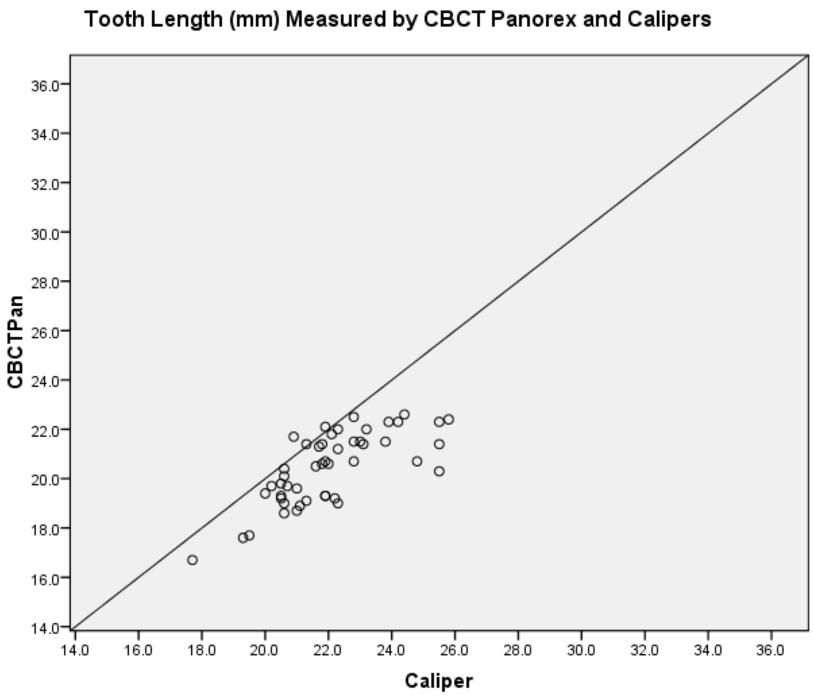

Figure 3-6: Scatter Plot of Tooth Length – Caliper vs. CBCT Reconstructed Panorex

One-way RM-ANOVA indicated that the measurements by all three techniques resulted in significantly different tooth lengths, as determined by a $p<0.001$ with Bonferroni correction. The mean tooth length for the conventional panorex was 6.3mm (95% C.I.: 5.6-7.1mm) longer than the caliper gold standard while the CBCT panorex mean was 1.6mm (95% C.I.: 1.1-2.0mm) shorter than the caliper (Table 3-1).

Orientation (A)	Orientation (B)	Mean Difference (A-B)	Significance p	95% CI for Difference
Caliper	Conventional Pan	-6.3	<0.001	-7.1, -5.6
	CBCT Pan	1.6	<0.001	1.1, 2.0
Conventional Panorex	CBCT Pan	7.9	<0.001	7.0, 8.8

Table 3-1: Repeated Measures ANOVA for Measured Tooth Length with Bonferroni Correction

An alternative analysis of the data using single measures intra-class correlation coefficient was used to determine the reliability between the three measurement techniques for each tooth individually. The modest ICC value of 0.504 (95% CI: 0.334, 0.660) when calculated with the consistency definition indicated that the measurement techniques provided only fair agreement in determining if teeth measuring larger by one technique were going to measure larger by the others. Using the absolute agreement definition, however, the very low ICC value of 0.093 (95% CI: -0.016, 0.271) indicated that the magnitude of length differences recorded by one technique did not correspond with equivalent differences in tooth lengths measured by the other techniques.

3.3.3 Sample Size Calculation

In order to facilitate future *in vivo* studies, sample sizes calculations were performed based on the variability of the measurement differences between the panoramic images and calipers. Considering the 44 samples as a pilot study, the minimum sample sizes required to identify length differences of 0.5 mm would be 192, and for a 1.0 mm difference, 48 (Table 3-2). The formula used for this calculation was:

$$n \geq \sigma^2 \left[\frac{z_\beta^* + z_{\alpha/2}^*}{\delta}\right]^2$$

Where $\alpha = 0.05$ $\beta = 0.1$ and $z_{\alpha/_2}^* = 1.96$ $z_\beta = 1.285$

	Mean Difference (mm)	Standard Deviation σ	Detectable Length Difference δ = 0.5 mm	Detectable Length Difference δ = 1.0 mm
Caliper – Conventional Pan Difference	-6.33	2.13	192	48
Caliper – CBCT Pan Difference	1.58	1.21	62	16

Table 3-2: Sample Size Calculation for Future Study based on Caliper and Panoramic Radiographs Measurement Differences

3.4 Discussion

Panoramic radiographs offer a technically simple and readily available method to measure tooth length. Monitoring root resorption, however, requires the ability to accurately determine root length and shape and compare them between serial images. Conventional panoramic radiographs have a manufacturer-determined focal trough width that may result in portions of the teeth falling outside of this area of focus and alternatively may include unwanted structures that reduce the clarity of root apices[1]. Other anatomical structures outside of the focal trough also produce ghost images and artifacts further reducing the images' clarity. The ability of reconstructed panoramic images from 3-D CBCT volumes to customize the focal trough position and thickness allows improved clarity of the structures of interest by ensuring that they fall completely within the area of focus. As the reconstruction only includes detail that falls within the focal trough, confounding artifacts are reduced.

