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Three-Dimensional Evaluation of the Effect of Maxillary Incisor Retraction on the Palatal Bone and Root Resorption

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Three-Dimensional Evaluation of the Effect of Maxillary Incisor Retraction on the Palatal Bone and Root Resorption

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Abstract

Introduction: The objective of this study was to compare pre-treatment and post-treatment cone-beam computed tomography images of patients to quantitatively evaluate the effect of orthodontically retracting maxillary incisors on the height and labiolingual thickness of labial and palatal alveolar bone and incisor apical root resorption. **Methods:** Maxillary central incisor apical root resorption and labial and palatal alveolar bone height and labiolingual thickness were assessed on pre-treatment and post-treatment cone-beam computed tomography scans of 59 subjects (mean age, 13.00 years) with premolar extractions and 63 subjects (mean age, 13.40 years) who were treated with non-extraction therapy. Independent-sample t-tests were used to distinguish any differences in resorption of labial and palatal alveolar bone and incisor root apex between groups. A Pearson correlation analysis was performed to determine any variables that were associated with increased alveolar bone and incisor apical root resorption. **Results:** The mean incisor apical root resorption in the extraction group was 1.47± 0.70 mm, compared to 0.70± 0.81 mm in the non-extraction group ($P< 0.001$). The extraction group also experienced greater palatal bone height loss (0.84± 1.08 mm) than the non-extraction group (0.22± 0.39 mm) ($P< 0.001$). Increased root resorption was correlated with treating Class II malocclusion, increased OJ and OB, greater number of extracted premolars, long duration of treatment, proximity of the incisor roots to the palatal cortex, and apical extrusion. Increased palatal alveolar bone height loss was correlated with greater number of extracted premolars, long duration of treatment, proximity of the incisor roots to the palatal cortex, and thin alveolar bone. **Conclusion:**

Clinicians should exert caution when excessive incisor movement is planned in patients with thin alveolar bone.

Introduction

The position of the maxillary incisors is an important factor during orthodontic treatment planning. The incisors are frequently retracted both to effectively reduce the overjet in a Class II malocclusion and to treat many cases with dentoalveolar protrusion. However, the effects of incisor repositioning on both root resorption and the palatal bone in the area of the maxillary incisors remain unclear.

Root shortening as a result of external resorption is a well-documented possible side effect of orthodontic treatment[1-4]. While the fundamental causes of treatment-associated root resorption remain unknown[5], among the factors implicated are orthodontic procedures[1], type[1] and duration[4] of treatment, magnitude of applied force[4], direction of tooth movement[4], and amount of apical displacement[4]. Apical root resorption of maxillary central incisors as a result of orthodontic treatment occurs in nearly all patients[6] and is usually less than 2.5 mm[4], with averages in the range of 1.24 mm to 2.93 mm[2,5-12]. Even though orthodontically-treated patients have an increased risk for root resorption[8,13-15], root-end loss usually ceases after appliance removal[1,9,16,17]. Root resorption, usually mild to moderate in severity, is a minor problem in most patients, but some teeth may lose their function and may be exfoliated by severe resorption[14,18,19].

Since maxillary incisors have been consistently found to be affected more often and more severely than any other tooth[2,4,17,19-22], several studies targeting various treatment variables and their impact on maxillary incisor apical root resorption (IARR) have been conducted. The severity of root-end loss in the maxillary incisor area was found to be higher in subjects who had undergone extractions as part of orthodontic

treatment compared to patients without extractions in the studies of Sharpe *et al.*[22]; Sameshima and Sinclair[23]; and VonderAhe[16]. On the other hand, no increased risk for root resorption was demonstrated in patients with extraction therapy compared to those without extractions in the studies of Horiuchi *et al.*[18]; Baumrind *et al.*[5]; and McFadden *et al*[11].

The relationship between changes in maxillary central incisor axial inclination, the amount of incisor movement, and IARR have also been examined with varying results. Approximation of maxillary incisors against the palatal cortical plate was found to be the most significant measure associated with IARR according to the findings of Horiuchi *et al.*[18] and Kaley and Phillips[24], in contrast to the results of Mirabella and Artun[25]. Horizontal incisor movements[2,5,14,23,25], intrusion[8,26], extrusion[18], and lingual root torque[4,16,24] have been implicated as important factors influencing the amount of IARR. In contrast, other authors could not correlate IARR with horizontal movments[20], intrusion[5,11,27-29], extrusion[2,5], lingual root torque[20], or with changes in axial inclination[14,20,22,28,29].

In addition to possibly increasing the risk of IARR, maxillary incisor retraction has been linked with other periodontal consequences. No statistically significant differences in terms of periodontal condition, plaque situation, and gingival status were found between patients with premolar extractions and untreated individuals according to Alstad and Zachrisson[30]. However, loss of attachment was slightly, but significantly greater in patients with Class II division 1 malocclusions treated with four premolar extractions than untreated controls in a separate study by Zachrisson and Alnaes[31]. Similarly, Sjolien and Zachrisson, examining intraoral radiographs, compared a study

group treated with four premolar extractions with a group of untreated individuals[32]. The study group demonstrated significantly less bone support on the interproximal surfaces of the maxillary incisors. While these studies offer important information regarding the loss of attachment and interproximal bony changes associated with incisor retraction, they do not report on the amount of incisor retraction or its effect on the palatal bone.

Edwards examined the anterior portion of the palate during maximum lingual movement of maxillary incisors in 188 orthodontic patients with severe class II malocclusions, each having three cephalograms taken pre-treatment, during-treatment, and post-treatment[33]. After lingual root-torquing forces were continued from 4-6 months after a cephalogram showed the incisor roots were against the palatal cortical plate, the author found that the position of the palatal plate could be altered in both adults and growing patients with the greatest change in the marginal area of the alveolus, and progressively less alteration of the bone toward the apex of the root. While the alveolar bone directly supporting the incisors could be moved distally, the anterior portion of the palate, described as the palatal plate that curves downward from a horizontal position to the more vertical alveolar process, did not seem to move lingually with the retraction of the maxillary incisors. The author observed that the incisors seemed to move through bone as opposed to stimulating the actual movement of bony structures until the teeth came against the palatal plate of the anterior palatal process, an anatomic limitation to the distal movement of maxillary incisor teeth. Edwards also commented on the difficulty in treating patients with a narrow maxillary anterior alveolus, but found no statistically significant difference in the labiolingual width of the anterior portion of the palate when grouping patients by mandibular divergence.

In attempts to establish cephalometric norms of the width of the anterior alveolus around the maxillary incisors, Handelmann examined lateral cephalograms of 107 patients, assessing palatal bone thickness in the area of the incisor apex[34]. In contrast to Edwards' findings, palatal bone was narrower in this area in patients with class II malocclusions and high mandibular plane angles. While individuals of any facial type could have a thin alveolus, it was rarely seen in low mandibular plane angle groups or in the Class I average mandibular plane angle group.

Ten Hoeve and Mulie[35] reported on case observations of 23 patients with severe Class II malocclusions using laminagrams and cephalograms to evaluate the effect of maxillary incisor retraction on the palatal cortex with the Begg technique. Immediately after orthodontic treatment, a palatal cortex could not be detected on cephalograms, and the tracings indicated that the incisors were through or outside the palatal cortex. In most cases, a thin irregular sliver of bone appeared in patients that had laminagrams six months after orthodontic treatment. Patients observed 1-5 years post-treatment demonstrated a remodeled and reshaped palatal cortex with a normal appearance along with relapse of the incisor roots. The authors concluded that although no anatomical limit to tooth movement existed in the marginal area of the alveolar process, movement of the root apex against the palatal cortex presented a definite limit to further retraction. The authors also noticed a characteristic type of lingual root apical resorption sometimes accompanied by notching and scalloping.

Re-examining 15 out of the 23 patients from the previous study, Remmelink and Van Der Molen utilized identical observation techniques to demonstrate a well-defined, dense cortical plate seven to ten years after treatment[36]. The palatal bone apposition was

accompanied by some relapse of root torque, prompting the authors to conclude that perforation of the cortical plate during overjet reduction should be avoided.

While the studies by Ten Hoeve and Mulie [35], and Remmelink and Van Der Molen [36] take into account the inaccuracies of measuring the palatal bone with a cephalogram, laminagraphy is not a common image modality in orthodontics. The authors did not report quantitative measurements of the changes in the palatal bone or anteroposterior incisor movement.

By analyzing the maxilla of a deceased 19-year old woman who had undergone orthodontic therapy, Wehrbein *et al.* quantitatively investigated the sagittal movements of the maxillary incisors and also observed the accompanying hard tissue changes[37]. The incisors first underwent uncontrolled tipping, then palatal root torque. In accordance with the radiologic findings of Ten Hoeve and Mulie [35], Wehrbein *et al.* [37] discovered palatal bone apposition in histological sections, with no evidence of cortical perforation. Root resorption with an apical slope from facioapical to linguocoronal, induced by the palatal root torque, was evident in histologic sections but not in radiologic findings. The authors advised that patients with a narrow apical base and a thin labial or lingual hard tissue and soft tissue covering warrant careful consideration when pronounced sagittal anterior tooth movements are required if long-term stability is to be guaranteed.

The relationship between marked tooth movements and the surrounding periodontium have prompted several researchers to examine the periodontal conditions subsequent to moving teeth through the facial cortical plate in monkeys and dogs. In separate studies, Batenhorst *et al.*[38], Wennstrom *et al.*[39], Steiner *et al.*[40], and Wainwright[41] observed crestal bone loss and facial bone dehiscences after subjecting

monkeys to labial tooth movement. Although observing continued osteogenesis on the buccal surface of the perforated cortical plate, Wainwright[41] observed that the root apex of the buccally positioned premolar was not completely covered during a four-month retention period.

After lingually repositioning facially moved teeth in independent studies, Wainwright[41], Karring *et al.*[42], and Engelking and Zachrisson[43] discovered that bone tissue would reform in facial dehiscences, with further slight thickening of the cortical plate according to Wainwright's findings [41]. Wainwright[41]also noted that resorption of increasing severity toward the root apex was evident on the buccal root surface when under pressure and on the lingual surface on reversal of the force system. Similarly, as the experimental teeth were facially moved in Batenhorst *et al.*'s study[38], resorption of cementum and dentin occurred despite minimal tipping forces.

While these studies of monkeys and dogs suggest the importance of the alveolar housing to the health of the periodontium and the risk of root resorption with orthodontic tooth movement, they fail to make quantitative observations regarding the buccolingual bony changes that occur with an exaggerated tooth position. Also, the results of facially moving teeth in animals may not be applicable to lingually retracting maxillary incisors in humans. Even though evaluating the periodontal effects of labial displacement of teeth in monkeys and dogs provides valuable information to orthodontists, the clinical implications of these studies may come into question.

