Title
A Novel Technique to Measure Changes in Alveolar Bone Coverage of Lower Incisor Roots Before and After Orthodontic Treatment Utilizing CBCT

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A Novel Technique to Measure Changes in Alveolar Bone Coverage of Lower Incisor Roots Before and After Orthodontic Treatment Utilizing CBCT

by

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THESIS

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[redacted]

DEDICATION

I would like to dedicate this thesis to my wife Nicole and our children Ashytn and Jack. You have been a great support to me through this entire educational journey and have helped keep my life balanced. Thank you for your love and your understanding. Nicole, you truly are my better half and I thank you for helping me become more than I ever could have on my own. I love you.

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I would like to acknowledge a few key individuals who made this project and its development possible. Dr. Gerald Nelson, who originally pointed me in the direction of this research project and played a key role in its development. Thank you Dr. Nelson for sharing your vast knowledge of orthodontics and for speaking on this topic at national meetings and always striving to utilize technology to its fullest potential, in order to improve patient care and outcomes. Thank you Dr. David Hatcher for your unparalleled knowledge in the field of dental radiology and CBCT which was vital to the development of the methodology used in our study. Dr. Sneha Oberoi, thank you for your help in setting up meetings to ensure questions were answered and checking in to ensure constant progress was underway. Dr. Jeffrey Miller, thank you for developing the original method and for sharing your ideas on public forums. You have posed important questions that, when answered, will help orthodontists avoid/reduce negative outcomes in high risk patients. Dr. Art Miller, you have been a great help in instilling confidence and providing much needed direction, especially at the beginning of this project. Thank you for your positive outlook on life and your patience and support while I found a project that truly fascinated me. Dr. Mehreen Baig, thank you for all of your help in identifying subjects for our study, improving the methods, and for helping with all of the data collection. Dr. Nancy Hills, thank you for your help with the statistical analysis. Finally, a thank you to my parents, John and Robin Hagge. Thank you mom and dad for your support and for your love. You worked so very hard to instill in your five sons the values that would help us attain our dreams.

ABSTRACT

Introduction: The anatomic limits of the alveolar bone defines the boundaries of orthodontic movement and challenging these limits may cause undesirable effects on the periodontal tissues [1, 2]. The most critical orthodontic tooth movements include dental arch expansion and incisor buccal-lingual movements [1, 3]. Prior to computed tomography, visualization of labial/buccal and lingual bone plates was not possible due to superimpositioning of structures in 2D radiography and gingival covering of the bone during clinical examination. With the advent of computed tomography, dental professionals were able to visualize what conventional radiographs never showed, the thickness and level of the labial/buccal and lingual alveolar bone. Hyperdivergent patients present with a thinner symphysis thickness than do hypodivergent and normo-divergent patients [4]. With this thinner amount of bone coverage, orthodontic tooth movement in hyperdivergent patients may lead to an increase in bone loss around the roots of the lower incisors.

Objectives: 1) To test the reliability of a novel technique to measure changes in the supporting alveolar bone around lower incisors. This was quantified using cone beam computed tomography to measure vertical levels of the labial, lingual, and interproximal alveolar bone as well as taking perimeter measurements at standardized axial slices and calculating the approximate percent of the root surface area covered by any measurable amount of bone (bone thickness was not evaluated). 2) To utilize this novel technique to evaluate the changes in alveolar bone support for the roots of lower incisors before and after orthodontic treatment in subjects with high mandibular plane angles.

Materials and Methods: The sample consisted of n=20 hyperdivergent patients (SN-MP ≥ 39 degrees which is 1 standard deviation above the norm), with a full complement of permanent dentition, who underwent comprehensive orthodontic treatment in a university setting. There were 7 males and 13 females. The ages of the subjects at the beginning of treatment ranged from 13.2 to 42.6 years with a mean age of 17.6 years. Treatment time took an average of 2.2 years. 10 subjects underwent premolar extraction in conjunction with their orthodontic treatment and 10 had no extractions. Pre-treatment crowding was estimated from pre-treatment photos and ranged from mild to severe (1-3 mm = mild, 4-6 mm = moderate, >/= 7 mm = severe). 9 were mild, 8 were moderate, and 3 were severe. Using three-dimensional cone-beam computed tomography taken before and after treatment on the same imaging machine and uploaded to Dolphin Imaging, the bone surrounding each lower incisor root was measured in all 3 planes of space (sagittal, coronal, and axial). After following a standardized orientation protocol, each lower incisor root was analyzed to determine the location of specified zones: No Bone Zone (NBZ), Partial Bone Zone (PBZ), Full Bone Zone (FBZ). Specific measurements were obtained: Highest Vertical Bone Height (HVBH), Root Length (RL), Lowest Vertical Bone Height (LVBH), Root perimeter (RP), Defect perimeter (DP). Calculations were performed to determine: Bone Coverage Area (BCA), Root Partial Bone Zone (rPBZ), Axial Radicular Bone Coverage (ARBC), and Total Root Bone Coverage (TRBC). Statistical analyses were performed. As this is an unpublished method originally proposed by Dr. Jeffery Miller, details having to do with each measurement were specified by us. We also modified certain elements of the methods so as to be more accurate and complete. Further, the original method as outlined could not be used on teeth with fenestrations, an issue that we were able to resolve in this study.

Results: On average, the total root bone coverage of lower incisors significantly decreased after orthodontic treatment by approximately 10% and root length shortened an average of 0.9 mm. Intra-agreement appeared to be good-to-excellent on root length and HVBH. Intra-agreement appeared to be fair in regards to TRBC. There were a significantly greater amount of both buccal and lingual dehiscences found after orthodontic treatment, while the number of fenestrations generally decreased. Due to power issues, analyses performed were not found to be significant.

Discussion: The accuracy of our measurements was affected by the voxel size of 0.25 mm. More testing is needed to support the reliability of this method and to compare the findings for hyperdivergent individuals with a control group. There are bony limitations to tooth movement. In patients that are diagnosed to have compromised boney housing prior to orthodontic treatment, care should be taken in the treatment planning, treatment execution, and post-treatment evaluation phases to ensure that long-term outcomes for our patients are as favorable as possible.

Conclusions: During orthodontic treatment, patients with hyperdivergent mandibles can experience significant negative changes in bone coverage around lower incisor roots. Dehiscences increased during orthodontic treatment. Using a sagittal slice to examine root bone coverage can significantly under-represent the amount of bone surrounding the root 3 dimensionally (e.g., does not take into consideration inter-radicular bone). The boundaries of lower incisor tooth movement are compromised in hyperdivergent patients and significant sagittal tooth movements may cause adverse sequelae. This type of approach must be carefully monitored to avoid negative iatrogenic effects.

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INTRODUCTION

The anatomic limits of the alveolar bone defines the boundaries of orthodontic movement and challenging these limits may cause undesirable effects on the periodontal tissues [1, 2]. The most critical orthodontic tooth movements include dental arch expansion and incisor buccal-lingual movements [1, 3]. Tooth movements that decentralize teeth from their alveolar bone represent the most critical movement for developing bone dehiscences. Thus, buccal-lingual movements present more risk for breaking the limits of the alveolar bone, causing buccal and lingual bone plate resorption. Garib points out that there is a clear correlation between buccal-lingual tooth movement and the occurrence of buccal bone dehiscences. Studies in animals showed that the labial movement of the incisors, even using light forces, produces an increase in the distance between buccal al veolar crest and CEJ [1].

A dehiscence is defined as the loss of alveolar bone that leaves a characteristic oval, root-exposed defect from the cementoenamel junction apically. A Fenestration is a "window" of bone loss on the facial or lingual aspect of a tooth that places the exposed root surface directly in contact with gingiva or alveolar mucosa. It can be distinguished from the dehiscence in that the fenestration is bordered by alveolar bone along its coronal aspect. Since dehiscences and fenestrations are found in the general population, Rupprecht reported on the prevalence, distribution and features of alveolar dehiscences and fenestrations in modern American skulls [5]. A dehiscence was present in 40.4% of the skulls and a fenestration was present in 61.6% of skulls. Similarly Nimigean [6], looking at white South-East European population and studying 138 skulls of specimens ranging from 21 to 54 years of age, found more fenestrations than dehiscences in the skulls they studied. They also found more dehiscences in the mandibles and more fenestrations in the maxillas.

