Evaluation of the Bone Thickness Surrounding the Mandibular Incisors Before and After Orthodontic Treatment

by

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Submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry

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Abstract

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Objectives: To develop a reliable method to measure the thickness of bone labial and lingual to the mandibular incisors. To report the mean and range of bone thickness labial and lingual to the mandibular incisors before and after orthodontic treatment. To detect a difference in the bony support of the mandibular incisors resulting from orthodontic treatment. To highlight a relationship between the change in the thickness of bone labial and lingual to the mandibular incisors and the change in the angulation of the mandibular incisors that occurred during orthodontic treatment. Methods: The sample population consisted of 19 males and 21 females with an average age of 13.42 ± 1.75 years who completed comprehensive orthodontic treatment and whose records include both pre-treatment and post-treatment CBCT scans.

Using OnDemand 3D Software (Accurex, Cybermed Inc - Seoul, Korea) the CBCT scans were oriented along the long axis of each mandibular incisor in all three planes and axial scans were constructed at positions corresponding to 1/3 and 2/3 of the root length. A visual evaluation in conjunction with a graphical Hounsfield density display permitted the assessment of bony thickness labial and lingual to each tooth. Cephalograms constructed from each CBCT scan (Dolphin Imaging, Patterson Companies Inc - St. Paul, Minn.) permitted the evaluation of the angulation of the lower central incisor relative to the mandibular plane (IMPA) as well as the generation of regional superimpositions on the mandible. Results: The method was found to be highly reliable in all sites with the exception of the facial surface, 1/3 root level. Statistically significant changes in bony thickness were noted at multiple sites. No correlation was found to exist between the final IMPA or change in IMPA and the change in bony thickness surrounding the incisors. Conclusions: Changes in bony thickness included the general trend of minimal gains on the facial surface and minimal losses on the lingual. However, these changes were extremely small and were not considered to be

clinically significant. There appears to be no association between bony thickness and incisor inclination. These findings may influence treatment planning or mechanics employed in future orthodontic cases.

LITERATURE REVIEW

Orthodontists have always paid particular attention to the mandibular incisors, especially since the birth of cephalometrics. Many feel that the positioning of these teeth is the single most important aspect of orthodontic treatment planning. Furthermore, the final positioning and inclination of the lower incisors has long been considered a major contributor to the stability (or lack thereof) of orthodontic results. However, there are few issues in orthodontics that are as controversial as the "ideal" position and inclination of the lower incisors.

Edward Angle believed that the proper inter-digitation of the dentition would stimulate growth of the basal bone structures. He thus paid little attention to the final inclination of the mandibular incisors, as he assumed normal function would induce compensatory growth of the basal bone. As a result, Angle was steadfast in his philosophy of non-extraction orthodontics.

Charles Tweed, on the other hand, became the predominant proponent of orthodontic extractions after he

noticed that many of his non-extraction cases had results he determined to be of poor esthetics. In fact, he noted "those patients with facial harmony had mandibular incisors that were upright over the basal bone, while those without facial balance had proclined incisors…it was noted that the lack of harmony in facial contour was in direct proportion to the extent to which the denture had been displaced mesially into protrusion."

Tweed's impact on the orthodontic community was enormous, and for the next several decades the initial and final inclination of the mandibular incisors was the primary factor in orthodontic treatment planning for many orthodontists. This trend continues even today as many orthodontists feel that "positioning the incisors upright in the basal bone improves the support around the root of each incisor and also leads to better periodontal conditions" (Sarikaya et al, 2002).

An orthodontist must have a thorough understanding of how the periodontium is affected upon proclination of the mandibular incisors. However this subject remains controversial. A review of the literature will demonstrate that while some authors claim that

orthodontic therapy may lead to deleterious periodontal effects, others have found no association between orthodontic tooth movement and gingival recession or attachment loss.

Artun and Krogstad (1987) examined the periodontal status of mandibular incisors that were excessively proclined during the pre-surgical phase of orthodontic treatment in those patients being treated for mandibular prognathism. Excessive proclination was defined as an increase in more than 10 degrees of the IMPA. The study sample was comprised of 21 patients with excessive proclination and 19 patients with minimal changes in the inclination of the lower incisors. Examinations performed included the Visible Plaque Index, Gingival Bleeding Index, probing pocket depth and length of supracrestal connective tissue. Clinical crown height was measured on models taken before and after orthodontic therapy, 3 years post-operatively and at a follow-up examination.

Results demonstrated that within those patients whose lower incisors were excessively proclined, significantly more teeth developed recession during both

the active treatment (mean difference of 0.45 ± 0.27mmm, $p < 0.001$) and during the period from appliance removal to 3-year postoperative control (mean difference of 0.18mm ± 0.22mm, $p<0.01$) when compared to the patients with minimal changes in incisor inclination. The authors did not detect any bone dehiscences in either group, suggesting that perhaps the link between excessive proclination, gingival recession, and bony lesions is not as clear as some may expect.

However, this study is limited by the fact that clinical crown height and recession were determined from dental cast measurements and clinical photographs, not from periodontal probing as is the gold standard. Furthermore, the mean difference in clinical crown heights between the two treatment groups, as reported by the authors, approached approximately 1mm. It is up to the reader to consider the clinical significance of such a difference.

In contrast to Artun and Krogstad's findings, Ruf et al, (1998) found that orthodontic proclination of lower incisors in children and adolescents does not often result in gingival recession. They hypothesized that

this was because children's "general tissue response is one of repair." Their conclusions were based upon a study in which they examined 98 patients with a Class II malocclusion that were treated with a Herbst appliance. The Herbst therapy resulted in an average of 8.9 degrees of lower incisor proclination (range = 0.5-19.5 degrees). The researchers found that "in 380 of the surveyed teeth (97%) either no recession developed or preexisting recession remained unchanged during Herbst therapy. In only 12 teeth (3%) did recession develop or preexisting recession deteriorate during treatment. The authors concluded that there was no association between the development of gingival recession and the amount of incisor proclination. It must be noted that periodontal probing is considered the gold standard for the detection of gingival recession and attachment loss, yet in this study crown height was assessed from dental casts while intraoral photographs were used to determine gingival health status and gingival recession.

While these studies investigated the effects of proclination on the gingival architecture and alveolar bone, others have investigated the effect of incisor

retraction and uprighting upon the periodontium. Wehrbein, et al (1996) examined the mandible of a deceased 19 year old woman who had been treated with an edgewise appliance. Her autopsy allowed retrospective inspection of the mandible and the alveolar bone supporting the lower incisors in a patient who had undergone orthodontic treatment. Treatment records indicated that the dentition in the mandibular arch had been treated with reciprocal space closure along with lingual root torque of the lower incisors. Using pre-treatment and progress cephalograms, an attempt was made to investigate the sagital movements of the lower central incisors via regional superimpostions on the mandible. The superimposition suggested the mandibular central incisors were extruded 1mm with 12 degrees of lingual root torque resulting in lingual root movement of nearly 3mm. Furthermore, the lateral cephalograms showed that this particular patient had an extremely "narrow and high" symphysis. Examination of the dry skull revealed moderate dehiscences on the labial aspect of the lower incisors while the "lingual aspects of the roots were largely without bony covering and protruded some millimeters out of the lingual surface of the alveolar

bone." They researchers suggest that in the case of a narrow and high mandibular symphysis, marked movements of the lower incisors may lead to extensive bone loss on both the labial and lingual surfaces.

Sarikaya et al, (2002) evaluated the changes that occurred in the anterior alveolar bone in 19 patients with bimaxillary protrusion that were treated with extraction of 4 first bicuspids. Cephalograms and CT scans were taken before orthodontic treatment as well as 8-10 weeks after completion of incisor retraction. Measurements of alveolar bone thickness were made at 6 sites (3 labial and 3 lingual) and included the crest level, mid-root level, and the apical level. Angular and linear measurements of the central incisors were also made using the lateral cephalogram in order to determine if retraction was accomplished via bodily movement or tipping.

Results of this study show that the maxillary and mandibular incisors were retracted primarily by controlled tipping. Comparison of alveolar bone thickness showed there were statistically significant decreases in lingual bone thickness in both arches after

incisor retraction. In the mandibular arch the labial bone maintained its original thickness except at the crest level, which showed a significant decrease in bone thickness ($P < .001$) after incisor retraction. At these sites a mean reduction in bone thickness of 0.40mm, 0.32mm, 0.25mm and 0.38mm were observed on the four incisors. On the lingual aspect of the mandibular incisors, statistically significant reductions were seen at 9 of the 12 sites tested.

Bimstein et al. (1990) evaluated the changes of the alveolar bone labial to procumbent mandibular incisors that were uprighted during the course of orthodontic treatment. The authors hypothesized that uprighting these teeth would lead to an increase in the height of the labial alveolar bone. However, their results showed that in only 58.8% of the cases did the height of the alveolar bone actually increase. They also noted that no significant correlation was found to exist between the angulation of the lower incisors (IMPA) and the alveolar bone height. However, this sample size in this study was only 17 subjects, far below the requirement of 30 set forth by the central limit theorem, and no controls were

used with which to make comparisons. Furthermore, the researchers used an arbitrary point (the "D" point) as a reference for measurement of alveolar bone height yet there is little evidence to suggest that this point is stable and acceptable for use in the comparison of measurements. Finally, the authors did not describe the mechanics employed in these cases. The authors did allude to the use of intrusion mechanics, which would likely lead to an increase in bone height, yet no certain mention is made. Given these limitations, the results of this study must be considered with skepticism.

However, a consistent limitation with these studies is that examination of the alveolar bone support was often assessed with lateral cephalograms. Two-dimensional images limit the clinician's ability to properly visualize the anatomy in the mandibular anterior region due to a superimposition of cortical and dental structures (Leung). This superimposition of structures impedes the detection of bony lesions on the buccal and lingual cortical plates (Farman et al and Leung). Furthermore, surface characteristics and changes that appear over time (relating to healing or deterioration of

the lesion) cannot be assessed (Andreasen et al, and Friedman et al). However, the development of recent technology such as CT and especially CBCT has provided the means to visualize these defects 3-dimensionally (Leung).

In contrast to the previously discussed studies, Nauert and Berg (1999), used computed tomography to evaluate the labial and lingual bony support of the mandibular incisors in orthodontically untreated adults. In this study the researchers examined the existing CT scans of 20 adult men with a near-to-normal occlusion and a healthy periodontium. The researchers measured the length of the each root, which was then divided into 10 intervals of equivalent length. The CEJ was defined at the 0% root level while the apex marked the 100% root level. The labial and lingual bony support was then measured at each root interval, perpendicular to the long axis of the incisor.

Results of this study showed that there was little, if any, bony support at the cervical parts of the root, but that the bony support increased from the CEJ to the apical third. "At the 10% root level, no bony support

was registered in 80% of the teeth. At the 20% root level no bone could be seen in 35% of cases. At the border between the middle and apical third, bony support was missing in 25% of all teeth. At the lingual aspects, low values of bony support were found, with an average of 0.1mm at the 30% root level."

The researchers also noted that there were marked differences in the incidence of fenestrations and dehiscences at the labial and lingual aspects of the incisors. The data showed that dehiscences and fenestrations were both commonly seen on the labial aspect of the teeth, while on the lingual aspect dehiscences were much more common. Furthermore, the researchers showed that the bone density surrounding the mandibular incisors was generally lower on the lingual aspect of the tooth. Finally, they noted that there was no statistically significant correlation between the amount of labial bony support and the inclination of the incisors in relation to the A/Pog line.

Because this as well as future investigations will employ 3-dimensional technology to assess the bone support of the lower incisors, it is important to

investigate the validity and accuracy of detecting periodontal defects using cone beam computed tomography.

Mengel et al (2005) investigated the ability of panoramic radiographs, periapical radiographs, CT, and CBCT radiographs to detect and represent artificially prepared periodontal defects in the mandibles of six pigs and 7 deceased human subjects. The intrabony defects (14 dehiscences, fenestrations, and 2-to-3 walled defects respectively, as well as a multitude of lesions with Class I, II and III furcation involvement) were prepared with a bur following a standardized procedure. The authors found that the CT and CBCT scans "permitted imaging of anatomic osseous structures in three plans, true to scale, and without overlay or distortion." They noted that the CBCT scans offered the best image quality. However, this investigation was limited by its study design. The lesions in this study were artificially produced with a bur and handpiece and thus do not represent true physiologic bony lesions in their size, shape and roughness. For example, all dehiscences in this study were prepared under a standardized protocol resulting in a height of 12mm, a width of 3mm, and had

parallel walls with a perpendicular base at the apical extent of the lesion. Furthermore the use of a bur resulted in the production of bony lesions with much greater surface roughness when compared to true bony defects. Finally, the visualization of these lesions was increased through the use of gutta percha points. These likely resulted in an over-estimation of the CBCT to detect bony lesions.

The results in the previous study are reflected by those found by a number of other researchers. Using a one-quarter dental bur, Misch et al (2006) created artificial intrabony defects of various sizes in the mandibles of two human cadaver skulls. The authors compared CBCT scans, periapical radiographs, and direct measurements using a periodontal probe and determined that "within the limits of this study, the present results are evidence that CBCT is as accurate as direct measurements using a periodontal probe and as reliable as radiographs for interproximal areas." The authors also noted that the CBCT was able to detect 100% of the periodontal defects but that the size of these lesions was over-estimated by 0.41mm. Interestingly, the size of

the voxel used in this study was 0.4mm, thus the sizing of lesions in this study was accurate to within one voxel.

Pinsky et al (2006) evaluated the accuracy and reliability of CBCT to detect the depth and diameter of simulated bone defects in acrylic blocks as well as with human mandibles. Within the acrylic blocks, the researchers placed 64 artificial cavities and in the two human mandibles 21 simulated bone defects of various sizes were prepared. Results showed that intraclass and interclass reliability was high despite the fact that the five examiners used in this study had no previous training in the use of CBCT. This suggests that the method of detection for bony lesions using a CBCT in not dependent upon the examiners. Furthermore, the sizes of the lesions were found to be accurate to within 0.3mm. However this study shares the same limitations as those previously mentioned. The lesions were artificially prepared and were of a known size, shape, and location. Thus the study lacked proper blinding and an over-estimation in the accuracy of detection was likely introduced. Furthermore, artificial defects do not

represent true bony lesions, thereby potentially influencing the detection, reliability and accuracy in detection of lesions using CBCT.

In response to such limitations Leung et al evaluated the accuracy and reliability of CBCT in the diagnosis of naturally occurring fenestrations and bony dehiscences. In addition, the accuracy and reliability of CBCT to measure alveolar bone margins and the position of a tooth's CEJ was evaluated. A sample of 13 dry human skulls with 334 teeth was selected for evaluation in this study and measurements made on the CBCT were compared to direct measurements using digital calipers. The scanning parameters for this study were 110kVp, 2mA, and 12-inch field of view, producing a voxel size of 0.38mm. The data showed that locating the CEJ using CBCT was accurate to within 0.4mm compared to direct measurements on dry human skulls while detection of the bone margin was accurate to within 0.6 mm. The data also demonstrated high negative predictive values of over 0.95 for dehiscences and fenestrations, providing evidence that when a defect is not found with CBCT, the lesion likely does not exist. Finally, the author noted that the

"spatial resolution limitations of the CBCT meant that areas with bone less than 0.6mm thick were seen on the image as areas without bone." Thus, under these settings, the smallest thickness of bone that can be measured on a CBCT scan and distinguished from root surface is 0.6mm. However, this study was limited by the fact that only dry skulls were used and thus the lack of soft tissue may have altered the attenuation of the x-ray beams when compared to CBCT scans of live persons.

Baumgaertel et al, (2009) took CBCT scans on 30 human skulls and compared ten measurements made using the CBCT scans to measurements made using digital calipers. The results showed that the measurements made using both the digital calipers as well as the CBCT scans were highly reliable and that "dental measurements from CBCT volumes can be used for quantitative analysis." However, they noted that the CBCT data tended to slightly underestimate measurements as compared to the digital calipers. The authors introduced two theories concerning this small difference. One possibility is a potential measurement error. While calipers measure the distance between two end-points, in this case the mesial and

distal contours of a tooth, the software may have measured the distance between the most mesial and distal voxels of the tooth. Furthermore, because the software defines the center of the voxel as the point from which to measure, the software may have actually measured the distance between the midpoints of the voxels. If this were in fact the case, half of the voxel on either side would not have been included in the measurement. The researchers also introduced a second theory—the concept of the partial volume effect.

In his commentary of the study by Baumgaertel et al, Halazonetis (2009) shed light on the partial volume effect. He suggested that this effect exists when real world objects are represented "using discrete samples on a regular grid" such as in a digital photograph or a CBCT scan. While real world objects have outlines with finite boundaries of an infinitesimal width, digital media must display these objects with pixels and voxels that are geometric shapes with finite size. Therefore, within an image the pixels or voxels may straddle the boundary of an object, thus leading to blurry images and making

detection of the true boundary on a CBCT scan extremely challenging.

