Alveolar Bone Remodeling In Response to Orthodontic Tooth Movement

Matthew Raymond McGrady
Marquette University

ALVEOLAR BONE REMODELING IN RESPONSE TO ORTHODONTIC TOOTH MOVEMENT

by

Matthew Raymond McGrady, DMD

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ABSTRACT

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Objective:

Dental protrusion and retrusion are common malocclusions in clinical orthodontics. When teeth are moved orthodontically, the alveolar bone surrounding the teeth remodels. In the past, incisor retraction-associated alveolar bone remodeling has been studied. However, less is known about the alveolar bone remodeling after incisors are proclined. This study aimed to assess the changes in alveolar bone thickness after proclination of maxillary incisors. The null hypothesis was that there was no difference in the surrounding alveolar bone thickness after orthodontic tooth movement.

Materials and Methods:

Patients were selected under the inclusion criteria of moderate-to-severe bimaxillary dental retrusion (U1-SN < 97°, L1-MP < 88.0°), absence of craniofacial anomalies, non-extraction, absence of missing teeth, with quality pre-and post-treatment lateral cephalometric images. Nineteen patients (10 males, 9 females; mean age 14.7 years) were selected, and their pre-treatment and post-treatment lateral cephalograms were digitally traced using a customized cephalometric analysis to compare changes in labial and lingual alveolar bone thickness (ABT) after orthodontic treatment. A two-sample t-test with R statistical software version 4.1.2 was used to measure the differences between the pre- and post-treatment cephalometric measurements. A p value less than 0.05 was considered statistically significant.

Results:

According to the SN-7° measurement method, ABT increased at the labial(b) SN-7 (0.27 mm ± 0.70; $p < 0.05$) and U1 labial(c) SN-7° (0.79 mm ± 1.56; $p < 0.05$) levels; however, ABT decreased at the U1 lingual (c) SN-7° (1.13 mm ± 1.35; $p < 0.05$) level. According to the perpendicular of the long axis of U1 root measurement method, ABT increased at the U1 labial(c) ⊥U1 (0.55 mm ± 1.35; $p < 0.05$) level, while ABT decreased at the U1 lingual (b) ⊥U1 (0.79 mm ± 1.03; $p < 0.05$) and U1 lingual (c) ⊥U1 (1.61 mm ±1.39; $p < 0.05$) levels. Statistically significant changes were also found in post-treatment incisor angulation U1-SN° (8.05° ± 8.25; $p < 0.05$), U1 – NA° (7.44° ± 8.08; $p < 0.05$) and post-treatment incisor position U1–NA (mm) (1.64 mm ± 2.63; $p < 0.05$).

Conclusion:

The null hypothesis was rejected based on our results. There are statistically significant changes to the labial and lingual alveolar bone (ABT) after the proclination of the maxillary incisors. Our data support previous findings in orthodontics literature. Further studies should be conducted that can employ larger sample sizes with imaging methods that overcome the limitations of conventional two-dimensional imaging.

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CHAPTER 1
INTRODUCTION

Class II Division 2 malocclusion is a type of dental misalignment characterized by retroclination of the incisors and a deep overbite. Its prevalence in the United States has been estimated to be as high as 4%. Individuals experiencing this condition often report esthetic issues and injuries to the palatal or lower labial gingivae. In some cases, the deep overbite is so extreme that the front teeth excessively bite into the gums, causing damage either behind the upper front teeth or in front of the lower front teeth (Millett et al., 2018).

It is a common perception that retroclined incisors appear unesthetic to the general population. Najafi et al. explored the preferences for incisor inclinations in cases of mandibular protrusion, retrusion, and normal mandibular position among professional groups and laypeople. Najafi's findings suggest a general preference for normal incisor inclinations in protruded and retruded mandibles, with less labial or lingual inclination being preferred (Najafi et al., 2016).

Given the functional and esthetic consequences of Class II Division 2 malocclusions, orthodontists have sought to correct incisor angulations and occlusal relationships through treatment with fixed and removable appliances. As the dentition is straightened to a normal position, the alveolar bone remodels; however, the orthodontist must be careful to place the incisors within a reasonable limit inside the alveolus. If there is inadequate bone surrounding the teeth, this can lead to periodontal compromise in the form of bone dehiscence and gingival recession (Morris et al., 2017). As such, investigation into the changes in facial and lingual alveolar bone thickness after orthodontic tooth movement is warranted to better understand the limits of orthodontic treatment.

CHAPTER 2
LITERATURE REVIEW

The occurrence of Class II Division 2 malocclusion in the Caucasian population has been approximated to vary from 2.3% to 5% (Barbosa et al., 2017). Edward Angle initially defined Class II Division 2 malocclusions based on the mandibular molar relationship being more distal to the maxillary molars; however, many further characterized Class II Division 2 malocclusions by retroclined incisors and a deep overbite (Millett et al., 2018). Some have suggested that this type of malocclusion has a skeletal component whereby the mandible is deficient in relation to the maxilla due to development or the mandible's position in relation to the cranial base (Barbosa et al., 2017).