Evangelista pointed out that, dehiscences are more frequently found in the mandible, while fenestrations are more frequently found in the maxilla. Many studies have also found alveolar defects on the buccal surfaces and the data from these studies suggest greater caution about tooth proclination in the mandibular arch, especially in the incisor region. In addition, Evangelista reported on many alveolar defects in the lingual faces of the mandibular incisors; and pointed out that greater care is needed in planning treatment for patients who need extraction of mandibular premolars and retraction of incisors [7]. Wehrbein et al evaluated the alveolar bone/symphysis complex of deceased patients who were undergoing orthodontic treatment and found severe bone loss on the labial and lingual cortical plates. These bony defects were not evident on macroscopic inspection, and this can happen without excessive proclination of teeth in patients with narrow and high alveolar bones [8]

The development or exacerbation of dehiscences and fenestrations can increase a patient's risk for developing gingival recession [9, 10]. However, gingival recession is the final result of the impact of many etiological factors, not just one [11, 12]. Dominiak outlines many of these factors as: primary morphological conditions, functional factors, inflammation factors, age and sex factors as well as general diseases that all play important roles in the development of recession [11]. Evangelista noted that for patients with a thin attached gingiva, a correct diagnosis of bone support is necessary [7]. High quality clinical and animal studies in regards to the association of orthodontic treatment and gingival recession are lacking in the literature [13]. Interestingly, a systematic review done in 2011 concluded that there was no association between appliance-induced labial movement of mandibular incisors and gingival recession [14]. It has been shown that hyperdivergent patients present with a thinner symphysis thickness than do hypodivergent and normo-divergent patients [4]. Garib et al, in 2010 highlighted that facial pattern has an influence on the morphology of labial/buccal and lingual bone plates. They stated that hyperdivergent patients have a thinner mandibular symphysis and a thinner alveolar ridge in the anterior region of the mandible, compared to the other facial patterns. With this thinner amount of bone coverage, orthodontic tooth movement in hyperdivergent patients may lead to an increase in bone loss around the roots of the lower incisors [1, 10, 15].

Hyperdivergence or a high mandibular plane angle is a result of many different etiological factors; one of the most important of these factors is mandibular growth. Nielson explains that hyperdivergent patients display unique differences in the development of the anterior facial height (AFH) and posterior facial height (PFH). "These differences in height development lead to rotational growth or positional changes of the mandible that greatly influence the position of the chin. The factors that determine the increase in AFH are the eruption of the maxillary and mandibular posterior teeth and the amount of sutural lowering of the maxilla. PFH, on the other hand is determined by the lowering of the temporomandibular fossae and condylar growth. When vertical condylar growth exceeds dentoalveolar growth, i.e. eruption of the teeth in the jaws, forward rotation of the mandible occurs. In contrast, if dentoalveolar growth is greater than vertical condylar growth, the resulting change in mandibular position is backward or posterior rotation of the mandible. The two extreme mandibular growth patterns also show differences with respect to the amount of effective vertical condylar growth. Patients with an anterior condylar growth pattern usually have a greater amount of vertical growth than patients with posteriorly directed growth, a factor that further accentuates the differences" [16].

What is the best way to visualize dehiscences and fenestrations? Often times the extent of a dehiscence or fenestration isn't appreciated until a periodontal flap is laid. Prior to computed tomography, minimally invasive visualization of labial/buccal and lingual bone plates was not possible, due to superimpositioning of structures in 2D radiography and gingival covering of the bone during clinical examination. With the advent of computed tomography, dental professionals were able to visualize what conventional radiographs never showed, the thickness and level of the labial/buccal and lingual alveolar bone [1, 17]. CBCT can show bone dehiscences and fenestrations [18-21]

As far back as 1996, invivo CT studies have reported on bone dehiscences in relation to tooth movement [22]. This was done with high resolution computed tomography (HR-CT) and axial sections of the jaws were used to show absence of bone. Graber noted critically in 1995 that with dental and panoramic radiographs and lateral cephalograms we see little more than 50% of the real anatomical structures and there should be an integration of alternative imaging techniques [23]. Furmann, in 1996 went on to discuss his findings using CT to visualize fenestrations and dehiscences noting that 3D imaging will permit more detailed assessment of the various periodontal risk factors involved in the use of removable and fixed appliances [22].

Sarikaya studied nineteen patients with dentoalveolar bimaxillary protrusion who were treated by extracting the 4 first premolars and were evaluated with lateral cephalograms and computed tomography (CT). Using CBCT, measurements were taken at apical level, mid-root level and crest level to compare buccal and lingual thickness of alveolar bone. Sarikaya also demonstrated the value of using axial slices in assessing bone loss around teeth. The paper concluded that, “There were statistically significant decreases in lingual bone width in both arches after retracting the incisors. Some of the patients demonstrated bone dehiscence that was not visible macroscopically or cephalometrically. When tooth movement is limited, forcing the tooth against the cortical bone may cause adverse sequelae. This type of approach must be carefully monitored to avoid negative iatrogenic effects” [24].

Our aims in the current study were to: 1) Test the reliability of a novel technique to measure changes in the supporting alveolar bone around lower incisors. This was quantified using cone beam computed tomography to measure vertical levels of the labial, lingual, and interproximal alveolar bone in sagittal and coronal slices, as well as taking perimeter measurements at standardized axial slices and calculating the approximate percent of the root surface area covered by any measurable amount of bone (bone thickness was not evaluated). 2) Utilize this novel technique to evaluate the changes in alveolar bone support for the roots of lower incisors before and after orthodontic treatment in subjects with high mandibular plane angles.

MATERIALS AND METHODS

Study Design

The study was a retrospective study, which consisted of 20 test subjects selected from the patient population at the University of California San Francisco Orthodontic Clinic. There were 7 males and 13 females. The ages of the subjects at the beginning of treatment ranged from 13.2 to 42.6 years with a mean age of 17.6 years. Treatment time took an average of 2.2 years. 10 subjects underwent premolar extraction in conjunction with their orthodontic treatment and 10 had no extractions. Pre-treatment crowding was estimated from pre-treatment photos and ranged from mild to severe (1-3 mm = mild, 4-6 mm = moderate, ≥ 7 mm = severe). 9 were mild, 8 were moderate, and 3 were severe. Average pre-treatment SN-MP angle was 42.8. Inclusion criteria were: patients with high mandibular plane angles (aka hyperdivergent): MP-SN ≥ 39 degrees, patients with full complement of permanent dentition, patients who underwent comprehensive orthodontic treatment (not just limited tx), patients who had pre and post treatment CBCT images that were taken on the same CBCT machine (ie, Carestream 2012-2016). Those patients who had an apparent CR-CO shift in the lateral ceph (e.g., wax bite visible), which would affect the SN-MP angle, were excluded from this study.

Table 1. Characteristics of cohort (n=20)

Characteristic	n	(%)
Age pre-treatment, mean (sd)	17.6	(7.1)
Age post-treatment, mean (sd)	19.8	(7.1)
Sex		
Male	7	(35.0)
Female	13	(65.0)
Length of treatment (years), mean (sd)	2.2	(0.5)
Extraction	10	(50.0)
SN-MP pre-treatment	42.8	(3.4)
Mn-ant crowding pre-treatment (mm), median (IQR)	4	(3, 6)
Severity of crowding		
1	9	(45.0)
2	8	(40.0)
3	3	(15.0)
Change in IMPA, median (IQR)	1.2	(-2.8, 3.8)

A pilot study was performed on 3 subjects (12 teeth) by 2 different examiners at 2 different time points at least 2 weeks apart to test reliability of the technique.

The method utilized in our study was originally introduced by Jeffery Miller in various public domains [25]. His original methods focused on approximating the total root bone coverage of teeth with dehiscences. Some of the methodology that Miller described was based off of the capabilities of the imaging software that he used at the time (CS 3D Imaging). We proposed several changes to his original methodology and also applied the same basic principles in order to approximate the total root bone coverage of teeth with fenestrations as well (Figures1-3).