Orthodontists require a more clinically applicable method to evaluate root resorption and the palatal bone surrounding the central incisors. Even though many studies investigating incisor retraction have been based upon two-dimensional (2D)

radiographic methods, comparisons of radiographic studies are limited because of the variables of technique standardization, time differentials, and tooth movement[44]. The bony structures palatal to the maxillary incisors in lateral cephalograms can be obscured, while the actual limit of the palate at the midline may be narrower than the image[34,35]. Periapical films also have consequential projection errors associated with the lack of standardization of the image-acquisition technique[44]. Because of the nature of 2D radiography, there might be overlapping of anatomic structures, making it difficult to identify reference points [45]. Conventional radiographic techniques can detect resorption only afer 60-70% of the mineralized tissue is lost, providing only 2D information primarily identifying apical change[46].

By contrast, cone-beam computed tomography (CBCT) is becoming popular in the field of dentistry as a more complete method for diagnosis and treatment planning in true 3 dimensions (3D) and a 1:1 perspective, providing reliable linear measurements in all planes of space, rather than with enlarged or distorted images[47,48]. Supplying detailed images of highly contrasting structures, CBCT is very useful for imaging osseous structures of the craniofacial area[49], including determination of hard tissue lesion size and volume[50]. In addition, difficulties associated with patient positioning and uncertainties of measurements accompanying patient asymmetry in conventional radiographs are not present in CBCT images as these scans are not affected by skull orientation[48,51].

Utilizing a medical CT with a scan thickness of 1.0 mm, Fuhrmann[52] examined initial and final images of 11 adult orthodontic patients with reduced periodontal bone tissue. The author presented a patient that required retraction of the four maxillary incisors with uncontrolled tipping in the palatal direction. The integrity of the palatal

bone covering the roots of the incisors was preserved, but the root apices perforated the facial cortical plate as the crowns moved distally.

By three-dimensionally evaluating the effects of maxillary incisor retraction, Fuhrman[52] disclosed valuable information regarding the hard tissue conditions. He reported on select findings without offering any measurements of incisor retraction and root angulation.

While CBCT has countless applications in orthodontics, its ability to detect orthodontically induced apical root resorption has not been sufficiently studied[53]. Comparing CBCT scans and conventional panoramic radiographs of 22 orthodontic patients, Dudic *et al.*[53] revealed that 69% of teeth were diagnosed as having apical root resorption by CBCT, but only 44% showed apical root resorption with the panoramic films, suggesting that apical root resorption might be underestimated by the latter method. The maxillary incisors showed the most pronounced differences between the two methods in evaluating apical root resorption.

Rationale

Lingually retracting the maxillary incisors is a very common practice in orthodontics. The results of the literature suggest that if the roots of retracted maxillary incisors are brought into contact with the palatal alveolar cortex, it will remodel to a limited extent, but further movement will lead to eventual penetration of the cortical plate, followed by bone loss, root resorption, and subsequent relapse[54]. While the aforementioned literature provides important observations of both the palatal bone surrounding orthodontically retracted maxillary incisors and subsequent root resorption, the use of 2D radiographs in many of the studies precludes the accurate assessment of the

hard tissue changes. With CBCT becoming more prevalent in many universities and practices, the use of 3D scans to examine the effect of orthodontically repositioning the maxillary incisors on the palatal bone and the risk of root resorption is clinically relevant, impacting the treatment plans of many orthodontists.

Any reduction in support of the periodonium apical to the crest of the alveolar bone by root resorption, loss of crestal alveolar bone height, or both would presumably enhance the tendency for relapse[22]. Root shortening and loss of alveolar bone could be potentially destructive to the stability of the dentition[15]. Loss of bone at the alveolar crest is particularly detrimental, as the bulk of the periodontal attachment fibers resisting horizontal plane tooth movement is at the alveolar crest[55].

The purpose of this study was to compare pre-treatment and post-treatment CBCT images of patients to quantitatively evaluate the effect of orthodontically retracting maxillary incisors on the height and labiopalatal thickness of labial and palatal alveolar bone and IARR.

Hypotheses

1. Lingually retracting maxillary incisors will cause statistically significant resorption in the height and width of palatal alveolar bone in the area of the incisors and the incisor root apex.

2. The amount of lingual retraction will positively correlate with an increasing amount of resorption of palatal bone height and root apex.

3. The amount of decrease in palatal bone and IARR will vary with the amount of tooth movement (such as tip, translation, and torque); with lingual root torque producing the greatest resorption values.

Specific Aims

1. To quantitatively measure the resorption in labial and palatal crestal alveolar bone height and labiopalatal width in the area of the maxillary incisors and resorption in incisor root apices that occur after lingually retracting maxillary incisors.
2. To evaluate the amount of lingual retraction and relate this value to the changes in labial and palatal bone and root apices measured.
3. To distinguish tipping, bodily translation, and lingual root movement and correlate these movements with values of resorption of crestal bone height and maxillary incisor root apices.

Materials and Methods

A power analysis was conducted to determine the sample size needed to detect differences in variables related to bone loss and root resorption. Analyses of differences between two independent groups were conducted using independent-samples t-tests. Assuming a medium-to-large effect size difference between groups (i.e., Cohen's **d** of .70 or more), the power analysis yielded a total sample size estimate of 68 participants at a conventional alpha-level (P= 0.05) and desired power ($1 - \beta$) of 0.80. These effect size estimates were based on previous literature, and were used to provide a conservative estimate of the sample size needed for this study. All calculations were performed with the computer application G-Power[56], which is based on the formulas of Cohen[57].

In accordance with the institutional review board protocol approved by the University of Connecticut, this retrospective case control observational study was comprised of 122 consecutively-treated patients at a private orthodontic office (Dr. Paul Rigali, Wallingford, CT) that routinely uses cone beam imaging for diagnostic purposes.

Approximately 710 debonded patient records (clinical examination notes, dental models, photographs, and CBCT scans) were searched to select patients that would fit into the following study criteria:

The inclusion criteria for the study group (SG) were as follows: (1) healthy patients with no history of systemic conditions or serious illnesses; (2) at least 10.5 years old at the time when initial records were taken with completed maxillary central incisor root formation; (3) no history of trauma, root canal therapy, restorations, or incisal edge abrasion of the maxillary incisors; (4) three millimeters or less of maxillary crowding; (5) class I or II malocclusion treated orthodontically with one right and one left maxillary premolar extraction therapy regardless of the treatment plan for the mandibular arch; (6) no previous orthodontic treatment; (7) no history of previous root resorption; (8) availability of previously acquired clear CBCT scans.

Exclusion criteria for the SG included: (1) patients with a history of systemic conditions and/or serious illnesses; (2) patients younger than 10.5 years old at the time initial records were taken and/or incomplete maxillary central incisor root formation; (3) history of trauma, root canal therapy, restorations, or incisal edge abrasion of the maxillary incisors; (4) more than three millimeters of maxillary crowding; (5) non-extraction orthodontic treatment for the maxillary arch; (6) previous orthodontic therapy; (7) previous root resorption; (8) CBCT scans not available or not of sufficient quality.

The inclusion criteria for the control group (CG) were as follows: (1) healthy patients with no history of systemic conditions or serious illnesses; (2) at least 10.5 years old at the time of initial records with completed maxillary central incisor root formation; (3) no history of trauma, root canal therapy, restorations, or incisal edge abrasion of the

maxillary incisors; (4) three millimeters or less of maxillary crowding, (5) class I malocclusion treated orthodontically without extraction therapy; (6) no previous orthodontic treatment; (7) no history of previous root resorption, (8) availability of previously acquired clear CBCT scans.

Exclusion criteria for the CG included: (1) patients with a history of systemic conditions and/or serious illnesses; (2) patients younger than 10.5 years old at the time initial records were taken and/or incomplete maxillary central incisor root formation; (3) history of trauma, root canal therapy, restorations, or incisal edge abrasion of the maxillary incisors; (4) more than three millimeters of maxillary crowding; (5) extraction orthodontic treatment; (6) previous orthodontic therapy; (7) previous root resorption; (8) CBCT scans not available or not of sufficient quality.

Seventy-six patients initially fulfilled the criteria of the SG, but 17 were eliminated due to illegible CBCT scans. The SG was therefore comprised of 59 patients (31 males, 28 females), with an average age of 13.00 ± 1.46 years at the beginning of active treatment, when fixed appliances were bonded (T1). Again, 17 of the initial 80 patients in the CG were eliminated due to illegible CBCT scans, leaving 63 patients to comprise the CG (22 males, 41 females), with an average age of 13.40 ± 1.28 years at T1.

All subjects were bonded with fixed orthodontic edgewise appliances (0.022" x 0.028" slot size). Space closure in the SG was completed with either a 0.019" x 0.022" stainless steel keyhole loop or elastomeric power chain.

Three-dimensional (3D) CBCT images were obtained of all subjects using the i-CAT Classic scanner (Imaging Sciences International, Hatfield, Pa). Each image was acquired using a 20 second scan time with a 16 cm (diameter) x 13 cm (height) field of

view at a resolution of 0.3 voxels. All images were collected at 120 kVp and 23.87 mAs. Raw data were reconstructed and exported as a 12-bit-depth Digital Imaging and Communications in Medicine (DICOM) file using Xoran (i-CAT software version 2.1.22). The DICOM files were imported into Dolphin 3D (Dolphin Imaging V11, Chatsworth, CA) for analysis.

CBCT images for each subject in both the SG and CG were taken at the following two time points: 1. Pre-treatment scans taken before active orthodontic treatment was initiated (T1). 2. Post-treatment scans taken after orthodontic treatment was completed (T2). The orientation of each CBCT scan was standardized with the midsaggital plane oriented vertically, Frankfort horizontal plane (FH) horizontally, and the transporionic line horizontally[58-62,63] (**Figure 1**). Both the volumetric rendering and multiple planar views of sagittal, axial, and coronal slices, were utilized to determine the reference planes.

All measurements were made for both the right and left maxillary central incisors in the CBCT slices, taking full advantage of the 3D CBCT information[62], because 3D virtual renderings are projected images and not actual surfaces[62] and it is more accurate to locate landmarks in the stack of slices than in the rendered volume[64]. All axial, coronal, and sagittal CBCT sections were analyzed at a thickness of 1 voxel and measured to the nearest 0.1 mm.

To assess the amount of incisor apical root resorption (IARR), two separate sagittal slices parallel to the long axis (par-to-LA) of the maxillary central incisors through the center of each root were utilized **(Figure 2).** The volumetric rendering and multiple planar views aided in determining both the long axis (LA) and the center of each

incisor root. Tooth length was measured from the incisal edge (IE) to the apex of the root, par-to-LA of each incisor **(Figure 3).** These values were collected from the T1 and T2 CBCT scans. IARR was calculated by subtracting the T2 tooth length from the T1 tooth length.