Halazonetis continues that by definition a voxel is able to display only 1° of density. Therefore, if a voxel lies entirely within an object it reflects that object's density. However, if a voxel lies at the boundary of 2 objects of different densities the voxel will reflect an average value of those two objects. For example a voxel lying entirely in bone appears white while a voxel lying entirely in soft tissue appears black. However, a voxel lying at the bone-to-soft tissue interface will appear as a shade of grey. How dense it appears depends on the ratio of the two objects within the voxel. This further complicates the detection of the true interface of two dissimilar objects on a CBCT. However, a proposal was offered that this true boundary could be mathematically discovered: "A boundary represents a change, or gradient, in density; as we cross the boundary, the density changes from 1 value to another, but the largest, most abrupt change happens exactly on the boundary." Thus, if a method is introduced that incorporates the detection of the

boundary using abrupt changes in Hounsfield densities, detection of the true boundary should be possible.

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STATEMENT OF THESIS

This study has three main objectives. 1) To develop an accurate and reliable method to measure the thickness of bone labial and lingual to the mandibular incisors. 2) To report the mean and range of bone thickness labial and lingual to the mandibular incisors before and after treatment. 3) To highlight any possible association between the change in the thickness of bone labial and lingual to the mandibular incisors and the change in the angulation of the mandibular incisors that occurred during orthodontic treatment

It is hypothesized that:

1) There is no difference in the thickness of bone labial to the lower incisors before and after orthodontic treatment;

2) There is no difference in the thickness of bone lingual to the lower incisors before and after orthodontic treatment;

3) There is no relationship between the change in the thickness of bone labial to the lower incisors after orthodontic treatment and the change in the inclination

of the incisors that occurred during orthodontic treatment;

4) There is no relationship between the change in the thickness of bone lingual to the lower incisors after orthodontic treatment and the change in the inclination of the incisors that occurred during orthodontic treatment.

Evaluation of the Bone Thickness Surrounding the Mandibular Incisors Before and After Orthodontic Treatment.

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Title: Evaluation of the Bone Thickness Surrounding the Mandibular Incisors Before and After Orthodontic Treatment

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Keywords: Cone beam computed tomography (CBCT), mandibular incisors, alveolar bone thickness, IMPA, tooth long axis, bone support, orthodontic treatment.

Objectives: To develop a reliable method to measure the thickness of bone labial and lingual to the mandibular incisors. To report the mean and range of bone thickness labial and lingual to the mandibular incisors before and after orthodontic treatment. To detect a difference in the bony support of the mandibular incisors resulting from orthodontic treatment. To highlight a relationship between the change in the thickness of bone labial and lingual to the mandibular incisors and the change in the angulation of the mandibular incisors that occurred during orthodontic treatment. **Methods:** The sample population consisted of 19 males and 21 females with an average age of 13.42 ± 1.75 years who completed comprehensive orthodontic treatment and whose records include both pre-treatment and post-treatment CBCT scans. Using OnDemand 3D Software (Cybermed Inc – Seoul, Korea) the CBCT scans were oriented along the long axis of each mandibular incisor in all three planes and axial scans were constructed at positions corresponding to 1/3 and 2/3 of the root length. A visual evaluation in conjunction with a graphical Hounsfield density display permitted the assessment of bony thickness labial and lingual to each tooth. Cephalograms constructed from each CBCT scan (Dolphin Imaging, Patterson Companies Inc - St. Paul, Minn.) permitted the evaluation of the angulation of the lower central incisor relative to the mandibular plane (IMPA) as well as the generation of regional superimpositions on the mandible. **Results:** The method was found to be highly reliable in all sites with the exception of the facial surface, 1/3 root

level. Statistically significant changes in bony thickness were noted at multiple sites. No correlation was found to exist between either the final IMPA or change in IMPA and the change in bony thickness surrounding the incisors. **Conclusions:** Changes in bony thickness included the general trend of minimal gains on the facial surface and minimal losses on the lingual. However, these changes were extremely small and were not considered to be clinically significant. There appears to be no association between bony thickness and incisor inclination. These findings may influence treatment planning or the mechanics employed in future orthodontic cases.

INTRODUCTION

Orthodontists have always paid particular attention to the mandibular incisors especially since the birth of cephalometrics. Many feel that the positioning of these teeth is the single most important aspect of orthodontic treatment planning. Furthermore, the final positioning and inclination of the lower incisors has long been considered a major contributor to the stability (or lack thereof) of orthodontic results. However, there are few issues in orthodontics that are as controversial as the "ideal" position and inclination of the lower incisors.

The orthodontic community's outlook on proper positioning of the mandibular incisors is continually evolving. Edward Angle believed that the proper inter-digitation of the dentition would stimulate compensatory growth of the basal bone structures. He thus paid little attention to the final inclination of the mandibular incisors and was steadfast in his non-extraction philosophy. Charles Tweed on the other hand became the predominant proponent of orthodontic extractions after he determined many of his non-extraction cases to be of poor esthetic quality. Tweed's impact on the orthodontic community was enormous and for the next several decades

the initial and final inclination of the mandibular incisors was the primary factor in orthodontic treatment planning for many orthodontists. This trend continues even today as many clinicians feel that positioning the incisors upright over the basal bone provides for optimal bony support and a healthy periodontium.

An orthodontist must have a thorough understanding of how proclination of the mandibular incisors affects the periodontium. While many clinicians assume that excessive proclination of the mandibular incisors may lead to the formation of gingival recession and/or mucogingival defects, a review of the literature demonstrates that this subject remains controversial and wrought with conflicting and/or unsubstantiated evidence based upon opinions.

The relationship between excessive proclination and the formation of bony dehiscences and fenestrations has also been investigated. In a series of animal studies, Steiner et al (1981), and Karring et al (1982), exhibited that bony dehiscences are produced in the alveolar bone if the mandibular incisors are moved anteriorly. However, other studies by Ericsson et al, (1978) and Wingard et al, (1976) were unable to support these findings.

Despite these conflicting results, these previous studies do share one common thread in that they were limited by the technology available at the time. Lateral cephalograms and other 2-dimensional films do not provide the investigator with the ability to properly evaluate the bony housing surrounding the lower incisors. However, the advent of CT scans and especially Cone Beam Computed Tomography

(CBCT) has provided clinicians and investigators with the means to accurately visualize and calculate alveolar bone thickness.

In contrast to previous studies, Nauert and Berg (1999) used computed tomography to evaluate the bony support of lower incisors in orthodontically untreated adults. In this study the researchers examined the CT scans of 20 adult men with a near-to-normal occlusion and a healthy periodontium. The root length was measured and divided into 10 intervals of equivalent length with the CEJ defined as the 0% root level and the apex defined as the 100% root level. The labial and lingual bony support was then measured at each root level, perpendicular to the long axis of the incisor.

Results of this study showed that there was little if any bone support at the cervical parts of the root but that bone support increased in an apical direction. They noted that at the 10% root level no bony support was registered in 80% of the teeth while at the 20% root level no bone could be seen in 35% of cases. Their data also illustrated marked differences in the incidence of fenestrations and dehiscences on the labial and lingual aspects of the incisors. Dehiscences and fenestrations were both commonly seen on the labial aspect of the teeth, while on the lingual aspect dehiscences were much more common than fenestrations. Furthermore, it was found that bone density was generally lower on the lingual aspect of the tooth. Finally, the researchers found no statistically significant correlation between the

amount of labial bony support and the inclination of the incisors in relation to the A/Pog line.

The accuracy and reliability of CBCT to measure alveolar bone margins was recently investigated. In this study the researcher took CBCT scans on 13 dry human cadaver skulls and compared the measurements made with the CBCT to direct measurements made using digital calipers. The data showed that for bone to be accurately distinguished from root surface a minimal thickness of 0.6mm of bone is necessary. Yet what about in cases where there is less than 0.6mm of bone thickness? The data detailed high negative predictive values of over 0.95 for dehiscences and fenestrations, providing evidence that when a defect is not found on the CBCT the defect likely does not exist. The question then becomes, how does one visualize and quantify a thickness of bone that is smaller than the spatial resolution capabilities of the CBCT?

Halazonetis (2009) shed light on this quandary with his description of the partial volume effect. This partial volume effect exists when real world objects are represented "using discrete samples on a regular grid" such as in a digital photograph or a CBCT scan. While real world objects have outlines with finite boundaries of an infinitesimal width, digital media must display these objects with pixels and voxels that are geometric shapes with finite size. Furthermore, by definition a voxel is able to display only 1° of density. Therefore, if a voxel lies entirely within an object it reflects that object's density. However, if a voxel lies at the boundary of 2 objects

of different densities, the voxel will reflect an average value of those two objects. For example a voxel lying entirely in bone appears white while a voxel lying entirely in soft tissue appears black. However, a voxel lying at the bone-to-soft tissue interface will appear as a shade of grey. How dense it appears depends on the ratio of the two objects within the voxel.

As a result, finding the true boundary between two objects of different densities on a CBCT proves extremely challenging due to a blurring of the image. However, it has been proposed that by mathematically representing changes in density, detection of this interface is possible.

The purpose of this study is to use this concept of mathematical detection of boundaries to 1) develop a reliable method to measure the thickness of bone labial and lingual to the mandibular incisors; 2) report the mean and range of bone thickness labial and lingual to the mandibular incisors before and after orthodontic treatment; 3) detect a difference in the bony support of the mandibular incisors resulting from orthodontic treatment; and 4) highlight a potential relationship between the change in the thickness of bone labial and lingual to the mandibular incisors and the change in the angulation of the mandibular incisors that occurred during orthodontic treatment. It is hoped that the results of this study help guide the clinician in his or her treatment planning by shedding insight into the effects of orthodontic therapy on the periodontium.

MATERIAL AND METHODS

The Case Western Reserve University Institutional Review Board (IRB) approved this retrospective cohort study. Subjects were randomly selected from those patients that completed comprehensive orthodontic treatment in the graduate clinic at the Case Western Reserve University School of Dental Medicine. Data were extracted from previously existing pre-treatment and post-treatment Cone Beam Computed Tomography scans (CB MercuRay™, Hitachi Medical Systems America Co. – Twinsburg, OH). All scans were taken in the Craniofacial Imaging Center at the Case Western School of Dental Medicine using the 2mA setting, 120kVp and an 8-inch field of view (0.377mm voxel size). Based on research by Leung (2009) sample size calculations using an expected effect size of 0.60 mm, a standard deviation of 0.80 mm, an α of 0.05, and β of 0.10 indicated that the minimum sample size should be 32 subjects. A total of 431 pretreatment patient records complete with CBCT scans, photographs, and medical history forms were available.

Inclusion into the study was based on the following parameters:

1. Patients undergoing comprehensive orthodontic therapy.
2. Fully erupted mandibular central and lateral incisors.
3. No previous orthodontic treatment based on medical history form.
4. No congenitally missing or supernumerary teeth in the mandibular arch based on the CBCT image.
5. No extracted permanent mandibular teeth before or during orthodontic treatment.
6. Landmarks (CEJ, apex of the root, root canal, cortical bone, etc) of the lower incisors must be clearly visible on the CBCT scan.
7. The CBCT scans must be of high quality.
8. All CBCT images must have initial and final scans comprised of a voxel size of 0.377mm

From the eligible patients, 40 were randomly selected for inclusion in this study using a table of random numbers. The sample population included 19 males and 21 females with an average age of 13.42 ± 1.75 years at the time of initial records and an average treatment time of 22.33 months. An independent sample t-test showed that there was no difference in age among males and females.

A single operator collected all data. Radiographic data was obtained from CBCT scans taken before and after orthodontic treatment. The OnDemand 3D software (Cybermed Inc – Seoul, Korea) was used to reconstruct the DICOM (Digital Imaging and Communications in Medicine) files and to measure the thickness of bone labial and lingual to the mandibular incisors. Each slice and associated Hounsfield density histogram was captured, stored as a jpeg file and labeled using a patient identifier. Dolphin Imaging 3D (Patterson Companies Inc - St. Paul, Minn.) was employed to

digitize cephalograms and to generate regional superimpositions on the mandible. The cephalograms were used to evaluate the angulation of the lower central incisor relative to the mandibular plane (IMPA), while the regional superimpositions were generated to visualize the specific effects of orthodontic treatment for the individual subjects within this sample population. Demographic information was collected from each patient's record and included gender, age at start of treatment, treatment duration and ethnicity. Measurements were repeated after a two-week interval in order to assess the reliability of the method. All data was collected and entered into Microsoft Excel spreadsheets for data management.

Method of measuring the thickness of bone labial and lingual to the mandibular incisors:

1. In the sagital view, align the coronal and axial planes along one mandibular incisor. Adjust the contrast to enhance the image (Figure 1).

2. In the coronal view, adjust the sagital plane such that it passes through the long axis of one mandibular incisor (Figurs 2).

3. In the sagital plane (Figure 3):
    a. Align the coronal plane along the long axis of the incisor.
    b. Place the axial plane along the tooth's cementoenamel junction

4. In the axial view, place the sagital plane through the "long axis" of the tooth, defined as a line connecting the most convex points on the labial and lingual aspects of the tooth (Figure 4).

5. In the sagital view, identify the CEJ and apex of the incisor. Mark these points with lines running perpendicular to the long axis of the tooth and parallel to the coronal plane (Figure 5).

6. Using these two lines as endpoints, measure the length of the root. Defining the CEJ as 0% and the apex as 100% root length, place two more marker lines at 1/3 and 2/3 the root length. Care must be taken to ensure they run exactly parallel to the axial plane. Capture an image including all measurements (Figure 6).

7. Place the axial plane over the line marking 2/3 root length (Figure 7).
8. Return to the axial view. Using the histogram function, place a line running along the sagital plane. Set the endpoints of the line just outside the extent of the bone (Figure 8).

9. To mark the labial extent of bone, adjust the left tail of the histogram to a likely boundary between the soft tissue and bone. The transition between these two different structures will be noted by a large change in Hounsfield units along the histogram (Figure 9). Visually confirm this position on the radiograph and make any necessary corrections.

10. To indicate the transition between tooth and bone, adjust the right tail of the histogram (Figure 10). Again visually confirm this position and make any necessary corrections. Capture an image including all measurements.

11. In order to assess the bone lingual to the incisor, return the endpoints of the line to their original positions and repeat steps (not shown).

12. Return to the sagital view and adjust the axial plane such that it passes over the line marking the 1/3 root length (Figure 11). Repeat all steps previously mentioned in order to calculate the thickness of bone labial and lingual to the mandibular incisor at the 1/3 root length. Capture images including all measurements.

Note that for the measurements on the post-orthodontic CBCT scans, the root lengths determined in the initial CBCT images were used once again in order to minimize changes in root length due to root resorption or continued development at the apex. In this manner, the same position on the tooth may be evaluated at both time points.

13. Using cephalograms constructed from the initial and final CBCT scans of each individual patient, measure the angulation of the lower incisor

relative to the mandibular plane (IMPA). Capture an image including all measurements (not shown).

14. Using cephalograms constructed from the initial and final CBCT scans of each individual patient, generate regional superimpositions on the mandible (not shown).

STATISTICAL ANALYSIS

Means, standard deviations, and ranges were calculated for each variable. Paired sample t-tests were used to compare the thickness of bone labial and lingual to the mandibular incisors before and after orthodontic treatment. Analysis of variance (ANOVA) was used to compare the outcomes for the potential explanatory variables (i.e. final IMPA, change in IMPA, treatment time, and age). An independent sample t-test was performed to assess whether a significant difference existed in the age and gender of the sample population. Pearson's Correlation Coefficient was used to evaluate potential relationships between: 1) the changes in bone thickness and IMPA and 2) the change in the bone thickness and final IMPA. Measurements were repeated after a two-week interval on 30 randomly selected teeth, chosen using a random number generator. Only the initial CBCT scans were used for these repeated measurements in order to minimize changes in root length due to root resorption or continued development at the apex. The intraclass correlation

was used to assess reliability of all continuous measurements. All statistics were calculated using the Statistical Package for the Social Sciences (SPSS 17.0, Inc. – Chicago, IL).

RESULTS

The study sample consisted of 19 males and 21 females for a total of 40 subjects. The majority of subjects (n=34) were Caucasian while four were African American and two represented other minorities. The average age at the time of initial records was 13.42 ± 1.75 years with a range from 10.08 - 16.42 years. An independent sample t-test showed that there was no significant difference in age between males and females. Treatment time ranged from 7 – 31 months with an average of 22.33 ± 4.84 months. A descriptive summary of demographic information is shown in Table 1.

The angulation of the mandibular incisors relative to the mandibular plane angle (IMPA) was assessed before and after orthodontic treatment. As shown in Table 2, fourteen of the subjects had initial IMPA values considered to be retroclined (less than 90 degrees), thirteen patients had IMPA values considered within normal limits (between 90 and 95 degrees), ten patients had proclined incisors (between 95 and 100 degrees), and three had severely

proclined incisors (100 degrees or more). Final IMPA values are also displayed and demonstrate that a number of cases were treated by proclination in order to achieve final results. Table 2 also shows the distribution of subjects relative to the overall change in IMPA values during orthodontic treatment. The IMPA value was considered maintained in a majority of the cases (62.5 percent), retroclined in 10 percent, proclined in 17.5 percent, and severely proclined in another 10 percent of the subjects.

