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LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
Faculty of Graduate Studies

CBCT Evaluation of Morphological Changes to Alveolar Bone Due to Orthodontic Tooth Movement

by

Jeremy M. Hoff

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

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September 2014

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

, Chairperson

Joseph Caruso, Professor of Orthodontics

Gregory Olson, Assistant Professor of Orthodontics

Kitichai Rungcharassaeng, Professor of Orthodontics

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ABBREVIATIONS

3D	Three dimension
$A_{(1-4)}$	Area (mm^2) of vertical area 1 through 4
ALD	Arch length discrepancy
ANS	Anterior nasal spine
$B_{(1-4)}$	Horizontal change (mm) on the buccal surface of the process
Ba	Basion
CBCT	Cone Beam Computed Tomography
CEJ	Cementoenamel junction
CRP	Cortical reference plane
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
$L_{(1-4)}$	Horizontal change (mm) on the lingual surface of the process
Md 1 Change	The amount of change in degree's of the lower incisor on the steiner cephalometric tracing, corresponding to IMPA
Or	Orbitale
PNS	Posterior nasal spine
RL	Reference line
T1	Pre-orthodontic treatment
T2	Post-orthodontic treatment
VRP	Vertical reference plane
$\Delta A_{(1-4)}$	Change in area (mm^2) in one of the 4 vertical areas (1-4)

ABSTRACT OF THE THESIS

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Jeremy M. Hoff

Master of Science, Graduate Program in Orthodontics and Dentofacial Orthopedics Loma
Linda University, September 2014
Dr. Joseph Caruso, Chairperson

Introduction: The mandibular process is the anatomic factor that limits the orthodontic movement of the mandibular incisors, and awareness of this structural limitation may reduce the risk of potential damage to tooth roots and alveolar bone. A decision regarding the correct placement of the lower incisors will be largely determined by the amount of adaptation possible within the alveolar bone.

Purpose: The purpose of this study was to use Cone Beam Computed Tomography (CBCT) to evaluate the adaptation of alveolar bone around the mandibular anterior teeth before and after orthodontic tooth movement.

Methods: This study compared changes in area (mm^2) and buccal/lingual linear variation of the anterior mandibular process on CBCT images acquired before (T1) and after (T2) orthodontic treatment. Initial (T1) and final (T2) digital imaging and communications in medicine (DICOM) CBCT images of thirteen non-growing patients were imported into InVivo software for measurement. The T1 and T2 volumes were then superimposed and twenty-five sagittal slices were obtained through the region of the anterior mandible. The changes in area (mm^2) and buccal/linigual variations were then averaged and compared using a Related Samples Wilcoxon Signed Rank Test, a One-

Sample Wilcoxon Signed Rank Test, and an Independent-Samples Kruskal-Wallis Test ($\alpha = 0.05$).

Results: Statistically significant differences in area changes for the entire sample between T1 and T2 were found. These differences included statistically significant differences in buccal/lingual adaptation in all areas except the inferior buccal surface at B_3 and B_4 with the sit of the most change being at the levels of B_1 and L_1. When the data was divided by tooth region there was a clear pattern showing that the greatest amount of change occurred at the central incisors and that the least amount of change occurred in the canine region. When the data was divided by facial type there was a statistically significant difference between the dolichofacial group and the mesofacial and brachyfacial groups. However, due to the small sample size of the dolichofacial group no clinically significant conclusions could be made.

Conclusion: Statistically significant adaptation of the alveolar process occurs in response to tooth movement, both in area (mm^2) and buccal/lingual linear dimension. Clinically relevant conclusions can not be made due in part to the small number of dolichofacial patients as well as the small amount of change seen in most of the parameters.

CHAPTER ONE

REVEIW OF THE LITERATURE

Siciliani et al[15] stated, ”The attempt to identify an orthodontically ideal, long-lasting, and equilibrated position of the incisors that will not cause periodontal problems, occlusal interference, joint instability, or crowding relapse, and yet will be esthetically pleasing, should include the theoretical determination of the anterior-most position of the incisors.” The final position of the mandibular incisors when centered in the bone is considered the anatomic factor limiting the movement of the incisors. Awareness and respect for this limitation reduces the risk of potential damage to tooth roots and alveolar bone during orthodontic movement.[1,2,3] One postulate in orthodontics states that “bone traces tooth movement,” meaning that, in an ideal scenario, orthodontic tooth movement to bone remodeling should be 1:1.[4,5] Fuhrmann, however, has shown that the loss of thin bone plates surrounding the teeth does occur due to orthodontic tooth movement.[6] Therefore, a decision regarding the final correct placement of the lower incisors should be largely determined by the amount of adaptation possible with the alveolar bone.

Over the years there have been several studies looking at the morphology of the basal bone around the incisors. Prior to the advent of Cone-Beam Computed Tomography (CBCT), a landmark study by Wehrben et al in 1996 evaluated the mandible of a deceased 19-year-old woman previously treated with edgewise orthodontics.[7] This was a groundbreaking case due to the fact that a full anatomic study could be conducted on the mandible of a patient who had undergone orthodontic treatment just a few years prior.[7] Wehrben et al. concluded that patients who presented with a narrow and high alveolar process may have already reduced boney support on the labial and lingual of the roots.[7] An additional finding in that case was that both pronounced sagittal incisor movement and de-rotation contributed to a much higher risk for bone loss.[7]

Most of the original studies regarding incisor position within the basal bone used lateral cephalometric radiographs. Due to these radiographic images being two-dimensional, their use in assessing the region of the mandibular process was plagued by a number of intrinsic errors. These errors included both difficulty isolating the individual teeth overlapping the superimposition of anatomic structures and magnification error of the radiograph due to the divergence of the radiant beam. In contrast, by using computed axial tomography one can achieve an accurate evaluation of the bony support of the mandibular incisors.[17,18]

Since its introduction in 1998, CBCT has become a popular modality in the evaluation of orthodontic diagnosis, treatment planning, and clinical outcomes.[9] Although detecting cortical bone thickness less than 0.5 mm[19] or periodontal ligaments of less than 200 μm[32] with CBCT can be relatively inaccurate, it is still the preferred method for evaluating the alveolar process due to its low radiation dose[8,10] and acceptable resolution.[14] CBCT enables examination of the shape and the size of the alveolar bone as well as the individual teeth within the mandibular process without the traditional disadvantages of conventional radiographs that were stated previously.[2, 6] However, due to the fact that a majority of orthodontic offices and schools do not routinely take CBCT records on orthodontic patients, there are only a few studies that have evaluated the mandibular bone with computerized tomography.