Labial and palatal crestal bone height (LPBH) adjacent to each central incisor was measured with two different methods using two different sections. First, two separate sagittal slices, each perpendicular to FH (perp-to-FH), were taken through the center of both maxillary incisor roots **(Figure 4).** The volumetric rendering and multiple planar views aided in determining the center of both incisors. These slices through the right and left central maxillary incisor were most representative of a traditional lateral cephalometric radiograph, with FH parallel (par) to the floor, but were taken at a tangent to the alveolar bone of each incisor. The sagittal slices were re-oriented for ease of measurement while keeping all planes the same, maintaining accuracy. The LPBH assessed from the most superior crest of bone (C) to the IE was measured par-to-LA **(Figure 5)**.

Using the same sagittal sections, perp-to-FH, LPBH were measured using a second method: a line from the cemento-enamel junction (CEJ) of each incisor to the C labially and a line from the CEJ to the C palatally were constructed and the lengths recorded **(Figure 6)**.

Both methods for measuring LPBH (IE-to-C and CEJ-to-C) of both the right and left central incisor for each time point for each subject were repeated on a separate section. This section was taken par-to-LA of both maxillary central incisors through the center of each root, the same orientation used to measure IARR, and which more

accurately reflected the bony morphology of the alveolus **(Figure 2).** The values recorded for each CBCT section and both methods of measuring were compared.

The labiopalatal thickness (LPBT) of the maxillary central incisor alveolar bone was measured utilizing three axial sections perp-to-LA of both central incisors **(Figure 7)**. In a study measuring changes in alveolar bone thickness on CT scans due to retraction of anterior teeth by Sarikaya *et al.*, the thickness of the labial and palatal alveolar plates of the maxillary incisors were measured in three slices: at the widest point of the labiopalatal root, 3 mm coronal to that point, and 3 mm apical to that point[65].

Since it was difficult to accurately identify the widest part of the incisor roots, a modification to measuring LPBT was made to Sarikaya *et al.*'s method. Three measurements were made on the labial and three were made on the palatal side of both central incisors. The first axial section was taken at the midpoint (MP) of each incisor root, determined from the sagittal section par-to-LA of the tooth in the T1 CBCT scan. Unlike locating the widest part of the root, determining the MP of the root could be accurately and objectively determined in every subject. The second and third axial sections were taken 2 mm and 4 mm, respectively, coronal to the MP of each incisor root. These slices represented areas of bone approaching the alveolar crest, where changes in bone were most likely to occur after incisor movements.

Each MP, 2 mm, and 4 mm coronal points determined on the T1 CBCT scan were transferred to the T2 scan for that subject, registered at the IE. Therefore, any IARR that occurred between time points for each subject did not affect the position of the root MP, 2 mm, or 4 mm points. LPBT was measured on a line perp-to-LA of the tooth. On the axial section, the labial bone thickness (LBT) was determined by a line from the labial-

most limit of bone to the outermost labial surface of the incisor. The palatal bone thickness (PBT) was found by a line from the palatal-most limit of bone to the outermost palatal surface of the incisor. All values were recorded and compared.

The type and amount of tooth movement was assessed by comparing T1 and T2 CBCT-derived cephalometric images. Two separate 2D lateral cephalograms with orthogonal projections of the right and the left maxillary central incisors were generated using the 3D function of Dolphin 11. Measurements on orthogonal projections are not statistically different from actual anatomic measurements[62].

T1 and T2 cephalograms were hand-traced and superimposed on the inner cortications of the maxilla, anterior part of the palate, and developing third molar crypt, if available. Positional changes of each maxillary central incisor were determined according to Parker and Harris[2]. On the T1 cephalogram, a horizontal line, from the anterior nasal spine (ANS) to the posterior nasal spine (PNS) of the palate, was used as the palatal plane (PP). A vertical line, perpendicular to the PP was constructed from PNS. These lines (PP and PNS-Perpendicular Plane) were transferred as a grid to the T2 lateral cephalograms and used as a reference to make all measurements of incisor movement. The stability of the inclination of the PP throughout growth validates using the PP as a reference plane for measurement[66].

The intersection of a line through the LA of the central incisor and the PP indicated the change of the axial inclination of the maxillary incisors. The horizontal distances that the IE and apex of each incisor moved were measured par-to-PP. Vertical movements of the apex and the IE were determined perp-to-PP. The center of resistance, estimated as the MP of the root, was transferred from the T1 tracing to the T2 tracing[28]

for both incisors. The horizontal and vertical positional changes of the center of resistance of each maxillary central incisor were also determined in a similar fashion to the IE and apical movements.

To account for the effect of IARR that may have occurred on root apical movements, both maxillary central incisors on the cephalogram derived from the T2 scans were assigned the same length they had on the cephalograms from the T1 scans according to Baumrind *et al*[5]. After calculating the distance from the maxillary IE to the apex on the T1 cephalogram, a line of equal length was overlaid along the LA of the incisor of the T2 films, registered at the IE. The most apical point of this line was considered the best estimate of where the apex would have been located if no changes in tooth length occurred[5].

The type of horizontal movements of the incisors were determined according to Upadhyay *et al*[67]. The quotient of the moved distance of the most apical point (Apex) and the moved distance of the most incisal point (IE) were calculated. If the apex moved in the opposite direction to the IE or vice versa, the amount received a negative sign. Tooth movements were classified on the basis of the quotient obtained (Apex/IE): <0, uncontrolled tipping: 0, controlled tipping; >0, controlled tipping and bodily movement; 1, bodily movement; and >1, root movement[67].

Based on the horizontal changes of the IE and apex the incisor movement fell into one of three categories:

1. Tipping- either controlled tipping where the center of rotation was the apex of the incisor or uncontrolled tipping, where the center of rotation was between the center of resistance and the root apex.

2. Translation- Lingual bodily movement of the incisors from their original position.

3. Torque- Lingual movement of the root with the center of rotation at the IE of the incisor.

Several variables for each subject were recorded: the age and sex of each subject, duration of treatment, extraction pattern, type of space closure (closing loop or elastomeric chain), duration of space closure, proximity of the apical third of the root to the palatal cortex scored subjectively as present or absent[25], Angle's molar classification, overjet (OJ) (defined as the horizontal distance from the lingual surface of the most protrusive maxillary incisor to the facial surface of the most protrusive mandibular incisor par-to-FH), overbite (OB) (defined as the vertical distance overlap of upper and lower incisors perp-to-FH), and the mandibular plane to FH (FMA). These variables for each subject were analyzed to determine if a relationship existed with bone and root resorption.

The same rater repeated all measurements on 20 randomly selected subjects four weeks later. A second calibrated examiner performed all of the measurements on the same 20 randomly selected subjects.

Results

Descriptive Results

Descriptive results for both the CG and SG can be found in **Table 1**.

Paired-samples t-tests comparing LPBH, LPBT, and IARR for right and left incisors were not significant (all P's > 0.60), so measurements for each subject were calculated by averaging values for the right and left incisors.

Reliability Analysis

Reliability was established using the intra-class correlation coefficient (ICC). The ICC indicates the ratio of systematic variability in measurements relative to unsystematic variability (i.e., error), and yields a value between 0 (no reliability) and 1.0 (100% reliability). The results are presented in **Table 2**.

Two sets of reliability analyses were conducted. One analysis assessed the reliability for the same rater on 20 randomly selected subjects, measured at two different points in time (roughly four weeks apart). The second analysis assessed the reliability of two independent raters on the same 20 randomly selected subjects. Data consisted of T1 and T2 measurements for right and left maxillary central incisors. Overall reliabilities were calculated across sets of measurements (e.g., right and left incisor, T1, T2) to establish average ICCs for the same rater and for the two independent raters. For the same rater, ICCs ranged from .66 to .99. For the two independent raters, ICCs ranged from .70 to .99. In general, ICCs between .60 and .80 are considered acceptable, while those greater than .90 are deemed to be exceptional[68]. ICC's were assessed statistically and were all found to be highly significant (all P's < 0.001).

IARR Results

Differences in IARR values for SG and CG at T1, T2, and (T1-T2) were evaluated with independent-samples t-tests **(Table 3).**

A chi-square analysis (df=1)= 7.32 revealed that the percentage of subjects with 2 or more mm of IARR from TI to T2 in the SG (23.7%) was significantly higher than the CG (6.3%) (P= 0.007).

A Pearson correlation analysis was completed to determine if those subjects with increased IARR from T1 to T2 were more likely to experience LPBH loss from T1 to T2.

No significant association was found between the degree of IARR and LBH loss (r = -.02, p = 0.81) or with IARR and PBH loss (r= -.01, P= 0.94).

LPBH Results

The design for analyzing LPBH consisted of three between-subjects factors (treatment condition: SG vs. CG, sex, and age), as well as four within-subjects factors (Time: T1 vs. T2; labial vs. palatal; perp-to-FH vs. par-to-LA; and IE-to-C vs. CEJ-to-C). The design was a 2 (time) X 2 (SG vs. CG) X 2 (sex) X Continuous (age) X 2 (labial/palatal) X 2 (perp-to-FH/par-to-LA) X 2 (IE/CEJ) ANOVA. Of interest was whether LPBH changed over time as a function of the between- and the within-subject factors.

T1 differences. There was a significant overall difference in LPBH between SG and CG at T1 when all measures were collapsed across the three measurement types (labial vs. palatal; perp-to-FH vs. par-to-LA; IE-to-C vs. CEJ-to-C) (P =0.001) such that the SG measurements were significantly larger (6.71 ± 0.35 mm) than those for CG (6.50 ± 0.33 mm), indicating 0.21 mm less total LPBH support in the SG than the CG at T1

Measurement type. LBH at T1 and T2 was significantly lower (6.72 ± 0.41 mm) than PBH (6.82 ± 0.62 mm) (P= 0.010), demonstrating 0.10 mm less palatal bone support in all subjects regardless of treatment condition. All perp-to-FH values, collapsed across T1 and T2 for both groups were significantly lower (6.75 ± 0.44 mm) than par-to-LA (6.79 ± 0.46 mm) measures (P= 0.006), a clinically insignificant finding. Collapsed across T1 and T2, IE-to-C measures were significantly higher (12.48 ± 0.67 mm) than CEJ-to-C (1.06 ± 0.37 mm) (P< 0.001). There were no significant effects involving sex or age, so these factors were dropped from the analyses.

Change across time from T1 to T2. There was a significant overall change across time (P < 0.001) such that all LPBH measurements were seen to increase significantly from T1 (6.60 ± 0.35 mm) to T2 (6.94 ± 0.65 mm), indicating 0.34 mm of bone loss. Specifically, LBH measurements were seen to increase significantly less from T1 (6.64 ± 0.37 mm) to T2 (6.80 ± 0.53 mm) than for the palatal measurements (T1: 6.56 ± 0.40 mm; T2: 7.08 ± 0.96 mm) (P< 0.001), indicating losses of 0.52 mm of PBH and 0.16 mm of LBH.