Bone thickness was evaluated on the labial and lingual surfaces of the four mandibular incisors at both the 1/3 and 2/3 root levels. Statistical significance of changes in bony thickness was evaluated with the paired sample t-test with a $p < 0.05$. Table 4 displays these changes and demonstrates a general trend of minimal gains at all facial surfaces and minor losses at all lingual surfaces. For example, at the facial surface 1/3 root level of the lower right lateral incisor there was a mean increase of 0.08 ± 0.24mm of bone while at the lingual surface there was a mean reduction of 0.14 ± 0.44mm in bony thickness. At the 2/3 root level there was a mean increase of 0.08 ± 0.52 on the facial surface and a mean reduction of 0.30 ± 0.70 on the lingual surface. Similar findings were observed for the other three mandibular incisors.

An independent sample t-test demonstrated that there was no statistically significant difference between males and females with respect to the changes in bony thickness of the lower incisors after orthodontic treatment. An analysis of variance (ANOVA) was performed to test for statistical significance

for explanatory variables such as final IMPA, the overall change in IMPA, treatment time, and age. Bonferroni corrections were also employed to investigate potential relationships within these variables.

1. Final IMPA values were broken into four groups: 1) $x < 90$ degrees; 2) $90 \leq x < 95$ degrees; 3) $95 \leq x < 100$ degrees; and 4) $x \geq 100$ degrees. Statistical significance was found to exist only at 2 of the 16 tested sites (the 1/3 root level of the lower right lateral incisor at both the facial and lingual surfaces).
2. The change in IMPA values were broken also broken into four groups: 1) $x < -3$ degrees; 2) $-3 \leq x < 5$ degrees; 3) $5 \leq x < 10$ degrees and 4) $x \geq 10$ degrees. Statistical significance was found to exist at only 1 of the 16 tested sites (the facial surface of the lower right central incisor at the 2/3 root level).
3. Treatment times for the subjects were broken down into three groups: 1) $x < 18$ months; 2) $18 \leq x < 24$ months; and 3) $x \geq 24$ months. No statistical significance was found to exist between treatment time and changes in bony thickness after orthodontic treatment.
4. Age groups were broken into three groups: 1) $x < 12$ years; 2) $12 \leq x < 14$ years; 3) $x \geq 14$ years. Statistical significance was found to exist at only 1 of the 16 tested sites the lingual surface of the lower left lateral incisor at the 1/3 root level).

The association between the change in IMPA values and the changes in bone thickness were evaluated with the Pearson's Correlation Coefficient. No general association was noted as statistical significance for this correlation was found at only 3 of the 16 tested sites (the facial surfaces of the lower right lateral and central incisors and the lower left central incisor at the 2/3 root level). Similarly, the final IMPA values and the changes in bony thickness surrounding the mandibular incisors were also evaluated using Pearson's Correlation Coefficient. A statistically significant correlation was found to exist at only 1 of the 16 tested sites (the lingual surface of the lower right lateral incisor at the 1/3 root level) suggesting that there is no overall association between final IMPA values and bony thickness.

Reliability was assessed by repeating measurements on 30 randomly selected teeth chosen using a random number generator. A single operator collected all measurements two weeks after the initial measurements. Only the initial CBCT scans were used in order to minimize changes in root length due to root resorption or continued development at the apex. Table 4 shows the intraclass correlation values for all sites. All sites were extremely reliable (.938 - .983) with the exception of the facial surface at the 1/3 root level.

DISCUSSION

The purpose of this study was to 1) develop a reliable method to measure the thickness of bone labial and lingual to the mandibular incisors; 2) report the mean and range of bone thickness labial and lingual to the mandibular incisors before and after orthodontic treatment; 3) detect a difference in the bony support of the mandibular incisors resulting from orthodontic treatment; and 4) highlight a potential relationship between the change in the thickness of bone labial and lingual to the mandibular incisors and the change in the angulation of the mandibular incisors that occurred during orthodontic treatment.

Two-dimensional films have historically hampered the assessment of labio-lingual bony thickness surrounding the mandibular incisors. Cephalograms make visualization of the bone difficult due to the superimposition of anatomical structures as well as the inherent inability to view the anatomy from a variety of perspectives. Yet despite these concerns, for decades clinicians have used the cephalogram as their primary determinant of bone thickness, all the while viewing the teeth solely from the sagital field of view. Clearly a new approach to

visualize the lower incisors was necessary. This became possible with the advent of CBCT technology, which offers the ability to view the lower incisors from any field of view desired.

Our study describes a new, reliable method to evaluate the thickness of bone labial and lingual to the mandibular incisors. By aligning the axial, coronal and sagital planes along the long axis of an individual incisor and viewing the resulting image from the axial view, the clinician is now able to truly assess the labio-lingual thickness of bone supporting the mandibular incisors.

Within our methodology, the decision was made to evaluate the thickness of bone labial and lingual to the lower incisors at two separate positions vertically along the root. The 1/3 root level was chosen for a variety of reasons. Based on clinical observations it has long been understood that there often is a minimal thickness of bone surrounding the mandibular incisors at the cervical portion of the root. Furthermore the incidence of gingival recession, attachment loss, dehiscences and fenestrations is often observed at the cervical 1/3 of the root. Finally, because the mechanics employed in an orthodontic case often include flaring of the lower incisors, some clinicians have inferred that orthodontic therapy was the stimulus behind these deleterious periodontal results. The evaluation of bone thickness at the 1/3 root level will finally offer the clinician quantitative evidence of what changes are possible with orthodontic therapy. The 2/3 root level was chosen as it represents the likely position of the center of resistance for these teeth and it was felt that perhaps the significance of bony

changes at this level had been ignored too long. Bone thickness at these levels was determined by visual assessment along with the usage of Hounsfield density histograms. These histograms were employed in an effort to reduce human error due to visual detection difficulties resulting from the partial volume effect as well as to offer a means to double check all thicknesses calculated.

Results of the intraclass correlation test provide evidence that this method is reliable at all sites tested (.938 - .983) with the exception of the facial surface at the 1/3 root level. However, this is not surprising due to the minimal thickness of bone at this position as well as the spatial limitations of the CBCT scan. The voxel size used in this study was set at 0.377mm and as a result for many subjects the entire thickness of bone at the facial 1/3 level was often encompassed within one or two voxels. For such subjects the resulting images were often blurry making a visual assessment of the bone difficult. Furthermore, because of the relatively large voxel size, the Hounsfield density histograms were potentially less than ideally precise. A smaller voxel size would certainly result in images of superior clarity with well-defined boundaries and sharper transitions along the Hounsfield density histograms. This would in turn result in a more reliable and accurate detection of the bony thickness at all sites.

This study is perhaps the first to report the means, standard deviations and ranges of bone thickness both labial and lingual to the mandibular incisors before and after orthodontic treatment. First glance confirms what many have always assumed: that on average there is significantly less bone in the cervical

third than in the apical third of the root and that on average there is slightly greater bone thickness on the lingual surface than on the labial surface. However, two surprising observations were extrapolated from the data: 1) There was a positive value of bone detected at every site tested; in no instance was a root surface found without bony support and 2) the extent of the range in bone thickness suggests that perhaps clinicians must reconsider their perception of the bony support in the mandibular anterior region. It is left to the reader to consider the manner in which these findings potentially impact the treatment planning and mechanics employed for orthodontic cases.

Table 4 depicts the changes in the thickness of bone labial and lingual to the mandibular incisors seen as a result of orthodontic treatment. A general trend is evident whereby there is an increase in bone thickness on the facial surfaces and a reduction of bone thickness on the lingual surfaces. It should be noted that this trend is observed even when the teeth were severely proclined (defined as a change of 10 degrees or more). This finding is in direct opposition to the popular belief that orthodontic therapy results in a decrease in labial bony support especially when the lower incisors are proclined. However, it is interesting to note that this trend is somewhat reversed in the cases that demonstrated significant uprighting (a change of -3 degrees or more) of the lower incisors during treatment. In such cases one would expect an increase in bone thickness at the facial surfaces of these teeth, yet reductions were observed at nearly every site at the 2/3 facial level.

A likely explanation for these observations is that tooth movement is osteogenic and therefore the thickness of bone is often actually increased in the direction of movement; thus proclination of the mandibular incisors actually carries the bone forward along with the tooth, rather than "blowing the tooth out of the bone" as some clinicians have hypothesized. An alternative explanation is the theory presented by DeAngelis that described the manner in which traebecular bone reorganizes such that the bone is best able to withstand the forces acted upon it. Perhaps proclination of the teeth into a position not ideally supported by the basal bone stimulates a biologic response within the alveolus to re-distribute bony support in a manner consistent with the forces of mastication.

The word "re-distribute" has been chosen carefully as it appears that this is exactly what occurs in nearly every instance. Careful inspection of the data showed that if significant reductions of bone occurred at one surface on a tooth there was nearly always a significant increase of bone on another site or sites; similarly if bone changes were minimal, the bone thickness appeared to have been maintained at nearly every site. In no instance were there gains or reductions in bone thickness at every site on a tooth. Thus it appears that the *volume* of bone is re-distributed and maintains some degree of order within a physiologic envelope.

The case of AD37 perhaps best exemplifies this observation. The initial IMPA value of 85.0 degrees and final IMPA value of 98.9 degrees demonstrates that this case was completed with considerable proclination of the mandibular

incisors (13.9 degrees). Many clinicians would argue that such a drastic alteration in the IMPA as well as the severity of the final IMPA value would place this child at risk for having little to no bony support on the facial aspects. However it was observed that at the facial and lingual 1/3 root levels, the bone was actually maintained despite such severe proclination. Small reductions in thickness at the lingual 1/3 were offset by nearly equal and opposite gains in thickness at the facial 1/3 root level. A similar but more pronounced trend was observed at the 2/3 root level where reductions of 0.8mm, 1.0mm, 1.3mm and 1.4mm on the lingual surfaces of the four incisors were offset by gains of 1.5mm, 1.8mm, 2.3mm and 2.6mm on the facial aspects. Clearly this case does not exhibit the consequences traditionally associated with severe proclination

Finally it is interesting to note there was no significant correlation between the changes in bone thickness and the changes in IMPA or with the final IMPA value. As previously mentioned, in cases that were severely proclined there were actually gains on the facial surfaces of the teeth and reductions on the lingual, which is in direct contrast with conventional wisdom. This relationship was nearly reversed in cases treated by uprighting the lower incisors, in which case reductions on the facial were actually observed despite popular belief that there would be increases in bone thickness due to placement of the tooth more upright over the basal bone as described by Tweed. Finally, it is interesting to note that there were significant changes in bone thickness even in cases that exhibited no change in IMPA values and whose vertical positioning of the incisors

did not change (as observed on the superimpositions). Again, this is in direct contrast to traditional beliefs held by the dental community on this subject.

This data has suggested several new claims concerning the effects of treatment on the bone thickness surrounding the mandibular incisors. It is hoped that research into this subject continues and that with better technology and smaller voxel sizes, a more precise and accurate assessment may be made in the future. Furthermore, research into the effects on bone thickness as a result of extractions and retraction of the anterior teeth is warranted.

CONCLUSION

This study is perhaps the first to illustrate a reliable method to calculate the thickness of bone labial and lingual to the mandibular incisors and to quantitatively report the means, standard deviations and ranges for this thickness both before and after orthodontic treatment. Although minimal, a statistically significant change in the thickness of bone resulting from orthodontic therapy was observed. No association was found to exist between the changes in bone thickness and the change in IMPA or the final IMPA values. These findings directly oppose long-held beliefs based on opinion and controversial evidence stemming from antiquated visualization techniques.

Table 1: Descriptive summary of the demographics within the study sample

Variable	Group	Total	Percent
Gender	Male	19	47.5
	Female	21	52.4
Ethnicity/Race	Caucasian	34	85
	African American	4	10
	Other	2	5
Initial Age	$10 \leq x < 12$	11	27.5%
	$12 \leq x < 14$	18	45%
	$14 \leq x$	11	27.5%

Table 2: Categorical representation of the study sample with regards to the initial, final, and change in lower incisor to mandibular plane angle (IMPA) measurements

	Subjects	**$x < 90°$**	**$90° \leq x < 95°$**	**$95° \leq x < 100°$**	**$100° \leq x$**
Initial	Number	14	13	10	3
	(Percentage)	(35%)	(32.5%)	(25%)	(7.5%)
Final	Number	11	5	14	10
	(Percentage)	(27.5%)	(12.5%)	(35%)	(25%)
		$x < -3°$	**$-3° \leq x < 5°$**	**$5° \leq x < 10°$**	**$10° \leq x$**
Change	Number	4	25	7	4
	(Percentage)	(10%)	(62.5%)	(17.5%)	(10%)

Table 3: Descriptive summary of bone thickness at specified locations before and after orthodontic treatment

	Surface	Initial		Final	
		Mean ± SD (mm)	Range (mm)	Mean ± SD (mm)	Range (mm)
LR2	1/3 Facial	0.68 ± 0.20	0.30 – 1.10	0.77 ± 0.19	0.40 – 1.20
	1/3 Lingual	1.23 ± 0.64	0.40 – 3.40	1.09 ± 0.51	0.40 – 1.20
	2/3 Facial	1.27 ± 0.57	0.70 – 2.80	1.35 ± 0.60	0.60 – 3.30
	2/3 Lingual	1.92 ± 0.88	0.70 – 4.90	1.62 ± 0.85	0.70 – 4.20
LR1	1/3 Facial	0.70 ± 0.17	0.40 – 1.00	0.83 ± 0.20	0.40 – 1.40
	1/3 Lingual	1.18 ± 0.61	0.40 – 3.40	0.93 ± 0.42	0.40 – 1.90
	2/3 Facial	1.39 ± 0.53	0.50 – 2.70	1.50 ± 0.77	0.70 – 3.80
	2/3 Lingual	1.71 ± 0.81	0.70 – 4.40	1.31 ± 0.80	0.40 – 3.80
LL1	1/3 Facial	0.76 ± 0.18	0.40 – 1.10	0.84 ± 0.17	0.40 – 1.20
	1/3 Lingual	1.14 ± 0.50	0.40 – 2.80	1.02 ± 0.40	0.40 – 2.30
	2/3 Facial	1.29 ± 0.54	0.40 – 2.70	1.51 ± 0.75	0.50 – 3.60
	2/3 Lingual	1.82 ± 0.81	0.70 – 4.60	1.41 ± 0.77	0.50 – 3.70
LL2	1/3 Facial	0.74 ± 0.21	0.40 – 1.50	0.81 ± 0.19	0.40 – 1.10
	1/3 Lingual	1.36 ± 0.56	0.40 – 3.10	1.20 ± 0.50	0.60 – 2.70
	2/3 Facial	1.17 ± 0.57	0.40 – 3.00	1.50 ± 0.67	0.50 – 3.00
	2/3 Lingual	2.05 ± 0.73	1.10 – 4.80	1.82 ± 0.90	0.60 – 5.00