Another concern with CBCT is its ability to achieve a high level of accuracy when superimposing two different images in three dimensions. Over the last few decades there have been a number of articles that have demonstrated different methods for superimposing lateral cephalograms, and within the last ten years several of these articles have discussed new methods for incorporating three-dimensional CBCT images. Park looked at two different methods of superimposition: surface superimposition and plane superimposition.[21] He concluded that the surface method of superimposition was more accurate when not selecting reference points due to their inaccuracy.[21] Bjork showed that the inferior border of the internal process is stable when superimposing only the mandible.[22] In addition, Krarup also demonstrated that the internal mandibular process was stable, along with the mandibular canals, however it was noted that the mandibular canals tended to move laterally.[23]

A number of studies in the last twenty years have focused solely on the relationship between facial type and the properties of incisal bone. In 1991, Siciliani et al conducted a teleradiographic study looking at the correlation between facial biotypes and the morphology of the mandibular process in 150 orthodontically untreated patients. Siciliani found that the alveolar process is thin and elongated in patients with long faces, whereas it is thicker in those with short faces.[15] In 1998, Tsunori et al was the first to use computed tomography (CT) to find a correlation between facial type, mandibular cortical bone thickness, and the buccolingual inclinations of the first and second molars.[16] In 2000, Maki et al showed that cortical bone mineralization varies with vertical facial dimension.[12,13] More recently, in 2010 Gracco et al evaluated mandibular incisor bony support in untreated patients with various facial types via computed volumetric tomography and found a statistically significant relationship between facial type and the total thickness of the mandibular process.[11] All of these studies agree that within the morphologic region around the mandibular incisors there is more mineralized bone in brachyfacial patients than in dolichofacial patients.[11,12,13,15,16]

Regarding the aforementioned postulate that cortical bone follows orthodontic tooth movement in a 1:1 ratio, there have been a number of studies that have shown that this is not the case. Studies have shown that this ratio changes based on the direction of movement (transverse/anteroposterior/vertical).[24] In orthodontic extrusion Kajiyama et al showed that alveolar bone remodeling follows tooth movement at a ratio of 0.8:1[25] Orthodontic intrusion has been demonstrated to be the only tooth movement that closely approximates the traditional postulate of 1:1 B/T ratio,[26] and in some cases intrusion was shown to even exceed bone reduction.[27,32] Bimstein showed that when mandibular incisors were retracted an increase occurred in bone volume in 58% of cases, while 42% had a decrease in bone volume.[28]

Research has also shown that when orthodontic tooth movement causes a root to come in to close proximity with the cortical plate, fenestrations and dehiscence are possible.[3,27,29] Lindhe described dehiscence as the lack of facial or lingual cortical bone over the cervical portion of a root, while fenestration was described as the presence of bone in the cervical region.[30] Dehiscence and fenestration have been found to be common following orthodontic treatment, as well as in untreated dental arches.[29,31] In addition, there have also been reports of lingual defects of mandibular incisors with orthodontic tooth movement.[29] Caution should be taken with tooth proclination in particular in the area of the mandibular incisors because the bone is thinnest in this region.[32,33,34,35]

In 2007 Yamada et al indicated that the morphology of the alveolar bone in the central incisor region might be associated with the inclination of the central incisors.[18] In 2012 Tancan et al looked at the relationship between incisal crowding and basal bone thickness, as diagnosis of mandibular incisor crowding can be a critical and also commonly a limiting factor in treatment, and it was found that a reduced labiolingual size of the alveolar process in this area would be thin and more prone to sustain iatrogenic damage.[36] In addition, a significant relationship was discovered between incisor crowding and basal bone dimensions in female subjects. It was theorized that crowding did not necessarily cause the thin mandibular process, rather that thin bone then resulted in crowding.[36]

In conclusion, in spite of past research, there is still much to be discovered regarding the health, stability, and appearance of the incisors before, during, and after orthodontic treatment. The relationship between tooth movement and the amount of cortical and cancellous bone adaptation is still being explored. Over the last five years, the introduction of CBCT has drastically increased our understanding of the relationship between the incisors and their supporting bone, however there still remain a number of questions that remain unanswered.

CHAPTER TWO

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Introduction

Statement of the Problem

The alveolar bone is traditionally and practically considered the anatomical limitation of orthodontic tooth movement.[1,2,3] A basic postulate in orthodontics states that “bone traces tooth movement,” which means that in an ideal scenario, orthodontic tooth movement to bone remodeling should be 1:1.[4,5] However, studies have shown that the loss of thin bone plates can be induced by orthodontic tooth movement.[6] Therefore, a decision regarding the correct placement of the lower incisors will be largely determined by the amount of adaptation possible within the alveolar bone.

This adaptation of the alveolar bone is clinically significant on a regular basis when it comes to treatment planning. The amount of correction required for crowding, as well as for other orthodontic mechanics that require anterior tooth movement, largely depends on the position of the lower incisor within the alveolar bone. Multiple studies in the past have evaluated the effects of tooth movement on the alveolar bone using cadavers and patients that have needed procedures involving periodontal flaps.[6,7] While this information was useful, it was based on a two-dimensional representation of a three-dimensional structure. CBCT now allows for a more accurate measurement of the three-dimensional changes that occur to the alveolar bone due to orthodontic tooth movement.[8,9,10]

There have also been a number of the studies in the last two decades that have demonstrated a direct relationship between a patient's facial type and their anterior-alveolar bone properties, the morphology of their alveolar bone, as well as in the amount of bone mineralization present. Patients showing dolichofacial growth can present with thin and elongated mandibular processes that can alter the alveolar response to orthodontic tooth movement.[7,11,12,13,14,15]

The purpose of this study is to evaluate the adaptation of alveolar bone around the mandibular anterior teeth in response to orthodontic tooth movement. This study compared the sagittal area (mm^2) of the anterior mandible on the CBCT images acquired before (T1) and after (T2) orthodontic treatment.

Hypothesis

The null hypothesis was that no change in area (mm^2) or buccal/lingual dimension of the alveolar process would occur in response to orthodontic tooth movement. The alternative hypothesis was that no significant adaptation of the alveolar process would occur in response to tooth movement, both in area (mm^2) and buccal/lingual dimension.

Materials and Methods

Patient Selection

The study used 3D CBCT radiographs taken at the beginning of orthodontic treatment (T1) and at the completion of orthodontic treatment (T2). Data was obtained from thirteen non-growing patients at the orthodontic clinic of Loma Linda University. Cases were selected using the inclusion/exclusion criteria shown in Table 1. The DICOM files from each patient were evaluated using the InVivo software, version 5.2 (Anatomage San Jose, CA). To keep measurements consistent, only one examiner was used for all of the reconstruction and assessment.

Table 1. Inclusion and exclusion criteria used in patient selection

Inclusion Criteria

1. Full treatment case with T1 and T2 records
2. Patients who finished growth, age 15 for females and age 19 for males
3. Between T1 and T2, a change in incisor proclination of ≥ 10 degrees according to Steiner's IMPA measurement

Exclusion Criteria

1. Missing anterior teeth
2. Phase one cases
3. Mandibular Surgery

Data Collection

The charts of thirteen non-growing patients treated at the Loma Linda University with NewTom 3G and 5G images were reviewed and the following data recorded:

- Chart Number
- Sex (male or female)
- Age at beginning of treatment
- Race (White, Black, Hispanic, Asian and others)
- Total length of treatment
- ALD (Arch Length Discrepancy) at T1

Volume Orientation

Each T1 DICOM file was recorded with a 0.2 mm voxel size and was reconstructed with 0.5 mm slice thickness. The T1 DICOM images were imported into InVivo, and each volume was oriented using the following reference landmarks:

- In the sagittal plane, the volume was oriented along the palatal plane with the sagittal line going through the anterior nasal spine (ANS) and the posterior nasal spine (PNS) [Figure 1a].
- In the coronal plane, the volume was oriented using the most inferior point on the anterior optical floor, which corresponded to orbitale (Or) in the 2D lateral tracing (Figure 1b).
- In the transverse plane, the volume was oriented along a line from the ANS to basion (Ba) (Figure 1c).