The significant limitation of both conventional and CBCT reconstructed panoramic images lies in their inability to account for changes in tooth angulation between serial images. During orthodontic treatment, changes in tip and torque introduce elongation and foreshortening errors that cannot be easily accounted for[29]. It is also possible to mistaken changes in root morphology as resorption as the tooth rotates during treatment and then projected in the buccolingual dimension[18]. An advantage of CBCT reconstructions over conventional panorexes is the ability to more precisely reorient the volumes with the imaging software in order to standardize the image's anatomical planes, thus reducing the error introduced by variable patient position when radiographs are taken by several staff members[12,25].

CBCT images created by the 12-bit i-CAT have voxel sizes of 0.25 mm. This translates into a resolution limitation and thus an error of 0.25 mm at each measurement point in the image. Measured tooth lengths from CBCT reconstructions would be expected to achieve accuracy within 0.5 mm of the caliper measurement. The comparable level of accuracy for the film panoramic radiographs would be determined by the size of the silver halide grains on the film. While this value is not known, it would be safe to assume that the effect of any limitation on resolution would fall far below that error introduced by artifacts and positional variations in the subjects and teeth of interest. The average tooth length measured by CBCT panorex reconstruction was 1.6 mm shorter than the direct measurement by calipers, but the precision of repeated measurements was comparably extremely high for both techniques. This would imply that difference in measured tooth length was not due to misidentification of the landmarks but to radiographic foreshortening or inadequate resolution of fine root apices compared to the surrounding bone.

Conventional panoramic radiographs achieved comparably reliable results for the 10 samples repeated in triplicate, as the caliper and CBCT reconstructions. The average tooth length measured 6.3 mm (or 29%) longer than the calipers and the range of values was almost twice that of the other measurement techniques. The error in the conventional panorex measurements in this study are even greater than those found by comparison of dry skulls: 10% by Tronje[3] and 18-21% by Larheim[4], but approached the levels of magnification (26%) found by Yitchaky's study[7].

This more dramatic departure from the gold standard measurement may have been a result of several factors contributing to the error. In addition to the to the tooth position, non-standardized head positions as a result of patient compliance and posture, in addition to technician ability and technique would also contribute to the radiographic elongation and foreshortening. Additional distortion was also introduced for those teeth whose roots fell outside of the predefined focal trough. This variability was diminished in the CBCT images as the focal trough path and width was customized for each volume ensuring the entire tooth lengths were encompassed and the centre of the trough aligned closely with the centre of the long axis, prior to panorex construction. The CBCT images also afforded greater clarity of tooth structures versus their conventional counterparts because the reconstructions only consisted of the volume within the designated focal trough. Additional artifacts and ghost images result from the film capturing the X-ray beams that have traveled through, and interacted with, the patient's entire head[1].

Although the CBCT reconstructions resulted in measurement values that more accurately corresponded with the direct caliper measurements compared to those of the conventional panoramic radiographs, it is interesting to note the data patterns that emerged from analysis of the scatter plots (Figs 3-5 and 3-6). The conventional panorexes appeared to result in a measurement bias that consistently overestimated tooth lengths regardless of the actual tooth size, where as the CBCT reconstructed images resulted in an underestimation bias that increased for larger tooth sizes. If this bias was shown to be consistent, it would allow serial panoramic radiographs to be compared to monitor root changes during orthodontic treatment. Unfortunately, other studies have shown that the magnification variability and inherent imaging errors throughout the panoramic images precludes the reliable use of this application[3,4,7].

Due to ALARA and HREB limitations, conventional panoramic radiographs were limited to historical records and while most were taken within 12 months of the CBCT images and tooth extractions, some records were almost 2 years earlier. As the patient population was in their early to mid teens, it can be expected that varying amounts of root development would have occurred during time between the conventional and CBCT imaging. While one would expect this to bias the conventional panorex measurements to be shorter than the caliper and CBCT tooth lengths, the opposite was in fact the case (Fig 3-9). This would indicate that the distortion and magnification errors in the conventional images far outweighed any dental growth and apical development.

While the tooth length measured from CBCT panorex reconstructions are statistically and clinically significantly (>1.0 mm) different from direct caliper measurements, these images provide improved clarity and accuracy compared to the measurements achieved by traditional film panorex. The underestimation of measurements on CBCT reconstructions compared to the direct caliper measurements was consistent with Ludlow's findings in which they showed panorex reconstructions to produce measurement errors of up to 2-4%[26]. The 1.6 mm average decrease in CBCT panorex tooth length compared to the 22.01 mm caliper mean, represents a 7% decrease. With fewer confounding variables compared to conventional techniques, the differences in these measurements were likely due to buccolingual tooth angulation and difficulty in landmark identification of cusp and root tips due to tooth rotation, position and anatomy.