The maxillary incisors, located prominently at the front of the mouth, serve a vital function in both facial esthetics and oral functionality (Jiang et al. al., 2019). Enhancing facial and dental aesthetics holds significant value in the lives of individuals pursuing orthodontic treatment. The majority of orthodontic patients prioritize enhancing their appearance and social acceptance over improving oral health or functionality (Badawi et al., 2009). This emphasis on esthetics is reinforced by research demonstrating that dental esthetics can influence how others perceive individuals. Poor dental esthetics in both children and adults has been associated with lower intelligence, while adults with ideal smiles are perceived as more intelligent and have a higher likelihood of securing employment compared to those with less-than-ideal smiles (Isiekwe et al., 2016). In orthodontic treatment, obtaining proper inclination of the anterior teeth is of utmost importance to achieve proper esthetics and occlusal relationships. Specifically, the faciolingual inclination of the maxillary front teeth plays a critical role in establishing a pleasing smile line, proper anterior guidance, and a harmonious Class I relationship between the canines and molars (Badawi et al., 2009).

Treatment of Class II Division 2 malocclusion requires proclination of the maxillary and mandibular incisors. When orthodontist achieves these treatment goals, they must be careful not to place the incisors too close to the cortical plate of the alveolus to avoid periodontal problems (Morris et al., 2017). Numerous studies have been conducted on the effects of proclination and retroclination of the incisors. Artun and Krogstad found that excessive proclination of the lower incisors led to more teeth developing recession during and after orthodontic treatment (Årtun & Krogstad, 1987). Fuhrmann used computed tomography to study adult orthodontic patients and found that incisor proclination and retroclination increase or cause periodontal lesions such as bone dehiscence and fenestrations (Fuhrmann, 1996). In contrast, a study by Ruf et al. suggested that proclination of the lower incisors in children and adolescents does not result in gingival recession; however, they postulated that severe Class II cases may be predisposed to gingival recession due to a small mandible and thus small apical base (Ruf et al., 1998). Ruf's findings are supported by Morris et. al, who suggested that orthodontic treatment does not significantly contribute to the likelihood of gingival recession. Surprisingly, Morris also stated that although a higher degree of maxillary expansion during treatment slightly raises the risks of recession after the treatment, the impact is negligible (Morris et al., 2017). In 2022, Colet et al. conducted a study and found that patients did not experience a gingival recession in the mandibular anterior incisors when treated with a Twin Force appliance and intermaxillary elastics (Colet et al., 2022). While it seems intuitive that excessive proclination of the incisors will lead to inadequate alveolar bone support and, thus, periodontal lesions, the relationship between tooth movement and alveolar bone remodeling may be more complex than it seems.

In 2002, Sarikaya et al. assessed changes in alveolar bone thickness due to retraction of anterior teeth. They assessed lateral cephalograms and computed tomography scans of nineteen patients with bimaxillary protrusion to assess alveolar bone changes after the extraction of four first premolars. Each radiograph and scan highlighted the maxillary and mandibular incisors at three levels: crest level (S1), midroot level (S2), and apical level (S3). Once characterized, they were able to measure the labial and alveolar bone thickness from the root of each tooth to the cortical plate of the alveolus. They found that retraction of the anterior teeth with controlled tipping led to no changes in the labial bone thickness of the maxilla, while there was a statistically significant decrease in lingual bone thickness in both the maxillary and mandibular alveolus.

Interestingly, they found that the labial bone thickness remained unchanged in both the maxilla and mandible, with one exception: the mandibular alveolar bone showed a significant decrease in labial thickness at the S1 level. Furthermore, they also noted that some patients exhibited bone dehiscences that were not visible with radiographs or at the macroscopic level. The authors concluded their study by stating incisor retraction can lead to alveolar bone loss and that two-dimensional imaging is inadequate for identifying periodontal lesions (Sarikaya et al., 2022).

In 2019, Hong et al. conducted a study to assess how alveolar bone is remodeled after incisor intrusion and retraction in patients treated with bicuspid extractions. They found similar results to Sarikaya with respect to the maxilla alveolus: labial bone thickness remained unchanged, except a statistically significant increase was noted 9 mm apical to the CEJ of U1. The increase, however, was deemed clinically minute as it was only 0.4 mm. Hong et al. suggested that additional studies utilize computed tomography to obtain higher-resolution images that can provide more accurate measurements beyond the limitations of two-dimensional imaging (Hong et al., 2019).

In 2021, Elnagar et al. conducted a study to assess alveolar cortical plate changes after incisor retraction with miniscrew anchorage. Their study included lateral cephalograms of twenty-nine South Korean patients treated with four bicuspid extractions. First, they identified the CEJ and root apices of the maxillary and mandibular central incisors in their tracings. Then, using the CEJ as a baseline reference point, they divided the root into fourths, with the CEJ at 0% and the root apex at 100%. To control for apical root resorption, pre-treatment incisors were superimposed upon post-treatment incisors. Using a custom analysis, they were then able to measure labial and lingual alveolar bone thickness using a reference line perpendicular to Sella and Palatal Plane in the maxilla and mandibular plane in the mandible (Elnagar et al., 2021). They then measured the thickness of labial and lingual alveolar bone from the margin of the root to the facial and lingual cortical plates, respectively. They found no significant change in the distance of the central incisor root to the labial cortical plate in the maxilla and mandible at any level along the root (0-100%). With regards to changes in the lingual alveolar bone, they found that the distance from the central incisor root to the lingual cortical plate decreased in the maxilla and the mandible at all levels with the exception of the root apex (100%), which remained unchanged. While Elnagar et al. al. attempted to produce pure translation with their retraction mechanics, they stated that controlled tipping was observed.