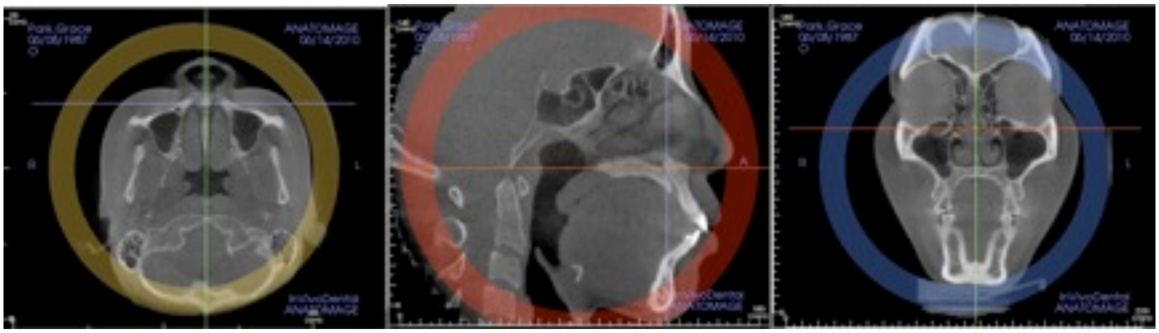

Figure 1: CBCT image showing orientation along the sagittal plane, coronal plane, and transverse plane.

Superimpositions

The T1 DICOM images were imported into InVivo and superimposed with the T2 DICOM images using the 3D superimposition tool. The two CBCT radiographs were first superimposed using the plane superimposition method utilizing five anatomical landmarks:

- The center of the left and right mental foramina

- The center of the mandibular lingual foramen (a consistent arterial foramen in the middle of the mandible).
- The center points at which the right and left inferior alveolar nerves enter the mandibular canals at the internal surfaces of the mandibular ramus (Figure 3)

The center of each foramina was selected by picking four points - the most superior, the most inferior, and the two most lateral points, after which the center of each foramen was identified by using an overlay grid on the computer monitor (Figure 2). The resulting superimposition was then examined using the surface-superimposition method to ensure that the internal border of the lower mandibular process and contours of the inferior alveolar nerve canal were coincident (Figure 4).

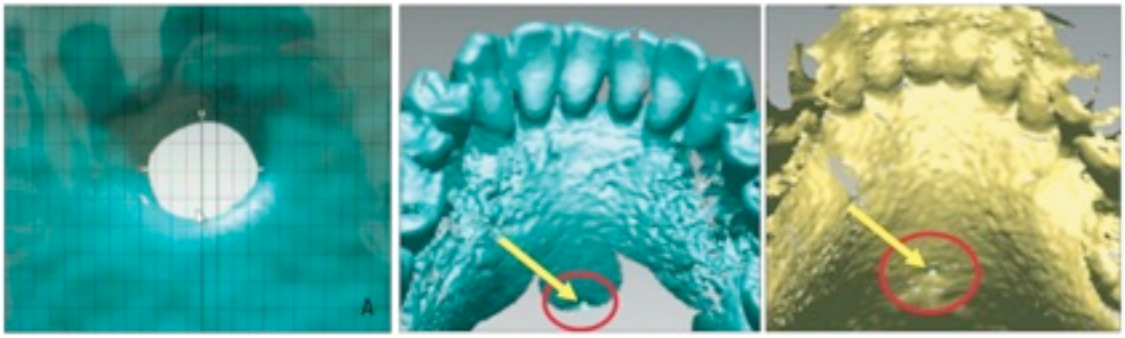

Figure 2. 3D CBCT image of the mental and mandibular lingual foramina, the center point being selected with a grid using the most superior, inferior, and lateral points.

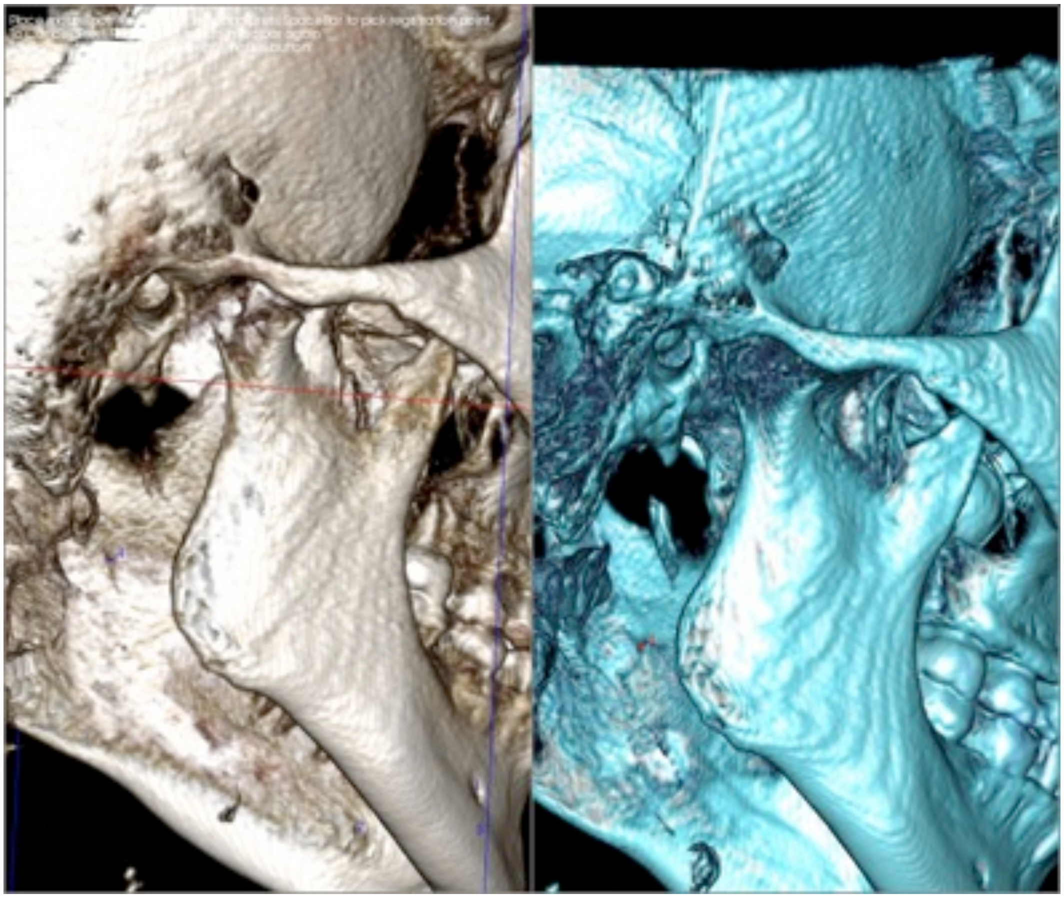

Figure 3. 3D CBCT image, the center point where the inferior alveolar nerve enters the mandibular canal.

