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An Evaluation of Root Length Change Measurements using Intraoral Scan and Panoramic Radiographs

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An Evaluation of Root Length Change Measurements using Intraoral Scan and Panoramic Radiographs

by

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A thesis submitted in partial satisfaction of
the requirements for the degree
Master of Science in Orthodontics and Dentofacial Orthopedics

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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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ABBREVIATIONS

CBCT	Cone-Beam Computed Tomography
T1	Initial Date of Treatment
T2	Final Date of Treatment
EARR	External apical root resorption
ALARA	“As Low As Reasonably Possible” principle
PSR	Periodontal Screening and Recording
FH	Frankfort Horizontal plane
DICOM	Digital Imaging and Communications in Medicine
CEJ	Cementoenamel Junction
PD	Probing Depth
STL	STereoLithography image
GIMP	GNU Image Manipulation Program
PSR	Periodontal Screening and Recording

ABSTRACT OF THE THESIS

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Elijah C. Wang

Master of Science in Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2016
Dr. Rodrigo Viecilli, Chairperson

Introduction: This study was intended to evaluate the accuracy of using panoramic radiographs to measure root length change over the course of orthodontic treatment, using intraoral scans of crowns, and a mathematical model to account for distortions in the radiographs. The study additionally evaluated whether a best-fit equation could be created from the calculated data to minimize differences to the measurements of root resorption made on CBCT scans.

Materials and Methods: Twenty-one patients were selected who had comprehensive orthodontic treatment, and all teeth in the upper right quadrant were evaluated in this study. T1 and T2 CBCT images were compared and a change in root length was determined. T1 and T2 crown inclination changes were also measured on the CBCT scan. At T2, intraoral scans were taken of each arch and the crown heights of teeth of interest were measured. Probing depths at the direct buccal surface were recorded for teeth of interest. T1 and T2 panoramic radiographs were evaluated and a change in root length was calculated based on a mathematical model using a distortion ratio determined from measured intraoral scans of the crowns. Root resorption values were calculated by subtracting T1 total tooth length from T2 total tooth length.

Results: Calculated root length change from panoramic radiographs had a trend towards being statistically significant compared to root length change when measured on CBCT scans. Using best curve equations, the disparity between the two classes of measurements could be accurately minimized, with the most accurate model fitting each tooth type individually with a unique quadratic equation. Adding probing depth and inclination changes into the mathematical models did not significantly increase accuracy.

Conclusions: A clinically accurate mathematical model can successfully yield root length changes during orthodontic treatment based on measurements made on panoramic radiographs and intraoral crown length.

CHAPTER ONE

REVIEW OF THE LITERATURE

External apical root resorption (EARR) is a well-studied phenomenon that has been documented in dentistry, especially in the field of orthodontics due to concerns of force induced resorption.[33] According to a retrospective study done by Apajalahti et al in 2007, there was a significant correlation between fixed orthodontics appliance and root resorption.[34] The study also found the most common teeth to have root resorption were maxillary incisors followed by mandibular incisors, while the severity of root resorption was highest in the maxillary incisors and maxillary premolars. The study concluded that in patients where treatment is prolonged, a 6-month radiographic follow-up is recommended.

Sameshima et al also evaluated EARR extensively in a series of papers intended on studying the prevalence, causes, prediction, and prevention of root resorption under orthodontic force.[9,37] His studies supported previous literature in finding root resorption to be most severe in the maxillary anterior teeth, with an average of over 1.4mm. He also wrote that root resorption can be dependent on a very large number of factors, from patient biology to treatment mechanics, and that root resorption seen in one practice may differ significantly from another practice. Thus, the importance of monitoring for root resorption becomes vital, due to the irregular nature of it's occurrence.

Studies performed on EARR tend to be limited by the ability to accurately visualize and measure actual loss of tooth structure. Among the literature available, the most common methods for evaluation are histological studies on extracted teeth, periapical radiographs, panoramic radiographs, and volumetric visualization with CBCT scans. A scanning electron microscope study performed by Han et al of 40 teeth highlighted the difficulty in quantifying root resorption without extraction by showing multiple patterns and shapes of pathological root resorption.[37] The authors conclude that on examination with SEM, the presence of EARR was not confined to any particular location on the root surface, and varied widely in degree of resorption.

Although the literature reports a wide variety of incidence of root resorption, most papers agree that EARR is fairly common among orthodontically treated patients. Rudolph and Bishara found from 0-5% of root resorption in non-orthodontically treated patients, Rudolph's study found that nearly 100% of all patients who underwent orthodontic treatment to have some level of root resorption.[38,39] This high number was supported by histological studied on extracted teeth in orthodontic patients, performed by independently by McLaughlin, Harry, and Stenvik, that found root resorption to occur in up to 90% of orthodontic patients.[40-42] Thus, the issue of root resorption is important to be addressed by any orthodontic practitioner.

Despite valid concerns of EARR during orthodontic treatment and recommendations for regular radiographic monitoring, the current modalities of radiographic imaging do not allow for accurate, quick, and low radiographic exposure for identification of the presence, prevalence, or extent of EARR. According to Sameshima et al, there are clear advantages to utilizing periapical radiographs over panoramic radiographs for evaluating root length changes in orthodontic treatment and general root morphology, such as the likelihood for panoramic radiographs to overestimate some root lengths by over 20%.[9] However, panoramic radiographs have been shown to have major advantages to other radiographic imaging techniques including patient comfort, ease of use, and low radiation exposure for the patient. Makedonas et al found that the 186 orthodontists in his study ranked panoramic radiographs as 7/10 in importance to diagnosis of root resorption, with the scale using 10/10 as great importance.[1] However, his study also reported Swedish orthodontists ranking panoramic radiographs as only 4/10 in importance to diagnosis of root resorption in anterior teeth.

Although research has shown that CBCT is the most accurate method of determining actual root resorption levels, the relatively high radiographic exposure from CBCT imaging compared to that from panoral exposure prevents regular or routine use to monitor EARR.[5,6,9,35] Both the American Acadamy of Oral and Maxillofacial Radiology (AAOMR) as well as the British Orthodontic Society hold strong positions against excessive radiation when treating orthodontic patients, and call for the use of CBCT radiographs only when necessary.[2,4] In regards to EARR, the AAOMR panel recommended the use of CBCT for monitoring dental anomalies at level 1, or likely recommended at the initiation of treatment. However, during or after treatment the panel determined that monitoring root resorption was at level 3, or likely not indicated. Additionally, under recommendation 1.2, the AAOMR states that to "use CBCT when the clinical question for which imaging is required cannot be answered adequately by lower-dose conventional dental radiography or alternate non-ionizing imaging modalities."

Although research has shown there to be a statistically significant difference between CBCT and panoral accuracy in linear measurements, whether the difference is clinically significant has not been determined.[27] The importance of determining clinically significant root length change is highlighted by research performed by Katona that showed that due to the thickness of the tooth and orientation of the tooth to the radiographic visualization plane, there are severe difficulties for accurately assessing the CEJ on periapical radiographs and therefore severe inaccuracies when attempting to measure root lengths.[20] Katona's paper encouraged the use of statistical studies to overcome this inherent limitation of radiographic measurements, and highlighted the importance of finding better techniques to accurately measure radiographic lengths.