Not too long after Elnagar's study, Kang et al. conducted and published a study in International Orthodontics (Kang et al., 2021). It was particularly interesting because it investigated alveolar bone remodeling changes in patients with retroclined incisors as opposed to other publications, which typically study incisor retraction in bimaxillary protrusive patients. Furthermore, computed tomography scans were utilized in order to avoid the obstacles of two-dimensional radiographs.

Kang's study focused on examining how maxillary incisor proclination affects alveolar bone height. Their sample included Caucasian adolescents: 20 with Class II Division 1 malocclusion and 20 individuals with Class II Division 2 malocclusion. High-resolution CT scans were utilized to evaluate the thickness of the labial and palatal bone following the proclination of retroclined incisors. In the Class II Division 2 group, they found an average proclination of 15 degrees did not result in a significant change in facial bone height, but a statistically significant decrease in palatal bone height was observed. On the other hand, in the Class II Division 1 group, mild crown retroclination led to a significant reduction in both facial and palatal bone height. Both groups experienced a significant decrease in total bone thickness across all levels, with the Class II Division 2 group exhibiting a greater decrease after treatment. They also found no statistically significant difference in root length between the two groups during treatment. The results of the study indicate that the retroclination and flaring of maxillary incisors carried out to correct their inclination, did not have any detrimental effects on the height of the facial alveolar bone in non-extraction treatment of Class II Division 2 cases. Furthermore, the degree of crown proclination itself did not show any correlation with the extent of root resorption in non-extraction treatments for both Class II Division 1 and Division 2 malocclusions in adolescent patients.

Chen et al. also conducted a study on the treatment of Class II Division 2 patients and was published in the American Journal of Orthodontics and Dentofacial Orthopedics (Chen et al., 2022). Like Kang's study, Chen used computed tomography to avoid the pitfalls of lateral cephalograms, namely a lack of reproducibility and midsagittal projection in the anterior region, which makes studying changes in the alveolar bone and roots difficult.

In Chen's study, fifty-nine Chinese Han patients with similar demographic characteristics were selected and divided into three groups: a conventional bracket group, a self-ligating bracket group, and a clear aligner group. All patients had CBCT's previously performed on them with medium volume, high-resolution settings (0.3 mm-voxel resolution). These images were then used to measure root resorption and alveolar bone thickness in each of the three groups via two forms: 2D sagittal CBCT views (1) and 3D volume volumetric reconstructions (2). Chen et al. also studied the positioning of the maxillary central incisors by defining two planes: the x-axis (ANS-PNS) and the y-axis (line perpendicular to the x-axis at the level of PNS). By using these two planes, they were able to assess the changes of defined points on U1, namely the center of resistance and incisal tip, by comparing pre- and post-treatment records. This interesting methodology in their study design aided in assessing the positional change of the incisors after orthodontic treatment.

When reviewing their results, they found that the center of resistance of the maxillary central incisor exhibited either upward or forward movement in all three groups. The clear aligner group demonstrated significantly less root volume loss compared to the fixed appliances. Following treatment, all three groups experienced a significant decrease in palatal alveolar bone and total bone thickness across three levels along the root surface apical to the CEJ. Conversely, labial bone thickness exhibited a significant increase, except at the crestal level. Among the three groups, the clear aligner group displayed a notable increase in labial bone thickness at the apical level. This data suggest that clear aligners could be used to limit periodontal lesions in orthodontic treatment. Some limitations in the study, however, were noted. For one, the study was limited to Han Chinese patients. Additionally, the study was retrospective, and patients were treated by multiple clinicians through multiple treatment methods. Regardless, Chen et al.'s study provided a contribution to the literature surrounding the remodeling of alveolar bone (Chen et al., 2022).

CHAPTER 3
MATERIALS AND METHODS

Study Design

All cephalograms used for this study were obtained with IRB approval (HR-4076) from treated patients at the Marquette University School of Dentistry (MUSoD) Graduate Orthodontics Clinic. Pre-treatment and post-treatment cephalograms for selected patients were used to measure changes in hard tissues. Cephalograms were taken of patients using the same machine in the Graduate Orthodontics Clinic (Orthoceph OC200D). Pre-treatment cephalograms were taken prior to treatment, and post-treatment lateral cephalograms were obtained on the day of appliance removal.