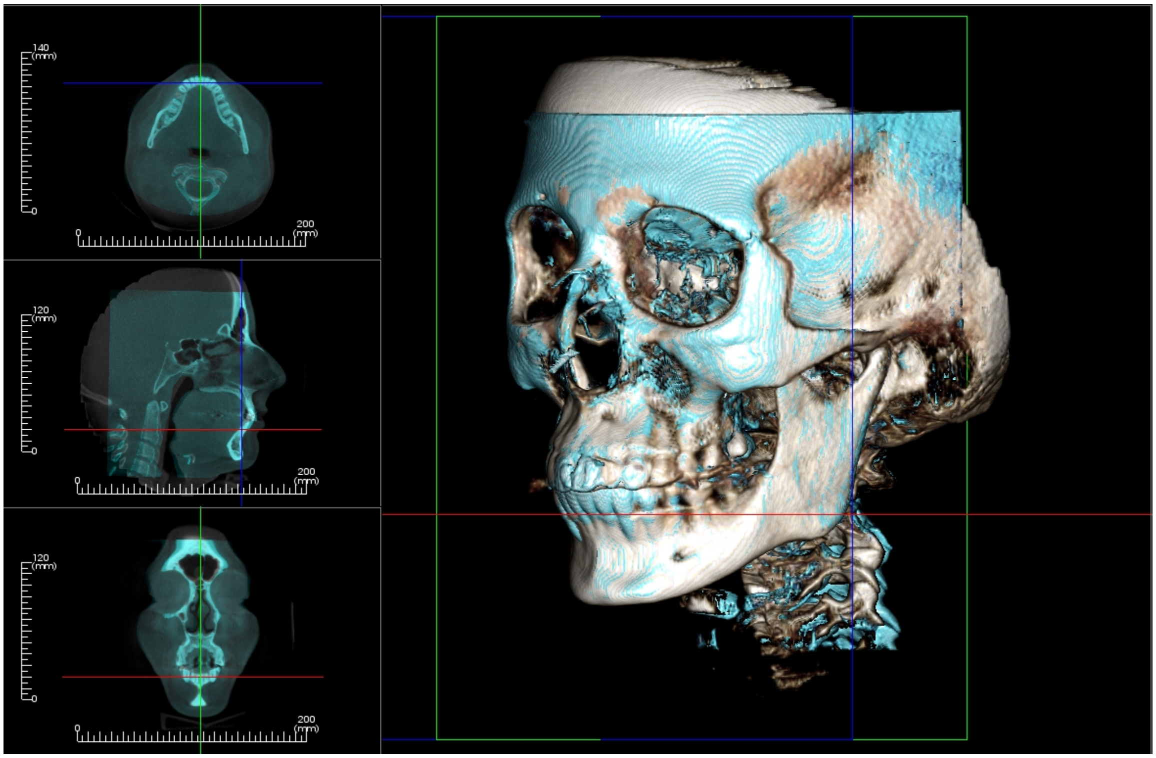

Figure 4. CBCT 3D superimposition showing the finished superimposition after plane and surface superimpositions.

To create the different planes of measurement a grid was constructed on the T1 CBCT image. A reference plane was then drawn at a point halfway between the labial and lingual cortical plates at the crest of the alveolar ridge, which was termed the Cortical reference plane (CRP). The CRP extended from the distal root of the right canine to the distal root of the contralateral canine, with a point placed at the center of each root. The line was then split in to twenty-five sections to create the sagittal reference lines. Each reference line ($RL_{1\text{-}25}$) represents a point where a slice was taken in the sagittal plane and used for measurement (Figure 5). The reference lines were divided as follows:

- One RL directly centered between the two central incisors
- Three RLs for the central incisor

- Four RLs for the lateral incisors
- Five RLs for the canine

This gave a total of twenty-five RLs with an even span of approximately 1.25 mm of space between each RL.

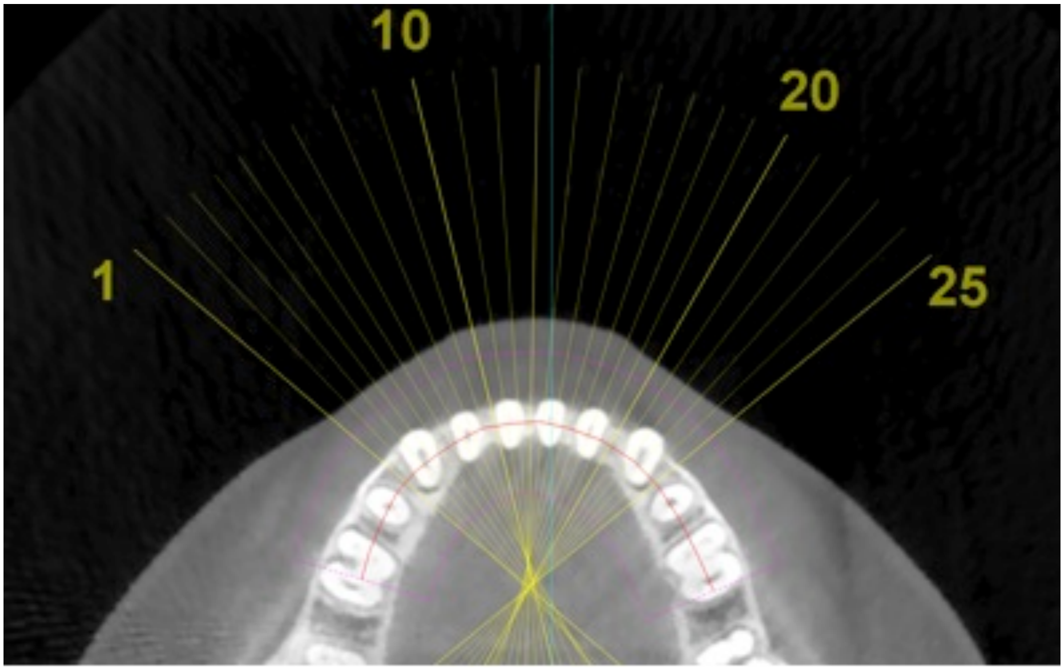

Figure 5. T1 CBCT transverse image of the Cortical reference plane (CRP) and all 25 reference lines ($RL_{1\text{-}25}$).

Vertical Reference Planes ($VRP_{1\text{-}4}$)

The Vertical Reference Planes (VRPs) were used to divide the process into four areas of measurement. Using the T1 CBCT image, a point was placed at the CEJ on the buccal and lingual surface of the tooth closest to the reference line and a line was drawn between these two points to create the CEJ line. All VRP's were constructed parallel to this CEJ line; the most coronal VRP was 3 mm bellow the CEJ line. The remaining three

VRP's were 3 mm coronal to the root apex of the T1 image, at the level of the root apex, and 3 mm apical to the root apex (Figure 6). If the reference line was exactly midway between two teeth the mesial tooth was used to construct the CEJ line. Additionally, when the reference line fell exactly at the midline between the two central incisors the left incisor was used.