Despite significant research indicating that panoramic radiographs cause tomographic distortion and image magnification, it has also been shown that the radiographs can yield quantitative measurements of certain teeth if the proper algorithms are used to offset the magnification.[15] Although periapical radiographs have been shown to be the most commonly used methodology in diagnosing root resorption, the inherent distortion makes exact measurements difficult. Researchers have circumvented this distortion by using algorithms that significantly reduce this factor. Linge et al found that by using the equation, $RR = r_1 - \left\{\frac{C_1}{C_2}\right\} \times\ r_2$, quantitative measurements could be made on periapical radiographs, with RR being root resorption, r_1 being the root length at radiographic exposure time point 1, c_1 being the crown length at radiographic exposure time point 1, c_2 being crown length at radiographic exposure time point 2, and r_2 being root length at radiographic exposure time point 2.[30] This equation has been modified and validated in further studies, with the methodology error reported at around 3%.[18]

In 2010, Yassaei et al., demonstrated that the length of the 1st premolar could be accurately identified on panoramic radiographs using the regression formula of $T_A=(T_R \text{ x } X)+Y$ which had coefficients of X and Y that varied depending on which quadrant the tooth was located.[36] This research was supported by various other publications that also applied linear regressions to accurately determine root lengths of other teeth utilizing panoramic radiographs.[6, 22-25,36] By adding data that intraoral scanners can supply regarding crown dimensions into the mathematical compensations for distortion, the accuracy of such calculations may be increased.

Intraoral scanners have become more prevalent in clinical dentistry, and offer the advantage of a high quality reproduction of intraoral structures with little tissue distortion. Ender et al., performed a study comparing accuracy between two scanning systems, the Lava COS™ and Cerec AC Bluecam™ with a conventional polyether impression on an in-vitro model. Both the trueness and precision of all 3 modalities of impression did not have a significant difference, which supports the idea that intraoral scanners are capable of producing scans that are as accurate as conventional impressions.[16-17]

Naidu et al., performed a study that evaluated the accuracy of measuring tooth sizes and Bolton ratios using the iOC scanner. Although this study found a statistically significant difference between the two methods of producing intraoral records, it also determined that this difference was not clinically significant. The study also noted that digital models seem to consistently produce larger measurements than physical models. This may be explained by one or more reasons proposed by the study including difficulty in scanning contact points, differences in software visualization, alterations in alginate impressions, and inability to judge surfaces on digital models for accurate measurement endpoint placement.[18] Other research has supported the fact that digital scanning produces measureable models that are more accurate than that of traditional alginate models.[16-17]

This accuracy in intraoral scanned data allows measurements to be made of crown dimensions that may be useful in determining tooth distortion ratios in panoramic radiographic data, by comparing crown measurements in the two imaging modalities.

CHAPTER TWO

AN EVALUATION OF ROOT LENGTH CHANGE MEASUREMENTS USING INTRAORAL SCAN AND PANORAMIC RADIOGRAPHS

Introduction

External apical root resorption (EARR) in the presence of orthodontic force is a phenomenon that occurs regularly during orthodontic treatment, yet there is a lack of accepted recommendations for screening patients for its presence or progression.[1,2] Historically there have only been a few methods to evaluate EARR, and these include histological studies on extracted teeth, periapical radiographs, panoramic radiographs, and volumetric visualization with CBCT scans. Clinical methods of evaluation in root length change are highly limited, with well quantified methods of clinically measuring change in root length in patients severely lacking.[3] While panoramic radiographs offer the least radiation exposure to patients, distortion and magnification errors are well documented in this radiographic modality. There is constant revision regarding the minimum amount of radiation required to diagnose, monitor, and treat orthodontic cases with the goal of achieving as low as reasonably achievable (ALARA) radiation exposure for patients. Although cone beam computed tomography (CBCT) radiographs allow for a large amount of information regarding root length and position, the amount of radiation that the radiograph exposes the patient to suggests that CBCT radiographs should not be used to monitor progress at regular points during orthodontic treatment.[2,4,5] Unfortunately, there are few modalities that offer the same level of detail and accuracy that could be used to view and record changes in root length over the course of treatment.[6]

Rotational panoramic radiography has been important to diagnosis and treatment of dentofacial pathology since its introduction in mainstream dentistry in the 1960's.[7] A major advantage of this type of radiological imaging is patient comfort, ease of use, and low radiation exposure for the patient. According to the United States Nuclear Regulatory Commission, the average United States resident receives natural radiation exposure of 3.1 mSv per year, while the average radiation dosage received from a single panoramic radiograph is 10 μSv.[7] Due to the large area visualized with panoramic radiographs, along with the relatively low radiation dose, panoramic radiographs have been considered as an ideal method of screening for a variety of dentofacial pathologies including cysts, fractures, and dental anomalies.

Although there are a variety of uses that panoramic radiographs are advocated for, there has also been significant debate regarding its sensitivity in quantitative measurements. Due to the nature of the radiographic technique, which combines tomography with slit beam radiography, panoramic radiographs tend to have a larger amount of radiographic image degradation and rotation compared to other methods of radiographic imaging. Specifically, the panoramic radiographs are subject to tomographic blurring, magnification, distortion, secondary images, and burn out.[8] These inherent limitations with panoramic radiographs has limited it's use in detecting and monitoring root resorption.[9]

Current literature continues to support use of panoramic radiographs solely as a method for screening general pathology and anatomy. Although periapical radiographs have less inherent distortion than rotational radiography, they are still susceptible to some level of distortion. Research has indicated that this distortion can be mathematically accommodated for by utilizing conversion equations.[10-13] Similarly, research also indicates that there is a possibility to mathematically account for the tomographic distortion in order to obtain relatively accurate quantitative measurements from panoramic radiographs.[14,15] Using clinical measurements of the patient's crowns with published methods of mathematical modeling to account for tomographic distortion, clinically accurate root length measurements from panoramic radiographs could be possible.

Intraoral scanners have steadily increased in popularity among orthodontic clinicians since their introduction into the market. Research has indicated that these scans allow for high quality reproduction of intraoral structures with minimal distortion.[16-19] Additional studies have also indicated that measurements on digitally scanned data are comparable to intraoral measurements or measurements on stone models. In order to facilitate future digital workflow for calculation of root length changes, and possible software development, digital measurements of the crown lengths were incorporated into the study.

The purpose of this retrospective study was to evaluate whether panoramic radiographs could yield clinically accurate measurements of root resorption, given a mathematical model to account for distortion, in conjunction with accurate crown measurements from intraoral scans. This study additionally looked at whether this accuracy could be improved with best fit equations to mimic CBCT measurements.

Null Hypothesis

1. Our first null hypothesis states that there will be no significant difference between change in root length measurements from T1 and T2 when calculated from combining panoramic radiograph and intraoral crown scan measurements and those measured from the CBCT scans.
2. Our second null hypothesis states that there will be no significant correlation between root length change measurements calculated from combining panoramic radiograph and intraoral crown scan measurements and those measured from the CBCT scans.
3. Our third null hypothesis states that there will be no significant linear or non-linear mathematical relationship that can be applied to the root length change measured on panoramic radiographs compared to measured on CBCT scans.

Materials and Methods

This study was approved by the Institutional Review Board (IRB) of Loma Linda University (LLU), Loma Linda, CA. The study sample consisted of 21 subjects who had completed orthodontic treatment at Loma Linda University Graduate Orthodontics clinic. Patients were selected based on completion date of orthodontic treatment, starting in January 2016 with patients meeting exclusion criteria recruited into the study until a total of 21 subjects were recruited. The sample size was determined by power analysis modeled after Dudic et al, as well as Yassaei et al.[5,18] Teeth studied were the maxillary right central incisor, lateral incisor, canine, 1st or 2nd premolar, and 1st molar. The 1st premolar was used if it was present at the T2 time point. Otherwise the 2nd premolar was substituted, with statistics calculated with the 1st or 2nd premolars grouped as one tooth category. Subjects for the study must have had a CBCT scan and panoramic radiograph taken at the T1 records phase, before any orthodontic tooth movement had taken place. Measurements taken on radiographic and intraorally scanned data were performed by one examiner, with measurement reliability statistically evaluated.