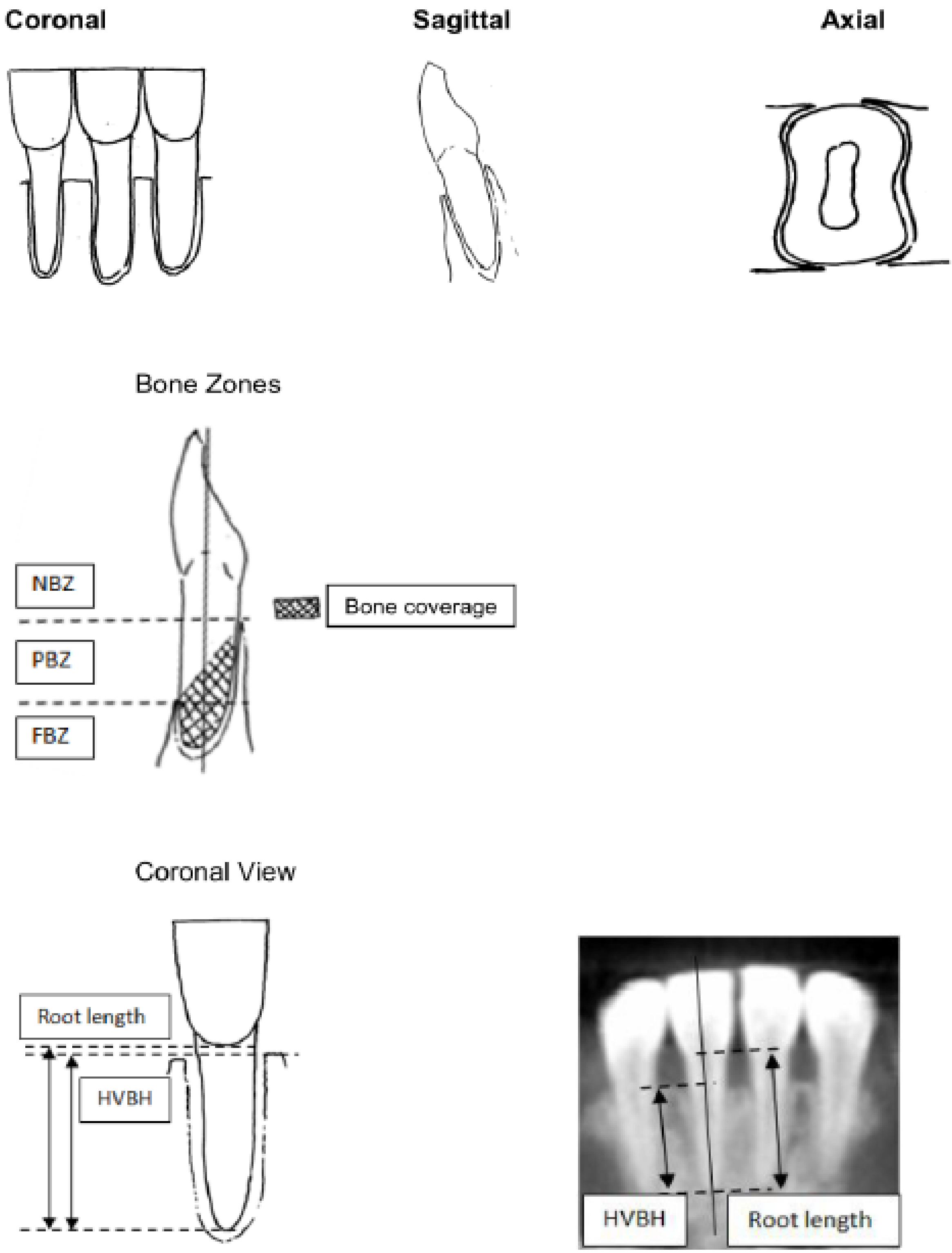
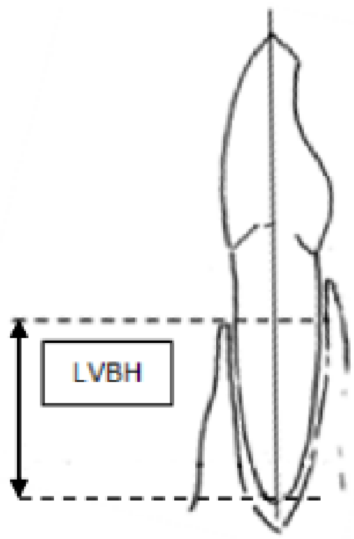


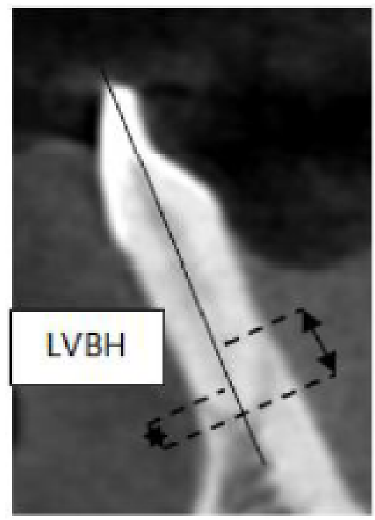
Figure 1: Key Terms Used

No Bone Zone (NBZ), Partial Bone Zone (PBZ), Full Bone Zone (FBZ), Highest Vertical Bone Height (HVBH), Lowest Vertical Bone Height (LVBH), Bone Coverage Area (BCA), Root Partial Bone Zone (rPBZ), Axial Radicular Bone Coverage (ARBC), and Total Root Bone Coverage (TRBC).

% Bone Coverage Area (BCA) = $\frac{\text{HVBH}}{\text{Root length}}$ x 100%
% No bone zone (NBZ) = 100% – % Bone Coverage Area (BCA)

Sagittal View



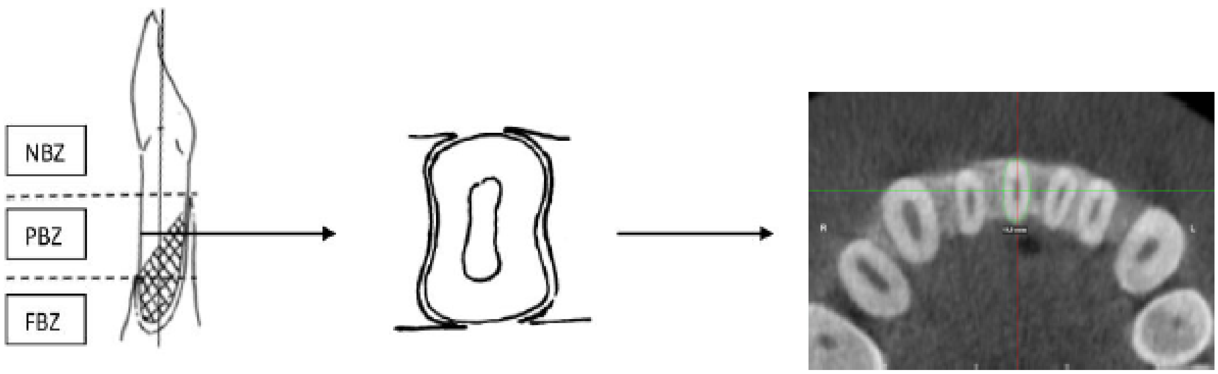


Calculating FBZ and rPBZ

% Full Bone Zone = $\frac{\text{LVBH}}{\text{Root length}}$ x 100%
% root of PBZ (rPBZ) = 100% – (% NBZ + % FBZ)

Figure 2: Equations

Axial Slice at Midpoint of PBZ



Calculating ARBC

$$\%\text{ Axial Radicular Bone Coverage} = \frac{(\text{Root Perimeter} - \text{Defect Perimeter})}{\text{Root Perimeter}} \times 100\%$$

Calculating PBZ

$$\%\text{ Partial bone zone (PBZ)} = \frac{\text{rPBZ}}{100} \times \frac{\text{ARBC}}{100} \times 100$$

Calculating TRBC

$$\%\text{ Total root bone coverage (TRBC)} = \%\text{PBZ} + \%\text{FBZ}$$

Figure 3: Modification to methodology

We proposed a modification (highlighted in red) to Miller's original method in calculating the % Axial radicular bone coverage. Using the ability of Dolphin Imaging to draw a 2D path around an object, we traced the root perimeter (RP) to obtain a mm measurement and then, using the same function, measured the perimeter of the boney defect (whether buccal, lingual, or both) and then calculated what percent of the whole root perimeter at that axial slice was covered by bone by subtracting the perimeter of the defect from the total perimeter and dividing that by the total perimeter and multiplying by 100.

CBCT Imaging

Each patient had a 17x11 cm CBCT scan as part of his or her beginning and final records on a Carestream 9300 Cone Beam machine which was later rendered in Dolphin Imaging, version 11.7, software. All CBCT measurements were acquired using Dolphin Imaging software.

The settings used to image the subjects were a voxel size of 0.25 mm. Leung explained that using a voxel size of 0.38 mm at 2 mA, CBCT alveolar bone height can be measured to an accuracy of about 0.6 mm, and root fenestrations can be identified with greater accuracy than dehiscences [26].

Measurement Software:

Dolphin Imaging (version 11.7) software was used for measurement acquisition. One feature that was particularly helpful was the 2D path measurement tool which allowed us to measure the perimeter of the tooth root and defect perimeter in a specified axial slice.

Standardized Orientation Protocol:

In order to obtain the needed measurements and decrease variability, a standardized orientation protocol was employed. The setting for each plane (sagittal, coronal, and axial) was set to 2mm. This was found by the observers to display the clearest images on the computers being used with the DICOMs that were being imaged. The observer would scroll through the axial slices until the tooth of interest was located and then place the crosshatch markers on that tooth. In the sagittal slice, the long axis of the tooth was then oriented vertically (using the green coronal slice line as a reference) [26, 27]. An approximation of the vertical mid-way point through the partial bone zone was obtained and the observers scrolled through the axial slices to orient the axial slice at this level. The axial slice was then rotated so as to orient the buccal and lingual cortical plates around the tooth of interest so that they were positioned at the vertical most part of the dental arch in the imaging software (if there was a difference between the two then preference was given to where the dehiscence/fenestration was = buccal or lingual). The long axis of the tooth was then oriented vertically in the coronal slice (using the red sagittal slice line as a reference). Any minor adjustments were then made as needed to ensure proper orientation in all 3 planes of space (Figure 4). An additional step was performed