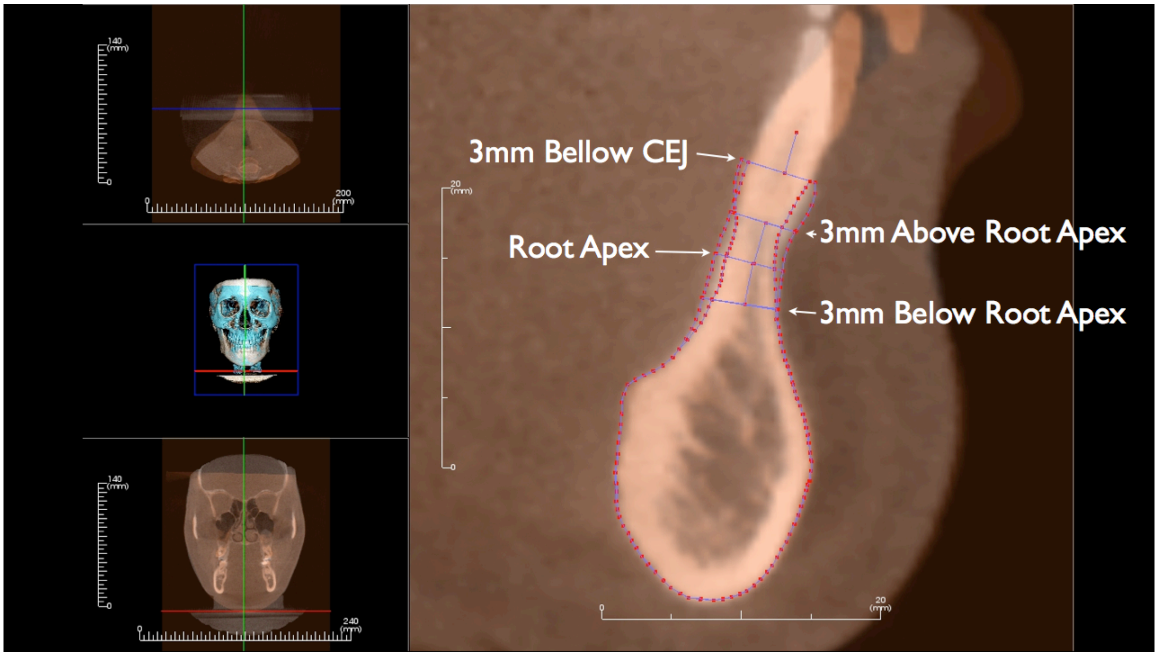

Figure 6. T1 image showing the SRP drawn parallel to the long axis of the tooth and 3 mm below the CEJ line.

Alveolar Bone Adaptation (Area)

Using InVivo, the green line that represented the sliced view in the sagittal plane was moved to the first reference line on the left side, or Reference Line 1 (RL_1). The "area tool" was used to outline the cortical bone in each of the four vertical areas (A_1 – A_4). This was repeated on both the T1 and T2 images resulting in the values $T_1A_1RL_1$ (T1-vertical area 1-RL1) for the most superior vertical area on the T1 image, and

$T_2A_IRL_1$ (T2-vertical area 1-RL1) for the most superior vertical area on the T2 image (Figure 7). This was repeated for all four vertical areas on all twenty-five sagittal reference lines, which allowed the location of the area of greatest change in the sagittal and the vertical planes to be determined. To provide an overall estimate of alveolar change, the area (mm^2) for all twenty-five reference planes was averaged for the T1 and T2 time points, yielding $\Delta A_{(1-4)}$. A negative value represented bone loss, whereas a positive number represented bone apposition.

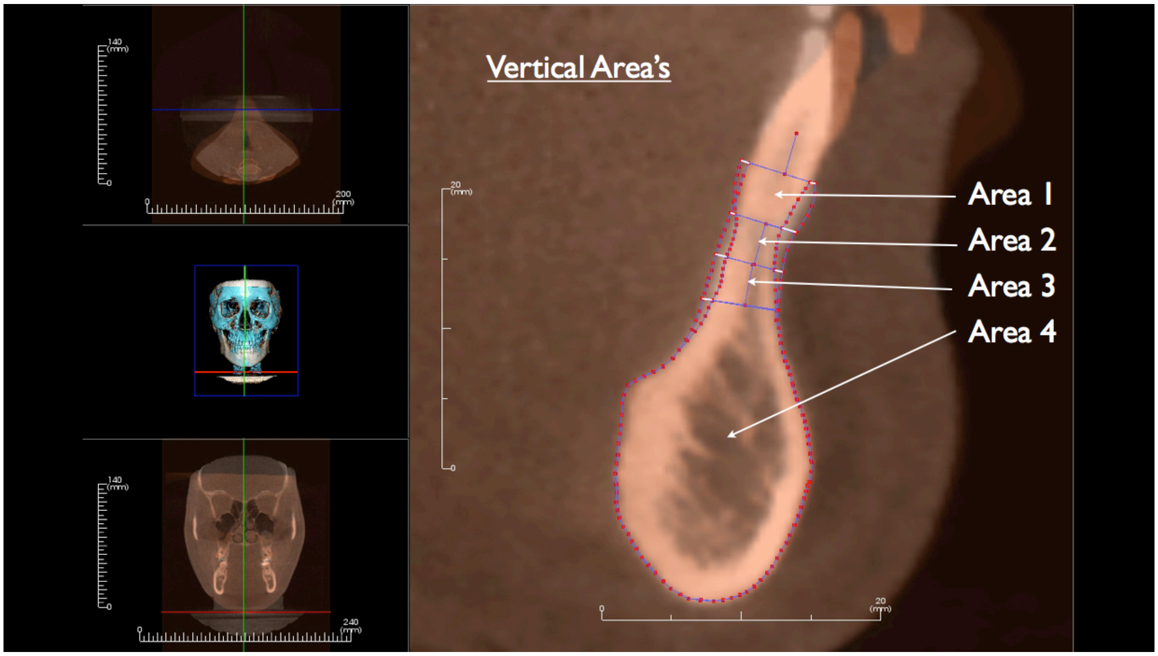

Figure 7. CBCT image with all four of the vertical area's measured on the T1 and T2 images.

Alveolar Bone Adaptation (Buccal/Lingual)

To measure the movement of the alveolar process, the change in cortical space between T1 and T2 images was measured on each of the four VRP's (Figure 8). Any change toward the labial was given a positive value, and any change toward the lingual was given a negative change. The notation for change on the labial of the T2 image was (B_{1-4}), and on the lingual the notation was (L_{1-4}).

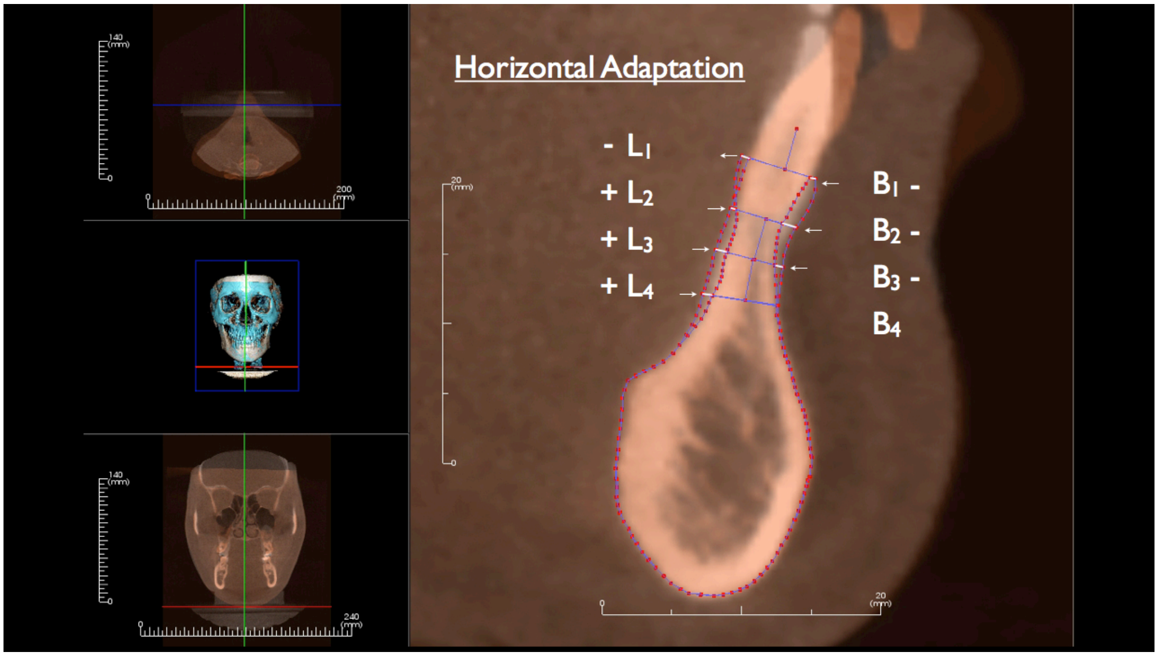

Figure 8. CBCT image showing measurement changes of the alveolar bone (white lines), measurements were made both labially and lingually.