3.5 Conclusions and Recommendations

Clinicians still must be aware of elongation/foreshortening errors that arise from changes in tip and torque of the teeth of interest when serial panorex images are compared during treatment. Substantial errors in linear measurement accuracy severely limit conventional panoramic radiography as a tool to identify changes in root length and as such alternative methods should be considered for quantitatively monitoring root resorption. Panoramic reconstructions from CBCT volumes improve measurement accuracy over conventional imaging by reducing several sources of magnification and distortion, however dental measurements are still significantly different from true anatomical lengths and their use diminishes the accuracy gains achieved by 3-D technology. While CBCT panoramic reconstructions provide more reliable representations of changes in tooth length, caution should be exercised when they are used for the diagnosis of early root resorption.

3.6 References

1. Tohnak S, Mehnert A, Crozier S, Mahoney M. Synthesizing panoramic radiographs by unwrapping dental CT data. Conference Proceedings: ... Annual International Conference of the IEEE Engineering in Medicine & Biology Society 2006;1:3329-3332.

2. Van Elslande DC, Russett SJ, Major PW, Flores-Mir C. Mandibular asymmetry diagnosis with panoramic imaging. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:183-192.

3. Tronje G, Eliasson S, Julin P, Welander U. Image distortion in rotational panoramic radiography. II. Vertical distances. Acta Radiologica: Diagnosis 1981;22:449-455.

4. Larheim TA, Svanaes DB. Reproducibility of rotational panoramic radiography: mandibular linear dimensions and angles. American Journal of Orthodontics & Dentofacial Orthopedics 1986;90:45-51.

5. Kjellberg H, Ekestubbe A, Kiliaridis S, Thilander B. Condylar height on panoramic radiographs. A methodologic study with a clinical application. Acta Odontologica Scandinavica 1994;52:43-50.

6. Turp JC, Vach W, Harbich K, Alt KW, Strub JR. Determining mandibular condyle and ramus height with the help of an Orthopantomogram--a valid method? Journal of Oral Rehabilitation 1996;23:395-400.

7. Yitschaky M, Haviv Y, Aframian DJ, Abed Y, Redlich M. Prediction of premolar tooth lengths based on their panoramic radiographic lengths. Dento-Maxillo-Facial Radiology 2004;33:370-372.

8. Batenburg RH, Stellingsma K, Raghoebar GM, Vissink A. Bone height measurements on panoramic radiographs: the effect of shape and position of edentulous mandibles. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 1997;84:430-435.

9. Catic A, Celebic A, Valentic-Peruzovic M, Catovic A, Jerolimov V, Muretic I. Evaluation of the precision of dimensional measurements of the mandible on panoramic radiographs. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 1998;86:242-248.

10. Schulze R, Krummenauer F, Schalldach F, d'Hoedt B. Precision and accuracy of measurements in digital panoramic radiography. Dento-Maxillo-Facial Radiology 2000;29:52-56.

11. Larheim TA, Svanaes DB, Johannessen S. Reproducibility of radiographs with the orthopantomograph 5: tooth-length assessment. Oral Surgery, Oral Medicine, Oral Pathology 1984;58:736-741.

12. Laster WS, Ludlow JB, Bailey LJ, Hershey HG. Accuracy of measurements of mandibular anatomy and prediction of asymmetry in panoramic radiographic images. Dento-Maxillo-Facial Radiology 2005;34:343-349.

13. Hardy TC, Suri L, Stark P. Influence of patient head positioning on measured axial tooth inclination in panoramic radiography. Journal of Orthodontics 2009;36:103-110.

14. McKee IW, Williamson PC, Lam EW, Heo G, Glover KE, Major PW. The accuracy of 4 panoramic units in the projection of mesiodistal tooth angulations. American Journal of Orthodontics & Dentofacial Orthopedics 2002;121:166-175; quiz 192.

15. Owens AM, Johal A. Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. Angle Orthodontist 2008;78:475-481.

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

17. Van Elslande DC, Heo G, Flores-Mir C, Carey J, Lam EW, Major PW. The accuracy of mesiodistal root angulation projected by the CBCT panoramic-like image. American Journal of Orthodontics & Dentofacial Orthopedics 2009;Accepted for Publication.

18. Kaley J, Phillips C. Factors related to root resorption in edgewise practice. Angle Orthodontist 1991;61:125-132.

19. Berco M, Rigali PH, Jr., 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. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:17.e11-19; discussion 17-18.

20. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:573-582.

21. Lagravere MO, Carey J, Toogood RW, Major PW. Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:112-116.

22. Kumar V, Ludlow JB, Mol A, Cevidanes L. Comparison of conventional and cone beam CT synthesized cephalograms. Dento-Maxillo-Facial Radiology 2007;36:263-269.

23. Kumar V, Ludlow J, Soares Cevidanes LH, Mol A. In vivo comparison of conventional and cone beam CT synthesized cephalograms. Angle Orthodontist 2008;78:873-879.

24. Lamichane M, Anderson NK, Rigali PH, Seldin EB, Will LA. Accuracy of reconstructed images from cone-beam computed tomography scans. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:156.e151-156; discussion 156-157.