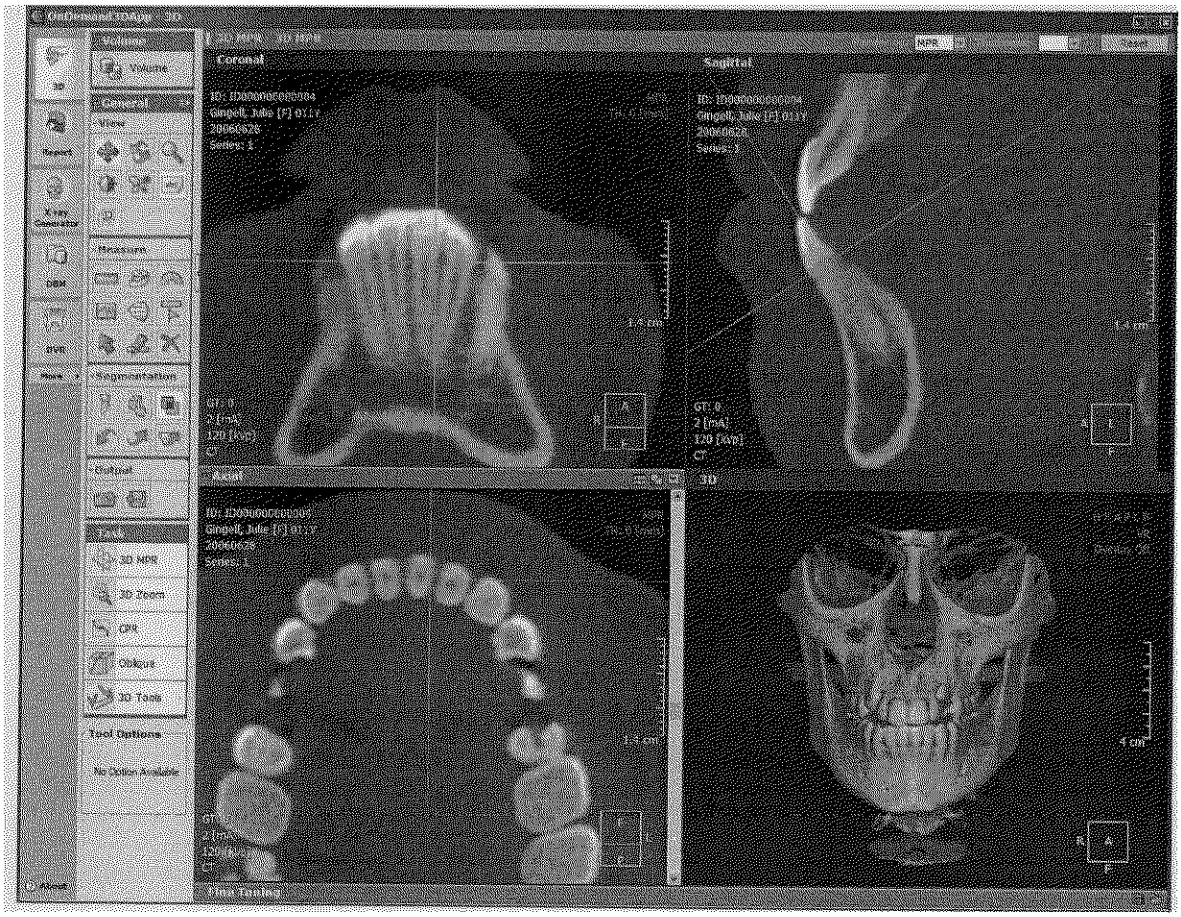
Table 4: Comparison of the change in bone thickness at specified locations before and after orthodontic treatment

		Mean ± S.D. (mm)	Range (mm)	p-value*
LR2	1/3 Facial	0.08 ± 0.24	-0.40 ± 0.60	.03**
	1/3 Lingual	-0.14 ± 0.44	-1.70 ± 0.50	.04**
	2/3 Facial	0.08 ± 0.52	-0.90 ± 1.80	.34
	2/3 Lingual	-0.30 ± 0.70	-1.90 ± 1.90	.00**
LR1	1/3 Facial	0.13 ±0.21	-0.40 ± 0.60	.00**
	1/3 Lingual	-0.25 ± 0.45	-1.60 ± 0.40	.00**
	2/3 Facial	0.10 ±0.70	-1.10 ± 2.60	.36
	2/3 Lingual	-0.40 ± 0.56	-1.90 ± 0.70	.00**
LL1	1/3 Facial	0.08 ±0.20	-0.40 ± 0.50	.01**
	1/3 Lingual	-0.13 ± 0.48	-1.30 ± 1.10	.10
	2/3 Facial	0.21 ±0.66	-1.10 ± 2.30	.04**
	2/3 Lingual	-0.41 ± 0.67	-1.80 ± 1.10	.00**
LL2	1/3 Facial	0.08 ±0.28	-0.80 ± 0.50	.09
	1/3 Lingual	-0.16 ± 0.38	-0.80 ± 0.90	.01**
	2/3 Facial	0.33 ±0.66	-0.70 ± 2.20	.00**
	2/3 Lingual	-0.23 ± 0.51	-1.20 ± 0.80	.01**

* p-value for paired sample t-test evaluating the difference in means

** indicates the value is significant at a p-value < 0.05

Figure 1: In the sagital view, align the coronal and axial planes along one mandibular incisor. Adjust the contrast to enhance the image.



Figures 2: In the coronal view, adjust the sagital plane such that it passes through the long axis of one mandibular incisor.

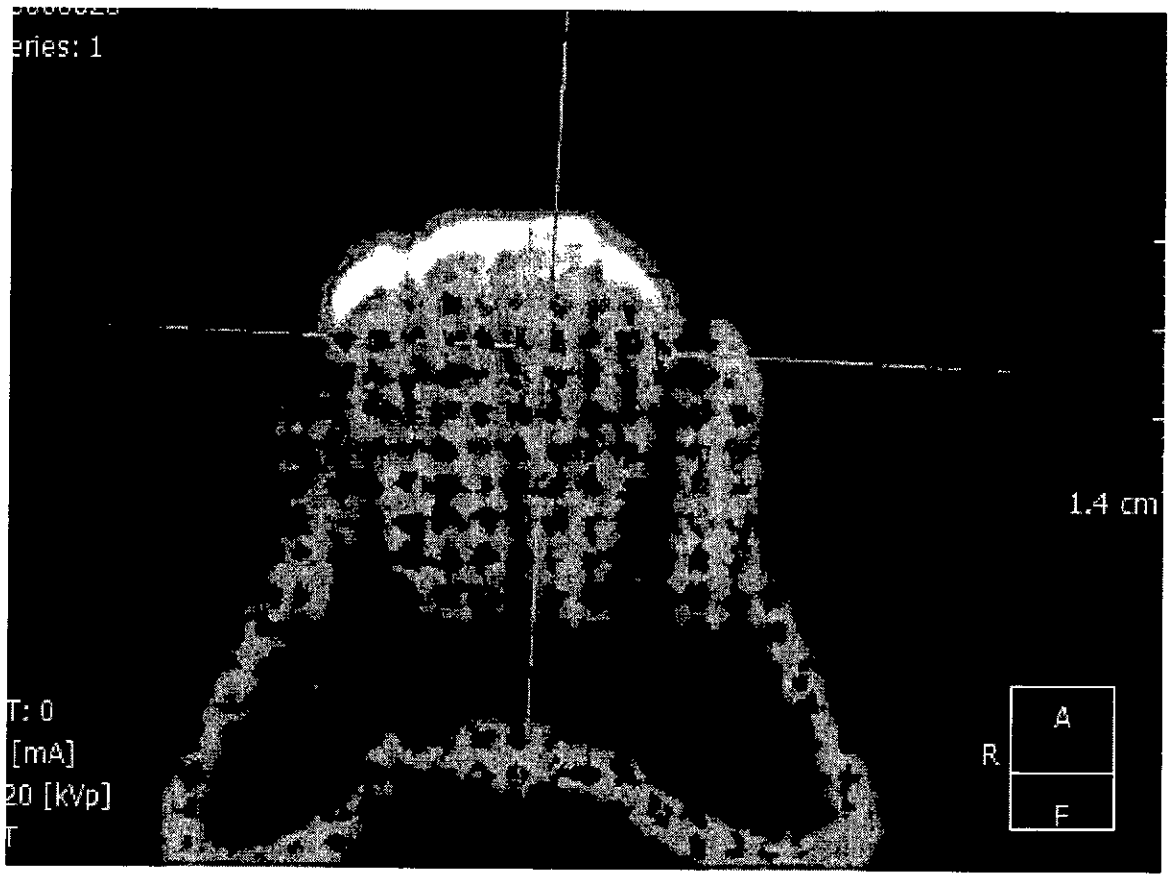


Figure 3: In the sagital plane, align the coronal plane along the long axis of the incisor. Place the axial plane along the tooth's cementoenamel junction.

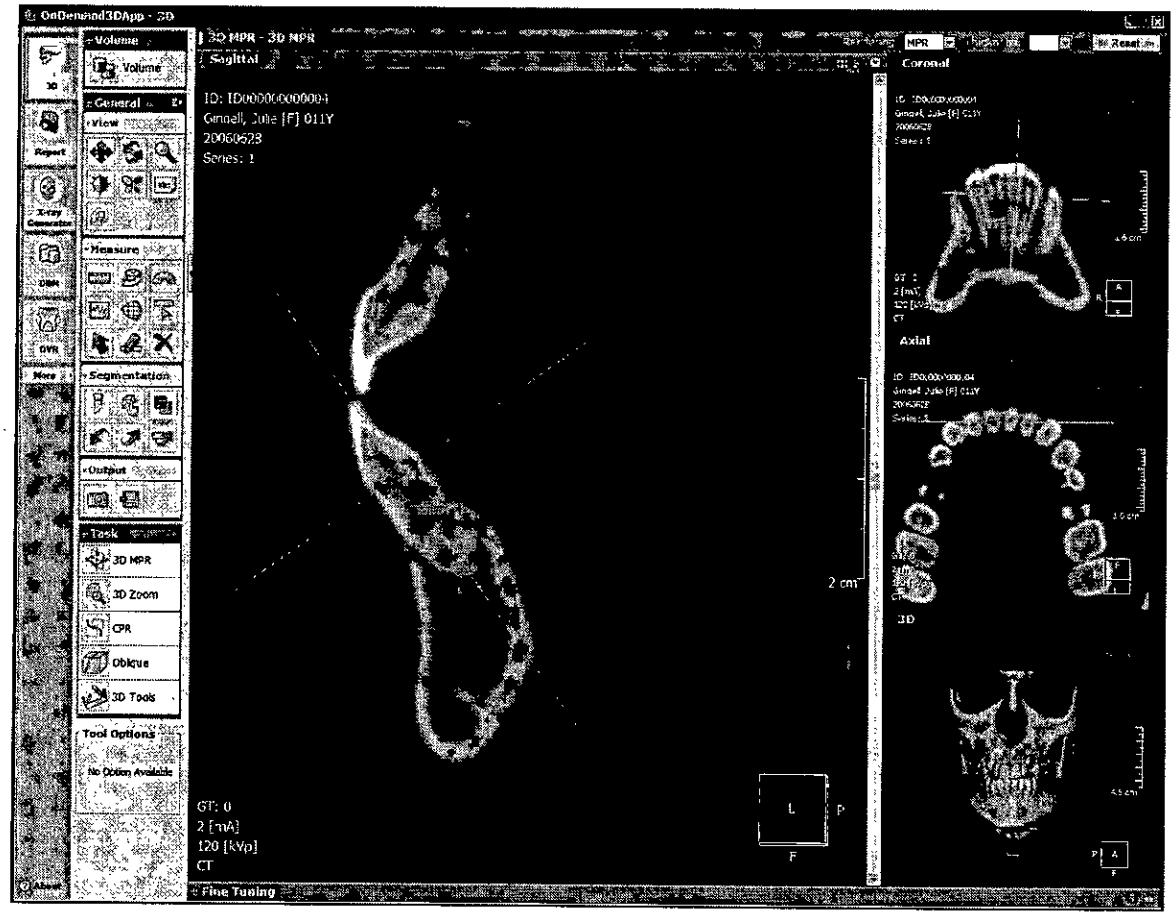


Figure 4: In the axial view, place the sagital plane through the "long axis" of the tooth, defined as a line connecting the most convex points on the labial and lingual aspects of the tooth.



Figure 5: In the sagital view, identify the CEJ and apex of the incisor. Mark these points with lines running perpendicular to the long axis of the tooth and parallel to the coronal plane.

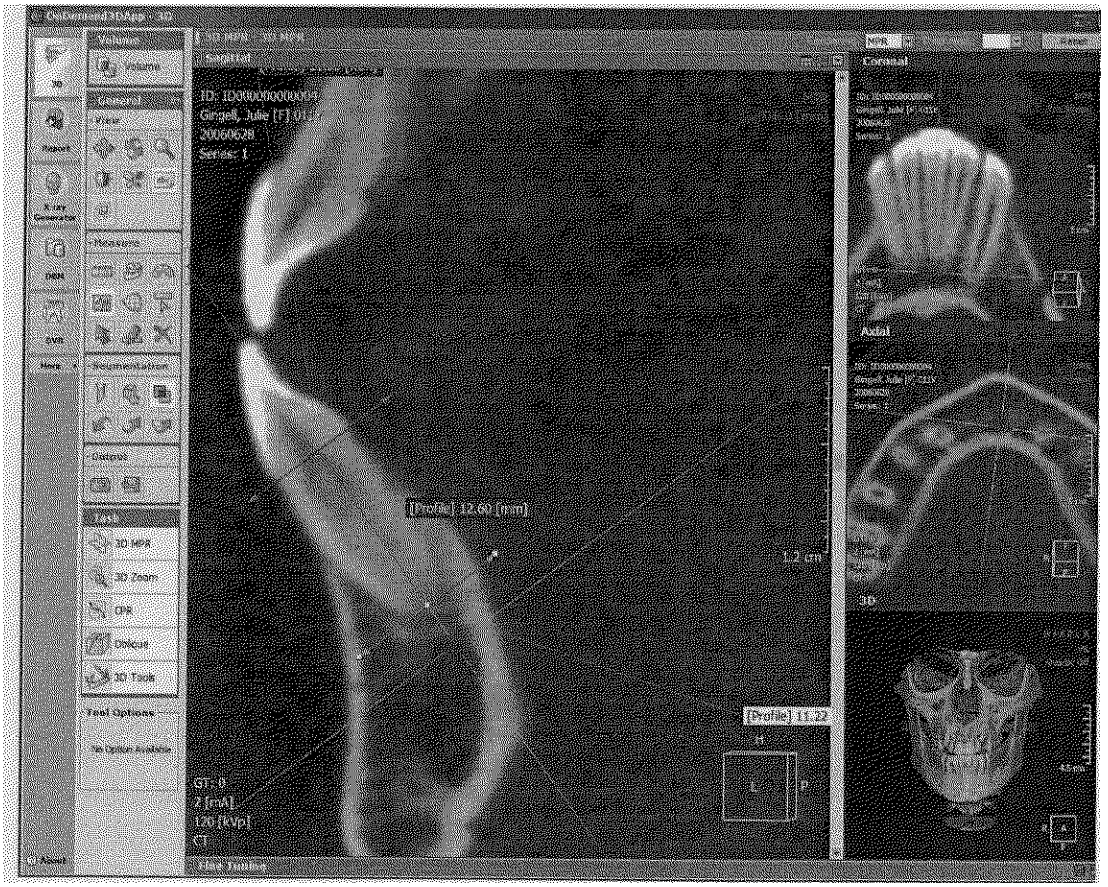


Figure 6: Using these two lines as endpoints, measure the length of the root. Defining the CEJ as 0% and the apex as 100% root length, place two more marker lines at the 1/3 and 2/3 root length levels.

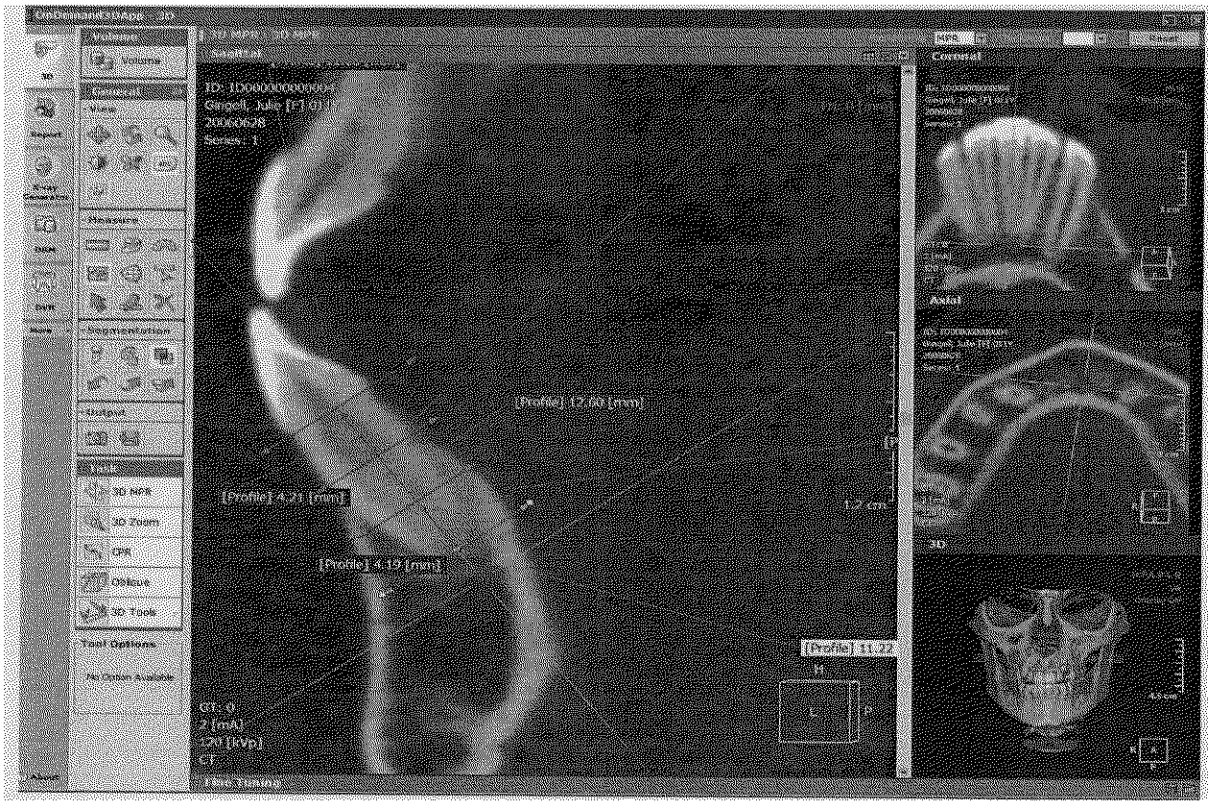


Figure 7: Place the axial plane over the line marking the 2/3 root length level.