Patient Selection

A search was conducted within Marquette University's Dolphin Imaging patient database for patients with retroclined maxillary and mandibular incisors based upon U1-SN and L1-MP normal values 102.8° ± 5.5° and 95.0° ± 7.0° respectively. Patients at least one standard deviation below both normal values were considered (U1-SN < 97°, L1-MP < 88.0°). A representative patient is presented in **Figure 1a, Figure 1b**. Exclusion criteria for this study were: patients with craniofacial anomalies, incomplete records, poor quality cephalograms, patients treated with extractions, and patients with missing or supernumerary teeth. Forty-six patients were obtained with the initial Dolphin search, and nineteen patients were eligible, with the vast majority being excluded due to the quality of cephalograms.

Cephalograms were traced and measured using a custom analysis with Dolphin Imaging 12.0.9.55 Premium software. The custom analysis, MM/Liu, was developed to measure changes in skeletal and dental tissues.

Skeletal tissues were assessed utilizing SNA, SNB, ANB, and SN-MP measurements to analyze the anteroposterior and vertical dimensions. Facial and lingual alveolar bone thickness (ABT) was assessed by measuring the distance between a point on the root of the maxillary central incisor to a point along the cortical plate of the maxillary alveolus. Specifically, this horizontal distance was calculated at three levels, utilizing two separate horizontal axes for reference: 1) SN-7° plane (**Figure 2**) and 2) perpendicular to the long axis of U1 (**Figure 3**). Measurements from the root surface of U1 to the cortical plate were taken at three levels: at the CEJ (a), 3 mm apical to the CEJ (b), and 6 mm apical to the CEJ (c).

Figure 1a. Typical intraoral records of a study patient pre-treatment.

Figure 1b. Typical intraoral records of a study patient post-treatment.

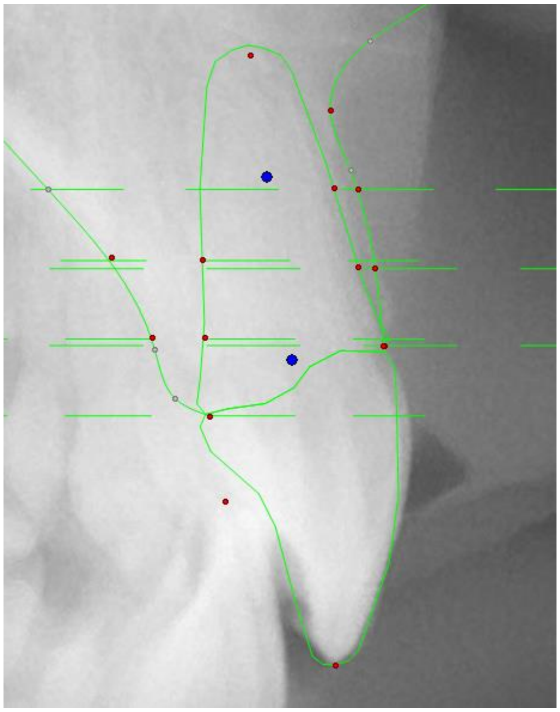

Figure 2. Sample tracing of lateral cephalogram using the customized MM/Liu analysis. This figure illustrates how the alveolar bone thickness was determined using a vertical line perpendicular to SN-7° plane as a horizontal reference. The dashed lines were used to find a point along the maxillary alveolus whereby alveolar bone thickness could be measured. Figure is only meant for illustrative purposes.

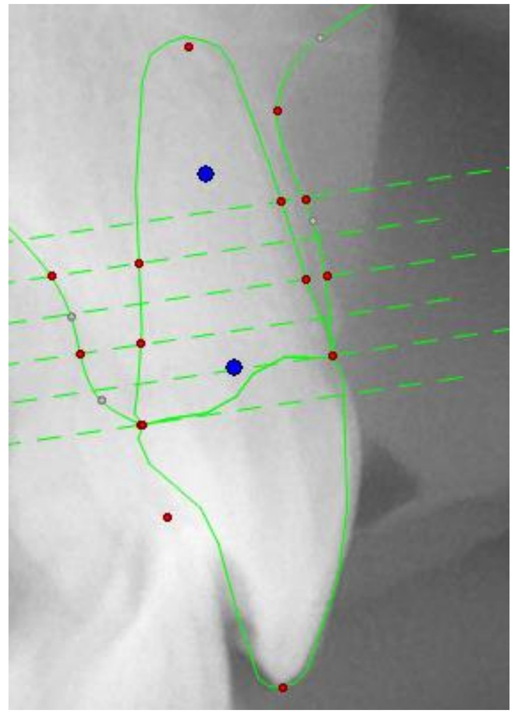

Figure 3. Sample tracing of lateral cephalogram using the customized MM/Liu analysis. This figure illustrates how the alveolar bone thickness was determined using the perpendicular line of the long axis of U1 root as a horizontal reference. The dashed lines were used to find a point along the maxillary alveolus whereby alveolar bone thickness could be measured. Figure is only meant for illustrative purposes.