The following were exclusion criteria for candidates:

1. No CBCT or panoramic radiographs at the T1 time point.
2. PSR readings of worse than 1 in any measured sextant at T1 or T2, with a reading of 1 defined as any presence of bleeding on probing.
3. Root dilacerations or significant deviations from normal anatomy.
4. Missing teeth in the upper right quadrant, except for 1st or 2nd premolar extractions.
5. Radiographic imaging data that is incomplete or with data loss
6. Damage, significant wear, or significant restorations on the crowns of any teeth of interest.

Measurements and Data Collection

At the T2 records phase, intraoral scans of the maxillary arch were created using the 3M True Definition^{TM} scanner (3M, St. Paul, MN, USA) for each of the subjects at the same time as a panoramic radiograph and CBCT scan were taken using the the NewTom 3G^{TM} or NewTom 5G^{TM} imaging system (NewTom, Bologna, Italy). 2 periodontal readings at the buccal and lingual points of each tooth were taken at the T2 timepoint to estimate pocket depth as an additional measure for the predictive modeling process. All periodontal readings were taken with a Marquis color-coded probe with the same individual, and each site was probed 2 times approximately 5 minutes apart. The True Definition™ scan data was imported into the Ortho Insight 3D™ software (MotionView Software LLC, Chattanooga TN, USA) as STL (STereoLithography) files, where the crown heights were measured from gingival level on the tooth to height of the crown, with the height of the crown defined as the center of the buccal central lobe.

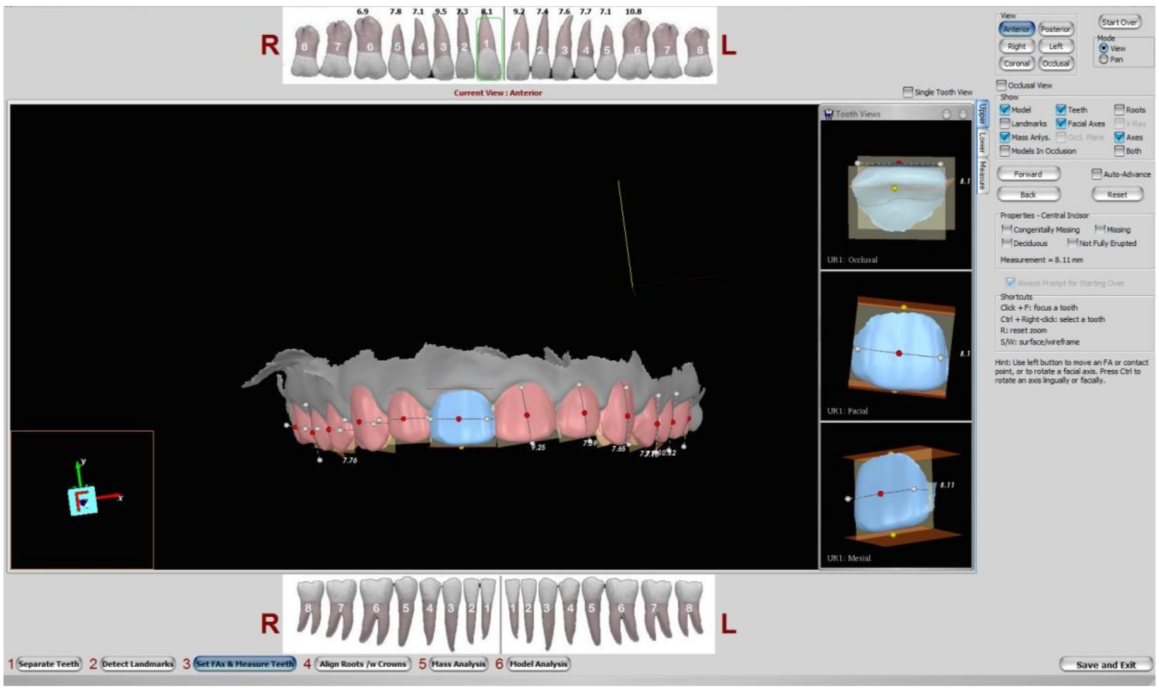


Figure 1. Crown measurement of upper right central incisor in Ortho Insight 3D™

CBCT images were taken with a 15 cm x 18 cm field of view (FOV) and an exposure time of 5 seconds set to 110kV and were imported into OsiriX MD 6.5.2 Imaging Software™ (Pixmeo, Bernex, Switzerland) as Digital Imaging and Communications in Medicine (DICOM) files for measurement. After importing the DICOM file for CBCT data into Osirix MD™, the full volume was visualized with a 100mm slice in order to orient the volume to the Frankfort Horizontal plane, with FH plane defined as a plane that passes through the inferior margins of the orbits, and the superior margin of the external auditory meatus (Figure 2). The slice was then reduced to 4mm to obtain measurements through the axis of each tooth from the most apical point of the root to the most incisal point of the middle buccal lobe of the crown (Figure 3). The inclination of each tooth was measured and reported as an angle against a parallel line to Frankfort Horizontal. For multi-rooted teeth, the most buccal and mesial root was measured (Figure 4).

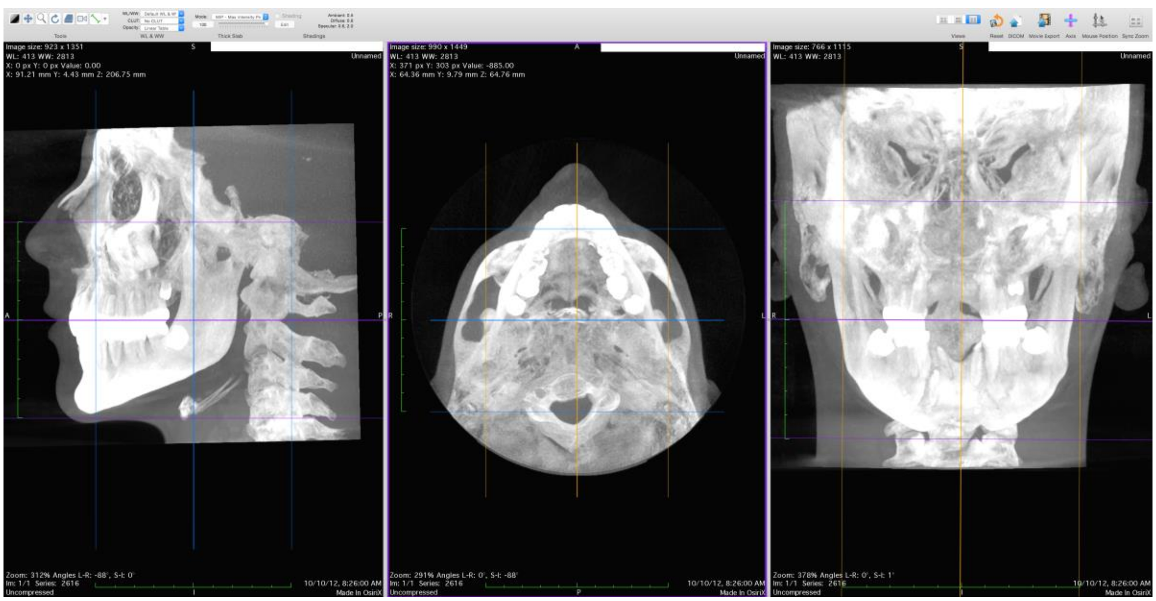


Figure 2. Full volume DICOM file with 100mm view to orient volume to Frankfort Horizontal plane.