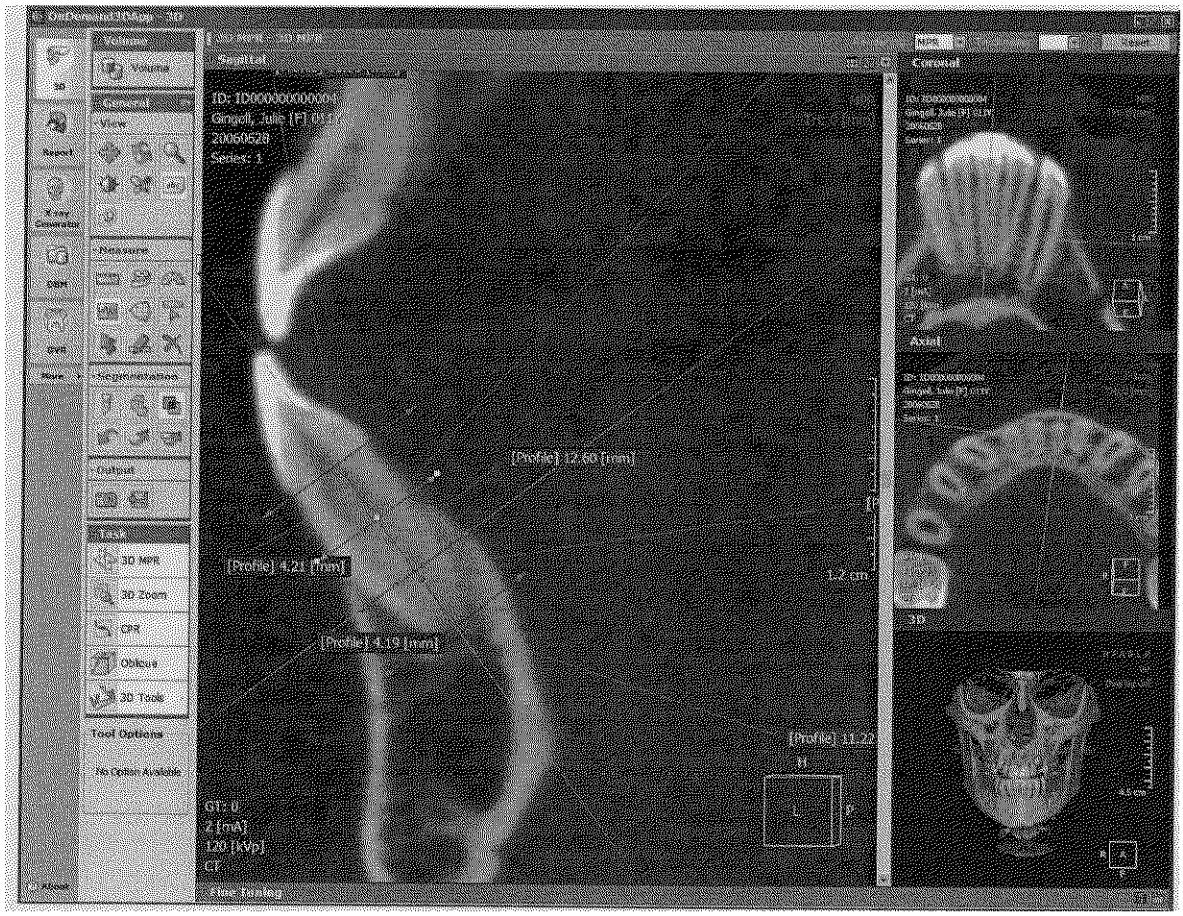
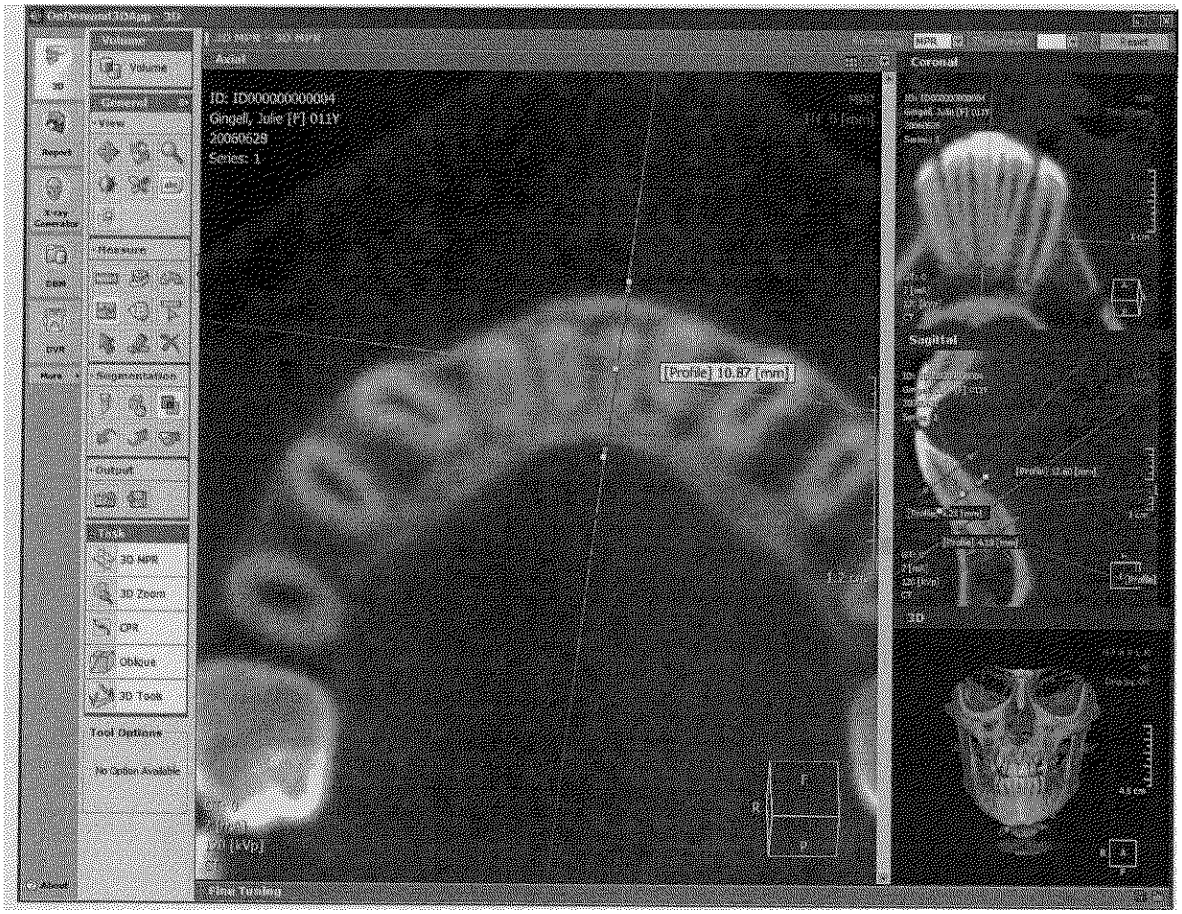


Figure 8: Return to the axial view. Using the histogram function place a line running along the sagital plane. Set the endpoints of the line just outside the extent of the bone.



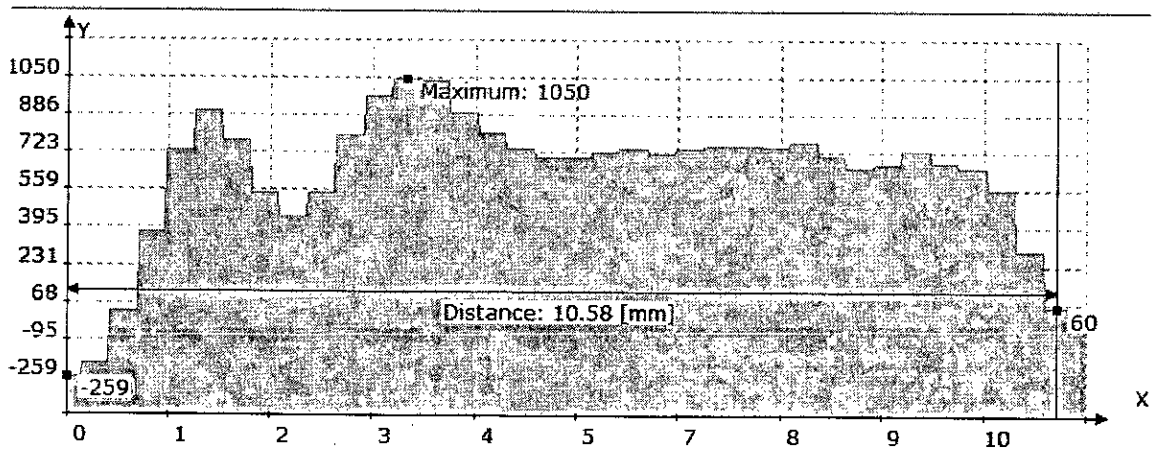
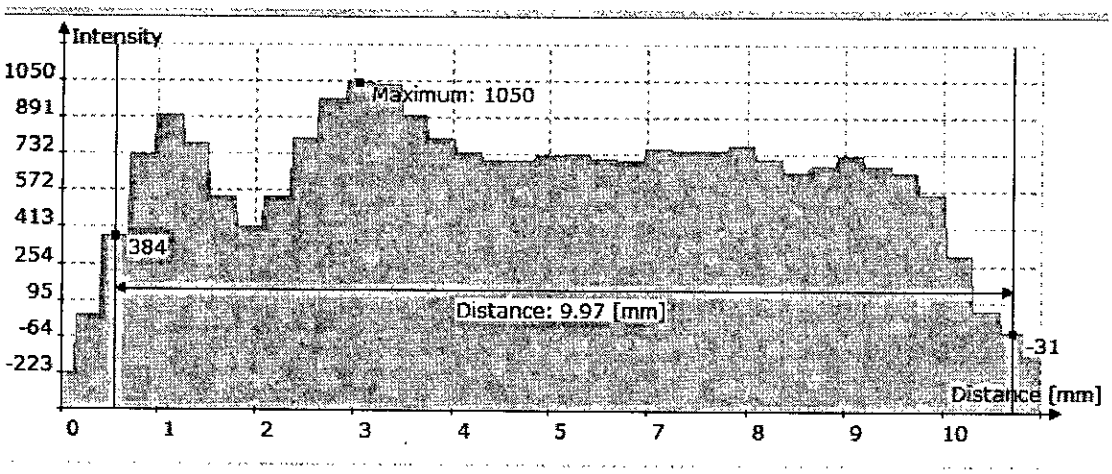
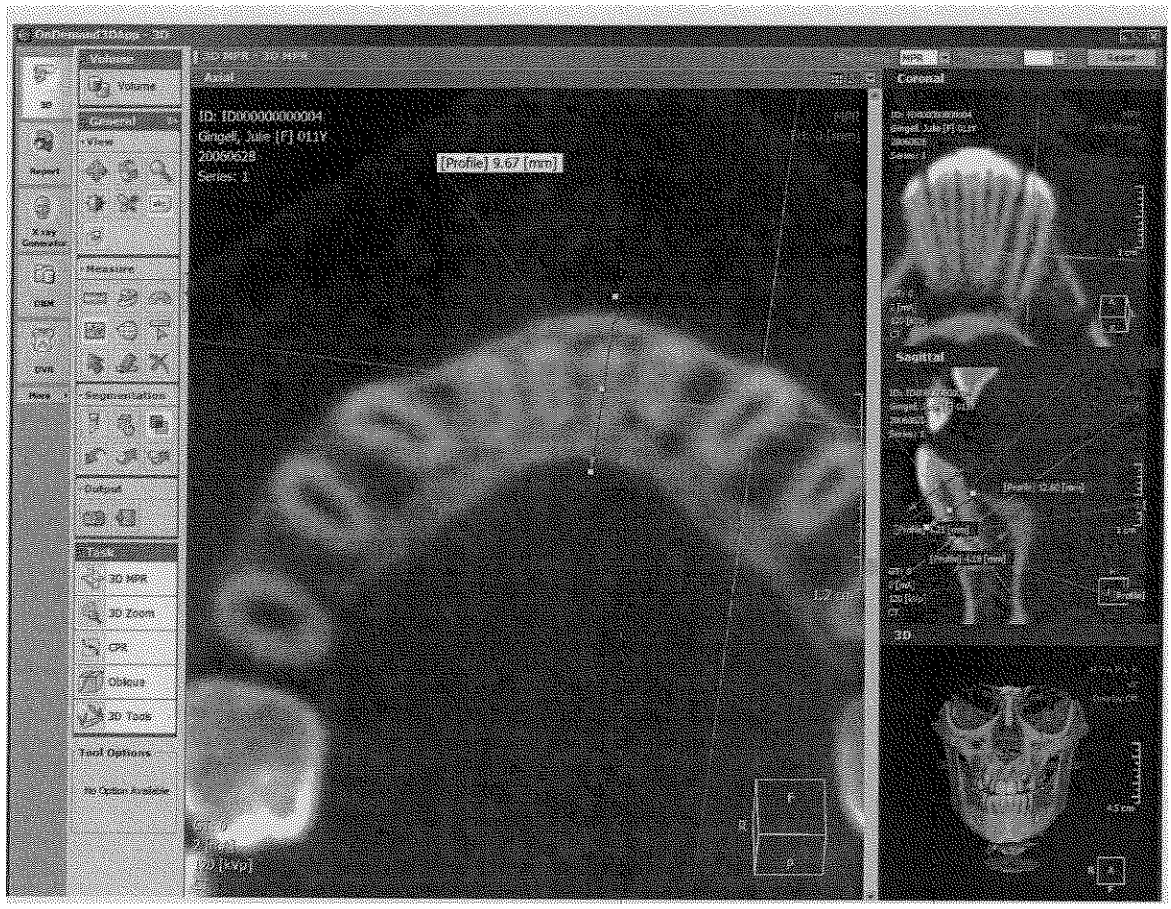
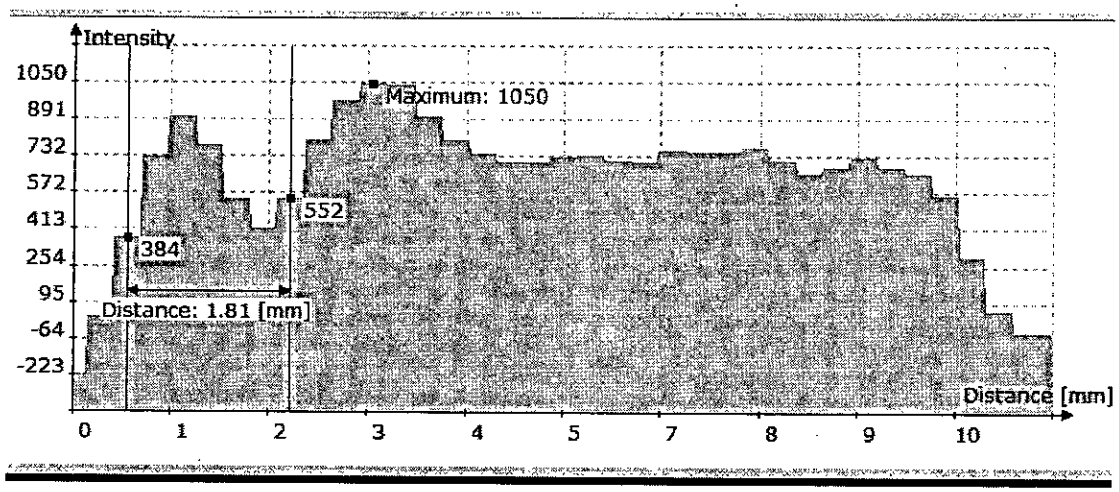