LPBH values were seen to increase equally from T1 to T2 when measuring perp-to-FH (T1: 6.60 ± 0.37 mm; T2: 6.91 ± 0.63 mm; difference 0.31 mm) vs. par-to-LA (T1: 6.61 ± 0.35 mm; T2: 6.97 ± 0.68 mm; difference 0.36 mm) (P= 0.19) and when measuring from the IE-to-C (T1: 12.31 ± 0.64 mm; T2: 12.65 ± 0.82 mm; difference 0.34 mm) vs. CEJ-to-C (T1: 0.88 ± 0.23 mm; T2: 1.23 ± 0.60 mm; difference 0.35 mm) (P= 0.47).

Differential change across time from T1 to T2 as a function of treatment condition (SG vs. CG). There was a significant differential change from T1 to T2 as a function of treatment condition (P <0.001) such that LPBH measures were seen to increase significantly more for the SG from T1 (6.71 ± 0.35 mm) to T2 (7.26 ± 0.71 mm) than for the CG (T1: 6.50 ± 0.33; T2: 6.64 ± 0.39 mm), indicating 0.55 mm of LPBH loss in SG compared to 0.14 mm in CG.

Furthermore, LBH measures differed significantly from PBH (P= 0.002). Specifically, the LBH measurements were seen to increase only somewhat more for the SG from T1 (6.71 ± 0.35 mm) to T2 (6.96 ± 0.49 mm) than for the CG (6.56 ± 0.37 mm; T2: 6.64 ± 0.39 mm) (P= 0.014), demonstrating 0.25 mm of LBH loss in the SG and 0.08

mm in the CG. However, PBH was not only seen to increase significantly but markedly in the SG from T1 (6.71 ± 0.42 mm) to T2 (7.55 ± 1.12 mm) relative to the increase in the CG (6.43 ± 0.34 mm; T2: 6.65 ± 0.49 mm) ($P < 0.01$), revealing 0.84 mm of PBH loss in the SG and 0.22 mm in the CG.

When considering the methods separately, measuring LPBH by perp-to-FH and par-to-LA did not yield significant changes from T1 to T2 ($P = 0.55$). There was, however, a statistically significant, though clinically insignificant, differential change from T1 to T2 as a function of treatment condition contingent upon measuring IE-to-C vs. CEJ-to-C ($P = 0.014$). For IE-to-C, LPBH measures were seen to increase significantly in the SG from T1 (12.44 ± 0.64 mm) to T2 (12.94 ± 0.88 mm) relative to the increase in the CG (T1: 12.20 ± 0.61 mm; T2: 12.37 ± 0.66 mm) ($P = 0.002$), showing a decrease of bone support of 0.50 mm in the SG and only 0.17 mm in the CG. For CEJ-to-C, however, LPBH measures were seen to increase significantly and markedly for the SG from T1 (0.98 ± 0.24 mm) to T2 (1.57 ± 0.67 mm) than for the CG (T1: 0.79 ± 0.19 mm; T2: 0.92 ± 0.28 mm) ($P < 0.001$), yielding LPBH loss of 0.59 mm in the SG and 0.13 mm in the CG.

A comparison of mean values for all methods of evaluating LPBH loss for the CG and SG was assessed using independent-samples t-tests **(Table 4).**

Since evaluating LPBH loss by measuring perp-to-FH, parallel-to-LA, IE-to-C, and CEJ-to-C yielded results that were clinically similar, a chi-square analysis was used to examine subjects who had 2.0 mm or more of LPBH loss measured par-to-LA, IE-to-C from T1 to T2 (**Table 5**). This method was chosen due to its more accurate portrayal of the bony changes that occurred for both incisors. The percentage of subjects with 2 or

more mm of LBH loss from T1 to T2 in the SG (3.4%) was not significantly higher than the percentage of subjects with 2 or more mm of labial bone loss in the CG (0.0%) (P= 0.17). However, 11 of 59 patients (18.6%) experienced 2 or more mm of PBH loss from T1 to T2 in the SG contrasted with 1 of the 63 (1.6%) subjects of the CG (P= 0.002).

LPBT Results

The design for analyzing LPBT consisted of three between-subjects factors (treatment condition: SG vs. CG, sex, and age), as well as three within-subjects factors (Time: T1 vs. T2; labial vs. palatal; and MP distance). The design was a 2 (time) X 2 (SG vs. CG) X 2 (sex) X Continuous (age) X 2 (labial/palatal) X 3 (0, 2, and 4 mm from MP) ANOVA. Of interest was whether LPBT changed over time as a function of the between- and the within-subject factors.

T1 differences. There was a trend toward significance in overall T1 differences in LPBT between SG and CG when all measures were collapsed across two measurement types (labial/palatal and MP distance) (P = 0.080) such that SG measures were significantly smaller (1.67 ± 0.47 mm) than CG (1.84 ± 0.54 mm), indicating 0.17 mm less LPBT in the SG than the CG at T1.

Measurement type. Labial measures were significantly lower (1.26 ± 0.42 mm) than palatal (1.93 ± 0.78 mm) (P< 0.001) averaged across T1 and T2, a difference of 0.97 mm. Values at all three locations used to measure LPBT (MP, 2 mm coronal to MP, and 4 mm coronal to MP) decreased significantly the further they were from MP (MP: 2.04 ± 0.57 mm; 2mm coronal: 1.63 ± 0.46; and 4 mm coronal: 1.12 ± 0.47) (P< 0.001), showing that bone became thinner the closer the measures were to the alveolar crest. There was also a significant overall quadratic trend for MP Distance measures averaged

across T1 and T2 ($P < 0.001$) such that the difference from MP to 2mm ($\delta = 0.41$) was less than the difference from 2mm to 4mm ($\delta = 0.51$). Again, no significant effects involving age or sex were observed, so these factors were dropped from the analyses.

Change across time from T1 to T2. LPBT measures were seen to decrease significantly from T1 (1.76 ± 0.51 mm) to T2 (1.43 ± 0.48 mm) ($P < 0.001$). Specifically, LBT measures increased significantly from T1 (1.06 ± 0.47 mm) to T2 (1.47 ± 0.60 mm) but PBT measures decreased (2.45 ± 0.91 mm); T2: 1.40 ± 0.80 mm) ($P < 0.001$), indicating that LBT increased by 0.41 mm but PBT decreased by 1.05 mm. LPBT values for all subjects were seen to decrease equally at all 3 points (MP: T1: 2.20 ± 0.61 mm; T2: 1.88 ± 0.61 mm); (2 mm coronal: T1: 1.81 ± 0.52 mm; T2: 1.45 ± 0.47 mm); (4 mm coronal: T1: 1.26 ± 0.53 mm; T2: 0.97 ± 0.49 mm) ($P = 0.55$).

Differential change across time from T1 to T2 as a function of SG vs. CG. There was a significant differential change from T1 to T2 as a function of treatment group ($P = 0.022$) such that LPBT measures were seen to decrease significantly less for the SG from T1 (1.67 ± 0.47 mm) to T2 (1.42 ± 0.49 mm) (difference of 0.25 mm) than for the CG (T1: 1.84 ± 0.54 mm; T2: 1.45 ± 0.47 mm) (difference of 0.39 mm). Comparing SG and CG, there was no significant differential change from T1 to T2 contingent further upon labial vs. palatal measures ($P = 0.40$) or the MP Distance ($P = 0.41$).

A comparison of mean LPBT values for the CG and SG at T1, T2, and (T1-T2) was assessed using independent-samples t-tests **(Table 6).**

Incisor Movement Results

The incisor movements can be found in **Table 7**. Differences between SG and CG were assessed using independent-samples t-tests.

Inclination of Incisors

The design for analyzing Incisor inclination (II) consisted of three between-subjects factors (treatment condition: SG vs. CG, sex, and age), as well as one within-subjects factor (time: T1 vs. T2). The design was a 2 (time) X 2 (SG vs. CG) X 2 (sex) X Continuous (age) ANOVA. Of interest was whether II changed over time as a function of the between- and the within-subject factors.

T1 differences. At T1, II was similar between SG (115.37 ± 7.68^o) and CG (113.85 ± 6.23^o) ($P = 0.24$).

Change across time from T1 to T2. There was a significant change from T1 to T2 for all measures averaged ($P = 0.005$) such that II was seen to increase significantly from T1 (114.60 ± 6.99^o) to T2 (117.53 ± 5.96^o), indicating an increase in inclination of 2.93^o.

Differential change across time from T1 to T2 as a function of treatment condition (SG vs. CG). II measures were seen to increase significantly less for the SG from T1 (115.37 ± 7.68^o) to T2 (116.46 ± 5.74^o) than for the CG (113.85 ± 6.23^o; T2: 118.59 ± 6.03^o) ($P = 0.001$), revealing that II increased 1.09^o in SG and 4.74^o in CG. There was a significant differential change from T1 to T2 as a function of age ($P < 0.019$) such that the older the patient at T1, the more toward a change from an increase in inclination from T1 to T2 to a decrease in inclination. More specifically, those patients under the median age at T1 (≤13.0 years, 48.7%) exhibited increases from T1 to T2 (4.35 ± 6.97^o), whereas those above the median age (≥13.1 years; 51.3%) exhibited virtually no change (0.18 ± 16.73^o). Viewing age at T1 as being divided into three roughly equal groups, those in the lowest third in age (≤12.7 years; 35.3%) exhibited increases (4.69 ± 7.60^o) from T1 to T2. Those in the middle third (between 12.8 years and 13.6 years, 31.9%) also exhibited

increases (3.18 ± 5.06°), but those in the higher third (≥13.7 years, 2.8%) exhibited decreases in inclination (-1.97 ± 20.45°).

Table 8 presents the percentage of subjects falling into the categories of tooth movement according to Upadhyay *et al*[67]. Of the five categories suggested by Upadhyay *et al.*[67], subjects in this study fell into only three of them. The SG had few subjects (6.8%) with uncontrolled tipping, approximately one-third (35.6%) with uncontrolled tipping and bodily movement, and over half (57.6%) with lingual root torque. By contrast, the CG had two-thirds of the subjects (63.9%) with uncontrolled tipping, some (13.1%) with uncontrolled tipping and bodily movement, and approximately one-quarter (23.0%) with lingual root torque.

Correlation Results

Tables 9,10,11,12 display the results of Pearson correlation analyses for IARR, LPBH and LPBT loss.

IARR. IARR was moderately negatively correlated with treatment condition (SG vs. CG, r= -.39 P< 0.001), indicating less IARR in the CG and increased IARR in the SG. Molar classification was also moderately correlated with IARR (r= .34, P< .001), demonstrating that Class II malocclusions were more likely to experience IARR than Class I malocclusions. At T1, OJ (r= .26, P= 0.004) and OB (r= .22 P= 0.004) were weakly correlated with IARR, indicating that the greater the OJ and OB at T1, the greater the IARR. Extraction pattern was also weakly correlated with IARR (r= .28, P= 0.002), such that the greater the number of extracted teeth, the greater the IARR. Treatment length was also correlated moderately with IARR (r= .36, P< 0.001), indicating that

longer treatment length was associated with increased IARR. IARR was weakly correlated with proximity of incisor roots to the cortical plate (r= .21, P= 0.022).