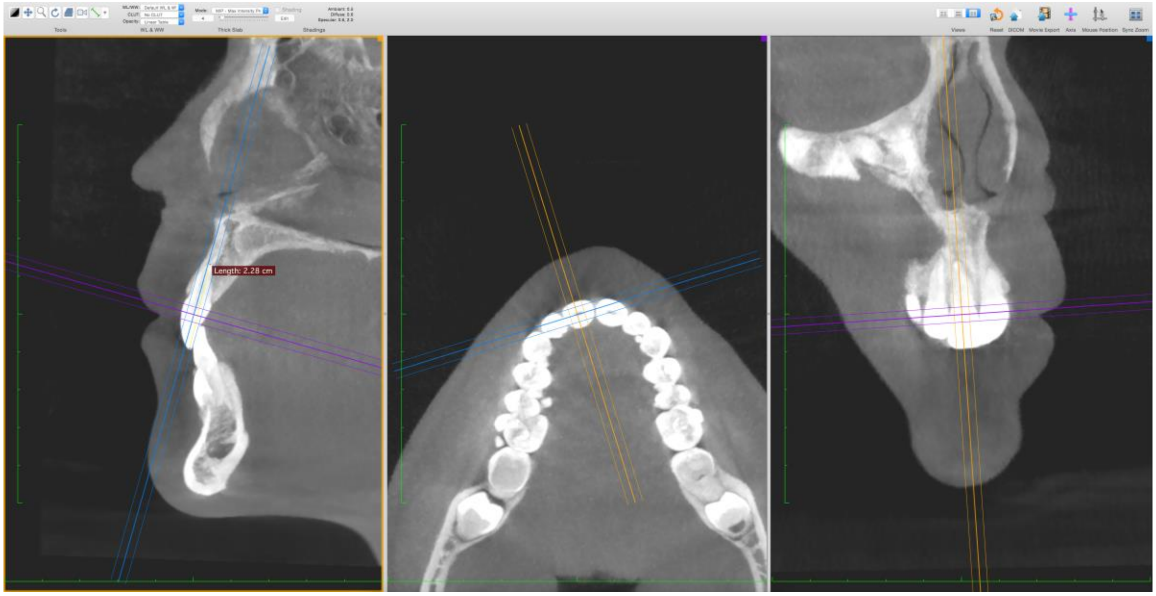


Figure 3. DICOM file with 4mm view and total incisor length measured.

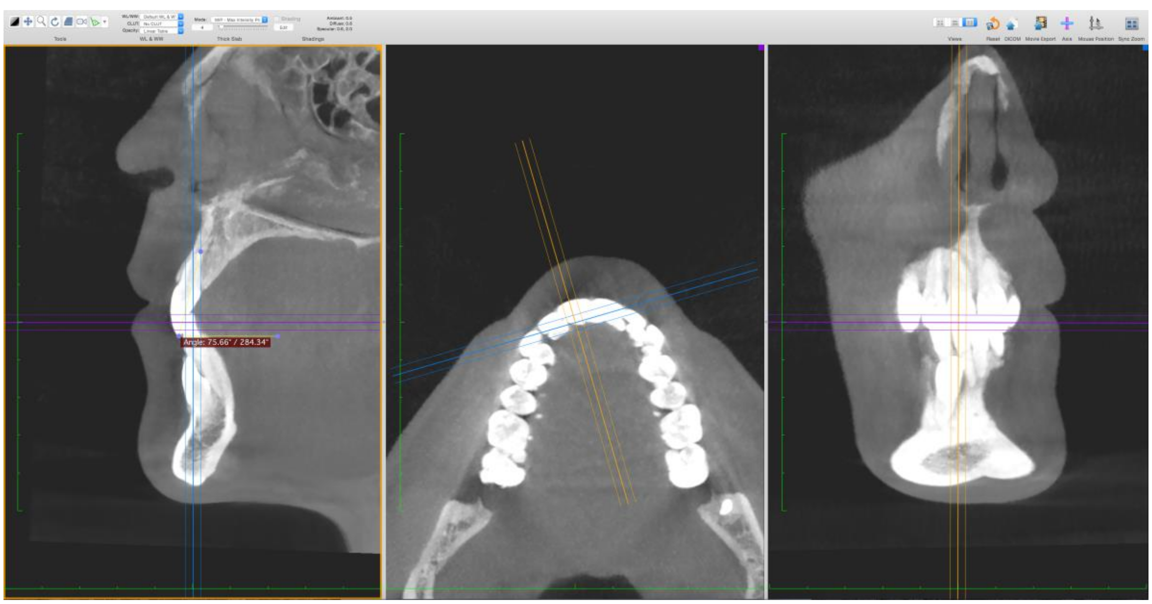


Figure 4. DICOM file imported into Osirix MD^{TM} with 4mm view and incisor inclination measured against a parallel plane to Frankfort Horizontal plane.

Panoramic radiographs were taken using Sirona Orthophos XG Plus™ (Sirona Dental, Salzburg, Austria) with the head oriented to Frankfort Horizontal, and saved into Dolphin Imaging™ software (Dolphin Image Solutions, Chatsworth, CA, USA). The teeth of interest were then measured on the panoramic radiograph of each patient using the open source photo viewer GIMP 2.8.10 software after the full resolution file was imported as a JPEG file with the dimensions of 2048x1536 pixels. Crown lengths were measured from the most incisal point in the middle buccal lobe of the crown, to the most gingival point of the CEJ as seen on the buccal surface of the crown (Figure 6), with the CEJ in this study defined as the most apical point of the most significant and rapid change in grayscale between the crown to the root. Total tooth length was measured from the most incisal point in the middle buccal lobe of the crown to the most apical point of the root (Figure 5). Measurements made in the JPEG were recorded as units of pixels, and were converted to a millimeter measurement based on the conversion factor determined from the intraoral scan crown measurements.

Figure 5. Incisor length of upper right central incisor measured in units of pixels on panoramic radiograph in GIMP software.

Figure 6. Crown length of upper right central incisor measured as units of pixels in GIMP software.

The T2 intraoral scanner measurements of the crowns were compared to the panoramic radiograph data for each tooth at the T2 time point and a mathematical relationship of magnification and distortion ratio was calculated. Using this conversion factor, a quantitative measurement for total tooth length was calculated for both T1 and T2 phases, and any changes in root length were documented between the time points. This change in tooth length was compared to the change in tooth length that was measured directly from the CBCT data and a determination of whether the difference between the two values is statistically significant was made.

The calculated root length at the beginning of treatment T1 was calculated as:

$$TotalLength[time(T1)] = \frac{PanoTotal[time(T1)] \times IntraoralCrown[time(T2)]}{PanoCrown[time(T1)]}$$

With the TotalLength[time(T1)] being the calculated entire tooth from most apical point of the root to the most incisal point in the center buccal lobe of the crown at the initiation of treatment, IntraoralCrown[time(T2)] being the measured crown height from the intraoral scan at the completion of treatment, PanoTotal[T1] being the length of the tooth as measured on the panoramic radiograph at the initiation of treatment, and PanoCrown[T1] being the height of the crown of the tooth as visible on the panoramic radiograph at the initiation of treatment.

The calculated root length at completion of treatment T2 was calculated as:

$$TotalLength[time(T2)] = \frac{PanoTotal[time(T2)] \times IntraoralCrown[time(T2)]}{PanoCrown[time(T2)]}$$

With the TotalLength[time(T2)] being the calculated entire tooth from most apical point of the root to the most incisal point in the center buccal lobe of the crown at the completion of treatment, IntraoralCrown[time(T2)] being the measured crown height from the intraoral scan at the completion of treatment, PanoTotal[T2] being the length of the tooth as measured on the panoramic radiograph at the completion of treatment, and PanoCrown[T2] being the height of the crown as visible on the panoramic radiograph at the completion of treatment.

The equation used to calculate the estimated amount of change in root length was calculated with the following equation:

$$\Delta\ Root\ Length = TotalLength[time(T2)] - TotalLength[time(T1)]$$

The same calculations are repeated with data that takes into account the probing depths, in an attempt to see whether a more accurate mathematical model can be created with the probing depths estimating the difference from CEJ to gingival margin. In this case, the value for IntraoralCrown is added to buccal probing depth and the new value, IntraoralCrownPD, is substituted at each time point into the equations above, with the estimated root resorption is recalculated.