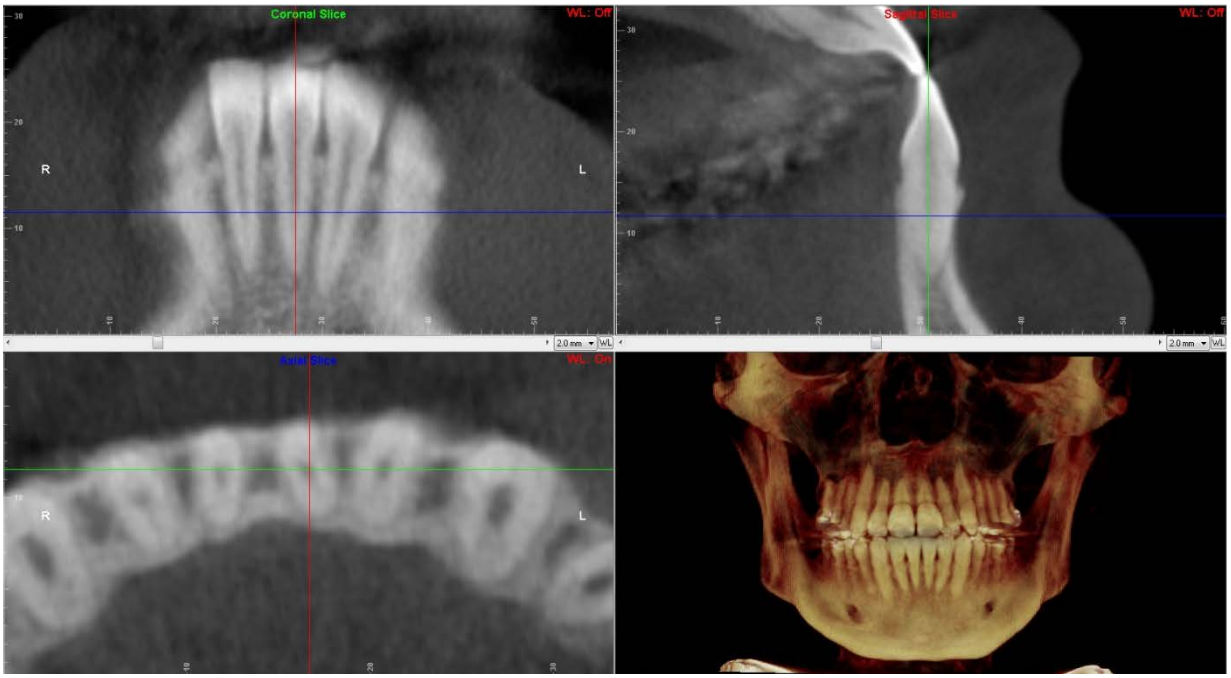


Figure 4: Standardized Orientation for LL1

if the tooth of interest was significantly rotated (past 45 degrees): ensured that the sagittal slice intersected midway between buccal and lingual of tooth and obtained the root length measurement. Once root length had been measured then the image was re-oriented to the standardized orientation). This was done in an effort to avoid an increased root length measurement if the tooth was rotated 90 degrees as the CEJ is located more coronal on the mesial and distal surfaces of the tooth and more apically on the buccal and lingual surfaces of the tooth. After this standardized orientation the methods proceeded as outlined in Figure 5.

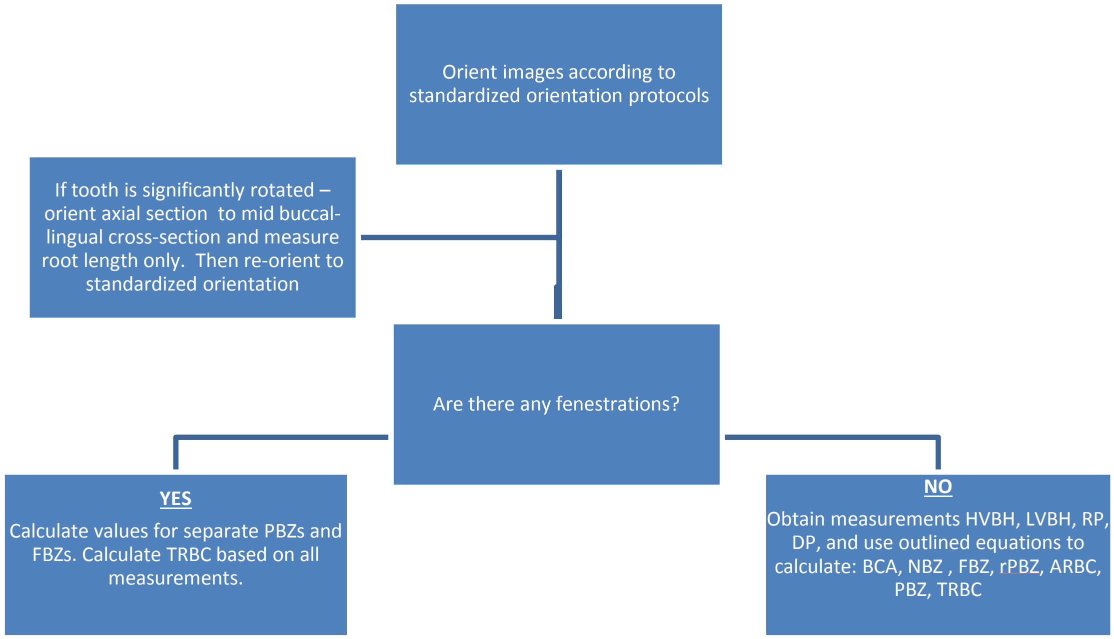


Figure 5 – Methods Flowchart

Measurement Protocol:

The blue axial slice line was positioned at the root apex of the tooth of interest in both the sagital and coronal slices and the 2D line feature of Dolphin Imaging was used to draw a reference line parallel to this line in both the sagittal and coronal slices (Figure 6).

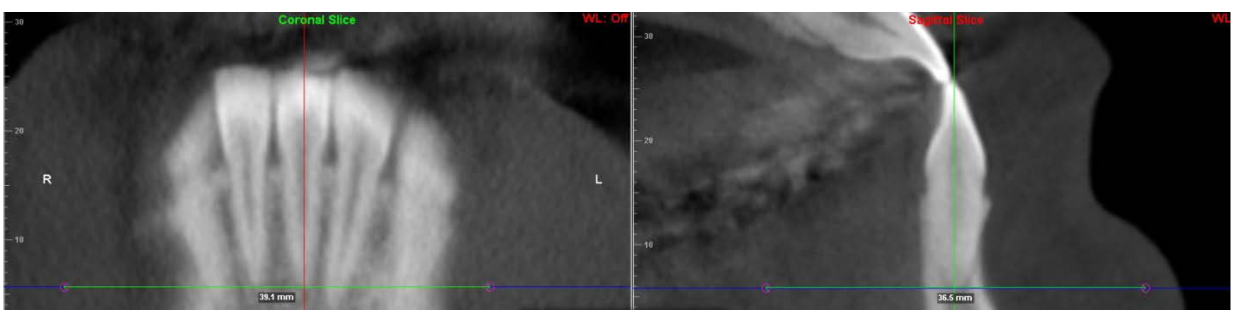


Figure 6: Reference line positioned at apex in sagittal and coronal slices

In the sagittal slice, a reference line was drawn to connect the buccal and lingual CEJ. Root length was measured from the reference line at the apex of the root to midway through the CEJ reference line in the coronal slice [2, 27]. Highest vertical bone height (HVBH in mm) was measured in the coronal (Figure 7).

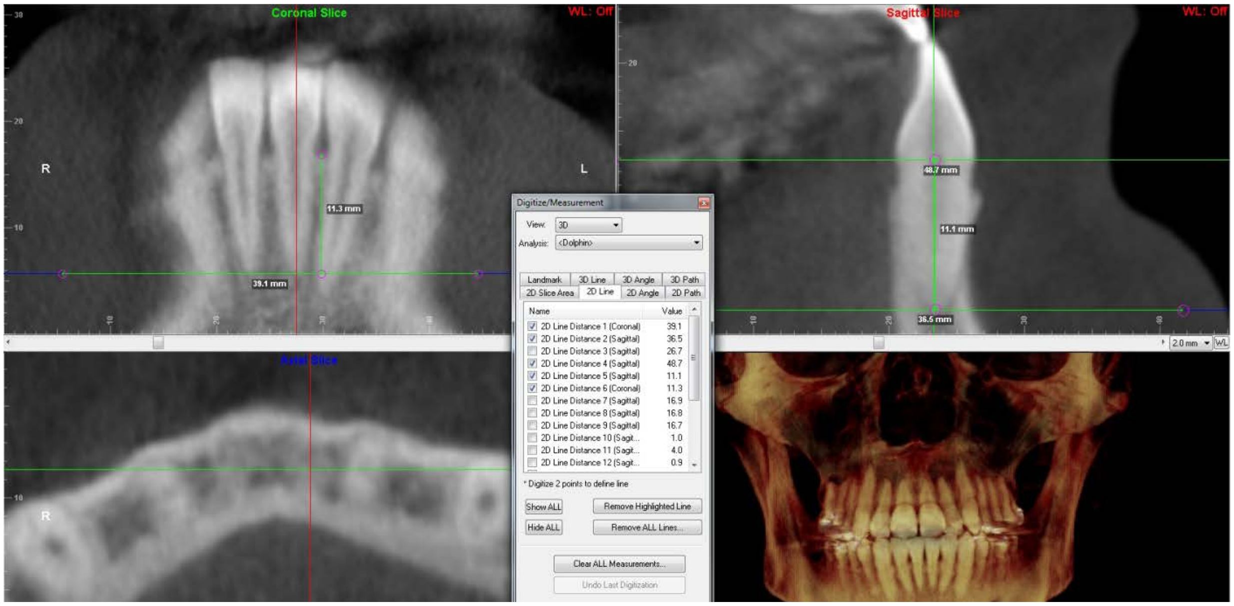


Figure 7: CEJ marked and root length measured in sagittal. HVBH measured in coronal.