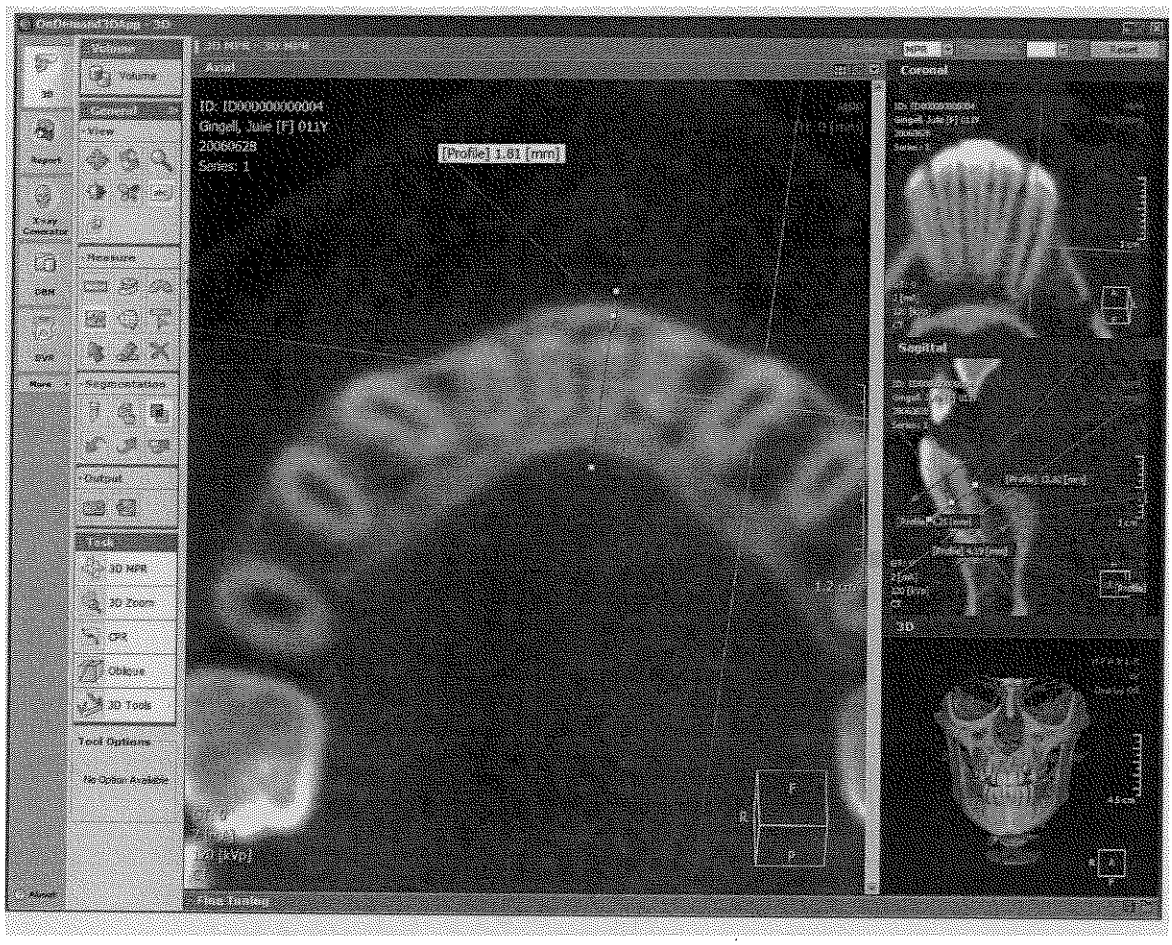
Figure 9: To mark the labial extent of bone, adjust the left tail of the histogram to a likely boundary between the soft tissue and bone. The transition between these two different structures will be noted by a large change in Hounsfield units along the histogram. Visually confirm this position on the radiograph and make any necessary corrections.



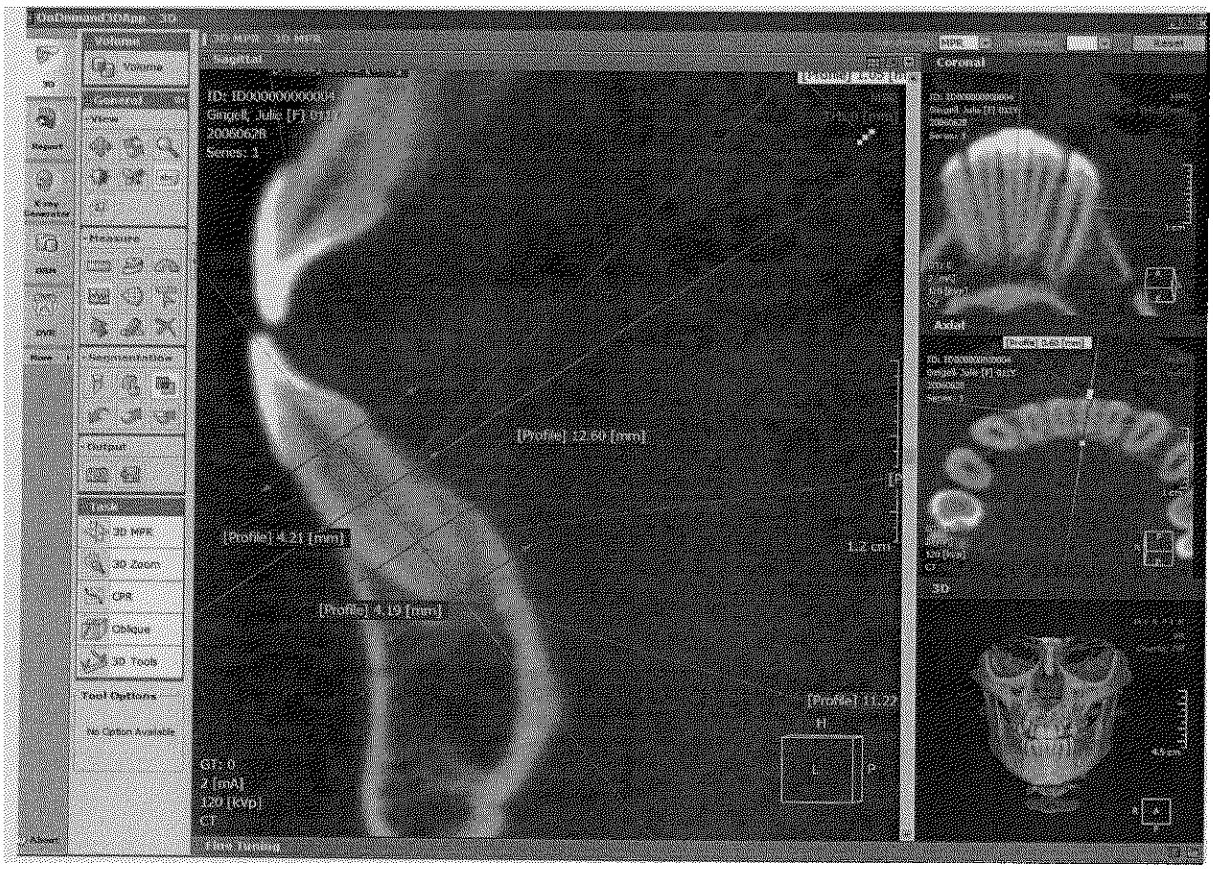

Axial
Coronal
Sagittal
3D
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Gingell, Julie [F] 011Y
20080628
Series: 1
[Profile] 9.67 [mm]
Volume
View
Measure
Segmentation
Output
3D MPR
3D Zoom
CPR
Oblique
3D Tools
Tool Options
No Option Available

Figures 10: To indicate the transition between tooth and bone, adjust the right tail of the histogram. The transition between these two different structures will again be accompanied by a large change in Hounsfield units along the histogram. Note that the thickness of bone labial to the incisor is calculated automatically.




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20060628
Series: 1
[Profile] 1.81 [mm]
Axial
Coronal
Sagittal
3D
Volume
View
Measure
Segmentation
Output
Tools
3D MPR
3D Zoom
CPR
Oblique
3D Tools
Tool Options
No Option Available

Figures 11: Return to the sagital view and adjust the axial plane such that it passes over the line marking the 1/3 root length. In order to measure the thickness of bone at the 1/3 root level, repeat all steps listed above.



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APPENDIX 1

IRB Approval

Case Western Reserve University Institutional Review Board

NOTICE OF EXEMPTION

Responsible Investigator: **J. Martin Palomo**
Department: **Dental Orthodontics**
IRB Protocol Number: **20110406**
Title: ***Evaluation of the Bone Thickness Surrounding the Mandibular Incisors Before and After Orthodontic Treratment***
Co-Investigator: **Jesse Carmen**

Exemption Date: May 2, 2011

The Institutional Review Board (IRB) has deemed the above protocol EXEMPT under 45 Code of Federal Regulations (CFR) part 46.101b. The IRB will not conduct subsequent reviews of this protocol.

Any changes to the protocol that put it under the purview of the IRB would require a formal application to, and approval of, the IRB prior to implementation of the change IRB applications are available at the CWRU IRB Pages.

APPENDIX 2

RAW DATA

Table 1: Demographic information

Patient ID	Gender	Race	Age (years.month)	Tx Time
AD37	F	Cauc	13.5	23
AL97 **	F	Cauc	13.6	22
BL67	F	Cauc	14.3	24
BU123	F	Cauc	12.8	31
CA71	F	Cauc	13.1	22
CA201	M	Cauc	11.1	24
CA202	F	Cauc	11.4	27
CO237 **	F	Cauc	11.7	24
DU53	F	Cauc	12.2	28
DU69 **	M	Cauc	14.1	24
FO74	M	Cauc	11.1	25
FR89 **	F	A.A	16.5	17
GI61	M	Cauc	13.0	19
HA316	F	Cauc	15.5	19
HA340	M	Cauc	11.4	25
IS24	F	OTHER	11.1	23
JO34 **	F	A.A	11.1	7
JU21	M	Cauc	14.5	28
KN3 **	M	Cauc	15.9	16
LA77	F	Cauc	14.9	19
MA257	M	A.A	13.4	14
MA339	M	Cauc	16.1	10
ME14	F	Cauc	10.5	21
MI171	M	Cauc	11.4	28
MU83	M	Cauc	12.5	24
PI67	M	Cauc	15.2	27
PO112 **	F	A.A	14.3	23
PR74 **	F	Cauc	15.2	22
RO159 **	F	Cauc	13.1	22
RU47	M	Cauc	16.5	24
SC142	F	Cauc	10.1	23
SH129	F	Cauc	15.0	24
SI56 **	M	Cauc	15.0	24
SI96	M	Cauc	15.1	16
TA109	F	Cauc	16.0	27
WI227	M	Cauc	13.7	21
ZA27	F	OTHER	13.1	24
ZI25	M	Cauc	15.5	26
ZO7	M	Cauc	11.8	20
ZU16	M	Cauc	14.7	26

Table 2. Raw data for pre-treatment bone thickness

	LR2 Initial					LR1 Initial				
Patient ID	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual
AD37	11.5	0.7	0.8	1.5	2.6	10.5	0.6	1.0	1.2	1.6
AL97 **	11.7	0.4	1.1	1.5	1.7	10.6	0.7	1.1	1.6	2.3
BL67	13.5	0.9	0.7	1.9	1.9	12.0	0.6	0.7	1.4	1.5
BU123	11.2	0.4	1.6	2.0	2.7	10.3	0.5	3.4	1.9	3.8
CA71	14.3	0.6	1.1	0.8	2.7	12.6	0.7	1.3	0.8	2.7
CA201	11.1	1.0	0.9	2.4	1.7	10.7	1.0	1.0	2.5	1.7
CA202	11.1	0.8	2.8	1.4	3.5	10.1	1.0	0.8	1.6	1.1
CO237 **	13.0	0.8	1.2	2.6	2.6	11.9	0.7	2.6	1.5	3.0
DU53	11.2	0.6	2.0	1.0	3.0	11.0	0.4	1.5	1.6	3.0
DU69 **	11.5	0.8	0.8	0.9	0.8	10.3	0.8	2.3	1.1	1.4
FO74	14.2	0.8	1.2	0.8	2.4	11.7	0.8	1.4	1.1	1.5
FR89 **	9.8	0.8	0.7	1.7	1.0	9.4	0.4	1.0	1.9	1.2
GI61	12.2	1.1	1.0	2.3	2.3	11.8	0.8	1.1	2.7	1.7
HA316	11.9	0.6	1.1	0.9	1.6	10.5	0.8	0.7	1.2	0.8
HA340	13.6	0.8	3.4	2.8	4.9	12.2	0.9	2.7	1.9	4.4
IS24	12.2	0.8	1.2	1.2	2.4	10.9	0.8	1.1	1.9	1.8
JO34 **	12.6	0.4	0.8	0.7	0.7	10.8	0.6	0.7	0.8	1.5
JU21	14.4	0.5	1.2	1.2	2.3	12.5	0.5	1.2	1.7	1.9
KN3 **	11.1	0.8	0.5	0.8	0.8	9.6	0.4	0.7	1.1	0.7
LA77	11.9	0.4	1.9	1.1	3.1	10.7	0.8	1.3	1.8	1.6
MA257	11.2	0.4	1.2	0.8	1.7	9.8	0.9	1.3	0.8	1.9
MA339	13.0	0.3	0.4	0.8	1.8	11.5	0.8	0.9	0.6	1.1
ME14	9.7	0.8	0.9	0.8	1.1	9.2	0.7	1.0	1.2	1.1
MI171	12.5	0.8	0.4	1.8	1.9	11.2	0.7	0.7	1.5	1.5
MU83	11.2	0.8	1.0	1.1	1.3	11.5	0.4	0.7	0.8	0.8
PI67	11.7	1.0	1.1	0.9	1.6	11.5	0.7	0.7	1.5	1.4
PO112 **	13.1	0.7	1.8	0.7	2.3	10.6	0.4	1.1	1.0	1.5
PR74 **	11.5	0.4	0.8	0.9	1.4	10.9	0.8	0.7	1.1	1.1
RO159 **	11.9	0.7	1.5	1.1	1.5	10.3	0.8	1.1	1.1	1.5
RU47	11.9	0.7	0.7	0.8	1.1	11.7	0.6	0.4	0.7	0.7
SC142	11.8	0.7	1.5	1.5	1.4	10.8	0.7	1.1	1.9	1.2
SH129	10.8	0.8	1.2	1.2	2.0	10.2	1.0	0.8	2.1	1.8
SI56 **	10.9	0.7	1.9	0.8	2.9	11.7	0.8	1.2	1.5	2.5
SI96	11.8	0.6	0.5	1.0	0.8	11.6	0.7	0.7	0.9	0.9
TA109	10.3	0.4	0.7	0.7	0.7	10.0	0.7	0.7	0.5	1.3
WI227	12.4	0.7	1.1	1.0	1.9	10.9	0.4	1.2	0.9	1.9
ZA27	10.8	0.7	1.9	0.8	0.8	10.3	0.8	1.5	1.2	2.2
ZI25	9.5	0.9	1.2	0.9	1.8	9.7	0.8	0.8	1.0	1.3
ZO7	11.8	0.4	2.4	1.8	2.7	11.0	0.7	1.7	2.2	2.4
ZU16	12.1	0.7	1.0	2.0	1.5	10.3	0.8	1.1	1.9	1.1

Table 2. Raw data for pre-treatment bone thickness

	LL1 Initial					LL2 Initial				
Patient ID	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual
AD37	10.1	0.8	0.8	1.1	1.9	11.7	0.7	0.8	1.2	1.6
AL97 **	10.6	0.8	1.5	1.5	2.3	10.7	0.8	1.1	1.1	1.9
BL67	12.5	0.7	0.6	1.9	1.1	13.9	0.5	0.8	1.5	1.7
BU123	10.2	0.9	1.5	1.9	2.3	11.1	0.4	1.5	0.8	2.6
CA71	13.2	0.5	1.5	1.0	3.4	13.8	0.7	1.5	0.8	2.6
CA201	10.1	1.0	1.0	2.3	2.0	11.6	0.8	1.2	1.8	2.3
CA202	9.5	0.9	0.8	1.2	1.5	11.0	0.8	1.8	1.2	1.9
CO237 **	11.3	0.7	2.3	0.8	3.5	12.3	1.5	1.9	3.0	2.2
DU53	11.5	0.6	0.8	2.0	2.9	11.6	0.9	2.2	1.5	2.9
DU69 **	10.3	0.4	1.9	0.8	1.2	11.4	1.1	1.5	0.8	1.2
FO74	13.0	0.4	1.9	1.5	1.7	14.1	0.4	1.2	0.6	2.3
FR89 **	9.3	0.9	0.4	1.0	0.8	9.8	0.9	0.8	1.1	1.3
GI61	11.8	0.8	1.5	1.8	2.4	12.9	0.8	1.9	0.9	3.1
HA316	10.5	1.0	1.1	1.1	1.0	11.6	0.8	1.2	1.9	1.9
HA340	12.2	1.1	2.8	2.3	4.6	13.2	0.9	3.1	2.3	4.8
IS24	11.0	0.8	1.2	1.5	2.0	12.1	0.8	2.0	1.2	2.3
JO34 **	11.0	0.8	0.8	1.1	1.6	12.3	0.5	0.4	0.8	1.2
JU21	11.6	0.8	1.0	1.4	1.5	14.3	0.8	1.0	0.8	2.0
KN3 **	9.3	0.8	0.4	1.2	1.1	10.1	0.8	0.8	0.8	1.2
LA77	11.0	1.0	1.3	2.7	2.3	11.5	0.8	1.5	2.0	2.2
MA257	10.2	0.4	1.6	0.4	2.0	11.0	0.4	1.5	0.4	2.2
MA339	11.1	0.4	0.9	0.8	1.1	12.9	0.8	0.8	0.8	1.3
ME14	9.6	0.8	0.9	1.0	1.7	10.3	0.8	1.4	1.5	2.3
MI171	11.9	0.7	0.8	1.5	1.6	13.0	0.7	1.4	1.6	2.3
MU83	10.4	0.6	0.9	0.8	1.0	11.6	0.7	0.8	1.1	1.2
PI67	10.9	0.9	1.1	1.5	1.2	11.7	0.7	1.4	0.8	1.6
PO112 **	10.3	0.5	1.1	1.0	1.9	12.2	0.4	1.6	0.8	1.9
PR74 **	10.7	0.8	1.1	1.1	1.4	11.5	0.7	1.7	0.8	2.3
RO159 **	11.1	0.6	0.7	1.2	1.2	12.2	0.8	0.8	1.2	1.2
RU47	12.2	0.7	0.4	0.6	0.7	11.0	0.4	0.8	0.4	1.7
SC142	10.9	0.8	1.6	1.3	1.8	11.9	0.5	1.6	0.8	2.0
SH129	10.1	0.9	1.2	1.5	1.9	10.9	0.7	0.8	1.5	1.8
SI56 **	10.9	0.8	1.5	0.8	2.3	10.6	0.9	1.9	1.0	2.6
SI96	11.7	0.6	0.7	0.7	1.0	11.5	0.6	0.8	0.9	1.1
TA109	10.0	0.8	1.0	0.8	0.8	10.8	0.7	0.8	0.8	1.5
WI227	10.8	0.8	1.1	0.9	2.1	12.0	0.8	1.1	0.9	2.0
ZA27	10.4	0.9	1.2	1.0	2.7	10.8	0.8	1.9	0.8	3.4
ZI25	9.6	0.8	0.9	1.1	1.9	9.7	0.7	1.3	0.9	2.2
ZO7	10.7	0.9	1.2	2.5	2.2	11.2	0.8	2.6	2.7	2.9
ZU16	10.7	0.8	0.8	1.1	1.0	11.9	0.8	1.2	1.0	1.3