25. Hutchinson SY. Cone beam computed tomography panoramic images vs. traditional panoramic radiographs. American Journal of Orthodontics & Dentofacial Orthopedics 2005;128:550.

26. Ludlow JB, Laster WS, See M, Bailey LTJ, Hershey HG. Accuracy of measurements of mandibular anatomy in cone beam computed tomography images. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2007;103:534-542.

27. Copeland S, Green LJ. Root resorption in maxillary central incisors following active orthodontic treatment. American Journal of Orthodontics 1986;89:51-55.

28. Mohandesan H, Ravanmehr H, Valaei N. A radiographic analysis of external apical root resorption of maxillary incisors during active orthodontic treatment. European Journal of Orthodontics 2007;29:134-139.

29. Garcia-Figueroa MA, Raboud DW, Lam EW, Heo G, Major PW. Effect of buccolingual root angulation on the mesiodistal angulation shown on panoramic radiographs. American Journal of Orthodontics & Dentofacial Orthopedics 2008;134:93-99.

Chapter 4: General Discussion

4.1 General Discussion

Computed tomography has introduced the ability to three dimensionally visualize the body's hard tissues, and created the potential to diagnose and treatment plan with a level of confidence not possible with conventional radiographic records. Cone beam CT has provided a more accessible, cost effective and user friendly technology that afforded dentistry with a 3-D radiographic alternative for craniofacial imaging, at a lower radiation exposure to patients. As image resolution improved, the apparent lack of distortion and magnification errors in the reconstructed volumes allowed the opportunity to use the images for quantitative analyses. In orthodontics, craniofacial measurements could be used to identify growth patterns, quantify growth rate, assess bone volume and defects, and monitor root resorption.

In order for clinicians to justify the additional time, expense and radiation exposure in the adoption of CBCT technology, research must demonstrate that the advantages of the 3-D volumes are significantly greater than that of the conventional 2-D radiography. There are many stages of digital processing between image capture and final volume display in an imaging software program that have the potential to introduce error.

The initial study in this thesis was the first *in vivo* measurement analysis of dentoalveolar structures. It demonstrated that CBCT reconstructions could provide accurate and reliable tooth length measurements when images were compressed, stored and reconstructed in 3rd party software image management software common to orthodontics, such as Dolphin 3D. While the CBCT measurements were significantly shorter than direct caliper measurements statistically, the average difference of 0.34-0.38 mm was clinically insignificant and represented a dramatic improvement for early detection of root shortening due to iatrogenic and idiopathic resorption. Since this measurement bias has been noted in other studies[1,2] and appears to be independent to measurement direction, clinicians can confidently compare the linear measurements from serial volumes to assess changes to tooth morphology during treatment. The study also concluded that there was no significant difference in measurement accuracy or reliability with respect to the orientation at which the volume is viewed or serially sliced. This allows clinicians to select landmarks from any orientation that provides the best visualization of the dental anatomy in order to achieve accurate length measurements.

In order to ease the transition from 2-D to 3-D radiographic records, software manufacturers have developed algorithms to reconstruct the CBCT volumes into the conventional 2-D radiographic projections. Lateral cephalogram reconstructions have been studied thoroughly and investigators have determined that depending on the type of projection applied, craniofacial measurements have been very comparable to direct dry-skulls and conventional lateral cephalograms[3-5].

CBCT reconstructions into panoramic radiographs have the opportunity to offer a distinct advantage over their conventional counterparts if they are able to overcome the variable magnification and distortion inherent in the images. While clinicians often use panoramic radiographs to assess root angulation and to identify root resorption during orthodontic treatment, studies have shown this to be a very unreliable method[6-11]. The second part of this thesis advanced the results an earlier *in vitro* study[12], which found significant magnification resulting in inaccurate dentoalveolar measurements.

Consistent with previous studies[13], the conventional panoramic radiographs approached levels of magnification in the maxillary premolar regions that were so large (26%), measurements in the dentoalveolar region would be of very limited benefit. While the tooth lengths measured from CBCT panoramic reconstructions were statistically and clinically significantly (>1.0 mm) different from direct caliper measurements, the images provided improved clarity and accuracy compared to the measurements achieved by conventional panorexes and the modest underestimation of dentoalveolar measurements (7%) was consistent with previous findings[12]. The panoramic reconstructions improved the measurement accuracy over conventional imaging by reducing several sources of magnification and distortion, however the dental measurements were still significantly different from true anatomical lengths and their use diminished the accuracy gains achieved by 3-D technology. In general, using CBCT volumes to produce panoramic reconstructions can offer a means to compare historical 2-

D records, but the persistent prevalence of variable magnification and distortion severely limits their use for making quantitative dentoalveolar assessments and thus clinicians should not rely upon them to confidently diagnose early root resorption.

4.2 Study Weaknesses

1) While many studies have shown the high level of intraexaminer and interexaminer reliability with respect to length measurements from 3-D CBCT volumes, the strength of this study could have been increased by including repeated measures from other trained clinicians to substantiate the high level of reliability and accuracy achieved by the principle investigator.