Measurements using the SN-7° reference plane produced the thickness of labial and lingual alveolar bone and were defined as U1 labial(a) SN-7° (mm), U1 labial(b) SN-7° (mm), U1 labial(c) SN-7° (mm) for the labial and U1 lingual (a) SN-7° (mm), U1 lingual (b) SN-7° (mm), and U1 lingual (c) SN-7° (mm) for the lingual. Measurements using the perpendicular of the long axis of U1 root reference plane also produced the thickness of labial and lingual alveolar bone and were defined as U1 labial(a) ⊥U1 (mm), U1 labial(b) ⊥U1 (mm), U1 labial(c) ⊥U1 (mm) for the labial and U1 lingual (a) ⊥U1 (mm), U1 lingual (b) ⊥U1 (mm), and U1 lingual (c) ⊥U1 (mm) for the lingual (**Table 1**).

Labial – SN-7°	**Lingual – SN-7°**	**Labial – ⊥U1**	**Lingual - ⊥U1**
U1 labial(a) SN-7° (mm) Level*: CEJ*	U1 lingual (a) SN-7° (mm) Level*: CEJ*	U1 labial(a) ⊥U1 (mm) Level*: CEJ*	U1 lingual (a) ⊥U1 (mm) *Level*: *CEJ*
U1 labial(b) SN-7° (mm) Level*: 3mm apical to CEJ*	U1 lingual (b) SN-7° (mm) Level*: 3mm apical to CEJ*	U1 labial(b) ⊥U1 (mm) Level*: 3mm apical to CEJ*	U1 lingual (b) ⊥U1 (mm) Level*: 3mm apical to CEJ*
U1 labial(c) SN-7° (mm) Level*: 6mm apical to CEJ*	U1 lingual (c) SN-7° (mm) Level*: 6mm apical to CEJ*	U1 labial(c) ⊥U1 (mm) Level*: 6mm apical to CEJ*	U1 lingual (c) ⊥U1 (mm) Level*: 6mm apical to CEJ*

Table 1. The measurements used to measure labial and lingual alveolar bone thickness (ABT). Two horizontal reference planes were used: perpendicular to SN-7° plane and perpendicular to the long axis of U1 (⊥U1). The thickness of the alveolar bone was measured at three levels: CEJ (a), 3 mm apical to CEJ (b), and 6 mm apical to CEJ (c).

Dental tissues, specifically U1 angulation, and position, were assessed by tracing U1-SN (°), U1-NA°, and U1-NA (mm).

Radiographs were enhanced by adjusting the sharpness, gamma, and contrast of the films to obtain the clearest image. One operator traced each pre-treatment and post-treatment cephalograms. Once Porion, Orbitale, Sella, and Nasion points were landmarked, the films were oriented to an SN-7° position for the remainder of the tracing. The labial and lingual alveolar bone thicknesses (ABT) were then measured by placing a point on the labial or lingual CEJ of U1. Once this initial point was placed, horizontal and vertical helper lines were automatically generated to help plot points that measured the distance between the root and the cortical plate of the alveolus at 3 mm successive heights.

Statistical Analysis

All data collected from pre- and post-cephalometric measurements of 19 patients were recorded onto an Excel spreadsheet and then transferred to statistical software R, version 4.1.2, to perform statistical tests. A two-sample t-test (for the data normally distributed) or Wilcox test (for the data not normally distributed) was used to measure the differences between the pre- and post-treatment cephalometric measurements. A p-value less than 0.05 was considered statistically different.

Examiner Reliability Test

One patient was randomly selected for pre- and post-treatment tracings. Three tracings were completed a week apart for a total of six tracings.

Measurements were then analyzed to determine the intra-examiner reliability – intraclass correlation coefficient (ICC).

CHAPTER 4
RESULTS

Nineteen patients were eligible for this study. Descriptive data were as follows: 10 males (average age 14.1 years) and 9 females (average age 15.3 years), SNA (°) 79.48 ± 4.48, SNB (°) 77.08 ± 3.51, U1-SN (°) 92.03 ± 2.74, U1-NA (°) 12.56 ± 5.85, U1-NA (mm) 1.97 ± 2.44, L1-NB (mm) 1.35 ± 1.96, and SN-MP (°) 32.87 ± 6.83.

The pre- and post-treatment cephalograms results were gathered while mean, standard deviation, and standard error values were calculated for these measurements (**Table 2, Table 3**).

Pre-treatment Cephalometric Statistics				
Measurement	**N**	**Mean**	**Std. Deviation**	**Std. Error**
U1 labial(a) SN-7 (mm)	19	0.6	0.4876	0.1119
U1 labial(b) SN-7 (mm)	19	1.1105	0.3604	0.0827
U1 labial(c) SN-7 (mm)	19	1.1947	0.4684	0.1075
U1 lingual (a) SN-7 (mm)	19	0.5211	0.7036	0.1614
U1 lingual (b) SN-7 (mm)	19	3.0737	1.0311	0.2366
U1 lingual (c) SN-7 (mm)	19	5.3684	1.2574	0.2885
U1 labial(a) ⊥U1 (mm)	19	0.6316	0.5313	0.1219
U1 labial(b) ⊥U1 (mm)	19	1.1	0.3575	0.082
U1 labial(c) ⊥U1 (mm)	19	1.1263	0.4874	0.1118
U1 lingual (a) ⊥U1 (mm)	19	0.4895	0.6163	0.1414
U1 lingual (b) ⊥U1 (mm)	19	2.7526	0.8255	0.1894
U1 lingual (c) ⊥U1 (mm)	19	4.8474	0.9559	0.2193
SNA (°)	19	79.4789	4.4757	1.0268
SNB (°)	19	77.0789	3.5126	0.8058
ANB (°)	19	2.3947	2.1864	0.5016
U1 - SN (°)	19	92.0316	2.7372	0.628
U1 - NA (°)	19	12.5631	5.8470	1.33
U1 - NA (mm)	19	1.9737	2.4365	0.559
L1 - NB (mm)	19	1.3474	1.9648	0.4508
SN - MP (°)	19	32.8684	6.8265	1.5661