Table 3: Raw data for post-treatment bone thickness

	LR2 Final					LR1 Final				
Patient ID	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual
AD37	11.5	0.6	0.8	3.3	1.3	10.5	1.0	0.7	3.8	0.8
AL97 **	11.7	0.9	0.8	1.4	1.2	10.6	0.8	0.8	1.5	1.1
BL67	13.5	0.7	0.8	1.6	1.9	12.0	0.7	0.8	1.1	2.0
BU123	11.2	0.7	1.2	1.5	2.3	10.2	0.7	1.9	2.3	3.0
CA71	14.3	1.2	0.4	1.2	0.8	12.6	1.1	0.4	1.2	0.8
CA201	11.1	1.1	0.4	1.5	0.8	10.7	1.4	0.4	2.4	0.4
CA202	11.1	0.6	1.1	1.3	1.9	10.1	0.8	0.9	2.1	0.8
CO237 **	13.0	0.4	1.1	2.4	1.9	11.9	0.9	1.5	2.3	2.3
DU53	11.2	0.9	2.3	1.2	3.0	11.0	0.6	1.1	1.0	1.9
DU69 **	11.5	0.6	0.8	1.2	0.9	10.3	0.7	0.7	0.7	1.0
FO74	14.2	0.6	1.2	1.6	1.4	11.7	0.4	1.4	1.5	0.8
FR89 **	9.8	0.6	1.2	0.8	1.4	9.4	0.7	1.1	0.8	1.7
GI61	12.2	0.8	1.4	1.6	2.3	11.8	1.1	0.6	2.7	1.0
HA316	11.9	0.6	0.8	1.3	1.3	10.5	0.8	0.5	1.1	0.7
HA340	13.6	0.8	2.4	2.5	4.2	12.2	0.9	1.9	2.2	3.8
IS24	12.2	0.4	1.5	0.8	2.2	10.9	0.7	0.7	1.4	1.2
JO34 **	12.6	0.7	0.7	0.8	0.8	10.8	0.7	1.0	1.0	1.1
JU21	14.4	0.7	1.1	1.9	1.1	12.5	0.8	1.1	1.1	1.9
KN3 **	11.1	0.8	0.8	0.8	0.7	9.6	0.7	0.8	0.8	0.6
LA77	11.9	0.9	1.9	1.2	3.2	10.7	0.9	0.7	1.8	2.1
MA257	11.2	0.6	1.1	0.6	2.2	9.8	0.8	1.7	0.8	2.2
MA339	13.0	0.6	0.4	0.8	0.8	11.5	0.6	0.8	0.8	1.0
ME14	9.7	0.9	0.7	1.1	1.0	9.2	0.7	0.7	1.2	0.9
MI171	12.5	1.0	0.8	2.9	0.8	11.2	1.3	0.4	3.8	0.8
MU83	11.2	0.7	0.8	0.8	0.8	11.5	0.7	0.8	0.7	0.8
PI67	11.7	1.1	1.0	1.5	0.8	11.5	0.9	0.6	1.6	0.6
PO112 **	13.1	0.8	2.1	0.8	2.8	10.6	0.7	1.3	1.1	1.7
PR74 **	11.5	0.4	1.2	0.8	2.2	10.9	0.7	0.7	1.6	0.7
RO159 **	11.9	0.7	0.8	1.8	1.6	10.3	0.8	0.9	1.2	1.0
RU47	11.9	0.9	0.8	1.2	0.7	11.7	0.9	0.8	1.4	0.8
SC142	11.8	0.8	0.8	1.1	1.4	10.8	1.0	0.8	1.0	0.7
SH129	10.8	0.9	1.4	1.6	2.0	10.2	1.2	0.8	2.2	1.1
SI56 **	10.9	0.9	1.5	1.1	2.0	11.7	0.7	1.0	2.3	1.1
SI96	11.8	1.1	0.8	1.1	0.7	11.6	1.0	0.5	1.1	0.4
TA109	10.3	0.7	0.8	0.8	0.9	10.0	0.7	0.8	0.8	0.7
WI227	12.4	0.8	0.9	0.8	1.9	10.9	0.7	0.7	0.8	1.6
ZA27	10.8	0.8	1.6	1.0	2.7	10.3	0.8	1.9	1.0	2.9
ZI25	9.5	0.9	0.9	1.1	1.1	9.7	0.7	0.6	0.8	0.7
ZO7	11.8	0.7	2.1	1.9	3.0	11.0	0.7	1.6	1.2	2.7
ZU16	12.1	0.7	0.4	1.4	0.8	10.3	1.0	0.8	1.6	1.0

Table 3 continued: Raw data for post-treatment bone thickness

	LL1 Final					LL2 Final				
Patient ID	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual
AD37	10.1	1.0	0.4	3.4	0.5	11.7	0.8	0.6	2.7	0.6
AL97 **	10.6	0.8	0.9	1.5	1.1	10.7	1.1	1.2	1.2	2.1
BL67	12.5	0.6	0.4	2.2	1.1	13.9	0.5	0.8	2.4	1.2
BU123	10.2	0.7	1.5	2.3	2.3	11.1	0.8	1.6	2.7	2.3
CA71	13.2	0.8	1.2	0.8	1.6	13.8	0.8	0.8	1.1	1.7
CA201	10.1	0.7	0.7	1.5	1.1	11.6	1.1	0.8	2.3	1.1
CA202	9.5	0.9	1.1	1.5	0.8	11.0	1.0	1.0	1.9	1.9
CO237 **	11.3	0.8	1.5	1.2	1.9	12.3	0.7	1.1	2.3	2.3
DU53	11.5	0.4	1.1	1.4	1.8	11.6	0.5	2.3	1.1	3.7
DU69 **	10.3	0.7	1.1	1.1	1.8	11.4	1.1	1.2	1.2	1.6
FO74	13.0	0.6	1.5	1.8	1.7	14.1	0.8	0.8	2.3	1.9
FR89 **	9.3	0.9	1.2	0.8	1.2	9.8	0.8	1.2	0.8	1.1
GI61	11.8	1.2	0.6	3.5	0.8	12.9	0.9	1.4	1.6	2.6
HA316	10.5	0.6	0.7	1.8	1.0	11.6	0.9	1.2	2.3	2.3
HA340	12.2	0.9	1.5	2.6	3.7	13.2	0.4	2.7	1.9	5.0
IS24	11.0	0.8	0.9	1.5	1.0	12.1	0.8	1.4	0.8	2.1
JO34 **	11.0	0.9	1.0	1.1	1.2	12.3	1.0	1.1	1.0	1.4
JU21	11.6	0.9	1.2	1.2	1.3	14.3	1.1	1.1	1.5	1.3
KN3 **	9.3	0.8	0.8	0.9	0.7	10.2	0.5	0.7	0.8	0.8
LA77	11.1	0.9	0.8	2.3	1.5	11.5	0.7	1.2	1.9	2.9
MA257	10.2	0.5	1.5	0.5	2.6	11.0	0.6	1.2	0.5	2.2
MA339	11.1	0.8	0.5	0.8	1.0	12.9	0.7	1.1	0.6	1.7
ME14	9.6	1.1	0.8	1.3	1.0	10.3	0.8	1.0	1.1	1.3
MI171	11.9	1.2	1.0	3.6	0.8	13.0	0.9	0.8	2.5	1.2
MU83	10.4	0.8	0.8	0.9	0.8	11.6	0.6	0.8	0.9	1.1
PI67	10.8	0.9	0.9	1.3	0.9	11.7	1.0	1.0	1.8	1.1
PO112 **	10.3	0.8	1.2	0.8	1.9	12.2	0.8	1.4	1.1	1.5
PR74 **	10.7	1.0	1.0	1.8	1.0	11.5	0.4	2.6	3.0	3.0
RO159 **	11.1	0.8	0.7	1.5	0.8	12.2	0.8	1.2	1.9	1.2
RU47	12.2	0.9	0.8	1.0	0.8	11.0	0.8	0.8	0.8	0.8
SC142	10.9	1.0	0.8	1.1	1.3	11.9	1.0	1.1	1.1	1.4
SH129	10.1	1.0	1.0	1.9	1.1	10.9	0.8	1.0	1.5	1.8
SI56 **	10.9	1.0	1.0	1.5	1.3	10.6	0.9	1.2	1.2	1.8
SI96	11.7	0.9	0.8	1.2	0.8	11.5	1.0	0.8	1.2	0.8
TA109	10.0	0.8	0.7	0.9	0.9	10.8	0.8	0.9	1.1	0.9
WI227	10.8	0.8	1.0	0.8	2.6	12.0	0.8	0.8	0.8	1.6
ZA27	10.4	0.9	2.0	1.2	3.3	10.8	0.9	1.9	1.0	3.1
ZI25	9.6	0.8	0.9	0.8	1.1	9.7	1.0	1.1	0.9	1.9
ZO7	10.7	0.7	2.3	1.4	3.3	11.2	0.7	2.2	2.0	3.2
ZU16	10.7	0.9	1.0	1.5	0.8	11.8	0.8	1.0	1.2	1.2

Table 4 Raw data for IMPA measurements

Patient ID	Initial IMPA	Final IMPA	Δ in IMPA
AD37	85.0	98.9	13.9
AL97 **	94.4	94.1	-0.3
BL67	95.9	98.4	2.5
BU123	91.3	98.2	6.9
CA71	93.3	93.1	-0.2
CA201	92.3	92.3	0.0
CA202	87.5	87.9	0.4
CO237 **	89.1	102.8	13.7
DU53	98.3	101.3	3.0
DU69 **	88.7	95.3	6.6
FO74	96.7	99.8	3.1
FR89 **	100.9	95.2	-5.7
GI61	94.4	99.0	4.6
HA316	98.8	98.4	-0.4
HA340	81.7	89.8	8.1
IS24	97.6	100.0	2.4
JO34 **	89.5	89.3	-0.2
JU21	92.9	94.6	1.7
KN3 **	107.2	105.9	-1.3
LA77	105.8	104.4	-1.4
MA257	95.4	100.2	4.8
MA339	93.9	97.4	3.5
ME14	88.7	88.1	-0.6
MI171	92.3	101.9	9.6
MU83	98.0	98.0	0.0
PI67	88.9	95.5	6.6
PO112 **	99.4	100.7	1.3
PR74 **	94.3	99.6	5.3
RO159 **	88.2	87.2	-1.0
RU47	78.5	86.1	7.6
SC142	81.5	79.1	-2.4
SH129	93.1	104.9	11.8
SI56 **	81.8	81.7	-0.1
SI96	90.5	94.5	4.0
TA109	88.5	101.7	13.2
WI227	90.9	82.8	-8.1
ZA27	97.4	99.6	2.2
ZI25	87.2	83.3	-3.9
ZO7	97.6	98.2	0.6
ZU16	94.0	85.1	-8.9

Table 5: Raw data for reliability testing

	Test #1						Test #2					
Patient ID	Tooth	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual	Tooth	Root Length	1/3 Facial	1/3 Lingual	2/3 Facial	2/3 Lingual
AD37	LR1	10.5	0.6	1.0	1.2	1.6	LR1	10.6	0.7	0.8	1.1	1.6
AL97	LR1	10.6	0.7	1.1	1.6	2.3	LR1	10.7	0.7	1.1	1.7	2.2
CA201	LL2	11.6	0.8	1.2	1.8	2.3	LL2	11.7	0.8	1.2	2.0	2.3
CO237	LL1	11.3	0.7	2.3	0.8	3.5	LL1	11.2	0.7	2.1	0.7	3.4
DU53	LL2	11.6	0.9	2.2	1.5	2.9	LL2	11.4	0.8	2.2	1.6	2.8
DU69	LR2	11.5	0.8	0.8	0.9	0.8	LR2	11.6	0.8	0.6	0.7	0.8
FO74	LR1	11.7	0.8	1.4	1.1	1.5	LR1	12.0	0.6	1.5	1.5	1.6
FR89	LL1	9.3	0.9	0.4	1.0	0.8	LL1	9.1	0.6	0.6	0.9	0.7
GI61	LL1	11.8	0.8	1.5	1.8	2.4	LL1	12.0	0.6	1.4	1.9	2.5
HA316	LL2	11.6	0.8	1.2	1.9	1.9	LL2	11.3	0.7	1.1	1.5	2.2
HA340	LL1	12.2	1.1	2.8	2.3	4.6	LL1	12.4	0.8	2.6	2.5	4.5
IS24	LR1	10.9	0.8	1.1	1.9	1.8	LR1	11.1	0.8	1.1	1.7	2.0
JO34	LR1	10.8	0.7	1.0	1.0	1.1	LR1	10.6	0.8	0.7	0.8	1.2
JU21	LR2	14.4	0.5	1.2	1.2	2.3	LR2	14.5	0.7	1.2	1.4	2.4
KN3	LL2	10.1	0.8	0.8	0.8	1.2	LL2	10.4	0.8	0.7	0.8	1.1
LA77	LR2	11.9	0.4	1.9	1.1	3.1	LR2	12.1	0.4	1.9	1.1	3.1
MA257	LL2	11.0	0.4	1.5	0.4	2.2	LL2	11.1	0.4	1.2	0.4	1.9
MA339	LR2	13.0	0.3	0.4	0.8	1.8	LR2	12.6	0.5	0.5	0.8	1.7
ME14	LL1	9.7	0.8	0.9	0.8	1.1	LL1	9.9	0.8	1.1	1.0	1.4
MI171	LL1	11.9	0.7	0.8	1.5	1.6	LL1	11.9	0.6	1.1	1.7	1.7
PI67	LL1	10.9	0.9	1.1	1.5	1.2	LL1	10.8	0.6	0.8	1.3	1.2
PO112	LR2	13.1	0.7	1.8	0.7	2.3	LR2	12.7	0.7	1.7	0.7	2.7
PR74	LR1	10.9	0.8	0.7	1.1	1.1	LR1	11.4	0.7	0.9	1.1	1.2
RO159	LR2	11.9	0.7	1.5	1.1	1.5	LR2	11.8	0.6	1.4	1.1	1.4
RU47	LL1	12.2	0.7	0.4	0.6	0.7	LL1	12.3	0.7	0.5	0.6	0.9
SC142	LR1	10.8	0.7	1.1	1.9	1.2	LR1	11.0	0.7	1.1	1.8	1.5
SH129	LR2	10.8	0.8	1.2	1.2	2.0	LR2	11.0	0.9	1.1	1.1	1.9
SI56	LL2	10.6	0.7	1.9	1.0	2.6	LL2	10.9	0.9	1.8	1.0	2.6
WI227	LR1	10.9	0.4	1.2	0.9	1.9	LR1	10.7	0.7	1.1	0.8	1.9
ZU16	LR2	12.1	0.7	1.0	2.0	1.5	LR2	11.9	0.8	1.2	1.7	1.4

APPENDIX 3

All descriptive information related to the demographics of the sample population including age, gender, ethnicity, initial IMPA, final IMPA and change in IMPA.