IARR was weakly negatively correlated with vertical apical movements (r= -.26, P= 0.004), indicating that IARR increased with extrusive apical movements and decreased with intrusive apical movements.

IARR was not correlated with sex, age at T1, race, FMA, retraction method, or duration of space closure. There was also no correlation found between IARR and tooth length, LPBH or LPBT values at T1 or LPBH loss. Additionally, no relationship existed with IARR and any incisor movements of the apex, center of root, IE, II, or with the type of movement that occurred (tip, translation, or root torque).

LBH. LBH was weakly correlated with retraction method (r= .27, P= 0.043) indicating that subjects treated with power chain were likely to experience more LBH loss instead of a closing loop. LBH showed a trend toward significance with proximity of the incisor root to the palatal cortex (r= .17, P= 0.061) and was moderately positively correlated to PBH loss (r= .33, P< 0.001).

LBH loss was weakly negatively correlated with PBT 2 mm coronal to the MP of the root (r= -.21, P= 0.018) and 4 mm coronal to the MP (r= -.18, P= 0.047) and showed a trend towards significance at root MP (r= -.18, P= 0.051) at T1, indicating that the thinner the palatal bone at these points before orthodontic treatment, the more likely to experience LBH loss. LBH loss was correlated weakly with II at T1 (r= .24, P= 0.008), indicating that incisors that were more proclined at the beginning of treatment have an increased risk of LBH loss. There was a trend toward significance for the association

between the type of incisor movement and LBH loss such that the more root movement that occurred, the more the LBH loss.

LBH loss was not correlated with treatment condition (SG vs. CG), sex, age, race, molar classification, OJ, OB, FMA, duration of space closure, duration of treatment, tooth length, LPBH or LPBT at T1, or any incisor movements.

PBH. PBH loss was moderately negatively correlated with treatment condition ($r = -.32$, $P < 0.001$), suggesting that the subjects in the SG were more correlated with increased PBH loss compared to the CG. Extraction pattern was moderately correlated with PBH loss ($r = .33$, $P < 0.001$), suggesting that those subjects with four premolars extracted experienced more PBH loss than those with two premolar extractions, who in turn had more PBH loss than subjects treated without extractions. PBH loss was also moderately positively correlated with increased duration of treatment ($r = .30$, $P < 0.001$) and proximity of the incisor roots to the cortical plate ($r = .46$, $P < 0.001$). OB at T1 ($r = -.18$, $P = 0.052$) and race ($r = .18$, $P = 0.054$) showed a weak trend towards significance such that increasing OB was correlated with decreased PBH loss and non-Caucasians were correlated with increased PBH loss.

PBH loss was weakly negatively correlated with tooth length at T1 ($r = -.19$, $P = 0.038$), indicating that subjects with longer tooth lengths were correlated with less PBH loss. PBH loss was also weakly negatively correlated with PBT at T1 at the root MP ($r = -.25$, $P = 0.005$), 2 mm coronal ($r = -.25$, $P = 0.006$), and 4 mm coronal to MP ($r = -.29$, $P = 0.001$), indicating that more PBH loss was correlated with PB that is thinner before orthodontic treatment. Additionally, PBH loss was weakly correlated with initial LBT 2 mm coronal to MP ($r = -.20$, $P = 0.028$), moderately correlated at 4 mm coronal to MP (r= -

.34, P< 0.001), and showed a weak trend towards significance at MP (r= -.17, P= 0.066), indicating that thinner LB before orthodontic treatment is correlated with greater PBH loss.

PBH loss was not correlated with sex, age at T1, molar classification, OJ, FMA, retraction method, LPBH at T1, or with any incisor movements.

FMA. FMA was weakly negatively correlated with PBT at the root MP (r= -.257, P= 0.16) and 2 mm coronal (r= -.202, P= 0.026) at T1 and showed a trend towards significance with the change in PBT 2 mm coronal to MP (r= -.154, P= 0.092), indicating that subjects with steeper FMA's were correlated with thinner palatal bone. FMA was not correlated to LBT at T1 or T1-T2.

Discussion

In this study, the average IARR (SG: 1.47 ± 1.04 mm; CG: 0.70 ± 0.81 mm, P< 0.001) is on target with values reported in the literature[2,5-12,18], but there was marked variation in IARR between individuals. In addition, 23.7% of the SG subjects had 2 or more mm of IARR from T1 to T2 compared with 6.3% of the CG subjects (P= 0.007), similar to Sameshima and Sinclair's finding that 25% of subjects undergo greater than 2 mm of IARR in the maxillary anterior teeth[7].

Fortunately, these subjects with more severe IARR can benefit from a 2-3 month pause[69]. The subjects displaying approximately 2 mm of IARR whose orthodontic treatment was paused for 2-3 months had an average of 0.4 mm compared to 1.5 mm more IARR with no pause, facilitating reorganization of damaged periodontal tissues and allowing healing with cementum[69].

Similar to several studies, neither sex[1,7,8,11,12,14,20] nor age[5,8,11,12,18,20] were variables related to increased severity of IARR. By contrast, Massler and Malone found that patients starting orthodontic treatment before the age of 11 years had significantly less root resorption than those after age 11[13]. Since patients had to be at least 10.5 years of age with completed maxillary incisor root formation to be included in this study, only three subjects were under the age of 11, making comparison with Massler and Malone's results impossible.

Interestingly, a longer tooth length was not positively correlated with increased IARR, in contrast to some studies[7,25,70]. FMA was also not found to be a factor in IARR, similar to the findings of Parker and Harris[2], Beck and Harris[8], and McFadden *et al*[11].

Subjects with Class II malocclusions were more likely to experience IARR than those with Class I malocclusions, unlike other studies that found that molar classification was not related to IARR[5,18,25]. IARR was weakly correlated with both OJ, similar to Sameshima and Sinclair's[7] findings, but in contrast to others[1,2,8,25] and OB, in contrast to the observations of Parker and Harris[2], Sameshima and Sinclair[7], Beck and Harris[8], and Linge and Linge[1]. Similarly, subjects treated orthodontically with premolar extractions were more likely to experience greater IARR than those treated by non-extraction, similar to Sameshima and Sinclair[7], VonderAhe[16], and Sharpe *et al.*'s[22] findings. Based on the relationship of excessive incisor movements associated with treating class II malocclusions, increased OJ and OB, and extraction therapy with increased IARR, one would suspect that greater incisor movement would be the culprit.

IARR, however, was only weakly associated with certain incisal movements and was unrelated to most. Horizontal movement of the IE, MP, and apex was not associated

with IARR similar to Phillips' study but in contrast to many[2,5,14,23,25]. Several studies[2,5,14,23,25] found that horizontal movements were associated with more IARR in contrast to the findings in this and Phillips'[20] study. Subjects with apical extrusion were weakly associated with increased IARR, similar to Horiuchi *et al.*'s[18] observation. Vertical movements of the IE and root MP did not reveal any association with increased IARR, similar to the findings of several authors[14,23-25]. The observation that intrusion was not related to IARR was in accordance with previous authors[5 11,27-29] many who achieved greater intrusion than in this study[27-29]; the mean vertical movements of the apex, root MP, and IE were less than 1 mm, an amount that may be too small to confidently make any conclusions about the relationship between vertical incisal movements and increased IARR.

Root approximation to the cortical plate was weakly correlated to IARR, similar to Horiuchi *et al.*[18] and Kaley and Phillips[24] who found a stronger relationship. In accordance with several publications[2,8,14,20,28,29], II at T1 or change in II from T1 to T2 was not related to increased IARR. Surprisingly, the type of horizontal incisal movement that occurred (tip, translation, or lingual root torque) did not correlate with increased IARR, differing from reports in the literature that lingual root torque[4,16] and lingual root torque in combination with intrusion[2,25] were factors most related in IARR.

Even though IARR was not correlated with most incisal movements, longer treatment duration was related to increased IARR, in accordance with the findings of Segal *et al.*[71], Sameshima and Sinclair[7], DeShields[14], Liou and Chang[29]. Length of treatment could be a summation of all factors disposing a patient to IARR[29], allowing

forces and inflammatory processes to be exerted on the incisors for a longer period of time.

While IARR may be inevitable during orthodontic treatment, Remmington *et al.* observed that severely resorbed teeth appeared to be functioning in a reasonable manner many years after orthodontics and displayed a progressive remodeling of the root surface[17]. Levander and Malmgren found less risk of mobility associated with severely resorbed maxillary incisors with root lengths greater than 9 mm and a healthy periodontium[72]. However, teeth with unfavorable crown/root ratios in some instances may be less suitable as abutments for prosthetic replacements[17].

There is no conclusive evidence that implicates a definitive treatment-related factor for apical root resorption[71], which helps explain some of the differing correlation results in this study compared to others. The etiologic factors are complex and multifactorial, but it appears that apical root resorption results from a combination of individual biologic variability, genetic predisposition, and the effect of mechanical factors[17]. Since the susceptibility is largely intrinsic to the patient, variation in outcome associated with IARR is largely beyond the practitioners'control[71].

Severe IARR is of clinical significance, especially when it is coincident with alveolar bone loss[71]. However, bone loss is a more serious problem, due to the importance of the cervical third of the periodontal attachment, the unfavorable increase of clinical crown to root ratio and the increase of supracrestal root surface available for colonization by plaque[73] .

As this is one of the first studies in the orthodontic literature to evaluate LPBH with CBCT images, several methods were utilized in hopes to reveal a more accurate and

reliable approach. When combining all subjects to evaluate LPBH, the four methods (perp-to-FH, perp-to-LA, IE-to-C, CEJ-to-C) demonstrated equal losses of approximately one-third mm, similar to the findings of Lupi *et al.*[73] who found 0.3 mm of interproximal BH loss of the maxillary incisors using periapical films[73]. Specifically, all methods revealed greater LPBH loss in the SG (LBH: 0.25 mm; PBH: 0.84 mm) compared to the CG (LBH: 0.08 mm; PBH: 0.22 mm) (P= 0.002). Again, there was great variation of LPBH loss among individuals.

Since evaluating LPBH loss by all four methods yielded results that were clinically similar, further analyses were conducted using only those values obtained by measuring LPBH par-to-LA, IE-to-C. Measuring par-to-LA was thought to most accurately reflect the bony morphology of the alveolus and would take into account any lateral incisal movements that may have occurred during treatment that may not be discerned by measuring LPBH perp-to-FH. The minimal spatial resolution of the i-CAT CBCT, found to be 0.86 mm[47], means that measuring the distance between two objects in close proximity, such as the distance from CEJ-to-C in certain subjects in certain subjects in this study, may not be accurate.

In addition to greater values of LPBH loss found in the SG, a larger percentage of these subjects experienced loss greater than 2 mm, measuring par-to-LA, IE-to-C (LBH: 3.4% of SG compared to 0.0% of the CG, P= 0.17) (PBH: 18.6% of SG and 1.6% of CG, P= 0.002), suggesting that clinicians should be careful when treatment planning for incisor retraction.