Statistical Analysis

Descriptive statistics were given as quantitative values in millimeters for change in root length between T1 and T2. Kolmogorov-Smirnov was used to test for normality, and Spearman's rho was used to evaluate correlations between change in root length in each category of CBCT, panoramic, and panoramic with probing depth measurements. Pearson's correlation was used for evaluation of correlation between both measured and calculated data groups. A Friedman's Two-Way Analysis of Variance was performed for pairwise comparisons between root length change categories. Predictive modeling for curve fit to panoramic radiograph measurements was performed with linear and quadratic equations. Cronbach's Alpha was used to evaluate the reliability of measurements within each tooth class. All statistical analyses were performed SPSS™ 23.0 software (SPSS Inc., Chicago, IL, USA). Alpha was set at 0.05 significance level. The calculated intraclass coefficient was between 0.963 to 0.987, indicating high reliability in the measurements.

Results

The measured change in root length between T1 and T2 time points as measured on the CBCT radiographs, calculated from the panoramic radiograph, and calculated from the panoramic radiograph with the probing depths added can be seen in Figure 7. There is a slightly larger range in the root length change when estimated on panoramic radiograph, increasing from the 3.20mm to 3.21mm. When probing depths were added to intraoral scan crown measurements to account for CEJ differences in the panoramic radiograph, the resulting calculated root length change further increases in range to 4.24 (Table 1).

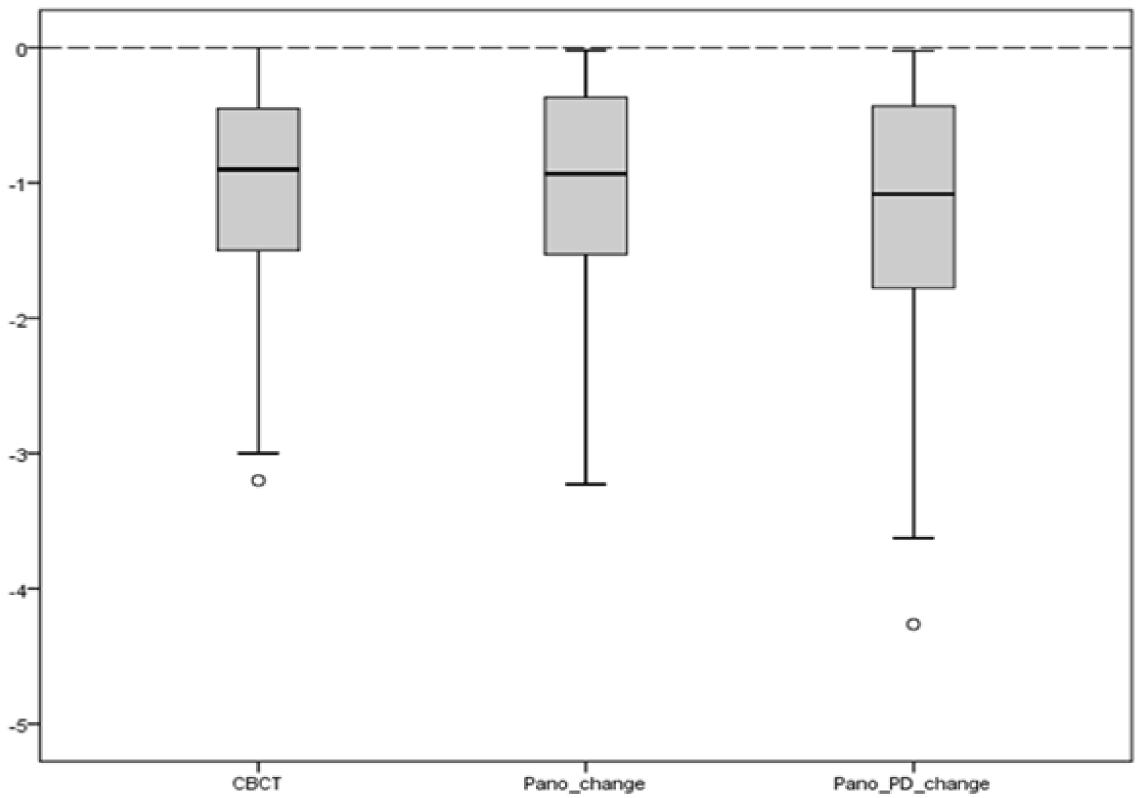


Figure 7. Root length change from T1 to T2 time points as measured on CBCT, as calculated from panoramic radiographs, and when calculated with probing depths added to intraoral crown scans.

Table 1. *Statistical comparison between root length changes measured or calculated from each modality.*

Modality	Mean	Median	Standard Deviation	Range
CBCT change	-1.0606	-0.9000	0.75946	3.20
Calculated Pano change	-1.0397	-0.9319	0.79349	3.21
Calculated Pano and PD change	-1.2151	-1.0835	0.93765	4.24

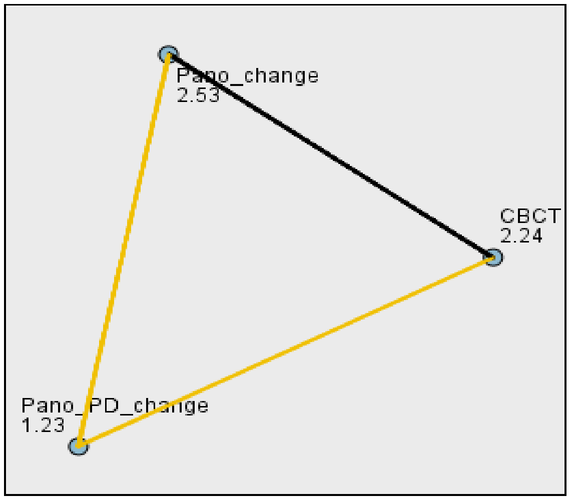
Correlation between the CBCT measurements of root length change, and root length change when calculated from panoramic radiograph and intraoral scans of crowns can be seen in Table 2. There is a high correlation of 0.976 between the CBCT measurements and calculated root length change from panoramic radiographs, with the correlation slightly dropping to 0.974 when the probing depths are added to the panoramic radiograph estimates.

Table 2. *Correlation between root length changes measured or calculated from each modality as determined by Spearman's rho.*

		CBCT	Calculated Pano change	Calculated Pano and PD change
CBCT	Correlation Coefficient	1.000	.976**	.974**
	Sig. (2-tailed)		.000	.000
	N	104	104	104
Calculated Pano change	Correlation Coefficient	.976**	1.000	.997**
	Sig. (2-tailed)	.000		.000
	N	104	104	104
Calculated Pano and PD change	Correlation Coefficient	.974**	.997**	1.000
	Sig. (2-tailed)	.000	.000	
	N	104	104	104

When pairwise comparisons were completed between each data set, it was found that there was a significant difference between the CBCT root length change and the calculated root length change from panoramic radiograph with p=0.038. However, when the data was adjusted, the differences became non-significant with p=0.113 (Figure 8).