2) Imaging calibration of the i-CAT CBCT was performed prior twice daily during data collection, however no opportunity existed to standardize the imager with an object of known size for measurement standardization.

3) Digital caliper calibration with the Dolphin Imaging's digital ruler was performed for scanned film panoramic radiographs; however it could not be done for the measurements made by serial slice volumes or panoramic reconstructions.

4) Reliability tests by assessed landmark localization accuracy but did not account for other sources of formatting error. The CBCT images were not repeatedly reformatted from their raw DICOM datasets and image orientations

were not re-standardized in order to assess for errors arising from variability in the 3-D digital workflow or processing to the 2-D reconstructed images.

5) The length of time between conventional panoramic and CBCT records (and extractions) was variable and long enough to introduce error due to continued root development. This was not apparent in the results however.

4.3 Future Research

The results found herein could be bolstered by assessing the additional sources of error introduced in the 3-D digital workflow from the point of raw data upload to landmark identification. This includes the process of standardizing the image's head position for serial slicing and 2-D reconstructions as well as focal trough pattern and width selection for panoramic reconstructions. While the 3-D nature and isotropic size of the CBCT voxels has removed the error inherent in the patient cooperation and technician ability at the time of image capture, the increased requirement for post-capture manipulation has introduced many additional opportunities for error development and propagation.

Follow-up study from the research described in this thesis could include analysis of the lateral root surfaces to determine if current CBCT imaging technology offers resolution high enough to identify surface anomalies and resorptive changes accurately. While CBCT imaging has proved valuable to in the identification of cervical root resorption over periapical radiographs, no attempt has been made to quantify the size of these lesions[14,15]. The complexity of root surface analysis lies in the ability to identify the same location with great accuracy and precision in serial images. As the accuracy of linear measurements has been established, the vertical location on a root should be a repeatable landmark; however locating the same position along the root's circumference may prove to be a more challenging (and time consuming) proposition. In order to make the process clinically practical, software advances that are able to compare entire surfaces at once will need to be developed.

Another avenue of future research in the area of 3-D root analysis for root resorption could include automation software to improve speed and accuracy for clinical applications. Software transformations that are able to quantify orthodontic tooth movements from serial CBCT volumes use automated methods to find the best fit of unchanging regions of bony tissues away from the dentition to overlay the images[16]. As slice thickness decreases and image resolution and contrast range improves, dental tissues will be able to be separated from their surrounding hard and soft tissues with greater accuracy. Best fit algorithms could be automatically applied to the isolated dental isosurfaces of serial volumes of patients undergoing orthodontic treatment to assess for changes to the root morphology. The clinician could then be responsive to resorptive changes on any surface of the root and adjust treatment mechanics and goals accordingly to minimize the risk to the patient's dental health.

4.3 References

1. Baumgaertel S, Palomo JM, Palomo L, Hans MG. Reliability and accuracy of cone-beam computed tomography dental measurements. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:19-25; discussion 25-18.

2. Liu Y, Olszewski R, Alexandroni E, Enciso R, Xu T, Mah J. The validity of in vivo tooth volume determinations from cone-beam computed tomography. Angle Orthodontist 2010;80:160-166.

3. Kumar V, Ludlow JB, Mol A, Cevidanes L. Comparison of conventional and cone beam CT synthesized cephalograms. Dento-Maxillo-Facial Radiology 2007;36:263-269.

4. Kumar V, Ludlow J, Soares Cevidanes LH, Mol A. In vivo comparison of conventional and cone beam CT synthesized cephalograms. Angle Orthodontist 2008;78:873-879.

5. Lamichane M, Anderson NK, Rigali PH, Seldin EB, Will LA. Accuracy of reconstructed images from cone-beam computed tomography scans. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:156.e151-156; discussion 156-157.

6. McKee IW, Williamson PC, Lam EW, Heo G, Glover KE, Major PW. The accuracy of 4 panoramic units in the projection of mesiodistal tooth angulations. American Journal of Orthodontics & Dentofacial Orthopedics 2002;121:166-175; quiz 192.

7. Owens AM, Johal A. Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. Angle Orthodontist 2008;78:475-481.

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

9. Van Elslande DC, Heo G, Flores-Mir C, Carey J, Lam EW, Major PW. The accuracy of mesiodistal root angulation projected by the CBCT panoramic-like image. American Journal of Orthodontics & Dentofacial Orthopedics 2009;Accepted for Publication.

10. Larheim TA, Svanaes DB. Reproducibility of rotational panoramic radiography: mandibular linear dimensions and angles. American Journal of Orthodontics & Dentofacial Orthopedics 1986;90:45-51.

11. Laster WS, Ludlow JB, Bailey LJ, Hershey HG. Accuracy of measurements of mandibular anatomy and prediction of asymmetry in panoramic radiographic images. Dento-Maxillo-Facial Radiology 2005;34:343-349.

12. Ludlow JB, Laster WS, See M, Bailey LTJ, Hershey HG. Accuracy of measurements of mandibular anatomy in cone beam computed tomography images. Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics 2007;103:534-542.