Table 2. Pretreatment results highlighting the initial alveolar bone thicknesses and additional cephalometric measurements.

Post-treatment Cephalometric Statistics				
Measurement	**N**	**Mean**	**Std. Deviation**	**Std. Error**
U1 labial(a) SN-7 (mm)	19	0.3158	0.3594	0.0825
U1 labial(b) SN-7 (mm)	19	1.4211	0.5769	0.1323
U1 labial(c) SN-7 (mm)	19	2.0211	1.3895	0.3188
U1 lingual (a) SN-7 (mm)	19	0.5105	0.8627	0.1979
U1 lingual (b) SN-7 (mm)	19	2.6632	1.1147	0.2557
U1 lingual (c) SN-7 (mm)	19	4.1526	1.7053	0.3912
U1 labial(a) ⊥U1 (mm)	19	0.3789	0.4077	0.0935
U1 labial(b) ⊥U1 (mm)	19	1.2842	0.562	0.1289
U1 labial(c) ⊥U1 (mm)	19	1.7	1.1926	0.2736
U1 lingual (a) ⊥U1 (mm)	19	0.2632	0.4856	0.1114
U1 lingual (b) ⊥U1 (mm)	19	1.9368	0.7166	0.1644
U1 lingual (c) ⊥U1 (mm)	19	3.1895	1.314	0.3015
SNA (°)	19	79.9684	5.0127	1.15
SNB (°)	19	77.6158	4.7422	1.0879
ANB (°)	19	2.3421	2.3003	0.5277
U1 - SN (°)	19	102.0895	8.6256	1.9788
U1 - NA (°)	19	22.1623	7.6602	1.76
U1 - NA (mm)	19	3.8789	2.7827	0.6384
L1 - NB (mm)	19	4.2526	2.7828	0.634
SN - MP (°)	19	31.8158	8.1084	1.8602

Table 3. Post-treatment results highlighting the final alveolar bone thicknesses and additional cephalometric measurements.

Paired sample T-test and Wilcoxon test were performed to determine statistical significance with a ($p < 0.05$) threshold applied (**Table 4**).

Measurement	Measurement Changes		P Values	
	Δ Mean (Post-Pre)	Std. Deviation	T-test	Wilcoxon test
U1 labial(a) SN-7 (mm)	-0.2842	0.4207	0.0087	**0.0806**
U1 labial(b) SN-7 (mm)	0.2684	0.6992	0.0621	**0.0413***
U1 labial(c) SN-7 (mm)	0.7895	1.5581	0.0315	**0.0054***
U1 lingual (a) SN-7 (mm)	0.0789	1.0250	0.9673	**0.6724**
U1 lingual (b) SN-7 (mm)	-0.4523	1.1399	**0.1466**	0.1603
U1 lingual (c) SN-7 (mm)	-1.1263	1.3453	0.0013*	**0.0027***
U1 labial(a) ⊥U1 (mm)	-0.2526	0.4234	0.0181	**0.1397**
U1 labial(b) ⊥U1 (mm)	0.1632	0.6751	0.2436	**0.2276**
U1 labial(c) ⊥U1 (mm)	0.5526	1.3505	0.079	**0.0237***
U1 lingual (a) ⊥U1 (mm)	-0.1421	0.6449	0.1903	**0.1546**
U1 lingual (b) ⊥U1 (mm)	-0.7895	1.0257	**0.0023***	0.0044
U1 lingual (c) ⊥U1 (mm)	-1.611	1.3860	<0.0001	**<0.0001***
SNA (°)	0.6947	1.5587	0.2076	**1**
SNB (°)	0.7158	1.8060	0.2096	**0.9767**
ANB (°)	-0.0263	1.0049	**0.8249**	0.8152
U1 - SN (°)	8.0526	8.2481	**<0.001***	0.0003
U1 - NA (°)	7.4421	8.0768	**<0.001***	0.0003
U1 - NA (mm)	1.637	2.6292	**0.0085***	0.0381
L1 - NB (mm)	2.5789	1.9010	**<0.0001***	0.0022
SN - MP (°)	-1.0578	2.8582	**0.1305**	0.5991

Table 4. Measurement changes and P-values from two sample t-test (for the data normally distributed) and Wilcoxon test (for the data not normally distributed). Statistical significance threshold was determined if $p < 0.05$ (bold number with *).