Statistical Analysis

The means and standard deviations were calculated for all the parameters measured. The parameters $\Delta A_{(1-4)}$, $\Delta A_{(1-4)}$ average, $B_{(1-4)}$ and $L_{(1-4)}$ were analyzed using a one-sample Wilcoxon signed rank test at the significance level of $\alpha = 0.05$. Next, the data was separated by facial type and tooth region and the parameters were analyzed using a independent-samples Kruskal-Wallis test at the significance of $\alpha = 0.05$. To determine which variables were associated with treatment time and Md 1 change a

Pearson correlation analyses were performed at the statistical significance level of α = 0.05.

Results

Thirteen patients were found among the records that met the inclusion criteria. Of the thirteen patients six were male and seven were female with a mean age of 28.08 years (range 15-65) years old. There were five brachyfacial patients, six mesofacial patients, and two dolichofacial patients. The treatment time mean, ALD (arch length discrepancy) at T1, and degree of Md 1 change were 27.39 years, -4.04 mm, and 12.93° respectively (Table 2).

Table 2. Means, standard deviation and range of age, treatment time, ALD at T1, and Md 1 change

	Mean ± SD	Range
Age (years)	28.08 ± 15.05	15 - 65
Treatment Time (months)	27.39 ± 5.06	18 - 37
ALD at T1 (mm)	-4.04 ± 3.57	(-)15 – (-)3
Md 1 Change (degree's)	12.93° ± 4.89°	10° - 27°

Comparison of All Patients

Tables 3 and 4 shows the means and standard deviations of all measured parameters at T1 and T2 for the entire sample. A related samples Wilcoxon Signed Rank Test at a significance of α = 0.05 was used for statistical analysis of the area (mm^2) change between T1 and T2. A one-sample Wilcoxon Signed Rank Test at a significance of α = 0.05 was used for statistical analysis of the buccal/lingual change at T2-T1. Table

3 shows that the change to the area (mm^2) of the alveolar process in all measured vertical areas ΔA_1 through ΔA_4, and the $\Delta A_{(1\text{-}4)}$ average were significant following orthodontic tooth movement ($p < 0.05$). Table 4 shows that the changes on the buccal surface showed significant change at B_1 and B_2 ($p < 0.001$ and 0.015). The apical areas B_3 and B_4 did not show any significant change ($p = 0.497$ and 0.237). The changes on the lingual surface all showed significant differences at L_1 through L_4 ($p \leq 0.001$).

Table 3. Comparison of the area (mm^2) change between different time intervals (T2-T1) using a Related Samples Wilcoxon Signed Rank Test

Parameter	T1 (Mean ± SD)	T2 (Mean ± SD)	T2-T1 (Mean ± SD)	p-value
ΔA_1 Average (mm^2)	66.91 ± 17.73	66.27 ± 18.76	-0.64 ± 2.01	0.015*
ΔA_2 Average (mm^2)	28.08 ± 5.46	27.68 ± 5.76	-0.41 ± 0.50	0.000*
ΔA_3 Average (mm^2)	30.29 ± 5.38	30.09 ± 5.77	-0.20 ± 0.40	0.000*
ΔA_4 Average (mm^2)	185.09 ± 32.75	184.60 ± 31.17	-0.50 ± 1.71	0.000*
$\Delta A_{(1\text{-}4)}$ Average (mm^2)	310.37 ± 43.30	308.63 ± 42.96	-1.74 ± 3.80	0.000*

*Statistically significant

Table 4. Comparison of buccal/lingual change between different time intervals (T2-T1) using a One-Sample Wilcoxon Signed Rank Test

Parameter	T2-T1 (Mean ± SD)	p-value
B_1 Average (mm)	0.56 ± 0.83	0.000*
B_2 Average (mm)	0.08 ± 0.31	0.015*
B_3 Average (mm)	0.02 ± 0.14	0.497
B_4 Average (mm)	0.01 ± 0.02	0.237
L_1 Average (mm)	0.68 ± 0.58	0.000*
L_2 Average (mm)	0.13 ± 0.16	0.000*
L_3 Average (mm)	0.08 ± 0.15	0.000*
L_4 Average (mm)	0.04 ± 0.13	0.001*

*Statistically significant

Facial Type

Table 5 divides the data by facial type (brachyfacial, mesofacial, dolichofacial) and shows the means and standard deviations for the amount of change for each parameter between T2 and T1. An Independent-Samples Kruskal-Wallis Test with a significance level of $\alpha = 0.05$ was used to compare changes among different teeth. When looking at the change to the area (mm^2) of the alveolar process; vertical areas ΔA_1 through ΔA_4, and the $\Delta A_{(1-4)}$ average all showed significant changes between facial types ($p < 0.001$). When looking at the post-hoc tests for ΔA_1 through ΔA_4 and the $\Delta A_{(1-4)}$ average the brachyfacial and mesofacial groups did not show any significant differences ($p > 0.05$). However there were significant differences between both the dolichofacial and mesofacial groups as well as the dolichofacial and brachycfacial groups.

The horizontal change on the buccal surface showed significant differences for all of the areas B_1 through B_4 ($p < 0.05$). The post hoc tests showed a significant difference between all three facial types in the area of B_1 ($p < 0.05$). There was a significant difference only between the brachyfacial and mesofacial facial types in the area of B_2 and B_3 ($p = 0.001$ and 0.001). Area B_4 showed significant differences between all the groups except brachyfacial and mesofacial ($p = 0.694$).