13. Yitschaky M, Haviv Y, Aframian DJ, Abed Y, Redlich M. Prediction of premolar tooth lengths based on their panoramic radiographic lengths. Dento-Maxillo-Facial Radiology 2004;33:370-372.

14. Patel S, Dawood A. The use of cone beam computed tomography in the management of external cervical resorption lesions. International Endodontic Journal 2007;40:730-737.

15. Patel S, Kanagasingam S, Pitt Ford T. External cervical resorption: a review. Journal of Endodontics 2009;35:616-625.

16. Chen J, Li S, Fang S. Quantification of tooth displacement from cone-beam computed tomography images. American Journal of Orthodontics & Dentofacial Orthopedics 2009;136:393-400.

Appendix

Appendix A: Ethics Approval

Health Research Ethics Board

213 Heritage Medical Research Centre
University of Alberta, Edmonton, Alberta T6G 2S2
p.780.492.9724 (Biomedical Panel)
p.780.492.0302 (Health Panel)
p.780.492.0459
p.780.492.0839
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ETHICS APPROVAL FORM

Date: April 16, 2008

Name of Principal Investigator(s): Dr. Carlos Flores-Mir

Department: Dentistry

Title: Measurement accuracy and precision of tooth length with cone beam computed tomography (CBCT) image reconstructions using common 3rd party software

Protocol:

The Health Research Ethics Board (Biomedical Panel) has reviewed the protocol involved in this project which has been found to be acceptable within the limitations of human experimentation. The REB has also reviewed and approved the subject information material and consent form.

Specific Comments: The Research Ethics Board assessed all matters required by section 50(1)(a) of the Health Information Act. Subject consent for access to identifiable health information is required for the research described in the ethics application, and appropriate procedures for such consent have been approved by the REB Panel.

J.S. Bamforth, M.D.
Associate Chairman
Health Research Ethics Board (Biomedical Panel)

MAY 16 2008
Date of Approval Release

This approval is valid for one year

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Edmonton and area

CARITAS HEALTH GROUP

Appendix B: Subject Information Letter and Consent Form

Measurement accuracy and precision of root length with cone beam computed tomography (CBCT) image reconstructions using eFilm and Dolphin 3D

Background:

You have been asked to take part in this study because you have misaligned teeth requiring braces (orthodontics). The treatment plan you have chosen involves the removal of one or more adult teeth in order to make adequate space to improved tooth alignment and bite correction.

Study Purpose:

You are being asked to participate in a research study which will assess how accurately and precisely three-dimensional imaging programs are able to reconstruct and measure tooth size compared to teeth measured directly once they have been pulled out (extractions). Information collected in this study will allow a better understanding of this new technology for its use in orthodontic treatment and planning.

Procedures:

Your orthodontic treatment will be provided by Dr. ________________ in the Graduate Orthodontic Clinic at the University of Alberta. Extractions required by your treating orthodontist may be completed by the dentist of your choice.

Every patient that agrees to participate in the study will have one three-dimensional x-ray image (CBCT) taken from which diagnostic images will be produced to aid the referred dentist in extracting the planned teeth. The x-ray image will be taken at the University of Alberta orthodontic clinic. In the majority of cases, the CBCT will be taken in place of an updated panoramic radiography often required by the referred dentist, however in certain circumstances additional images may be needed for more complicated extractions. In situations where more than one tooth is to be extracted, some teeth will have permanent marks placed on them with a dental drill for the purposes of later identification once the extractions are complete.

Possible Benefits:

Participating in this study will not alter the quality of your treatment. As this imaging technology continues to develop, its better understood, and becomes more commonplace, we will be able to better monitor tooth movement, growth and development during orthodontic treatment. Information gained from this study will improve our ability to measure and monitor teeth for changes during treatment.

Possible Risks:

The risks associated with these procedures are similar to those expected with standard procedure needed to treat your type of bite problem. The x-rays taken for this study generate a total amount of radiation equal to less than 1% of annual dose expected in normal living.

Confidentiality:

Personal records related to this study will be kept strictly confidential. Only the investigators involved in this study and the Health Research Ethics Board will have access to your records. Any reports published as a result of this study will not identify you by name.

Voluntary Participation:

You are free to withdraw from the research study at any time, and your continuing orthodontic care will not be compromised in any way.

Reimbursement of Expenses:

You will be provided with a discount equivalent to the expected parking expenses for each visit related to the study but not for your regular orthodontic treatment.

Principal Investigators:

- Dr. Mark Rosenblatt
- Dr. Carlos Flores-Mir

Contact Names and Telephone Numbers:

If you have any concerns regarding your rights as a study participant, you may contact Dr. Milos, Chairperson of the Department of Dentistry, at 492-3312.