Dehiscences and fenestrations were identified on the buccal or lingual surfaces of the root in the sagittal slice by scrolling through the axial slices to determine the level at which the bone was no longer visualized. Dehiscence was defined in this study as the level of bone being a distance ≥ 3mm from the CEJ [7, 28, 29]. If a tooth was found to have a fenestration, a separate fenestration protocol was followed to calculate TRBC. Each zone (FBZ, PBZ, NBZ) was isolated (Figure 8).

The observer then proceeded to the outlined measurements/calculations (including those for the bone zones)

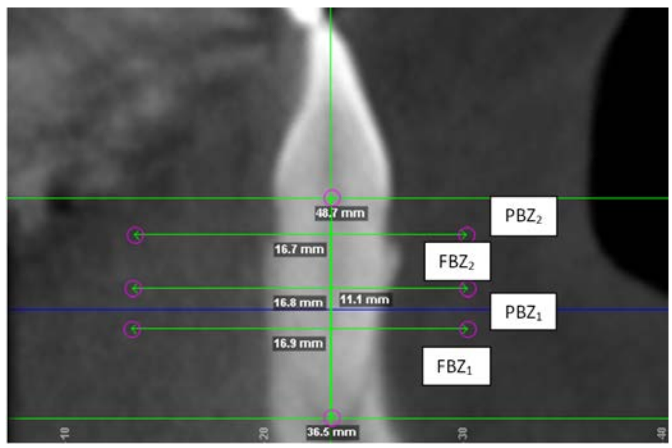


Figure 8: Bone zones isolated

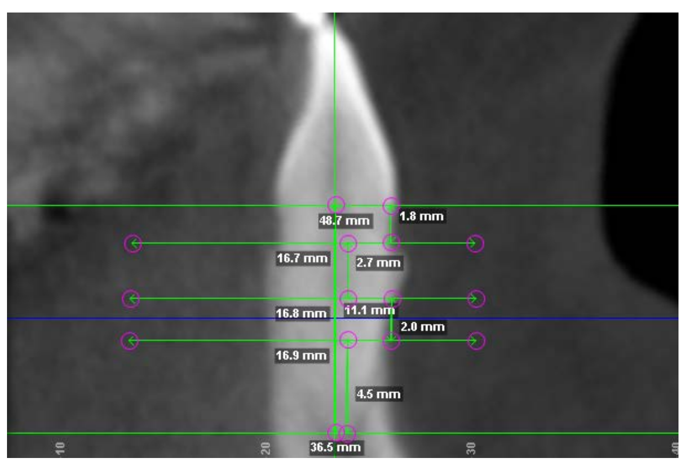


Figure 9: Zones measured in sagittal view

using 2D line tool in the measurement tool bar (Figure 9).

The exact halfway point through the PBZ was calculated and the axial slice was oriented to this level for root perimeter and defect perimeter measurements. Using the 2D path function in the measurement tool bar, Root Perimeter (mm) was measured at the axial level which was halfway through PBZ (HVBH-LVBH)/2 (Figure 10). Defect Perimeter (mm) was measured at same axial level as RP using the 2D path function (Figure 11). The observer then calculated: BCA (%) NBZ (%) FBZ (%) rPBZ (%) ARBC (%) PBZ (%) TRBC (%) using equations (Figures 2-3).

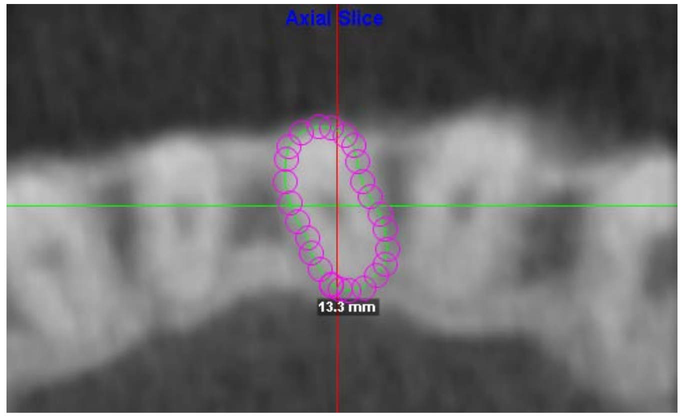


Figure 10: Root perimeter measured in axial slice

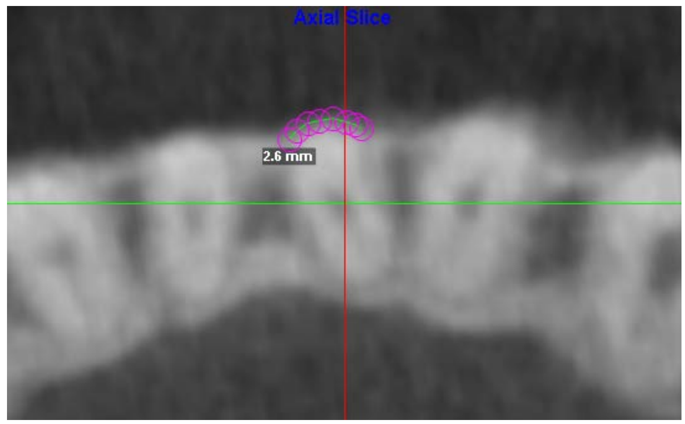


Figure 11: Defect perimeter measured in axial slice

Fenestration Protocol:

The same basic concepts described in the equations given by Miller were used to obtain measurements and calculations on teeth with fenestrations, with some modifications. For the %FBZ measurement, there is typically more than 1 FBZ for a tooth with a fenestration and so the equation as outlined by Miller (using the LVBH) would only describe the FBZ closest to the root's apex (Figure 7). Thus any other %FBZ was calculated and this value was added to the first %FBZ in order to fully describe the area of the root fully covered by bone.

There is also often more than 1 PBZ associated with a tooth with a fenestration. In order to ensure that the different PBZs were represented appropriately, in cases where there was more than one partial bone zone found (and the other PBZ was found to be greater than 0.5mm), each PBZ was treated separately (separate measurements/calculations for rPBZ, RP, DP, ARBC, and PBZ were obtained) and then these final PBZ values were added together (along with the FBZ) to determine the TRBC.

RESULTS

There were varied results with the inter-rater and intra-rater reliability testing as it was determined that a larger number of subjects would be needed to better support the reliability of this method. Intra-agreement appeared to be good-to-excellent on root length and HVBH. Intra-agreement appeared to be fair in regards to TRBC (Tables 1-4). TRBC of the teeth decreased by an average of 10% and root length shortened an average of 0.9 mm in the course of orthodontic treatment (Tables 5-6). There were a significantly greater amount of both buccal and lingual dehiscences found after orthodontic treatment (Table 7). The number of fenestrations generally decreased with orthodontic treatment (Table 7). Due to power issues, analyses performed were not found to be significant (Tables 8-13); the confidence intervals do cross 0 (= no difference) but they dip much farther below 0 than they rise above 0; this, in conjunction with the fairly low p-values suggests insufficient power.

Table 1: Intra-agreement, Rater 1

Intra agreement, Rater 1												
Tooth	ICC*--Rater 1, LL1			ICC*--Rater 1, LL2			ICC*--Rater 1, LR1			ICC*--Rater 1, LR2		
characteristic	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**
root	0.71	(0.05, 0.999)	0.02	0.85	(0.30, 0.999)	0.003	0.52	(0.00, 1.44)	0.06	0.00	(0.00, 0.75)	0.88
hvbh	0.84	(0.28, 0.999)	0.003	0.88	(0.37, 0.999)	0.002	0.76	(0.17, 1.35)	0.01	0.10	(0.00, 0.97)	0.28
lvbh	0.05	(0.00, 0.87)	0.31	0.24	(0.00, 1.21)	0.19	0.00	(0.00, 0.75)	0.55	0.06	(0.00, 0.90)	0.30
rp1	0.21	(0.00, 1.17)	0.20	0.72	(0.07, 0.999)	0.02	0.79	(0.25, 1.32)	0.008	0.94	(0.78, 1.11)	0.0002
rp2	0.00	(0.00, 09.75)	0.35	0.33	(0.00, 1.33)	0.13	n/a			n/a		
dpi_buc	0.78	(0.22, 1.33)	0.28	0.70	(0.00, 1.40))	0.02	0.48	(0.00, 1.43)	0.07	0.00	(0.00, 0.75)	0.88
dpi_ling	0.00	(0.00, 0.75)	0.63	0.01	(0.00, 0.78)	0.35	0.45	(0.00, 1.42)	0.09	0.41	(0.00, 1.39)	0.10
dp2_buc	0.00	(0.00, 0.75)	0.36	0.00	(0.00, 0.75)	0.36	n/a			n/a		
dp2_ling	n/a			0.33	(0.00, 1.33)	0.13	n/a			n/a		
bca_pct	0.33	(0.00, 1.33)	0.14	0.25	(0.00, 1.24)	0.18	0.76	(0.18, 1.35)	0.01	0.63	(0.00, 1.43)	0.03
nbz_pct	0.33	(0.00, 1.33)	0.14	0.25	(0.00, 1.24)	0.18	0.76	(0.18, 1.35)	0.01	0.63	(0.00, 1.43)	0.03
fbz1_pct	0.05	(0.00, 0.89)	0.31	0.00	(0.00, 0.75)	0.46	0.00	(0.00, 0.75)	0.84	0.16	(0.00, 1.09)	0.23
fbz2_pct	n/a			0.32	(0.00, 1.32)	0.14	n/a			n/a		
rpbz1_pct	0.04	(0.00, 0.85)	0.32	0.05	(0.00, 0.86)	0.31	0.00	(0.00, 0.75)	0.93	0.00	(0.00, 0.75)	0.41
rpbz2_pct	0.00	(0.00, 0.75)	0.36	0.27	(0.00, 1.25)	0.17	n/a			n/a		
arbc1_pct	0.00	(0.00, 0.75)	0.50	0.31	(0.00, 1.30)	0.15	0.00	(0.00, 0.75)	0.97	0.00	(0.00, 0.75)	0.57
arbc2_pct	0.00	(0.00, 0.75)	0.36	0.32	(0.00, 1.31)	0.14	n/a			n/a		
pbz1_pct	0.6	(0.00,0.89)	0.31	0.00	(0.00, 0.75)	0.46	0.00	(0.00, 0.75)	0.77	0.00	(0.00, 0.75)	0.42
pbz2_pct	0.00	(0.00, 0.75)	0.64	0.21	(0.00, 1.18)	0.20	n/a			n/a		
trbc_pct	0.00	(0.00, 0.75)	0.53	0.00	(0.00, 0.75)	0.36	0.00	(0.00, 0.75)	0.92	0.28	(0.00, 1.27)	0.16