The horizontal change on the lingual surface showed significant differences for all parameters except L_4 ($p = 0.480$). The post-hoc tests L_1 showed significant differences between all three regions ($p < 0.05$). L_2 showed significant differences in all three regions except between the lateral incisors and canines ($p = 0.079$). L_3 had significant differences between the central incisors and canines ($p = 0.044$ and 0.001)

Table 5. Comparison of all parameters based on facial type (T2-T1) using an Independent-Samples Kruskal-Wallis Test

	Brachyfacial	Mesofacial	Dolichofacial	
Parameter	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	p-Value
ΔA_1 Average (mm^2)	0.08 ± 1.61^{a}	-0.43 ± 2.00^{a}	-3.07 ± 1.90^{b}	0.000*
ΔA_2 Average (mm^2)	-0.09 ± 0.30^{a}	-0.44 ± 0.47^{a}	-1.09 ± 0.33^{b}	0.000*
ΔA_3 Average (mm^2)	-0.02 ± 0.03^{a}	-0.12 ± 0.33^{a}	-0.89 ± 0.48^{b}	0.000*
ΔA_4 Average (mm^2)	-0.10 ± 0.12^{a}	0.04 ± 0.21^{a}	-3.08 ± 4.36^{b}	0.000*
$\Delta A_{(1\text{-}4)}$ Average (mm^2)	-0.12 ± 1.85^{a}	-0.96 ± 2.02^{a}	-8.12 ± 6.40^{b}	0.000*
B_1 Average (mm)	0.88 ± 0.31^{a}	0.58 ± 0.76^{b}	-0.29 ± 1.73^{c}	0.000*
B_2 Average (mm)	0.20 ± 0.15^{a}	-0.01 ± 0.37^{b}	$0.07 \pm 0.55^{a,b}$	0.000*
B_3 Average (mm)	0.07 ± 0.06^{a}	-0.04 ± 0.15^{b}	$0.07 \pm 0.29^{a,b}$	0.002*
B_4 Average (mm)	0.01 ± 0.01^{a}	-0.01 ± 0.02^{a}	0.04 ± 0.02^{b}	0.000*
L_1 Average (mm)	0.80 ± 0.59^{a}	0.65 ± 0.69^{b}	$0.45 \pm 0.30^{a,b}$	0.021*
L_2 Average (mm)	0.08 ± 0.13^{a}	0.07 ± 0.08^{a}	0.41 ± 0.16^{b}	0.000*
L_3 Average (mm)	0.05 ± 0.07^{a}	0.03 ± 0.04^{a}	0.32 ± 0.33^{b}	0.000*
L_4 Average (mm)	0.00 ± 0.01^{a}	0.01 ± 0.02^{a}	0.24 ± 0.34^{b}	0.000*

*Statistically significant

^{a,b,c} : different letters denote statistically significant difference between facial types

Tooth Region

Table 6 separates the data by specific tooth region (central incisor, lateral incisor, canine) and shows the means and standard deviations for the amount of change at each parameter between T1 and T2. An Independent-Samples Kruskal-Wallis Test with a significance level of $\alpha = 0.05$ was used to compare the alveolar bone changes in these three regions. When looking at the change to the area (mm^2) of the alveolar process; only ΔA_1 and $\Delta A_{(1\text{-}4)}$ average showed significant differences ($p = 0.004$, 0.011 and 0.002). There was no significant difference in ΔA_2, ΔA_3 and ΔA_4 ($p = 0.644$, 0.350 and 0.504). When looking at the post-hoc tests for ΔA_1 only the central incisors and canines showed any significant difference ($p = 0.003$). The $A_{(1\text{-}4)}$ average only had a significant difference between the central incisors and canines ($p = 0.010$ and 0.001).

The horizontal change on the buccal surface only showed significant differences in the area of B_1 ($p < 0.001$). The post hoc tests for B_1 showed significant differences between all three teeth except for the central incisors and lateral incisors ($p = 0.089$).

The changes on the lingual surface all showed significant change at L_1 through L_4 ($p \leq 0.001$). The post-hoc tests showed a significant difference only between the brachyfacial and mesofacial groups at L_1 ($p = 0.048$). At L_2, L_3 and L_4 there was no significant change between the brachyfacial and mesofacial groups ($p = 1.000$, 0.880 and 1.000).

Table 6. Comparison of all parameters based on tooth region (T2-T1) using a Independent-Samples Kruskal-Wallis Test

	Central Incisor	Lateral Incisor	Canine	
Parameter	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	p-Value
ΔA_1 Average (mm^2)	-1.43 ± 2.31^{a}	-0.85 ± 2.39^{a,b}	0.08 ± 2.77^{b}	0.004*
ΔA_2 Average (mm^2)	-0.39 ± 0.89	-0.39 ± 0.69	-0.43 ± 0.43	0.644
ΔA_3 Average (mm^2)	-0.18 +/ - 0.53	-0.24 ± 0.59	-0.18 ± 0.37	0.350
ΔA_4 Average (mm^2)	-0.52 ± 1.50	-0.57 ± 2.34	-0.42 ± 1.38	0.504
$\Delta A_{(1\text{-}4)}$ Average (mm^2)	-2.52 ± 4.16^{a}	-2.05 ± 4.76^{a,b}	-0.95 ± 3.94^{b}	0.011*
B_1 Average (mm)	0.87 ± 1.04^{a}	0.62 ± 0.78^{a}	0.30 ± 0.82^{b}	0.000*
B_2 Average (mm)	0.12 ± 0.41	0.09 ± 0.40	0.05 ± 0.28	0.170
B_3 Average (mm)	0.08 ± 0.26	-0.02 ± 0.18	0.01 ± 0.11	0.088
B_4 Average (mm)	0.00 ± 0.00	0.01 ± 0.03	0.01 ± 0.04	0.742
L_1 Average (mm)	1.11 ± 0.92^{a}	0.79 ± 0.72^{b}	0.28 ± 0.35^{c}	0.000*
L_2 Average (mm)	0.25 ± 0.24^{a}	0.13 ± 0.17^{b}	0.04 ± 0.13^{b}	0.000*
L_3 Average (mm)	0.12 ± 0.19^{a}	0.10 ± 0.19^{a,b}	0.04 ± 0.11^{b}	0.027*
L_4 Average (mm)	0.05 ± 0.13	0.05 ± 0.19	0.03 ± 0.11	0.480

*Statistically significant

^{a,b,c} : different letters denote statistically significant difference between teeth

Pearson Correlations

The data measurements were compared against treatment time using the Spearman's Rho nonparametric correlations and respective p-values (appendices A and B). In regards to the change in the area (mm^2) of the alveolar process, only ΔA_4 showed a significant relationship to treatment time ($p < 0.001$) with a weak correlation value of -

0.243. Areas $\Delta A_{1\text{-}3}$, the $\Delta A_{(1\text{-}4)}$ average as well as the active zone showed no significant correlation to treatment time ($p > 0.05$).

In the horizontal direction all changes on the buccal surface of the alveolar process showed a weak correlation to treatment time. B_1, B_2 and B_3 all had very strong p-values ($p < 0.01$) with weak correlations of -1.64, 0.251 and 0.206 respectively. B_4 had a weaker but still significant correlation with $p < 0.05$ and a correlation value of 0.115.

On the lingual surface all values had significant but weak correlations except L_2 ($p = 0.819$) and $L_{(1\text{-}4)}$ Total ($p = 0.553$). Both L_1 and L_4 had very strong significance ($p < 0.01$) with weak correlations of -.151 and 0.203. L_3 had a significance of $p < 0.05$ and a correlation of 0.139.

The data measurements were compared against mandibular proclination using the Spearman's Rho nonparametric correlations and respective p-values. In regards to the change to the area (mm^2) of the alveolar process, ΔA_3 and ΔA_4 showed a significant relationship to mandibular incisor proclination ($p < 0.001$) with a weak correlation value of 0.206 and 0.226. Areas $\Delta A_{1,2}$ showed no significant correlation to mandibular incisor proclination ($p > 0.05$).

In the horizontal direction on the buccal surface of the mandibular alveolar process only B_1 showed a strong correlation to mandibular incisor proclination with $p < 0.001$ and correlations of 0.368 and 0.372. B_2-B_4 showed weak correlations to mandibular incisor proclination.