Pairwise Comparisons



Each node shows the sample average rank.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
Pano_PD_change-CBCT	1.010	.139	7.280	.000	.000
Pano_PD_change-Pano_change	1.298	.139	9.361	.000	.000
CBCT-Pano_change	-.288	.139	-2.080	.038	.113

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

Figure 8: Pairwise comparison between data set groups

When the root length change as calculated from panoramic radiograph is overlaid onto the CBCT measured root length change, and an attempt is made to fit a curve to account for the difference, both linear and quadratic equations yield results with the high R-square value of 0.979 indicating a highly accurate fit (Figure 9). The best fit linear equation was $y = -0.076x + 0.947$, and the best fit quadratic equation was $y = -0.11x^2 + 0.865x - 0.030$

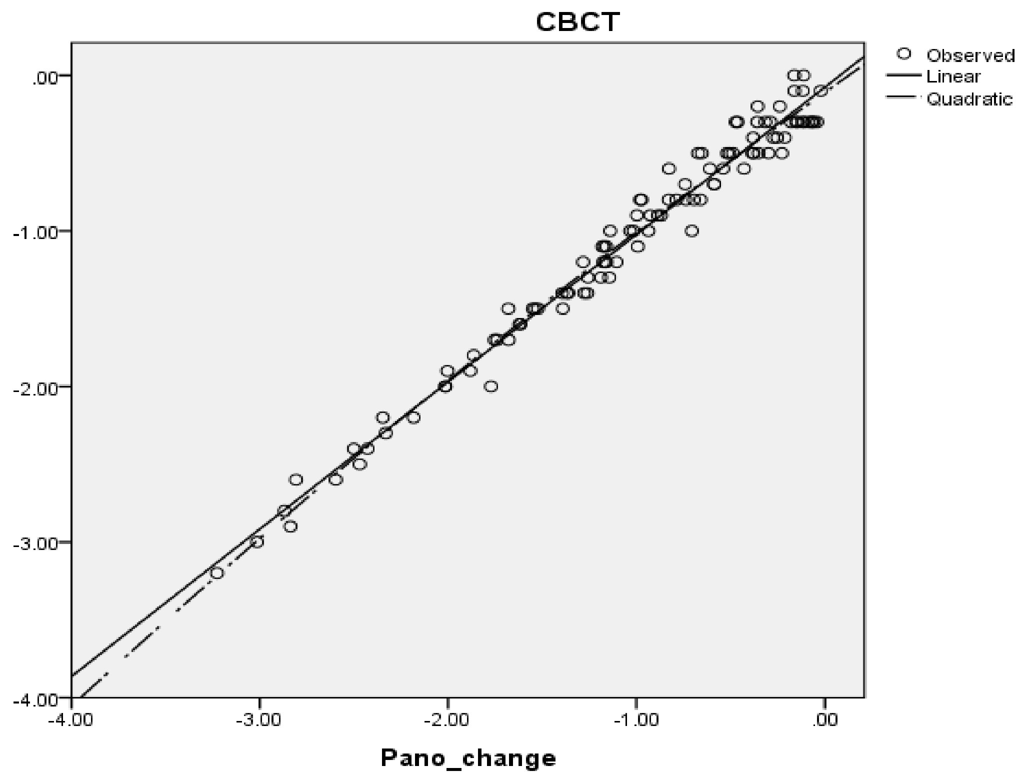


Figure 9. Best fit linear and quadratic equations to calculated root length change on panoramic radiograph and measured root length change on CBCT.

Taking the best fit linear equation, y = -0.076x + 0.947 and running the panoramic radiograph calculated root length changes yields a predicted root length change that has a Pearson's correlation to the CBCT measured root length change of 0.989, increasing from the correlation of the original calculated root length changes from panoramic radiograph of 0.976 (Figure 10). Adding inclination of the teeth as a further variable to increase the accuracy of the best fit equation yielded no additional increase in the correlation of the best fit equation to the CBCT, with the Pearson's correlation remaining constant at 0.989. The correlation of inclination to the CBCT measurement and calculated change by panoramic radiograph was low, at 0.172 and 0.184 respectively (Table 3).

Table 3. *Pearson Correlations for root length change as measured on CBCT, root inclination, and when calculated using the best fit linear equation with predicted root length change from the panoramic radiograph and intraoral crown scans.*

		CBCT	Calculated Pano change	Incline
Pearson Correlation	CBCT	1.000	.989	.172
	Calculated Pano change	.989	1.000	.184
	Incline	.172	.184	1.000
Sig. (1-tailed)	CBCT		.000	.041
	Calculated Pano change	.000		.031
	Incline	.041	.031	
N	CBCT	104	104	104
	Calculated Pano change	104	104	104
	Incline	104	104	104

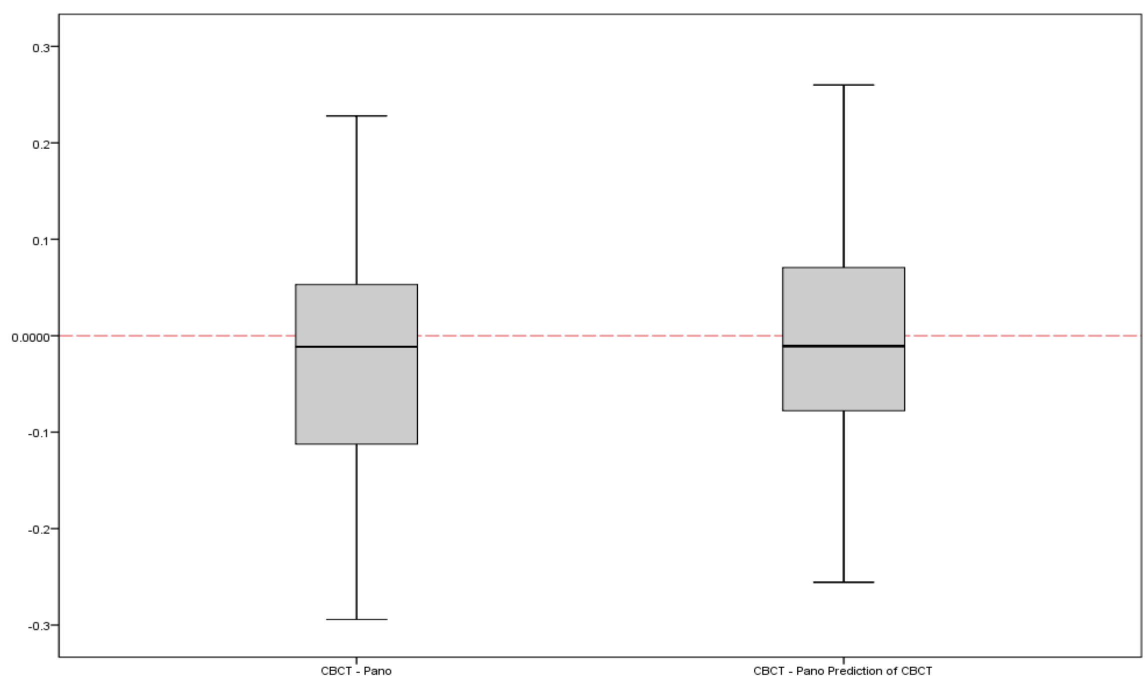


Figure 10. Comparison of the residual error between root length change when solely calculated from panoramic radiograph and when further processed with the best fit linear equation.

When the probing depths are added to the intraoral crown measurements, another best fit curve can be made, against the CBCT measured root length change values as seen in Figure 11. In this case, the best equation to fit the line marginally appears to be a quadratic equation, which presented with an R^2 value of 0.964, as opposed to the R^2 value of a linear equation of 0.963. The R^2 value using probing depths added to the intraoral scan crown measurements was lower than the R^2 value of the best fit equation with simply using intraoral scan crown measurements without the probing depths. The best fit linear equation was was y = -0.095x + 0.795, and the best fit quadratic equation was y = -0.07x^2 + 0.844x + 0.015