Table 6: Descriptive summary of the study sample demographics

Variable	Group	Total	Percent
Gender	Male	19	47.5
	Female	21	52.4
Ethnicity/Race	Caucasian	34	85
	African American	4	10
	Other	2	5
Initial Age	$10 \leq x < 12$	11	27.5%
	$12 \leq x < 14$	18	45%
	$14 \leq x$	11	27.5%

Table 7: Comparison of age and gender distribution within the study sample

Gender	N	%	Initial Mean Age	Std. Deviation
Male	19	47.5	13 years, 8 months	1.81
Female	21	52.5	13 years, 2 months	1.86

*Independent Sample t-test performed to test for significant difference between age and gender. A p-value of 0.39 demonstrated no significant difference within the study sample.

Table 8: Descriptive summary of the treatment time for the study sample

	Mean ± S.D.	Minimum	Maximum
Treatment Time (months)	22.33 ± 4.84	7	31

Table 9: Categorical description of the treatment time for the study sample

Treatment Time (months)	N (%)
$x < 18$	6 (15%)
$18 \leq x < 24$	14 (35%)
$24 < x$	20 (50%)
Total	40 (100%)

Table 10: Categorical representation of the study sample with regards to initial, final, and change in lower incisor to mandibular plane angle (IMPA) measurements

	Subjects	$x < 90°$	$90° \leq x < 95°$	$95° \leq x < 100°$	$100° \leq x$
Initial	Number (Percentage)	14 (35%)	13 (32.5%)	10 (25%)	3 (7.5%)
Final	Number (Percentage)	11 (27.5%)	5 (12.5%)	14 (35%)	10 (25%)
		$x < -3°$	$-3° \leq x < 5°$	$5° \leq x < 10°$	$10° \leq x$
Change	Number (Percentage)	4 (10%)	25 (62.5%)	7 (17.5%)	4 (10%)

Table 11: Intraclass correlation results for reliability testing

Variable	Intraclass Correlation	Significance
Root Length	.975	.000
1/3 Facial	.508	.002
1/3 Lingual	.956	.000
2/3 Facial	.938	.000
2/3 Lingual	.983	.000

Table 12: Descriptive summary of bone thickness at specified locations before and after orthodontic treatment

	Surface	Initial		Final	
		Mean ± SD (mm)	Range (mm)	Mean ± SD (mm)	Range (mm)
LR2	1/3 Facial	0.68 ± 0.20	0.30 – 1.10	0.77 ± 0.19	0.40 – 1.20
	1/3 Lingual	1.23 ± 0.64	0.40 – 3.40	1.09 ± 0.51	0.40 – 1.20
	2/3 Facial	1.27 ± 0.57	0.70 – 2.80	1.35 ± 0.60	0.60 – 3.30
	2/3 Lingual	1.92 ± 0.88	0.70 – 4.90	1.62 ± 0.85	0.70 – 4.20
LR1	1/3 Facial	0.70 ± 0.17	0.40 – 1.00	0.83 ± 0.20	0.40 – 1.40
	1/3 Lingual	1.18 ± 0.61	0.40 – 3.40	0.93 ± 0.42	0.40 – 1.90
	2/3 Facial	1.39 ± 0.53	0.50 – 2.70	1.50 ± 0.77	0.70 – 3.80
	2/3 Lingual	1.71 ± 0.81	0.70 – 4.40	1.31 ± 0.80	0.40 – 3.80
LL1	1/3 Facial	0.76 ± 0.18	0.40 – 1.10	0.84 ± 0.17	0.40 – 1.20
	1/3 Lingual	1.14 ± 0.50	0.40 – 2.80	1.02 ± 0.40	0.40 – 2.30
	2/3 Facial	1.29 ± 0.54	0.40 – 2.70	1.51 ± 0.75	0.50 – 3.60
	2/3 Lingual	1.82 ± 0.81	0.70 – 4.60	1.41 ± 0.77	0.50 – 3.70
LL2	1/3 Facial	0.74 ± 0.21	0.40 – 1.50	0.81 ± 0.19	0.40 – 1.10
	1/3 Lingual	1.36 ± 0.56	0.40 – 3.10	1.20 ± 0.50	0.60 – 2.70
	2/3 Facial	1.17 ± 0.57	0.40 – 3.00	1.50 ± 0.67	0.50 – 3.00
	2/3 Lingual	2.05 ± 0.73	1.10 – 4.80	1.82 ± 0.90	0.60 – 5.00

APPENDIX 4

Table 13: Comparison of the change in bone thickness at specified locations before and after orthodontic treatment

	Surface	Mean ± S.D. (mm)	Range (mm)	p-value*
LR2	1/3 Facial	0.08 ± 0.24	-0.40 ± 0.60	.03**
	1/3 Lingual	-0.14 ± 0.44	-1.70 ± 0.50	.04**
	2/3 Facial	0.08 ± 0.52	-0.90 ± 1.80	.34
	2/3 Lingual	-0.30 ± 0.70	-1.90 ± 1.90	.00**
LR1	1/3 Facial	0.13 ±0.21	-0.40 ± 0.60	.00**
	1/3 Lingual	-0.25 ± 0.45	-1.60 ± 0.40	.00**
	2/3 Facial	0.10 ±0.70	-1.10 ± 2.60	.36
	2/3 Lingual	-0.40 ± 0.56	-1.90 ± 0.70	.00**
LL1	1/3 Facial	0.08 ±0.20	-0.40 ± 0.50	.01**
	1/3 Lingual	-0.13 ± 0.48	-1.30 ± 1.10	.10
	2/3 Facial	0.21 ±0.66	-1.10 ± 2.30	.04**
	2/3 Lingual	-0.41 ± 0.67	-1.80 ± 1.10	.00**
LL2	1/3 Facial	0.08 ±0.28	-0.80 ± 0.50	.09
	1/3 Lingual	-0.16 ± 0.38	-0.80 ± 0.90	.01**
	2/3 Facial	0.33 ±0.66	-0.70 ± 2.20	.00**
	2/3 Lingual	-0.23 ± 0.51	-1.20 ± 0.80	.01**

* p-value for paired sample t-test evaluating the difference in means
** indicates the value is significant at a p-value < 0.05

Appendix 5

Comparison of means and standard deviations for the change in thickness of bone labial and lingual to the mandibular incisors before and after orthodontic treatment and potential explanatory variables

Table 14: Gender differences in the change in the thickness of bone labial and lingual to the mandibular incisors before and after orthodontic treatment

		Male	Female	p-value*
LR2	1/3 Facial	0.08 ± 0.20	0.09 ± 0.28	0.98
	1/3 Lingual	-0.12 ± 0.36	-0.16 ± 0.50	0.79
	2/3 Facial	0.07 ± 0.52	0.09 ± 0.54	0.94
	2/3 Lingual	-0.48 ± 0.51	-0.14 ± 0.81	0.12
LR1	1/3 Facial	0.13 ± 0.25	0.12 ± 0.17	0.85
	1/3 Lingual	-0.24 ± 0.49	-0.25 ± 0.47	0.97
	2/3 Facial	0.10 ± 0.68	0.10 ± 0.74	0.98
	2/3 Lingual	-0.40 ± 0.48	-0.40 ± 0.64	1.00
LL1	1/3 Facial	0.12 ± 0.21	0.05 ± 0.18	0.25
	1/3 Lingual	-0.13 ± 0.54	-0.12 ± 0.44	0.93
	2/3 Facial	0.21 ± 0.74	0.22 ± 0.58	0.94
	2/3 Lingual	-0.25 ± 0.66	-0.56 ± 0.65	0.14
LL2	1/3 Facial	0.09 ± 0.25	0.06 ± 0.30	0.67
	1/3 Lingual	-0.25 ± 0.25	-0.07 ± 0.46	0.13
	2/3 Facial	0.29 ± 0.56	0.37 ± 0.75	0.71
	2/3 Lingual	-0.34 ± 0.48	-0.14 ± 0.53	0.22

* Independent sample t-test was employed to test for statistical significance

Table 15: Comparison of the changes in bone thickness at specified locations among the final IMPA groups

Variable		x < 90°	90° ≤ x < 95°	95° ≤ x < 100°	100° ≤ x	p-value*
LR2	Facial 1/3	0.07 ± 0.13	0.38 ± 0.22	-0.01 ± 0.21	0.09 ± 0.29	0.14**
	Lingual 1/3	-0.53 ± 0.50	-0.26 ± 0.38	-0.01 ± 0.29	0.17 ± 0.18	0.00**
	Facial 2/3	0.04 ±0.39	0.04 ± 0.61	0.10 ±0.69	0.12 ± 0.41	0.98
	Lingual 2/3	-0.45 ± 0.53	-092 ± 0.69	-0.13 ± 0.84	-0.08 ± 0.50	0.09
LR1	Facial 1/3	0.07 ± 0.18	0.30 ± 0.12	0.07 ± 0.23	0.17 ± 0.21	0.12
	Lingual 1/3	-0.18 ± 0.34	-0.42 ± 0.33	-0.26 ± 0.58	-0.20 ± 0.45	0.79
	Facial 2/3	0.10 ± 0.49	-0.04 ± 0.38	0.07 ± 0.87	0.22 ± 0.83	0.92
	Lingual 2/3	-0.44 ± 0.39	-0.98 ± 0.74	-0.20 ± 0.54	-0.35 ± 0.53	0.06
LL1	Facial 1/3	0.10 ± 0.14	0.08 ± 0.25	0.07 ± 0.24	0.08 ± 0.20	0.98
	Lingual 1/3	-0.15 ± 0.52	-0.18 ± 0.33	-0.09 ± 0.59	-0.12 ± 0.38	0.97
	Facial 2/3	0.19 ± 0.30	-0.14 ± 0.47	0.39 ± 0.82	0.16 ± 0.76	0.47
	Lingual 2/3	-0.45 ± 0.45	-0.86 ± 0.68	-0.09 ± 0.72	-0.58 ± 0.65	0.09
LL2	Facial 1/3	0.13 ± 0.29	0.28 ± 0.11	-0.06 ± 0.35	0.08 ± 0.28	0.13
	Lingual 1/3	-0.22 ± 0.45	-0.18 ± 0.36	-0.04 ± 0.38	-0.25 ± 0.33	0.53
	Facial 2/3	0.16 ± 0.37	0.38 ± 0.23	0.68 ± 0.90	0.00 ± 0.50	0.06
	Lingual 2/3	-0.34 ± 0.44	-0.58 ± 0.54	-0.11 ± 0.48	-0.11 ± 0.57	0.25

* p-value calculated using the one-way ANOVA test
** indicates the value is significant at a p-value < 0.05

Table 16: Comparison of the changes in bone at specified locations among the change in IMPA groups

Variable		x < -3°	-3° ≤ x <5°	5° ≤ x < 10°	10° ≤ x	p-value *
LR2	Facial 1/3	-0.03 ± 0.13	0.12 ± 0.26	0.09 ± 0.17	-0.03 ± 0.30	0.55
	Lingual 1/3	0.15 ± 0.47	-0.18 ± 0.45	-0.09 ± 0.49	0.05 ± 0.13	0.78
	Facial 2/3	-0.38 ± 0.48	0.04 ± 0.41	0.21 ± 0.56	0.53 ± 0.88	0.08
	Lingual 2/3	-0.25 ± 0.54	-0.27 ± 0.77	-0.36 ± 0.63	-0.45 ± 0.69	0.96
LR1	Facial 1/3	0.18 ± 0.19	0.10 ± 0.21	0.16 ± 0.25	0.20 ± 0.16	0.72
	Lingual 1/3	-0.23 ± 0.25	-0.15 ± 0.32	-0.56 ± 0.77	-0.33 ± 0.54	0.20
	Facial 2/3	-0.43 ± 0.46	-0.08 ± 0.42	0.56 ± 0.84	0.95 ± 1.14	0.00**
	Lingual 2/3	-0.13 ± 0.46	-0.36 ± 0.65	-0.51 ± 0.32	-0.70 ± 0.02	0.49
LL1	Facial 1/3	0.03 ± 0.05	0.08 ± 0.21	0.11 ± 0.26	0.10 ± 0.08	0.91
	Lingual 1/3	0.23 ± 0.40	-0.10 ± 0.47	-0.26 ± 0.59	-0.43 ± 0.26	0.23
	Facial 2/3	-0.05 ± 0.31	0.06 ± 0.55	0.57 ± 0.73	0.80 ± 1.00	0.06
	Lingual 2/3	-0.03 ± 0.60	-0.44 ± 0.67	-0.24 ± 0.53	-0.93 ± 0.76	0.24
LL2	Facial 1/3	0.05 ± 0.17	0.11 ± 0.24	0.07 ± 0.35	-0.13 ± 0.45	0.47
	Lingual 1/3	-0.08 ± 0.32	-0.18 ± 0.37	-0.10 ± 0.50	-0.18 ± 0.45	0.93
	Facial 2/3	-0.05 ± 0.20	0.24 ± 0.51	0.91 ± 0.90	0.28 ± 0.	0.06
	Lingual 2/3	-0.25 ± 0.13	-0.21 ± 0.52	-0.21 ± 0.67	-0.38 ± 0.52	0.95

* p-value calculated using the one-way ANOVA test

** indicates the value is significant at a p-value < 0.05

Table 17: Comparison of treatment time (months) and the changes in bone thickness labial and lingual to the mandibular incisors

Variable		x < 18	18 ≤ x <24	24 < x	p-value*
LR2	Facial 1/3	0.18 ± 0.25	0.11 ± 0.29	0.04 ± 0.20	0.41
	Lingual 1/3	0.15 ± 0.25	-0.14 ± 0.40	-0.23 ± 0.48	0.18
	Facial 2/3	-0.15 ± 0.38	0.14 ± 0.60	0.11 ± 0.51	0.51
	Lingual 2/3	-0.03 ± 0.54	-0.18 ± 0.69	-0.47 ± 0.73	0.29
LR1	Facial 1/3	0.12 ± 0.22	0.14 ± 0.18	0.12 ± 0.23	0.92
	Lingual 1/3	0.10 ± 0.23	-0.31 ± 0.27	-0.30 ± 0.56	0.13
	Facial 2/3	-0.13 ± 0.51	0.07 ± 0.84	0.20 ± 0.66	0.60
	Lingual 2/3	-0.05 ± 0.39	-0.44 ± 0.62	-0.48 ± 0.55	0.25
LL1	Facial 1/3	0.15 ± 0.16	0.10 ± 0.23	0.05 ± 0.19	0.52
	Lingual 1/3	0.17 ± 0.41	-0.24 ± 0.48	-0.14 ± 0.48	0.23
	Facial 2/3	0.02 ± 0.28	0.27 ± 0.87	0.23 ± 0.58	0.72
	Lingual 2/3	-0.02 ± 0.42	-0.59 ± 0.81	0.58 ± 0.13	0.21
LL2	Facial 1/3	0.10 ± 0.32	0.08 ± 0.21	0.07 ± 0.32	0.96
	Lingual 1/3	0.17 ± 0.37	-0.19 ± 0.43	-0.23 ± 0.32	0.07
	Facial 2/3	0.02 ± 0.23	0.34 ± 0.77	0.42 ± 0.66	0.44
	Lingual 2/3	-0.05 ± 0.31	-0.19 ± 0.59	-0.32 ± 0.50	0.51

* p-value calculated using the one-way ANOVA test

Table 18: The association between the final IMPA and the change in thickness of bone before and after orthodontic treatment

		Correlation (r)	p-value*
LR2	1/3 Facial	-0.059	0.72
	1/3 Lingual	0.569**	0.00**
	2/3 Facial	0.123	0.44
	2/3 Lingual	0.227	0.15
LR1	1/3 Facial	0.058	0.72
	1/3 Lingual	0.019	0.90
	2/3 Facial	0.118	0.46
	2/3 Lingual	0.176	0.27
LL1	1/3 Facial	-0.072	0.65
	1/3 Lingual	0.069	0.67
	2/3 Facial	0.102	0.53
	2/3 Lingual	0.001	0.99
LL2	1/3 Facial	-0.302	0.06
	1/3 Lingual	0.134	0.41
	2/3 Facial	0.072	0.65
	2/3 Lingual	0.261	0.10

* Calculated using Pearson's correlation coefficient

** indicates the correlation is significant at a p-value < 0.05

Table 19: The association between the change in IMPA and the change in thickness of bone before and after orthodontic treatment

		Correlation (r)	p-value*
LR2	1/3 Facial	-0.087	0.59
	1/3 Lingual	0.251	0.11
	2/3 Facial	0.397*	0.01*
	2/3 Lingual	-0.080	0.62
LR1	1/3 Facial	0.047	0.77
	1/3 Lingual	-0.147	0.36
	2/3 Facial	0.578**	0.00**
	2/3 Lingual	-0.213	0.18
LL1	1/3 Facial	0.162	0.31
	1/3 Lingual	-0.296	0.06
	2/3 Facial	0.466**	0.00**
	2/3 Lingual	-0.204	0.20
LL2	1/3 Facial	-0.142	0.38
	1/3 Lingual	-0.042	0.79
	2/3 Facial	0.250	0.12
	2/3 Lingual	-0.077	0.63

* Pearson correlation coefficient

** indicates the correlation is significant at a p-value < 0.05

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