* ICC = intraclass correlation coefficient (i.e., how correlated are the observations within each group?)

ǂ correlation

** testing whether correlation between observations equals 0

Table 2: Intra-agreement, Rater 2

Intra agreement, Rater 2												
Tooth	ICC*--Rater 2, LL1			ICC*--Rater 2, LL2			ICC*--Rater 2, LR1			ICC*--Rater 2, LR2		
characteristic	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**	rǂ	95% CI	P-value**
root	0.90	(0.61, 1.18)	0.001	0.88	(0.54, 1.21)	0.002	0.41	(0.00, 1.40)	0.10	0.00	(0.00, 0.75)	0.76
hvbh	0.92	(0.71, 1.14)	0.004	0.94	(0.78, 1.10)	0.0002	0.63	(0.00, 1.43)	0.03	0.00	(0.00, 0.75)	0.40
lvbh	0.49	(0.00, 1.43)	0.07	0.43	(0.00, 1.41)	0.09	0.00	(0.00, 0.75)	0.89	0.00	(0.00, 0.75)	0.76
rp1	0.79	(0.26, 1.32)	0.01	0.80	(0.28, 1.31)	0.007	0.96	(.83, 1.08)	0.0001	0.62	(0.00, 1.43)	0.03
rp2	0.33	(0.00, 1.33)	0.13	0.00	(0.00, 0.75)	0.91	n/a			n/a		
dpi_buc	0.95	(0.81, 1.09)	0.0001	0.56	(0.00, 1.44)	0.05	0.32	(0.00, 1.32)	0.14	0.33	(0.00, 1.33)	0.13
dpi_ling	0.00	(0.00, 0.75)	0.92	0.00	(0.00, 0.75)	0.79	0.00	(0.00, 0.75)	0.50	0.00	(0.00, 0.75)	0.37
dp2_buc	0.30	(0.00, 1.30)	0.15	0.00	(0.00, 0.75)	0.77	n/a			n/a		
dp2_ling	0.00	(0.00, 0.75)	0.36	0.00	(0.00, 0.75)	0.86	n/a			n/a		
bca_pct	0.79	(0.27, 1.32)	0.01	0.28	(0.00, 1.27)	0.16	0.00	(0.00, 0.75)	0.99	0.24	(0.00, 1.22)	0.18
nbz_pct	0.79	(0.27, 1.32)	0.01	0.28	(0.00, 1.27)	0.16	0.00	(0.00, 0.75)	0.99	0.24	(0.00, 1.23)	0.18
fbz1_pct	0.68	(0.00, 1.41)	0.02	0.00	(0.00, 0.75)	0.93	0.00	(0.00, 0.75)	0.92	0.00	(0.00, 0.75)	0.60
fbz2_pct	0.27	(0.00, 1.25)	0.17	0.00	(0.00, 0.75)	0.74	n/a			n/a		
rpbz1_pct	0.00	(0.00, 0.75)	0.38	0.00	(0.00, 0.75)	0.89	0.00	(0.00, 0.75)	0.92	0.00	(0.00, 0.75)	0.86
rpbz2_pct	0.10	(0.00, 0.98)	0.27	0.00	(0.00, 0.75)	0.63	n/a			n/a		
arbc1_pct	0.75	(0.14, 1.36)	0.01	0.29	(0.00, 1.28)	0.16	0.00	(0.00, 0.75)	0.41	0.40	(0.00, 1.38)	0.11
arbc2_pct	0.33	(0.00, 1.33)	0.14	0.00	(0.00, 0.75)	0.93	n/a			n/a		
pbz1_pct	0.00	(0.00, 0.75)	0.66	0.00	(0.00, 0.75)	0.84	0.00	(0.00, 0.75)	0.86	0.00	(0.00, 0.75)	0.77
pbz2_pct	0.09	(0.00, 0.95)	0.28	0.00	(0.00, 0.75)	0.45	n/a			n/a		
trbc_pct	0.60	(0.00, 1.44)	0.04	0.00	(0.00, 0.75)	0.84	0.00	(0.00, 0.75)	0.5	0.49	(0.00, 1.43)	0.07

* ICC = intraclass correlation coefficient (i.e., how correlated are the observations within each group?)

ǂ correlation

** testing whether correlation between observations equals 0

Table 3: Inter-rater agreement

Inter-rater agreement												
Tooth	ICC*--Interrater, LL1			ICC*--Interrater, LL2			ICC*--Interrater, LR1			ICC*--Interrater, LR2		
characteristic	r‡	95% CI	P-value**	r	95% CI	P-value	r	95% CI	P-value	r	95% CI	P-value
root				0.98	(0.10, 0.999)	0.09	0.94	(0.02, 0.999)	0.01	0.52	(-0.29, 0.999)	0.26
hvbh				0.98	(-2.57, 0.999)	0.10	0.97	(2.11, 0.999)	0.15	0.94	(3.66, 0.999)	0.19
lvbh				0.999	(0.97, 0.999)	0.01	0.54	(-2.91, 0.,999)	0.36	0.60	(-2.59, 0.999)	0.34
rp1				0.99	(-0.94, 0.999)	0.07	0.97	(0.05, 0.999)	0.01	0.995	(0.26, 0.999)	<0.0001
rp2				-0.62	(6.51, 0.998)	0.56	n/a			n/a		
dpi_buc				0.97	(0.003, 0.999)	0.10	0.95	(-0.07, 0.999)	0.05	0.32	(-1.36, 0.999)	0.41
dpi_ling	N/A: Rater 2 rated an insufficient number of LL1 teeth.			0.31	(-0.35, 0.998)	0.35	0.51	(-1.35, 0.999)	0.35	0.89	(-0.12, 0.999)	0.08
dp2_buc				-0.89	(-1.30, 0.73)	0.75	n/a			n/a		
dp2_ling				-4.07	(2.00, 0.998)	0.58	n/a			n/a		
bca_pct				0.90	(-3.09, 0.999)	0.20	-0.02	(3.01, 0.999	0.5	0.93	(22.8, 0.999)	0.18
nbz_pct				0.90	(-3.09, 0.999)	0.20	-0.02	(3.01, 0.999)	0.50	0.93	(43.5, 0.999)	0.18
fbz1_pct				0.22	(-1.00, 0.998)	0.43	-0.47	(-0.58, 0.05)	0.78	0.74	(-2.90, 0.999)	0.28
fbz2_pct				0.65	(-1.54, 0.999)	0.3	n/a			n/a		
rpbz1_pct				0.40	(-14.3, 0.999)	0.42	-0.17	(--, -0.17)	0.96	0.58	(-9.65, 0.999)	0.36
rpbz2_pct				6.09	(3.63, 0.95)	0.78	n/a			n/a		
arbc1_pct				0.96	(-0.16, 0.999)	0.10	-0.69	(2.21, 0.999)	0.54	2.7	(--, 2.68)	0.95
arbc2_pct				0.24	(-13.2, 0.998)	0.46	n/a			n/a		
pbz1_pct				-3.03	(8.49, 0.99)	0.67	0.41	(-0.02, 0.999)	0.10	0.89	(205.5, 0.999)	0.22
pbz2_pct				2.38	(2.30, -2.82)	0.90	n/a			n/a		
trbc_pct				0.83	(10.4, 0.999)	0.27	-3.31	(3.69, 0.996)	0.63	0.57	(-1.82, 0.999)	0.34