Please contact any of the individual identified below if you have any questions or concerns about the study at any time:

Dr. Rosenblatt / Dr. Flores-Mir
Graduate Orthodontic Program
University of Alberta
492-7409
carlosflores@ualberta.ca

<u>Measurement accuracy and precision of root length with cone beam computed tomography (CBCT) image reconstructions using eFilm and Dolphin 3D</u>

Investigators: Dr. Mark Rosenblatt, Dr. Carlos Flores-Mir

<u>Please circle the answer:</u>

Do you understand that you have been asked to be in a research study? Yes No

Have you read and received a copy of the attached information sheet? Yes No

Do you understand the benefits and risks involved in taking part of this research study? Yes No

Have you had the opportunity to ask questions and discuss the research study? Yes No

Do you understand that you are free to refuse to participate or withdraw from the research study at any time? This will not affect the results of your orthodontic treatment. Yes No

Has the issue about confidentiality been explained to you? Do you understand who will have access to your records? Yes No

This research study was explain to me by: ______________________ <u>and</u> I agree to take part of the research study.

______________________ __________ ___________________________
Patient's signature Date Witness

______________________ ___________________________
Printed name Printed Name

______________________ __________ ___________________________
Parent's signature Date Witness

______________________ ___________________________
Printed name Printed Name

I believe the persons signing this form understands what is involved in this study and voluntarily agrees to participate.

______________________ _____________
Signature of Investigator or Designee Date

Appendix C: Differences between the average gold standard tooth length measurements and each corresponding axial, coronal and sagittal serial slice measurement

Code	Caliper Mean	Average Caliper Mean – Axial Slice Difference	Std Dev Caliper Mean – Axial Slice Difference	Average Caliper Mean – Coronal Slice Difference	Std Dev Caliper Mean – Coronal Slice Difference	Average Caliper Mean – Sagittal Slice Difference	Std Dev Caliper Mean – Sagittal Slice Difference
MR 005	25.5	-0.07	0.15	-0.10	0.17	-0.10	0.17
MR 007	20. 6	0.23	0.06	0.20	0.12	0.17	0.17
MR 009	22.8	0.47	0.06	0.47	0.15	0.67	0.06
MR 011	20.6	-1.0	0.06	-1.1	0.26	-0.73	0.21
MR 013	20.6	0.70	0.10	0.23	0.31	0.30	0.26
MR 014	21.6	0.33	0.21	0.40	0.10	0.27	0.15
MR 016	23.3	-0.13	0.25	-0.43	0.12	-0.23	0.38
MR 018	19.9	-1.07	0.26	-1.1	0.25	-1.3	0.21
MR 019	21.1	0.57	0.15	0.57	0.21	0.67	0.12
MR 021	21.8	-0.23	0.06	-0.23	0.06	-0.13	0.12

Appendix D: Differences between the average gold standard tooth length measurements and each corresponding conventional and reconstructed panorex measurement

Code	Caliper Mean	Average Caliper Mean – CBCT Reconstructed Panorex Difference	Std Dev Caliper Mean – CBCT Reconstructed Panorex Difference	Average Caliper Mean – Conventional Panorex Difference	Std Dev Caliper Mean – Conventional Panorex Difference
MR 005	25.5	4.1	0.06	-5.0	0.15
MR 007	20. 6	0.10	0.06	-7.8	0.06
MR 009	22.8	2.1	0.00	-6.2	0.06
MR 011	20.6	1.0	0.06	-5.8	0.06
MR 013	20.6	1.6	0.06	-6.7	0.12
MR 014	21.6	1.2	0.12	-2.4	0.06
MR 018	19.9	0.60	0.06	-8.9	0.17
MR 019	21.1	2.2	0.00	-6.4	0.06
MR 021	21.8	1.3	0.10	-9.0	0.06
MR 024	22.2	3.2	0.00	-4.7	0.12

Appendix E: Raw Measurement Data for Caliper and CBCT Slice Orientation Study

Code	Caliper			Axial Slice			Coronal Slice			Sagittal Slice		
MR 005	25.5	25.5	25.5	25.7	25.6	25.4	25.8	25.5	25.5	25.8	25.5	25.5
MR 006	25.8			25.3			25.4			25.3		
MR 007	20.6	20.6	20.5	20.4	20.3	20.3	20.5	20.3	20.3	20.3	20.3	20.6
MR 008	21.3			21			20.9			21		
MR 009	22.8	22.8	22.8	22.3	22.4	22.3	22.5	22.2	22.3	22.1	22.2	22.1
MR 010	21.8			22.3			22.2			22.2		
MR 011	20.7	20.6	20.6	21.6	21.6	21.7	21.4	21.8	21.9	21.6	21.2	21.3
MR 012	21.3			21.9			21.6			21.4		
MR 013	20.6	20.6	20.6	19.8	19.9	20	20.3	20.1	20.7	20	20.4	20.5
MR 014	21.6	21.6	21.6	21.2	21.1	21.5	21.3	21.1	21.2	21.2	21.3	21.5
MR 015	20.2			20			20.1			20		
MR 016	23.3	23.3	23.3	23.2	23.7	23.4	23.6	23.8	23.8	23.1	23.7	23.8
MR 017	23.4			22.8			23			23		
MR 018	20	19.9	19.9	20.8	21.3	20.9	21.1	21.3	20.8	21	21.3	21.4
MR 019	21.1	21.1	21.1	20.4	20.7	20.5	20.6	20.3	20.7	20.5	20.5	20.3
MR 020	21.9			21.8			22			21.8		
MR 021	21.8	21.8	21.8	22	22	22.1	22.1	22	22	21.8	22	22
MR 022	22			21.6			21.7			21.9		
MR 023	21.5			19.5			19.4			19.4		
MR 024	22.3	22.2	22.2	20.5			20.3			20.4		
MR 025	17.7			16.9			16.9			16.9		
MR 026	21.7			21.7			21.6			21.7		
MR 027	23.2			20.8			21.2			21		
MR 028	24.2			23.7			23.6			23.7		