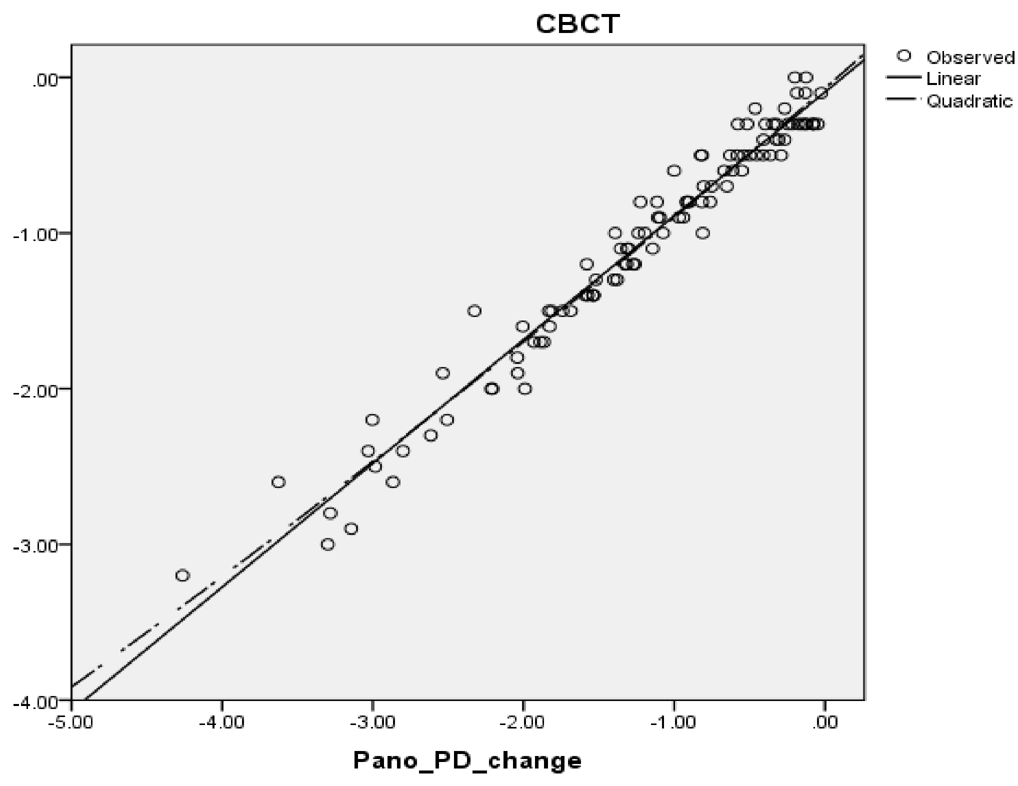


Figure 11. Best fit linear and quadratic equations to calculated root length change using panoramic radiograph with added probing depths and measured root length change on CBCT.

Table 4. *R^2 values and resulting equations for each tooth type when calculated tooth length on panoramic radiograph is best fit to a curve against CBCT measured tooth length.*

Tooth #, Equation	R^2	Constant	b1	b2
1 Linear	0.983	-.009	.971	
1 Quadratic	0.983	-.030	.910	-.026
2 Linear	0.998	-.011	.988	
2 Quadratic	0.998	.007	1.028	.013
3 Linear	0.977	-.080	.955	
3 Quadratic	0.980	-.139	.789	-.065
4 Linear	0.956	-.181	.878	
4 Quadratic	0.956	-.199	.830	-.019
6 Linear	0.974	-.100	.930	
6 Quadratic	0.975	-.148	.825	-.036

When the data is further broken down to attempt a best-fit equation via individual tooth type, we see the R^2 value increase in each tooth category, except the posterior teeth. Both premolars and molars appear to have a slightly decreased R^2 value from the best fit equation to the full data set of all teeth (Table 4). Figure 12 shows the spread of the data points along each best fit line.

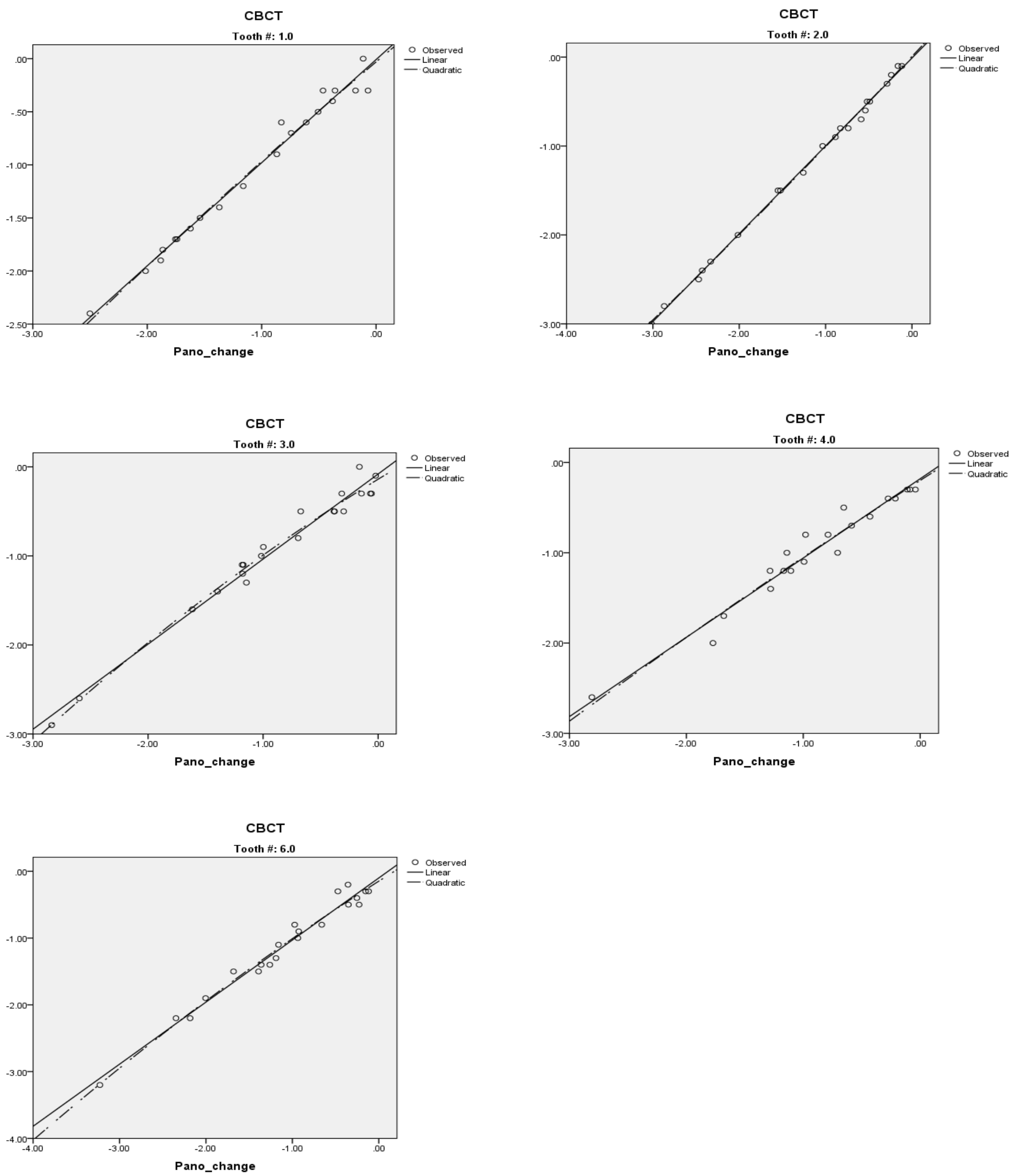


Figure 12. Best fit linear and quadratic equations to calculated root length change on panoramic radiograph and measured root length change on CBCT, divided by tooth type.

Taking into account probing depths on intraoral crown measurements, the best fit equations once again decrease in R^2 values, as we saw when taking the entire data set into account with all teeth grouped together. The decrease in R^2 value is seen across all teeth groups, but is most significantly seen in teeth numbers 1, 4, and 6 (Table 5).