Table 4: Inter-class correlation coefficient for TRBC

Tooth characteristic	r‡	95% CI	P-value**
Average trbc_pct across all teeth:	0.55	(-4.47, 0.999)	0.21

rater	target	tooth	rater	target	tooth
1	1	LL1	2	1	LL1
1	1	LL2	2	1	LL2
1	1	LR1	2	1	LR1
1	1	LR2	2	1	LR2
1	2	LL1	2	2	LL1
1	2	LL2	2	2	LL2
1	2	LR1	2	2	LR1
1	2	LR2	2	2	LR2
1	3	LL1	2	3	LL1
1	3	LL2	2	3	LL2
1	3	LR1	2	3	LR1
1	3	LR2	2	3	LR2

Red indicates that this tooth was not rated by rater; target 2 is the only subject with all four teeth rated by both raters

Table 5: Average Changes Pre-Intervention to Post-Intervention

	LL1		LL2		LR1		LR2	
Tooth	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Root length	-0.70	(0.93)	-0.96	(0.71)	-0.96	(0.88)	-0.84	(1.21)
HVBH	-0.76	(0.97)	-1.10	(0.89)	-1.08	(0.98)	-0.98	(1.11)
LVBH	-3.32	(1.98)	-2.11	(2.71)	-3.45	(2.86)	-4.53	(4.90)
RP1	-0.50	(1.64)	-0.16	(0.85)	-0.46	(0.81)	-0.28	(1.13)
RP2	-1.33	(6.59)	-7.26	(9.65)	-0.66	(5.92)	-1.84	(7.62)
DP1 Buccal	-0.26	(1.39)	-0.26	(1.28)	-0.10	(1.61)	0.62	(1.64)
DP2 Buccal	-0.24	(1.36)	-1.11	(1.84)	-0.01	(0.90)	-0.10	(1.54)
DP1 Lingual	0.95	(1.54)	0.26	(2.43)	0.80	(1.77)	-0.58	(2.26)
DP2 Lingual	-0.22	(1.31)	-0.57	(1.76)	-0.09	(1.30)	-0.21	(1.45)
BCA (%)	-0.81	(3.41)	-1.37	(3.93)	-1.23	(4.12)	-1.37	(3.37)
NBZ (%)	0.82	(3.41)	1.31	(3.94)	1.23	(4.12)	1.37	(3.37)
FBZ1 (%)	-26.6	(19.2)	-7.87	(22.8)	-27.0	(25.9)	-25.9	(22.1)
FBZ2 (%)	-2.51	(5.97)	-12.10	(17.7)	-1.99	(10.0)	-2.25	(11.7)
RPBZ1 (%)	30.2	(24.6)	29.6	(23.6)	29.3	(29.3)	28.8	(24.2)
RPBZ2 (%)	-1.80	(8.38)	-10.90	(13.2)	-1.76	(10.3)	-2.17	(10.4)
ARBC1 (%)	-3.32	(11.4)	-0.70	(15.0)	-5.55	(11.1)	-0.61	(11.4)
ARBC2 (%)	-5.96	(26.6)	-36.3	(42.7)	-4.85	(30.3)	-9.29	(32.1)
PBZ1 (%)	19.8	(19.6)	19.8	(18.9)	18.4	(22.1)	19.9	(17.7)
PBZ2 (%)	-1.32	(5.13)	-8.17	(9.72)	-1.45	(7.67)	-1.47	(7.43)
TRBC (%)	-10.5	(8.40)	-8.40	(12.2)	-12.0	(10.2)	-9.78	(6.65)

Table 6: Mean Change in TRBC and Root Length

```
. mean trbc

Mean estimation                   Number of obs    =          4

--------------------------------------------------------------
             |       Mean   Std. Err.     [95% Conf. Interval]
-------------+------------------------------------------------
        trbc |     -10.17       .7496     -12.55556   -7.784438
--------------------------------------------------------------

. mean root

Mean estimation                   Number of obs    =          4

--------------------------------------------------------------
             |       Mean   Std. Err.     [95% Conf. Interval]
-------------+------------------------------------------------
        root |      -.865    .0618466     -1.061823   -.6681766
--------------------------------------------------------------


Average change in trbc is 10% decrease (95% CI, 12.5 to 7.8% decrease).
Average change in root is .9% decrease (95% CI, 1.1% to 0.7% decrease).
```

Table 7: Dehiscence and Fenestration Changes Pre- to Post Intervention

	LL1				LL2				LR1				LR2			
Tooth	Positive	Negative	Zero	P-value*	Positive	Negative	Zero	P-value*	Positive	Negative	Zero	P-value*	Positive	Negative	Zero	P-value*
Dilac				**				**				**				**
Buccal dehiscenceǂ	9	0	10	0.003	10	0	8	0.002	7	2	8	0.07	10	0	8	0.002
Lingual dehiscenceǂ	9	0	10	0.003	8	1	9	0.02	9	1	7	0.01	6	0	12	0.01
Buccal fenestrationǂ	1	5	13	0.08	0	10	8	0.002	2	2	13	1.00	3	4	11	0.63
Lingual fenestrationǂ	1	0	18	0.32	1	0	17	0.32	1	0	16	0.32	0	1	17	0.32

* Wilcoxon signed rank test

** No changes

Table 8: Crowding as a Predictor of Change in TRBC

```
      Source |       SS           df       MS      Number of obs   =        20
-------------+----------------------------------   F(2, 17)        =      1.29
       Model |  120.436913         2  60.2184564   Prob > F        =    0.3005
    Residual |  792.669677        17  46.6276281   R-squared       =    0.1319
-------------+----------------------------------   Adj R-squared   =    0.0298
       Total |   913.10659        19  48.0582416   Root MSE        =    6.8284

------------------------------------------------------------------------------
   trbc_delt |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       crowd |
          2  |  -4.554051   3.318027    -1.37   0.188    -11.55448    2.446373
          3  |   1.432407   4.552295     0.31   0.757    -8.172096    11.03691
             |
       _cons |  -8.453241   2.276148    -3.71   0.002    -13.25549   -3.650989
------------------------------------------------------------------------------
```

1. Interpretation:

Compared to those with level 1 crowding, change in trbc is 4.55% lower in those with level 2 crowding (not significant, but could be a power issue.)

Compared to those with level 1 crowding, change in trbc is 1.43% higher in those with level 3 crowding (not significant).

Entire model is not significant (Prob>F = 0.3005).

Crowding explains 13.19% of change in trbc (R-squared).

Table 9: Extraction as a Predictor of Change in TRBC

Source	SS	df	MS
Model	108.50035	1	108.50035
Residual	804.606239	18	44.7003466
Total	913.10659	19	48.0582416

Number of obs	=	20
F(1, 18)	=	2.43
Prob > F	=	0.1366
R-squared	=	0.1188
Adj R-squared	=	0.0699
Root MSE	=	6.6858

trbc_delt	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
extraction	-4.658333	2.989995	-1.56	0.137	-10.94008	1.623413
_cons	-7.730833	2.114246	-3.66	0.002	-12.1727	-3.288968

Interpretation:

Compared to those **without extraction**, change in trbc is 4.65% lower in those with extraction (not significant, p=0.137)).

The model is not significant (Prob>F = 0.1366).

Extraction explains 11.9% of change in trbc (R-squared).

Table 10: Extraction and Crowding as Predictors of Change in TRBC

Source	SS	df	MS
Model	203.765595	3	67.9218649
Residual	709.340995	16	44.3338122
Total	913.10659	19	48.0582416

Number of obs	=	20
F(3, 16)	=	1.53
Prob > F	=	0.2446
R-squared	=	0.2232
Adj R-squared	=	0.0775
Root MSE	=	6.6584

trbc_delt	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
extraction	-4.28341	3.124352	-1.37	0.189	-10.90674	2.33992
crowd						
2	-3.304723	3.361267	-0.98	0.340	-10.43029	3.820845
3	2.860211	4.559445	0.63	0.539	-6.80538	12.5258
_cons	-7.025437	2.451652	-2.87	0.011	-12.22271	-1.828167

Interpretation:

The coefficients for crowding don't change direction. Extraction is slightly attenuated and less significant.

Model is not significant (Prob>F=0.2446).

Together these two explain 22.32% of change in trbc.