Several measurements were increased from pre-treatment to post-treatment: U1 labial(b) SN-7° (0.27 mm ± 0.70), U1 labial(c) SN-7° (0.79 mm ± 1.56), U1 labial(b) ⊥U1 (0.16 mm ± 0.68), U1 labial(c) ⊥U1 (0.55 mm ± 1.35), SNA (0.69° ± 1.56) , SNB (0.72° ± 1.81), U1-SN° (8.05° ± 8.25), U1-NA° (7.44° ± 8.08), U1-NA (mm) (1.64 mm ± 2.63), while others decreased: U1 labial(a) SN-7° (0.28 mm ± 0.42), U1 lingual (b) SN-7° (0.45 mm ± 1.14), U1 lingual (c) SN-7° (1.13 mm ± 1.35), U1 labial(a) ⊥U1 (0.25 mm ± 0.42), U1 lingual (a) ⊥U1 (0.14 mm ± 0.64), U1 lingual (b) ⊥U1 (0.79 mm ± 1.03), U1 lingual (c) ⊥U1 (1.61 mm ±1.39), and SN-MP° (1.06° ± 2.86) (**Table 3, Figure 4, Figure 5**).

Several measurements observed a statistically significant post-treatment change: U1 labial(b) SN-7° ($p = 0.413$), U1 labial(c) SN-7° ($p = 0.0315$), U1 lingual (c) SN-7° ($p = 0.0013$), U1 labial(c) ⊥U1 ($p = 0.0237$), U1 lingual (b) ⊥U1 ($p = 0.0023$), U1 lingual (c) ⊥U1 ($p < 0.0001$), U1 – SN° ($p < 0.001$), and U1 – NA (mm) ($p = 0.0085$) (**Table 4**).

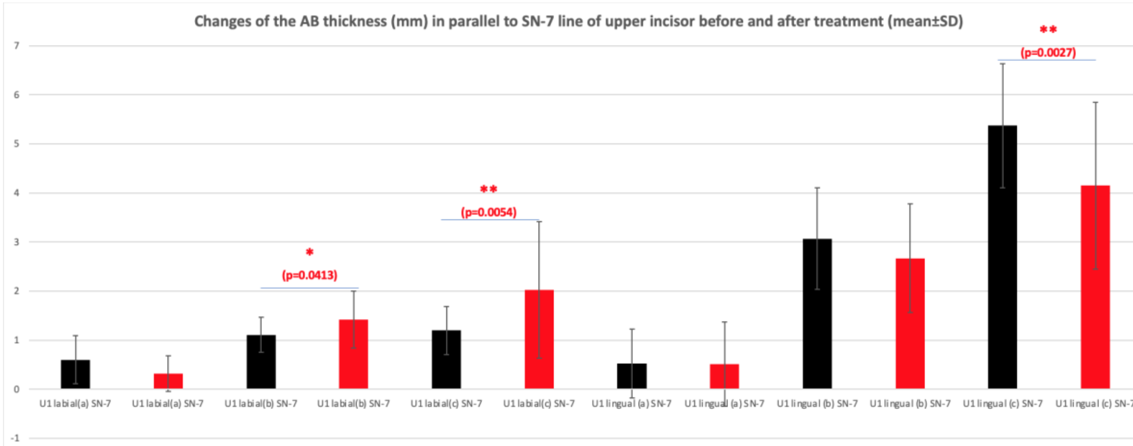

Figure 4. Pre- and post-treatment data illustrating changes in alveolar bone thickness using the perpendicular to SN-7° plane as a reference line. Statistically significant changes are marked with an asterisk and p-value. (* $p < 0.05$, ** $p < 0.01$)

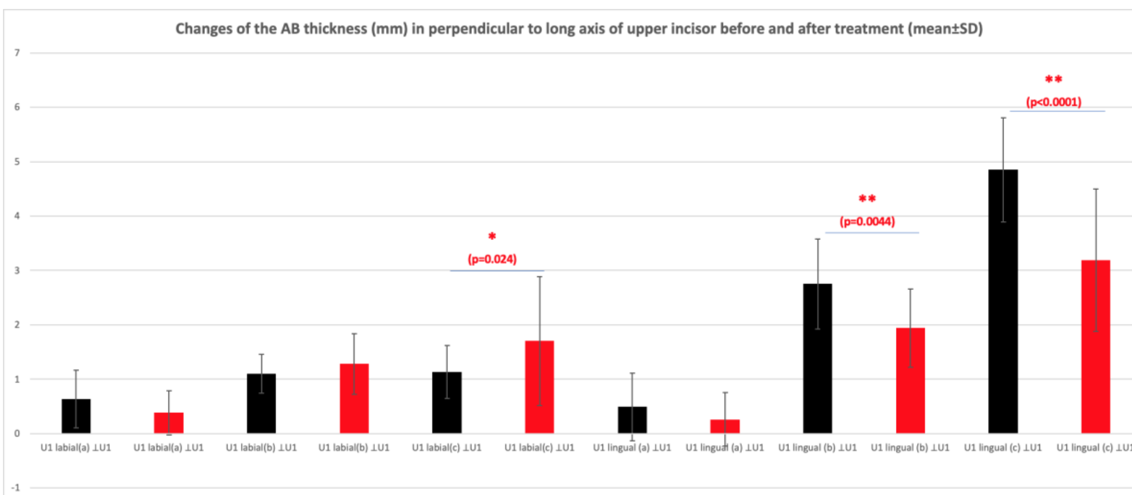

Figure 5. Pre- and post-treatment data illustrating changes in alveolar bone thickness using perpendicular to the long axis of U1 as a reference line. Statistically significant changes are marked with an asterisk and p-value. (* $p < 0.05$, ** $p < 0.01$)