MR 029	23.9			22.1			22.3			22.3		
MR 030	21			20.2			20.2			20.2		
MR 031	21			20.7			20.4			20.4		
MR 032	21.9			21.9			21.9			21.7		
MR 033	22.3			22.8			23			23.1		
MR 036	24.8			24.7			24.6			24.7		
MR 037	23.8			23.1			22.8			23		
MR 038	19.3			18.7			18.9			19		
MR 039	19.5			18.7			19			18.8		
MR 040	22.1			22.3			22			22.3		
MR 041	22.3			21.9			21.9			22.2		
MR 042	20.6			20			20			20.5		
MR 043	20.5			20.4			20.3			20.2		
MR 044	21.9			21.2			21.3			21.5		
MR 045	20.9			20.3			20.3			20.6		
MR 046	21.7			21.1			21.7			21.7		
MR 047	19			18.2			18.2			18.3		
MR 048	19.6			19.3			19.4			19.5		
MR 049	20.5			20			19.8			20.1		
MR 050	20.5			19.9			19.7			19.8		
MR 051	20.6			19.7			19.5			19.5		
MR 052	21.9			20.9			21.2			21		
MR 053	22.2			21.7			21.8			22		
MR 054	23.1			23			22.6			22.9		
MR 055	23			22.7			22.9			23		
MR 056	20.5			20.7			20.7			20.6		
MR 057	20.6			20.4			20.5			20.6		

MR 058	25.5			25.3			25.5			25.5		
MR 059	25.5			25.7			25.8			25.6		
MR 060	21			21			21			20.9		
MR 061	21			21.1			20.7			20.8		
MR 062	22.8			22.7			22.5			22.7		
MR 063	22.8			22.4			22.5			22.6		
MR 064	24.4			24			24.3			24		

Appendix F: Raw Measurement Data for Caliper and Panoramic Radiograph Image Study

Code	Caliper			Conventional Panorex			CBCT Reconstructed Panorex		
MR 005	25.5	25.5	25.5	30.7	30.5	30.4	21.4	21.4	21.5
MR 006	25.8			32.8			22.4		
MR 007	20.6	20.6	20.5	28.4	28.3	28.4	20.4	20.5	20.5
MR 008	21.3			30.3			21.4		
MR 009	22.8	22.8	22.8	29	29.1	29	20.7	20.7	20.7
MR 010	21.8			29.4			21.4		
MR 011	20.7	20.6	20.6	26.4	26.5	26.5	19.7	19.7	19.6
MR 012	21.3			28.1			19.1		
MR 013	20.6	20.6	20.6	27.2	27.4	27.4	19	18.9	19
MR 014	21.6	21.6	21.6	24	24	24.1	20.5	20.5	20.3
MR 015	20.2			23.8			19.7		
MR 018	20	19.9	19.9	28.7	29	28.7	19.4	19.3	19.3
MR 019	21.1	21.1	21.1	27.5	27.5	27.4	18.9	18.9	18.9
MR 020	21.9			29.6			19.3		
MR 021	21.8	21.8	21.8	30.8	30.8	30.7	20.6	20.4	20.5
MR 022	22			29.7			20.6		
MR 024	22.3	22.2	22.2	26.8	27	27	19	19	19
MR 025	17.7			24.6			16.7		
MR 026	21.7			30.1			21.3		
MR 027	23.2			30.4			22		
MR 028	24.2			32.7			22.3		
MR 029	23.9			29.2			22.3		
MR 032	21.9			29.9			20.7		
MR 033	22.3			29			21.2		

MR 036	24.8			30.2			20.7		
MR 037	23.8			30.1			21.5		
MR 038	19.3			27.2			17.6		
MR 039	19.5			24.3			17.7		
MR 040	22.1			22.2			21.8		
MR 041	22.3			21.1			22		
MR 042	20.6			27.3			20.1		
MR 043	20.5			26.2			19.8		
MR 044	21.9			29.1			22.1		
MR 045	20.9			29			21.7		
MR 049	20.5			27.6			19.2		
MR 050	20.5			28.3			19.3		
MR 051	20.6			26.1			18.6		
MR 052	21.9			28.2			19.3		
MR 053	22.2			28			19.2		
MR 054	23.1			29.2			21.4		
MR 055	23			29.1			21.5		
MR 058	25.5			26.9			22.3		
MR 059	25.5			34			20.3		
MR 060	21			27.2			19.6		
MR 061	21			27.7			18.7		
MR 062	22.8			31.1			21.5		
MR 063	22.8			29.9			22.5		
MR 064	24.4			31.3			22.6		