Table 11: Extraction and Crowding as Predictors of Change in TRBC with an Interaction Term Included in the Model

```
      Source |       SS           df       MS      Number of obs   =        20
-------------+----------------------------------   F(5, 14)        =      1.33
       Model |  293.371555         5  58.674311   Prob > F        =    0.3095
    Residual |  619.735034        14  44.2667882   R-squared       =    0.3213
-------------+----------------------------------   Adj R-squared   =    0.0789
       Total |   913.10659        19  48.0582416   Root MSE        =    6.6533

------------------------------------------------------------------------------
       trbc_delt |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-----------------+------------------------------------------------------------
    1.extraction |  -.5472222   4.704614    -0.12   0.909    -10.63762    9.543172
                 |
           crowd |
              2  |   1.251389   4.704614     0.27   0.794    -8.839005    11.34178
              3  |   1.645833   7.186417     0.23   0.822     -13.7675    17.05916
                 |
extraction#crowd |
            1 2  |  -9.033333   6.763309    -1.34   0.203    -23.53919    5.472522
            1 3  |  -.0465278   9.409228    -0.00   0.996    -20.22732    20.13426
                 |
           _cons |  -8.270833    2.71621    -3.04   0.009    -14.09652   -2.445142
------------------------------------------------------------------------------
```

Interpretation:

With only 20 observations, there really isn't enough power to see an interaction (and model is even less significant, Prob>F=0.3095), although it appears that level 2 crowding has a larger change when there is extraction

Table 12: Analyses of Crowding Stratified by Extraction

```
. regress trbc_delt i.crowd if extraction==0

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(2, 7)         =      0.05
       Model |  4.49068939         2  2.24534469   Prob > F        =    0.9542
    Residual |  332.851534         7  47.5502191   R-squared       =    0.0133
-------------+----------------------------------   Adj R-squared   =   -0.2686
       Total |  337.342223         9  37.4824692   Root MSE        =    6.8957

------------------------------------------------------------------------------
   trbc_delt |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       crowd |
          2  |   1.251389   4.875973     0.26   0.805    -10.27845    12.78123
          3  |   1.645833   7.448171     0.22   0.831    -15.96629    19.25796
             |
       _cons |  -8.270833   2.815144    -2.94   0.022    -14.92759   -1.614075
------------------------------------------------------------------------------

. regress trbc_delt i.crowd if extraction==1

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(2, 7)         =      2.20
       Model |  180.380516         2  90.1902578   Prob > F        =    0.1813
    Residual |  286.883501         7  40.9833572   R-squared       =    0.3860
-------------+----------------------------------   Adj R-squared   =    0.2106
       Total |  467.264016         9   51.918224   Root MSE        =    6.4018

------------------------------------------------------------------------------
   trbc_delt |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       crowd |
          2  |  -7.781945   4.675232    -1.66   0.140    -18.83711    3.273221
          3  |   1.599306    5.84404     0.27   0.792    -12.21965    15.41826
             |
       _cons |  -8.818056   3.696095    -2.39   0.048    -17.55793   -.0781794
------------------------------------------------------------------------------
```

Interpretation:

It looks like crowding level 2 has more of an effect in those who had extraction. The model is much closer to significance in the extraction group than in the non-extraction group, where level of crowding is pretty much identical for levels 2 and 3 when each are compared to level 1.

Table 13: Average Change in TRBC for Each Different Combination of Crowding and Extraction

crowd_ext	N	mean	sd	p25	p50	p75	min	max
0	6	-8.270833	7.556312	-8.3	-7.9	-2.2	-22.275	-1.05
1	3	-7.019445	4.866327	-12.53333	-5.2	-3.325	-12.53333	-3.325
2	1	-6.625	.	-6.625	-6.625	-6.625	-6.625	-6.625
3	3	-8.818056	5.255428	-12.2375	-11.45	-2.766667	-12.2375	-2.766667
4	5	-16.6	7.560981	-21	-20.375	-11.25	-24.2	-6.175
5	2	-7.21875	1.723573	-8.4375	-7.21875	-6	-8.4375	-6
Total	20	-10.06	6.932405	-12.38542	-8.2125	-5.6	-24.2	-1.05

0: crowding=1/extraction=0
1: crowding=2/extraction=0
2: crowding=3/extraction=0
3: crowding=1/extraction=1
4: crowding=2/extraction=1
5: crowding=3/extraction=1

Interpretation:

Biggest impact appears to be when crowding=2 and extraction=1.

But these are really small numbers (see below)! An ANOVA on these is not significant (Prob.F=0.3653).

```
. tab crowd extraction

           |      extraction
     crowd |         0          1 |     Total
-----------+----------------------+----------
         1 |         6          3 |         9
         2 |         3          5 |         8
         3 |         1          2 |         3
-----------+----------------------+----------
     Total |        10         10 |        20
```

```
. oneway trbc_delt crowd_ext

                        Analysis of Variance
    Source              SS         df      MS            F     Prob > F
------------------------------------------------------------------------
Between groups      293.371555      5   58.674311      1.33     0.3095
 Within groups      619.735034     14   44.2667882
------------------------------------------------------------------------
    Total            913.10659     19   48.0582416

Bartlett's test for equal variances:  chi2(4) =   2.1701  Prob>chi2 = 0.705

note: Bartlett's test performed on cells with positive variance:
      1 single-observation cells not used
```

DISCUSSION

The resolution of our images was a factor in the reliability of the measurements obtained, especially in regards to the reliability testing. As measurements were obtained on the subjects that were randomly chosen for the reliability testing, it became apparent that the images of these subjects were not the clearest from our sample. However, in an effort to be unbiased, we proceeded with those subjects. Reliability testing was performed at the same time as our final data analysis and had we understood earlier on that the reliability wasn't fully supported, we would have focused the reliability arm of our study on a larger number of subjects to better determine the reliability of the method. It has been reported that the 2 most common voxel sizes used in orthodontics—0.3 and 0.4 mm—provide lower spatial resolution than smaller voxel sizes and should be used with caution if the goal is to assess small variations in bone thickness. A smaller voxel size would be more appropriate for these studies and would also decrease the influence of partial volume averaging [30].

In 2010, Molen et al cautioned researchers to include specific information when reporting on a CBCT study. They pointed out that, "Cone-beam computed tomography (CBCT) has become a popular modality in research, but it can be misused and misunderstood. Several image quality, bone biology, and statistical factors must be considered before designing CBCT studies or interpreting their results. Studies making small measurements, such as changes in buccal bone thickness, are especially susceptible to these factors. The spatial resolution as determined by a line pair phantom, the CBCT settings used, and a statistical power analysis should be reported in studies that investigate small bony changes. Protocols should therefore be established and followed to minimize the misinterpretation of results and improve the quality of research in this field" [30].

Nahm et al further pointed out that, "Even though high resolution CBCT images were used, exact absolute quantitative measurements may differ slightly from in vivo anatomical bone conditions. In addition, in living patients with scan times of 17 s, the reconstruction process assumes that the patient does not move more than the size of one voxel over the entire scan time. Obviously, pure logical considerations strongly contradict this assumption. Hence, true optical resolution is around one to two line pairs per millimeter owing to patients' motion artefact" [31].

CBCT is an appropriate tool for linear measurements. The presence of soft tissue as well as different voxel size affect the precision of these measurements. Patcas et al advocated for a customized resolution protocol that should be chosen according to the accuracy needed. However, even when a voxel size as small as 0.125-mm voxel was used, they were unable to detect the thin buccal alveolar bone covering reliably. There is also a risk of overestimating fenestrations and dehiscences [32].

Our findings of increased dehiscences following orthodontic treatment as well decreased TRBC is supported by Castro et al who found that the distance from the cementoenamel junction to the bone crest changed after orthodontic treatment in a non-extraction population; the distance was greater than 2 mm in 11% of the surfaces measured before treatment and in 19% after treatment [29].

There are bony limitations to tooth movement. In patients that are diagnosed to have compromised boney housing prior to orthodontic treatment, care should be taken in the treatment planning, treatment execution, and post-treatment evaluation phases to ensure that long-term outcomes for our patients are as favorable as possible. One pre-treatment technique that is found in the literature for these types of patients is that of augmented corticotomies as a method to prevent dehiscences and/or fenestrations and marginal bone loss during presurgical decompensation. This technique has shown promising outcomes [33, 34].

In regards to gingival grafting prior to orthodontic treatment, a 2014 systematic review performed by the European Journal of Orthodontists found that, "Despite the clinical experience that soft tissue augmentation of bucco-lingual gingival dimensions before orthodontic treatment may be a clinically viable treatment option in patients considered at risk, this treatment approach is not based on solid scientific evidence. Moreover, the present data do not allow to draw conclusions on the best timing of soft tissue augmentation when a change in the inclination of the incisors is planned during orthodontic treatment and thus, there is a stringent need for randomized controlled trials to clarify these open issues" [35].

Other studies highlight that if significant movement of a tooth or teeth out of the alveolar housing has occurred, those teeth can be moved back into bone with favorable outcomes including bone re-forming around the root [13, 36]. This supports the need for progress imaging of these high risk patients during treatment to ensure that proper root position in relation to the alveolar bone is achieved.

Ideas for future research

With the ability to look at structures in all 3 planes of space, future studies will be able to better describe changes in supporting alveolar bone three dimensionally. Many of the current studies using CBCT imaging focus on one sagittal cross-section through an incisor and draw many conclusions based off this two-dimensional section. Using only a sagittal slice to examine root bone coverage can significantly under-represent the amount of bone surrounding the root 3 dimensionally (e.g., does not take into consideration inter-radicular bone). Ideally we would love for software to be able to map the three dimensional surface area of the tooth's root and determine how much of it is surrounded by bone and how much is not. The method that we used in our study, although limited, was a step towards this desire. With a method to determine how much bone is covering the roots of teeth three-dimensionally, we will be able to more effectively track changes in alveolar housing over time. This will also help us better understand the limits of orthodontic tooth movement and define the procedures which can and cannot be performed in each patient individually [1].

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