Interestingly, those subjects with greater loss of LPBH were not more likely to experience increased IARR, a finding that points to the individual susceptibility of patients to resorption of bone and root.

Increased PBH loss was, however, associated with several variables in addition to lingual incisor retraction worth noting: greater number of premolar extractions, long treatment duration, incisor proximity to the palatal cortex, and thinner labial and palatal bone at T1. Those subjects with greater PBH loss were also more likely to experience greater LBH loss. Patients with a thin alveolus inadequate to the demands of extensive tooth movement should be considered at risk for unfavorable sequelae due to orthodontic treatment[34]. The thin bone at the buccal and labial plates will often disappear entirely when teeth are moved for distances that exceed the thickness of the bone, a detrimental and sometimes permanent sequela[74].

Similar to the results of Handelman, subjects in this study with steeper FMA's were more likely to have thinner palatal bone, revealing a relationship between facial height and PBT[34]. However, facial height was not correlated with increased loss of LPBH or LPBT.

While the SG experienced greater LPBH loss than the CG, LPBT loss at all labial and palatal points was surprisingly similar between groups with the exception of the values obtained at the labial root MP (SG: 0.86 +- 1.03 mm; CG: 0.53 +- 0.62 mm, P= 0.037), a statistically significant but clinically insignificant finding. In contrast to Edwards[33] who reported that bone remodeling after significant incisor retraction will maintain a relatively constant LPBT, in this study LBT for all subjects increased an

average of 0.41 mm while PBT decreased 1.05 mm ($P < 0.001$), suggesting that bone may not follow tooth movement in a 1:1 ratio.

LPBT values for all subjects were seen to decrease equally at all three points from T1 to T2, in contrast to Sarikaya *et al.* who reported more alveolar bone loss at the marginal and midroot regions than towards the apex[65] and Edwards who observed greater changes in the marginal area of the alveolus and progressively less alteration of the bone towards the apex[33]. However, exact comparisons cannot be made as Sarikaya *et al.* and Edwards measured at slightly different points along the root than the ones selected in this study. Sarikaya *et al.* did observe dehiscences and fenestrations at the coronal and midroot levels[65], a finding similar to our study where bone was not visible in the T2 scans at the point 4 mm coronal to the root MP in several subjects. This phenomenon is in accordance with previous reports of crestal bone loss and facial bone dehiscences in monkeys that underwent labial tooth movement[38,39-41].

The spatial resolution limits of CBCT indicate that areas where bone was not visualized on CBCT could reveal that bone might truly be missing or its thickness was less than the limits of the minimal spatial resolution[75]. In either case, in orthodontics, alveolar thickness less than 0.5 mm represents a “quasi defect,” because it is extremely thin[76].

Even though CBCT imaging presents issues such as spatial resolution and partial averaging effects, several researchers have demonstrated that 3D imaging is an incredibly accurate[47] and reproducible[77] modality for orthodontic research. According to Ballrick *et al.*, the mean absolute differences between CBCT measurements and direct measurements of a phantom did not differ more than 0.067 mm for the i-CAT scanner

using the same image setting as in this study[47]. In Leung *et al.*'s study, CBCT scans of 13 dry human skulls found that the location of the CEJ was accurate to within 0.4 mm and the bone margin to within 0.6 mm[75]. Using CBCT to measure root length and marginal bone level *in vitro* and *in vivo*, Lund *et al.* found the *in vitro* mean difference between physical and radiographic measurements was 0.05 mm for root length and -0.04 mm for marginal bone level; *in vivo* the error was <0.35 mm for root length and <0.40 mm for marginal bone level assessments[77]. As most of the measurements in this study were greater than the aforementioned values reported in the literature, the results obtained in this study can be interpreted as being very accurate.

The inclusion of a CG, as in this study, might be the single most important factor when drawing conclusions from the results, thus removing the chance that any changes could simply be due to orthodontic movement in general and have no relevance to the technique used, allowing for more powerful comparisons[78].

A shortcoming of this study was the lack of follow-up for these subjects. To increase the impact to the field of orthodontics, measurements of LPBH taken during retention may better depict what alveolar changes occur after tooth movement[78]. Because alveolar bone undergoing turnover will appear less clearly and more lucent on a CBCT scan, a minimum of 1 year post-treatment may be required to evaluate bony changes[78]. Future studies utilizing CBCT should be undertaken to better elucidate the long-term change in bone and root that occur following orthodontic treatment.

The common practice of lingually retracting maxillary incisors to reduce both overjet and dentoalveolar protrusion warranted an accurate study examining the effect on the maxillary incisors and the adjacent palatal alveolar bone. This study was one of the

first of its kind to use 3D CBCT images to quantify the effect of lingually retracting maxillary incisors on resorption of the LPBH, LPBT, and maxillary incisor roots. The results were extremely accurate because CBCT images provide an accurate[47] and reproducible[77] method to evaluate bone and root changes associated with orthodontic treatment.

Conclusions

1. The SG experienced greater IARR and loss of LPBH than the CG.
2. Increased IARR was correlated with Class II malocclusions, increased OJ and OB, greater number of extracted premolars, long duration of treatment, proximity of the incisor roots to the palatal cortex and apical extrusion.
3. Increased LBH loss was correlated with using a power chain instead of a closing loop to close space, thinner palatal bone at T1, and more proclined incisors at T1.
4. Increased PBH loss was correlated with greater number of extracted premolars, long duration of treatment, proximity of the incisor roots to the palatal cortex, and thin palatal bone at T1.
5. Clinicians should exert caution when excessive incisor movement is planned in patients with thin alveolar bone.

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Figures

Figure 1. Standardized orientation of all subjects included in this study.

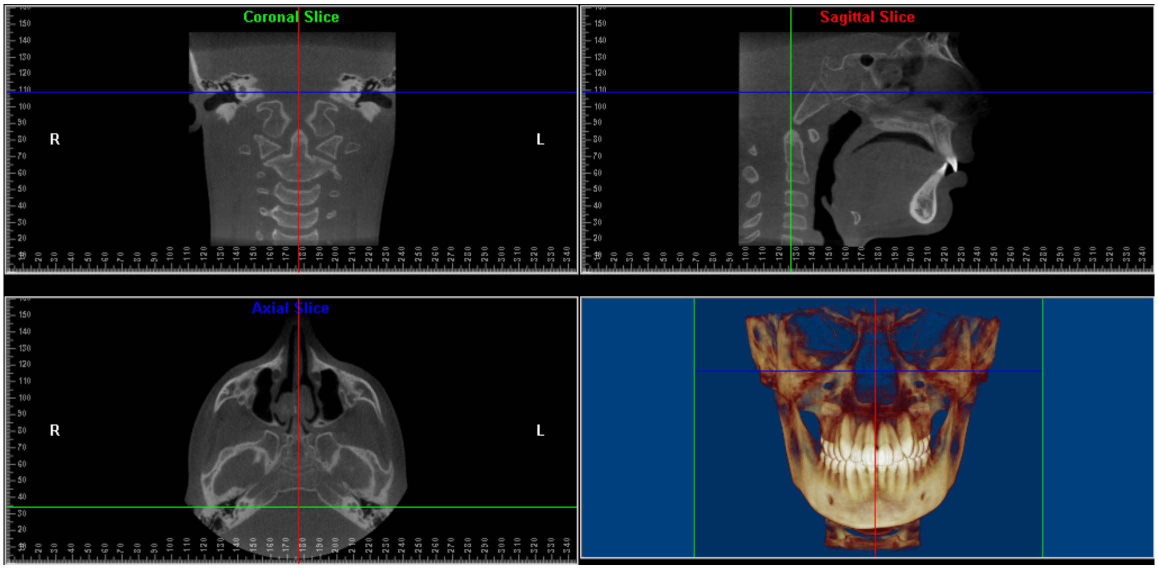


Figure 2. Volumetric rendering, sagittal, coronal, and axial views parallel to the long axis of maxillary central incisor, through the center of the incisor.

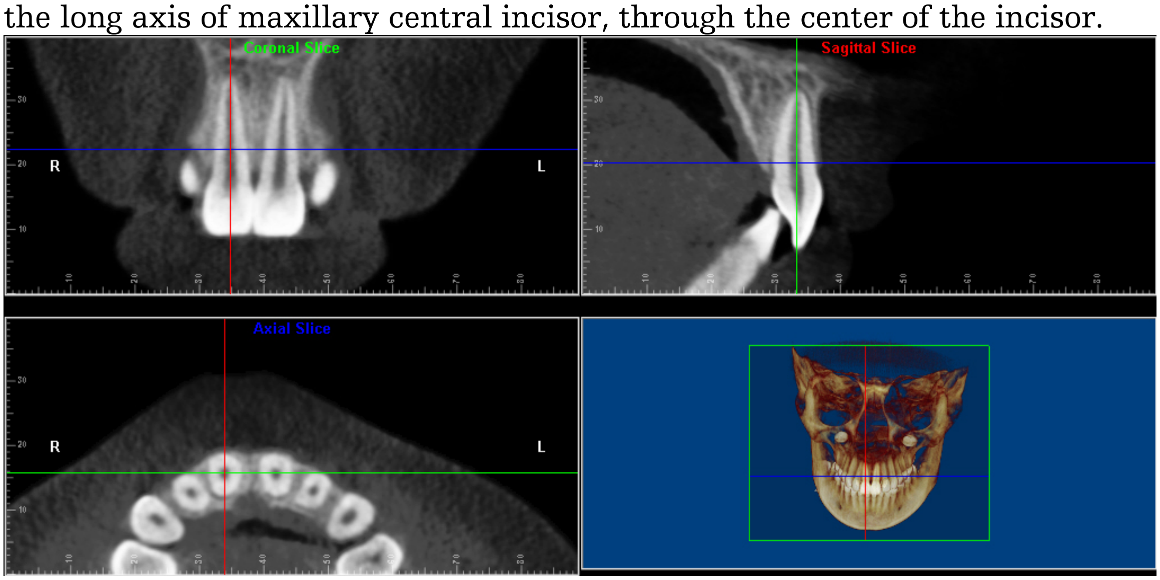


Figure 3. Sagittal slice used to measure incisor apical root resorption, parallel to the long axis of the incisor.