Table 5. *R^2 values and resulting equations for each tooth type when calculated tooth length on panoramic radiograph with probing depth added is best fit to a curve against CBCT measured tooth length.*

Tooth #, Equation	R^2	Constant	b1	b2
1 Linear	0.971	-.026	.843	
1 Quadratic	0.972	.014	.937	.035
2 Linear	0.996	-.015	.868	
2 Quadratic	0.996	.012	.921	.015
3 Linear	0.975	-.065	.862	
3 Quadratic	0.980	-.138	.676	-.065
4 Linear	0.935	-.219	.703	
4 Quadratic	0.938	-.170	.801	.030
6 Linear	0.964	-.124	.721	
6 Quadratic	0.964	-.116	.734	.004

Discussion

One of the accepted methods of accounting for radiographic distortion in periapical radiographs is with the equation suggested by Linge et al., which $RR = r_1 - \left\{\frac{C_1}{C_2}\right\} \times\ r_2$ where RR stands for root resorption, and r_1 and r_2 are projected root lengths that correspond to the same levels of distortion as crown measurements at c_1 and c_2.[12] This equation was modified by McFadden et al., and cited by various papers that utilized the method to predict root resorption via periapical radiographs.[10-13] While applying this method to panoramic radiographs, we find the error to be 2%. This is significant in that the low radiation output and fast process of taking a panoramic radiograph is preferable in a clinical situation to evaluate root length change than a full mouth series of radiographs.

An initial comparison of the data among the three groups, CBCT measured root length change, root length change as calculated from panoramic radiograph, and root length change as calculated from panoramic radiograph with the probing depth added to crown length measurements, shows a larger spread among data points with the lengths derived from panoramic radiographs. Previous studies that had attempted to use panoramic radiographs in measuring root length change without conversion factors found the discrepancy between CBCT measurements and panoramic measurements to be between 5-29%, while our study narrowed the range significantly to 2%, with 0.0209mm of difference.[6,9,27] Although differences between the CBCT measurements and panoramic calculated measurements were significantly different when compared as a group with $p=0.038$, when the significance was adjusted, the difference became non-statistically significant at $p=0.113$. One key point to note is that this difference is approximately 0.02mm of root length change. Studies have argued that the threshold for clinical significance of root length change to be at 0.5mm, due to the inability for radiographs to read accurately below that level.[20] Thus, although the difference has a trend towards being statistically significant, the clinical difference is negligible.

The average changes in root length as measured on CBCT and as calculated from panoramic radiographs and intraoral crown scans both lie at approximately 1mm, with approximate standard deviations of 0.8mm. Linge & Linge reports in thier study that the most severe average root length change of incisors during orthodontic treatment to be 1.34mm in 719 patients, and Llamas-Carreras et al reports the average root resorption after orthodontic treatment to be 1.1mm with a standard deviation of 1.0mm.[30,31] Our results corroborate the severity of root resorption as reported in the literature. Previous studies had shown that changes of less than 2.5mm are difficult to quantify in panoramic radiographs, but our results clearly indicate the values under 1mm are still fairly accurate when using a conversion ratio.[32]

Throughout the study, it appears that adding probing depths to intraoral scans of crown lengths to account for gingival coverage of the CEJ decreases the accuracy of the calculated root length changes from the panoramic radiographs. Both the range of the root length change is increased, as well as the average root length change, with and without mathematically modeling to account for the differences to measured root length change on CBCT. This was an expected result due to the inherent inaccuracy of measuring probing depth with standard periodontal probes, which often yield results that are +/-0.5mm of actual pocket depths resulting in up to 50% change in probing depth.[21] Using standard Marquis color coded periodontal probes only gives accuracy to the single digits. Additionally, probing depths do not reflect the position of the CEJ in the majority of cases. Due to the variety of factors that decrease the reliability of probing depth measurements, this study found that using mathematical modeling to account for intraoral scan crown measurement inaccuracies was significantly better than attempting to add probing depth measurements without significant improvements in probing methodology to locate the CEJ.

Attempting to use inclination of teeth to increase the accuracy of the predictive model was not achieved in this study. Due to the fact that panoramic radiographs have a specific focal trough, the inclination of teeth should theoretically affect the accuracy of measuring the length of teeth. However, the teeth in this study had fairly low range of inclinations, with the means of the inclination of each tooth type ranging from -8 degrees to 11 degrees. It is possible that these inclination changes are too small to be of significance when the measurements are compensated by the conversion factor.

Previous studies using panoramic radiographs for measuring root resorption studies found that a chief reason for inaccuracy in measurement is the difficulty in locating the CEJ on panoramic radiographs.[9] Although the same issue existed in this study, the relative accuracy of the panoramic radiograph calculated measurements may be attributed to the fact that identifying the exact CEJ point is not necessary with a conversion factor, as long as the point is relatively close to what was estimated in the intraoral crown scan. Additionally, it is possible that due to the fact that panoramic radiographs tend to elongate measurements, the inherent elongation trended the crown measurements on the panoramic radiograph towards more closely mimicking the crown measurements taken on the intraoral scans, which had an inherent error of being smaller than the distance to the CEJ.

By further investigating the data, we find that using a best-fit algorithm, we can further decrease the discrepancy between the CBCT and panoramic measurements. Although linear and quadratic equations both result in the high R^2 value of 0.989, it appears that splitting the data into tooth types and creating unique algorithms for each category yields the most accurate curve fit, with R^2 values peaking at 0.998 for the lateral incisor. The lowest R^2 values were found in the premolar and molars, which can be accounted for due to the fact they are multi-rooted teeth that are more likely to traverse through the focal trough of the panoramic radiograph and distort with a more complex process than with single rooted teeth.

Although both linear and quadratic equations yield the same R^2 value, it is important to note that the linear equation places very little value on the x variable, thereby significantly decreasing the impact that the variable has on output. This may be due to the fact that our study found an average root length change of only 1mm, with a fairly narrow range that then limits the range which the linear equation is accurate over. Thus, give the equal R^2 values between the quadratic and linear equations, it is likely that the quadratic equation will yield more accurate measurements over a wider range of root resorption values, given the more significant impact that the equation places on the x variable, which is the calculated root length change from the pano.

Limitations of Study and Recommendations for Future Studies

1. Low patient load meant segregation of data lost some power. Future studies would benefit from a larger sample size.
2. Grouping premolars into a single classification decreased the homogeneity of the sample, and separate groups would have been ideal.
3. Root resorption values of less than 0.5mm are difficult to quantify even on CBCT.
4. Possible crown wear over treatment time could not be identified and quantified.

5. Root resorption is a 3-dimensional change in root contour, and even CBCT has it's limitations in reading loss of root structure; it's important to classify what type of resorption that is most visible on traditional radiographs.
6. Mandibular teeth were not taken into account, especially incisors can have high inclination which may alter accuracy of algorithm.
7. Loss of tooth structure becomes clinically relevant after approximately 3mm of root length loss, according to literature, due to research that states that the apical portion of the root has fairly minor importance to overall periodontal support. However, the average root length change in this study was only 1mm.[29]

Conclusions

1. There was a trend towards statistically significant difference between calculating root length change using panoramic radiographs and intraoral scans compared to measurements on CBCT (p=0.038, adjusted p=0.113), although this difference would be clinically insignificant.
2. Adding probing depths to the intraoral crown scan measurements to attempt to estimate gingival coverage of the CEJ decreases the correlation between calculated root length change from panoramic radiograph and CBCT measured root length change.
3. Introducing a best fit equation for processing root length changes based on intraoral scans and panoramic radiographs reduces discrepancies to CBCT measurements, raising the correlation coefficient from 0.976 to 0.989. Both linear and quadratic

equations produce an R^2 value of 0.979, with the linear equation as $y = -0.076x + 0.947$, and the quadratic equation as $y = -0.11x^2 + 0.865x – 0.030$.

4. Adding inclination changes to the best fit equation does not increase or decrease the correlation of the predicted root length change to the CBCT measured root length change.
5. It is possible to even further reduce the discrepancy between CBCT measurements and calculated root length changes on panoramic radiograph and intraoral scans by introducing tooth specific equations to model the discrepancy, with R^2 values increasing up to 0.998.
6. We are unable to reject our first null hypothesis, but we must reject the second and third null hypotheses.

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