While U1 labial(a) SN-7° and U1 labial(a) ⊥U1 measurements decreased, their data did not follow a normal distribution pattern. As such, statistical significance was determined by a Wilcoxon test which did not reveal significance for U1 labial(a) SN-7° ($p = 0.08$) or U1 labial(a) ⊥U1 ($p = 0.14$). As such, changes in U1 labial(a) SN-7° and U1 labial(a) ⊥U1 were deemed to be statistically insignificant.

Intraclass Correlation Coefficient

An intra-examiner intraclass correlation coefficient (ICC) of 0.99 indicated a good consistency of measurements ($p < 0.001$).

CHAPTER 5
DISCUSSION

Of the previously published studies on alveolar bone remodeling with orthodontic treatment, many focused on the retraction of proclined incisors in four premolar extraction cases. Kang and Chen et al.'s publications are notable because, like this study, they assessed alveolar bone remodeling for incisor proclination. Interestingly, Chen et al. found that incisor proclination led to an increase in facial alveolar bone thickness and a decrease in lingual thickness. Our study produced similar findings.

We observed a statistically significant increase in U1 labial bone thickness at all levels except at the alveolar crest, where changes were deemed statistically insignificant (**Figure 5**). All labial measurements showed statistical significance with both the perpendicular to SN-7° reference line and the perpendicular of the long axis of U1 with the exception to U1 labial(b) ⊥U1. These findings are expected as correction of retroclined incisors requires proclination, which was observed in our sample with the increases in post-treatment U1-SN°, U1-NA°, and U1-NA (mm) values (**Table 3**).

With regards to the lingual, we found a decrease in bone thickness at all levels; however, changes at the crestal level were statistically insignificant (**Figure 5**). The perpendicular to the long axis of U1 provided more statistically significant results when measuring lingual alveolar bone thickness, suggesting that the measurement methodology for alveolar bone thickness is dependent on other variable(s). One possible explanation can be that severe incisor misangulations skew data. For example, if an incisor was severely retroclined or proclined, it would generate vastly different horizontal helper lines for the SN-7° perpendicular line method versus the U1 perpendicular long axis root line method used in our custom analysis and thus output different measurements.

To overcome this obstacle, it may be beneficial to use both a perpendicular to SN-7° horizontal reference line and a U1 perpendicular long-axis root line when studying 2-D images; however, volumetric assessment of alveolar bone quantity with 3-D reconstructions may be the desired standard.

Limitations

Our study was not without its limitations. A randomized clinical trial would be ideal for studying the changes in alveolar bone thickness; however, a retrospective study is more pragmatic and avoids potential ethical dilemmas. The sample size is another aspect of this study that could be improved upon, as our final sample size was limited to nineteen patients.

Ideally, this type of study would employ 3-D reconstructions generated from CT. The major drawback of lateral cephalograms is that they can only generate two-dimensional images of a three-dimensional object. As such, it can be challenging to obtain high-quality images that are not only eligible to read but also accurately measure. Over twenty potential patients were eliminated from the sample because their lateral cephalograms could not be reasonably well traced due to radiographic noise, patient angulation, and double imaging.

Another drawback of this study was that included patients were treated by multiple clinicians with various techniques. The exact number of students or faculty that treated each patient and if treatment mechanics were consistent with each patient is unknown. The patient sample may have had intrusive or extrusive mechanics on the incisors that confounded the results. Future studies should incorporate methods to account for vertical changes in incisor position via landmark superimposition or other obtainable means. They should also take total treatment time and growth into account.

Additionally, complete periodontal records were not available in the patient sample, making it impossible to rule out periodontal factors influencing the present study's results. Further studies are recommended to employ periodontal assessments before, during, and after treatment to account for periodontal considerations such as external root resorption and patients at risk for increased alveolar bone loss and dehiscence. Lastly, it is recommended that adequate time – 6 months to two years - be given before final records are obtained to allow full remodeling of the alveolar bone and root post-treatment (Ten Hoeve 1976).

CHAPTER 6
CONCLUSION

The findings of the current study led to the rejection of the null hypothesis. The study demonstrated statistically significant alterations in the alveolar bone surrounding the incisors following the proclination of incisors. Our findings suggest that proclination of the maxillary incisors leads to an increase in labial alveolar bone thickness and a decrease in lingual alveolar bone thickness.

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