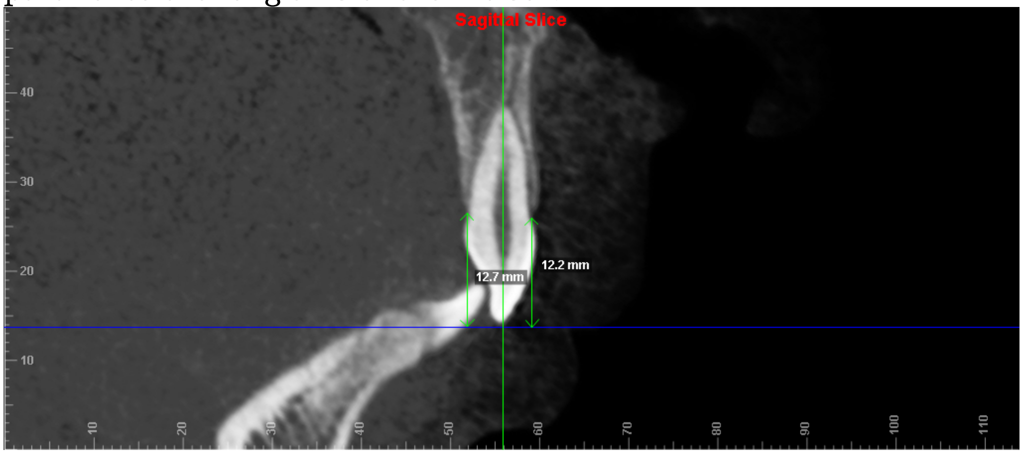


Figure 4. Voumetric rendering, sagittal, coronal, and axial views perpendicular to FH, through the center of maxillary incisor.

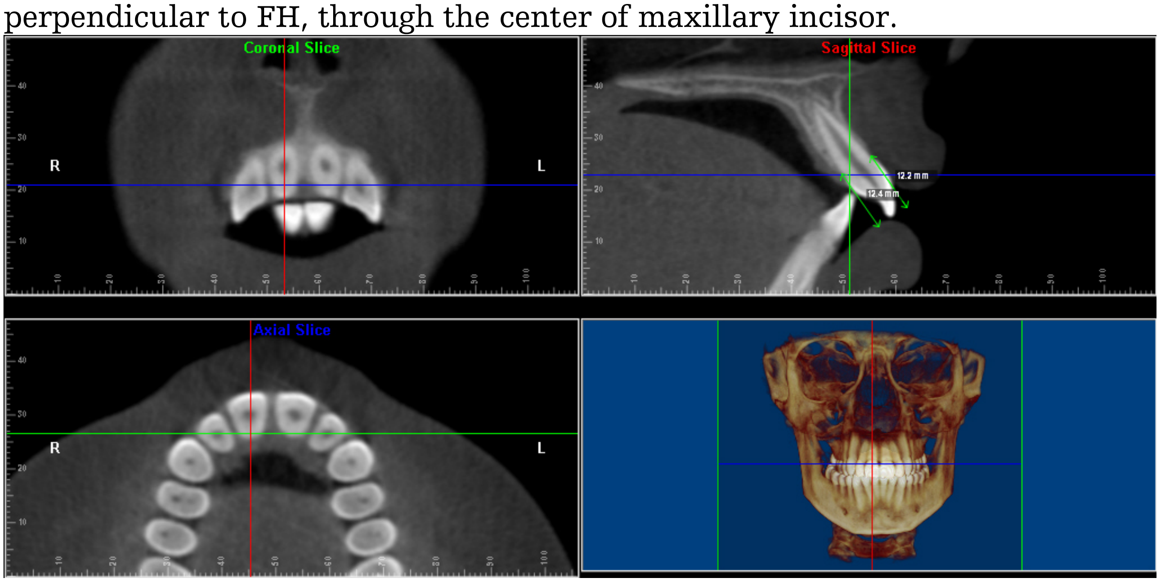


Figure 5. Measuring labial and palatal crestal alveolar bone height in the re-oriented sagittal view, perpendicular to FH, through the center of the incisor. Bone heights were assessed from the superior crest of bone to the incisal edge of the incisor.

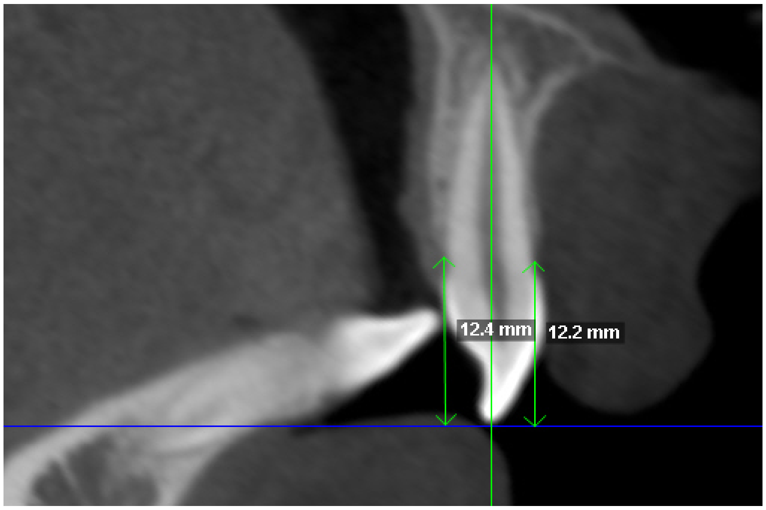


Figure 6. Measuring labial and palatal crestal alveolar bone heights in the re-oriented sagittal view, perpendicular to FH, through the center of the incisor. Bone heights were assessed from the superior crest of bone to the CEJ.

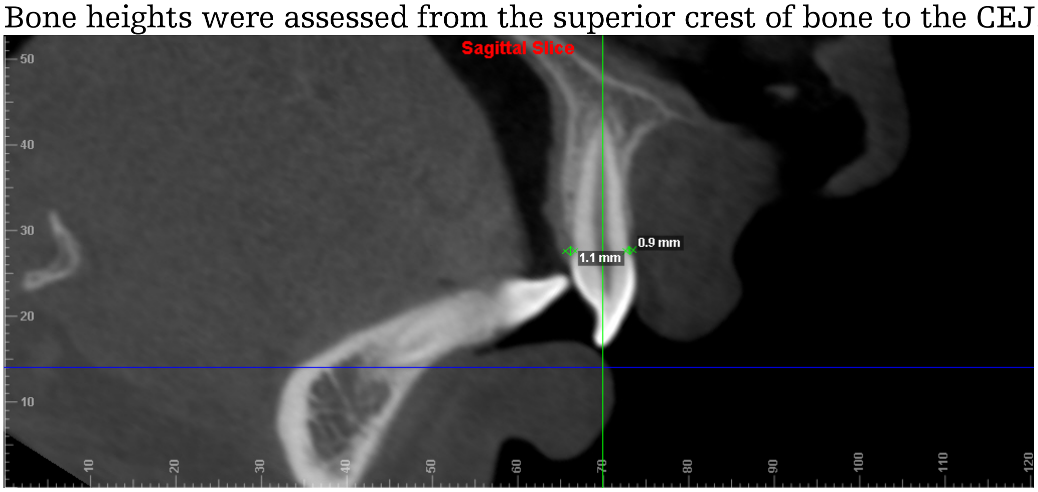
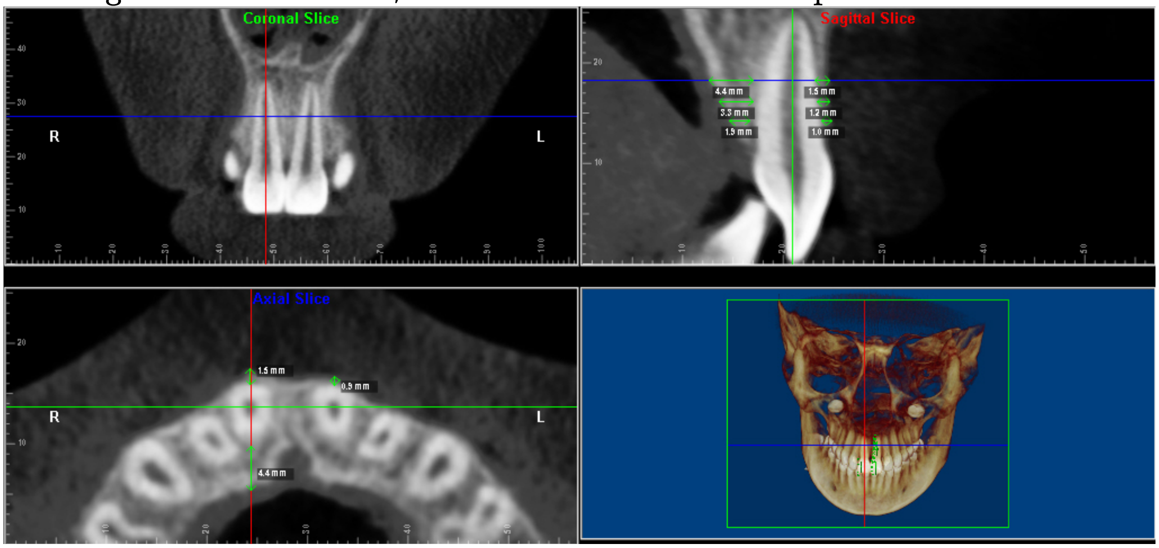


Figure 7. The multiple planar, sagittal, coronal, and axial views, parallel to the long axis of the incisor, used to measure labial and palatal bone thickness.



Tables

Table 1. Descriptive variables for the study group and control group.

Variables at T1		Study Group	Control Group
Molar Classification (n)	I	17	63
	II	33	0
	II Subdivision	9	0
Race (n)	Caucasian	49	57
	Hispanic	6	6
	Other	4	0
FMA		23.36 +- 5.78^{o}	21.96 +- 4.49^{o}
OJ		4.93 +- 2.55 mm	2.73 +-1.09 mm
OB		5.14 +- 4.51 mm	4.33 +- 1.30 mm
Treatment Duration		2.20 +- 0.4 yrs	1.46 +- 0.37 yrs
Extraction Pattern	Non-extraction	0	63
	Upper premolars	35	0
	Upper/lower premolars	24	0
Retraction Method	Closing Loop	44	0
	Power Chain	15	0
Retraction Time		6.33 +- 2.63 mos	0

Table 2. Measurement reliabilities for 20 randomly selected subjects for the same rater and for two independent raters.

Variable	Same Rater	Independent Raters
Tooth Length	.93	.93
Labial BH (perp-to-FH, IE-to-C)	.95	.95
Palatal BH (perp-to-FH, IE-to-C)	.67	.71
Labial BH (perp-to-FH, CEJ-to-C)	.83	.84
Palatal BH (perp-to-FH, CEJ-to-C)	.87	.85
Labial BH (par-to-LA, IE-to-C)	.85	.86
Palatal BH (par-to-LA, IE-to-C)	.66	.70
Labial BH (par-to-LA, CEJ-to-C)	.88	.86
Palatal BH (par-to-LA, CEJ-to-C)	.81	.81
Labial BT (Root MP, 2 mm coronal, 4 mm coronal)	.92	.92
Palatal BT (Root MP, 2 mm coronal, 4 mm coronal)	.89	.90
Apex Horizontal	.95	.94
Apex Vertical	.94	.95
Incisor Horizontal	.98	.99
Incisor Vertical	.96	.97

Note: All ICCs were significant at $P < .001$.

Table 3. IARR values for SG and CG.

	T1					T2					Difference (T1-T2)				
	SG		CG			SG		CG			SG		CG		
	Mean	SD	Mean	SD	P	Mean	SD	Mean	SD	P	Mean	SD	Mean	SD	P
Tooth Length (mm)	24.91	2.02	24.72	1.83	.58	23.44	2.16	24.02	2.04	.13	1.47	1.04	0.70	0.81	< .001**

** Differences are significant at the 0.01 level.

Table 4. Mean Labial and Palatal Bone Heights for SG and CG.

	T1					T2					Difference (T1-T2)				
	SG		CG			SG		CG			SG		CG		
Bone Height (BH) (mm)	**Mean**	**SD**	**Mean**	**SD**	**P**	**Mean**	**SD**	**Mean**	**SD**	**P**	**Mean**	**SD**	**Mean**	**SD**	**P**
Labial BH (perp-to-FH, IE-to-C)	12.38	0.69	12.25	0.72	.30	12.57	0.85	12.34	0.74	.11	-0.19	0.65	-0.09	0.42	.32
Palatal BH (perp-to-FH, IE-to-C)	12.42	0.79	12.06	0.64	.007**	13.21	1.29	12.33	0.76	< .001**	-0.80	1.26	-0.27	0.50	.003**
Labial BH (perp-to-FH, CEJ-to-C)	0.98	0.24	0.81	0.21	<.001**	1.30	0.46	0.88	0.27	< .001**	-0.33	0.44	-0.07	0.30	< .001**
Palatal BH (perp-to-FH, CEJ-to-C)	1.02	0.29	0.81	0.23	< .001**	1.81	1.11	0.94	0.37	< .001**	-0.79	1.04	-0.13	0.34	<.001**
Labial BH (par-to-LA, IE-to-C)	12.55	0.66	12.39	0.69	.21	12.70	0.97	12.43	0.68	.073	-0.16	0.73	-0.04	0.41	.27
Palatal BH (par-to-LA, IE-to-C)	12.41	0.71	12.09	0.62	.009**	13.28	1.23	12.38	0.76	< .001**	-0.87	1.11	-0.29	0.57	<.001**
Labial BH (par-to-LA, CEJ-to-C)	0.94	0.22	0.80	0.23	.001**	1.28	0.47	0.90	0.28	< .001**	-0.33	0.47	-0.10	0.28	.001**
Palatal BH (par-to-LA, CEJ-to-C)	0.99	0.35	0.74	0.20	< .001**	1.89	1.23	0.94	0.38	< .001**	-0.91	1.16	-0.20	0.36	<.001*
** Differences are significant at the 0.01 level.															

Table 5. Percentages of subjects with 2 mm or more of IARR, LBH loss, and PBH loss.

	Study Group (n= 59)		Control Group (n= 63)		P
Category	**N**	**%**	**N**	**%**	
IARR					
>= 2 mm change	14	23.7	4	6.3	.007**
Labial BH (LA, IE to C) (T1-T2)					
>= 2 mm change	2	3.4	0	0.0	.17
Palatal BH (LA, IE to C) (T1-T2)					
>= 2 mm change	11	18.6	1	1.6%	.002**
** Differences are significant at the 0.01 level.					

Table 6. LPBT means at root MP, 2 mm coronal to root MP, and 4 mm coronal to root MP for the SG and CG.

	T1					**T2**					**Difference (T2-T1)**				
	SG		**CG**			**SG**		**CG**			**SG**		**CG**		
Bone Thickness (mm)	**Mean**	**SD**	**Mean**	**SD**	**P**	**Mean**	**SD**	**Mean**	**SD**	**P**	**Mean**	**SD**	**Mean**	**SD**	**P**
Labial Root MP	1.12	0.76	1.04	0.51	.48	1.98	0.85	1.57	0.54	.002**	0.86	1.03	0.53	0.62	.037*
Palatal Root MP	3.06	1.13	3.55	1.20	.025*	1.76	1.06	2.20	1.14	.028*	-1.30	1.22	-1.34	0.80	.84
Labial 2 mm coronal to MP	1.18	0.62	1.11	0.40	.41	1.68	0.64	1.38	0.42	.003**	--0.49	0.75	0.28	0.49	.060
Palatal 2 mm coronal to MP	2.28	0.88	2.66	0.98	.027*	1.19	0.73	1.55	0.83	.012*	-1.09	0.93	-1.11	0.69	.92
Labial 4 mm coronal to MP	0.98	0.47	0.94	0.51	.65	1.19	0.65	1.01	0.52	.090*	0.21	0.60	0.07	0.49	.15
Palatal 4 mm coronal to MP	1.40	0.72	1.72	0.84	.027*	0.73	0.61	0.95	0.60	.042**	-0.68	0.60	-0.77	0.70	.44
** Differences are significant at the 0.01 level.															
* Differences are significant at the 0.05 level.															
(-) values at (T2-T1) indicate loss in bone thickness over time. (+) values indicate gain in bone thickness.															

Table 7. Mean values of incisor movement for SG and CG.

	Difference (T1-T2)				
	SG		CG		
Variable	**Mean**	**SD**	**Mean**	**SD**	**P**
Apex Horizontal	3.34	2.02	1.72	4.45	.012
Apex Vertical	0.09	1.49	-0.74	2.45	.028
IE Horizontal	2.88	2.42	-0.55	6.94	<.001
IE Vertical	0.52	2.93	0.10	3.69	.49
Root MP Horizontal	2.92	2.32	1.33	4.91	.026
Root MP Vertical	0.07	1.44	-0.83	1.75	.003
Ratio of Horizontal Movement	1.64	2.36	.58	7.01	.27

Table 8. Percentages of subjects with types of incisal movements.

Treatment Condition	Uncontrolled Tipping	Uncontrolled Tipping and Bodily Movement	Root Movement	Total
SG	6.8%	35.6%	57.6%	100.0%
CG	63.9%	13.1%	23.0%	100.0%
Total	35.8%	24.2%	40.0%	100.0%

Table 9. Pearson correlation analysis results determining the relationship between several variables and IARR, LBH loss, and PBH loss.

		Treatment Condition (SG vs. CG)	Sex	Age (T1)	Race	Angle's Molar Class	OJ (T1)	OB (T1)	FMA (T1)	Extract-ion Pattern	Retract-ion Method	Duration of Space Closure	Durat-ion of Treat-ment	Proxim-ity of Root to Palatal Cortex
IARR (T1-T2)	**r**	-.39**	-.15	-.14	.02	.34**	.26**	.22*	-.11	.28**	-.17	-.05	.36**	.21*
	P	< .001	.092	.14	.82	< .001	.004	.018	.23	.002	.11	.72	< .001	.022
Labial BH LA, IE to C) (T2-T1)	**r**	-.102	-.072	-.01	.15	-.09	-.14	-.01	.01	.13	-27*	-.15	.15	.17
	P	.27	.43	.28	.11	.34	.12	.93	.29	.16	.043	.26	.100	.061
Palatal BH (LA, IE to C) (T2-T1)	**r**	-.32**	-.016	.01	.18	.11	-.07	-.18	.01	.33**	.11	.-16	.30**	.46**
	P	<.001	.86	.92	.054	.22	.48	.052	.93	< .001	.40	.22	.001	< .001

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 10. Pearson correlation analysis results determining the relationship between tooth length, LPBH and LPBT with IARR, LBH loss, and PBH loss.

		Tooth Length (T1)	Labial BH (par-to-LA, IE-to-C) (T1)	Palatal BH (par-to-LA, IE-to-C) (T1)	Labial BH (LA, IE to-C) (T2-T1)	Palatal BH (LA, IE-to C) (T2-T1)	Labial BT, (Root MP) (T1)	Palatal BT, (Root MP) (T1)	Labial BT, 2 mm coronal to MP (T1)	Palatal BT, 2 mm coronal to MP (T1)	Labial BT, 4 mm coronal to MP (T1)	Palatal BT,4 mm coronal to MP (T1)
IARR (T1-T2)	**r**	.06	.13	.09	.05	-.01	-.02	.03	.01	-.01	.01	-.04
	P	.52	.16	.33	.52	.91	.87	.79	.93	.89	.90	.68
Labial BH (par-to-LA, IE-to-C) (T2-T1)	**r**	-.04	-.12	-.00	N/A	.33**	.02	-.18	.01	-.21*	-.15	-.18*
	P	.69	.18	1.0	N/A	<.001	.80	.051	.93	.018	.10	.047
Palatal BH (par-to-LA, IE-to-C) (T2-T1)	**r**	-.19*	-.05	-.06	.33**	N/A	-.17	-.25**	-.20*	-.25**	-.34**	-.29**
	P	.038	.59	.52	< .001	N/A	.066	.005	.028	.006	< .001	.001

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 11. Pearson correlation analysis results determining the relationships between incisal movements and IARR, LBH loss, and PBH loss.

		Apex Vertical Change (T1-T2)	Apex Horizontal Change (T1-T2)	MP of Root Vertical Change (T1-T2)	MP of Root Horizontal Change (T1-T2)	IE Vertical Change (T1-T2)	IE Horizontal Change (T1-T2)	Incisor Inclination (T1)	Incisor Inclination Change (T1-T2)	Horizontal Ratio of Incisor Movement
IARR (T1-T2)	**r**	-.26**	.14	.18	.08	.02	.09	.05	.03	.10
	P	.004	.14	.055	.36	.83	.33	.57	.72	.29
Labial BH (LA, IE to C) (T2-T1)	**r**	.04	-.05	.02	.01	-.08	.10	.24**	.14	.17
	P	.68	.57	.83	.90	.40	.27	.008	.12	.065
Palatal BH LA, IE to C) (T2-T1)	**r**	-.03	.04	.04	.04	-.04	.09	.06	.01	-.08
	P	.78	.63	.71	.69	.64	.33	.54	.88	.38
** Correlation is significant at the 0.01 level (2-tailed).										
* Correlation is significant at the 0.05 level (2-tailed).										

Table 12. Pearson correlation analysis results determining the relationship between FMA and LPBT at T1.

	FMA (T1)	
	r	**P**
Labial BT, Root MP (T1)	.128	.16
Palatal BT, Root MP (T1)	-.257**	.004
Labial BT, 2 mm coronal (T1)	.071	.44
Palatal BT, 2 mm coronal (T1)	-.202	.026
Labial BT, 4 mm coronal (T1)	.122	.18
Palatal BT, 4 mm coronal (T1)	-.043	.63
Labial BT, MP (T1-T2)	.100	.27
Palatal BT, MP (T1-T2)	-.127	.17
Labial BT, 2 mm coronal (T1-T2)	.058	.53
Palatal BT, 2 mm coronal (T1-T2)	-.154	.092
Labial BT, 4 mm coronal (T1-T2)	.024	.79
Palatal BT, 4 mm coronal (T1-T2)	-.063	.49
** Correlation is significant at the 0.01 level (2-tailed).		
* Correlation is significant at the 0.05 level (2-tailed).		