On the lingual surface all values had significant correlations except L_2 ($p = 0.416$). Both L_1 and L_4 had very strong significance ($p < 0.01$) with correlations of 0.336, -0.135 and -0.155. L_3 had a weaker significance of $p < 0.05$ and a correlation of -0.135.

Discussion

In this study, CBCT DICOM files of thirteen patients who completed orthodontic treatment were examined. The area (mm^2) and buccal/lingual linear change was measured on pre-treatment (T1) and post-treatment (T2) images using the InVivo software. The data was then compared using three different groupings: the first was a comparison among the entire patient sample, the second was between facial types, and the third was between specific tooth regions.

Total Patient Sample

A Statistically significant change was found between T1 and T2 in both the area (T1 vs T2; $p < 0.05$; Table 3) and buccal/lingual linear change of the alveolar process (T1 vs. T2; $p < 0.05$; Table 4). In the overall patient sample the only area that did not show significant change was the lower two vertical areas (B_3, B_4) on the buccal surface (T1 vs T2; $p > 0.05$; Table 3) which suggests that as you move away from the active area of tooth movement the effects on alveolar adaptation are diminished. The amount of change seen below the first vertical area appears minimal and the values start approaching a difference of 0.4 mm^2 or less, this may represent a difference in the resolution of the CBCT images more than real alveolar change.

The overall change in bone area (mm^2) for the four different vertical areas showed a decrease in bone volume (Table 3). However due to the fact that many of the T1 CBCT scans were acquired at a lower resolution than the T2 scans this may just be showing the difference in resolution between the T2 and T1 images.

Facial Type

Statistically significant changes were seen for all values when the data was separated by facial type (T2-T1; $p < 0.05$; Table 5). Parameters B_3 and B_4 which did not show a statistically significant difference in the overall patient population now have a p-value of 0.002 and 0.001. When looking at the adaptation to the area (mm^2) between facial types the parameters ΔA_1 to ΔA_4 as well as $\Delta A_{(1-4)}$ average show that the mesofacial and brachyfacial patients behaved in a similar manner (T2-T1; $p > 0.05$; Table 5). The dolichofacial patients were statistically different from either the brachyfacial or mesofacial patients in all of the above measurements (T2-T1; $p < 0.05$; Table 5).

There was a statistically significant difference seen between horizontal adaptation and facial type in all of the data parameters (T2-T1; $p < 0.05$; Table 5). On the buccal surface B_1 has a statistically different response between all three facial types (T2-T1; $p < 0.05$; Table 5). This may represent a different alveolar response between the three facial types or just the amount of tooth movement that was required between each patient. Areas B_2 and B_3 both behaved in a similar manor with only the mesofacial and brachyfacial patients showing a statistically significant difference. The Area B_4 shows a statistically significant difference only for the dolichofacial patients (T2-T1; $p < 0.05$; Table 5).

On the lingual surface a statistically significant difference was seen only between the mesofacial and brachyfacial patients at the level of L_1. However at parameters L_2, L_3, L_4 and $L_{(1-4)}$ total the dolichofacial patients show a statistically larger alveolar response than either the brachyfacial or mesofacial patients (T2-T1; $p < 0.05$; Table 5).

Dolichofacial patients typically have a longer and thinner alveolar process and this may make them more prone to horizontal alveolar adaptation on the lingual surface during orthodontic tooth movement.[7, 11, 15] Although the data showed statistical significance, due to the small number of dolichofacial patients included in the study no clinical conclusions can be made as to how the alveolar bone responds to orthodontic movement based on facial type.

Tooth Region

When the data was separated by tooth region (central incisor, lateral incisor, canine) a dramatic drop in the amount of statistically significant differences was seen, which suggests that the alveolar adaptation is somewhat uniform across the alveolar process. Most of the statistically significant differences were seen in the areas that saw the most change in tooth position. ΔA_1, $\Delta A_{(1\text{-}4)}$ average, B_1, L_1, L_2, and L_3 all saw statistically significant differences between tooth region (T2-T1; $p < 0.05$; Table 6). What was observed in almost all of the parameters is a gradual change from the most amount of change in the central incisors to the least amount of change in the canines. In the B_1-B_3 parameters there was more than twice the alveolar response when you compare the central incisors to the canines, which corresponds to the fact that there was much more tooth movement in the central incisor region compared to the canines. The lingual surface also saw more statistically significant differences when compared to the buccal surface (T2-T1; $p < 0.05$; Table 6). This may be influenced by the dolichofacial patients, which showed a large increase in lingual alveolar adaptation (T2-T1; $p < 0.05$; Table 6).

Pearson Correlations

Pearson correlations revealed that there was no significant correlation between treatment time and the change in area (mm^2) of the alveolar process with the exception of $\Delta A_{4.}$ There was a statistically significant but weak correlation to the horizontal adaptation of the alveolar process when compared to treatment time with the exception $L_{2.}$ This may indicate that when given more time the alveolar process is allowed to adapt to a greater degree, but no definitive conclusions can be made at this point.

Mandibular incisor proclination also showed weak correlations between the different parameters ($p < 0.01$; Appendix B). The most superior regions of B_1 and L_1 had correlations of 0.368 and 0.336 respectively ($p < .01$; Appendix B). The superior part of the alveolar process experiences the most influence from orthodontic tooth movement so you would expect the greatest alveolar response to be in this area. However the largest correlation seen in the area (mm^2) of ΔA_1 through ΔA_4 were the apical zones ΔA_3 and ΔA_4. This seems to go counter to the findings listed previously and due to the fact that the values and correlations were minimal, may just represent differences in the T2 and T1 CBCT resolutions.

When looking at the data as a whole it is important to consider the difference between statistically significant findings and clinically significant findings. Table 4 shows statistically significant changes for all of the parameters except B_3 and B_4, however, the amount of change that occurred in a horizontal direction was less than 0.5 mm. And Table 3 shows a net loss in the change in the alveolar area (mm^2) at -1.739 mm^2, which may simply reflect the difference in resolution between the T1 and T2

CBCT. However, the fact that alveolar adaptation is seen in relation to orthodontic tooth movement is a clinically pertinent finding and one that warrants further research.

Conclusions

Within the confine of this study, the following conclusions were drawn:

1. Statistically significant adaptation of the alveolar process occurs in response to tooth movement, both in area (mm^2) and buccal/lingual linear dimension.
2. The central incisors demonstrated the greatest change to area (mm^2) and buccal/lingual adaptation, followed by the lateral incisors and lastly the canines.
3. The data suggests that dolichofacial patients may show greater bone loss in response to orthodontic tooth movement. However due to the sample size of the dolichofacial group drawing any clinical conclusions is difficult.

CHAPTER THREE

EXTENDED DISCUSSION

When looking at the data obtained in this study, several factors must be considered in regards to the image quality of the CBCT images. Voxel size, noise, scatter, artifacts and bone density all affect the quality of the image and therefore the capability to record accurate measurements.[37, 38, 39, 40] The effects of these parameters on this study will be discussed below.

The Newtom 3g and 5g CBCT machines used to obtain the DICOM files are set at a voxel size of 0.2 mm. A voxel is a three dimensional pixel that the software uses to reconstruct an image.[37] Voxels are not the same size in all three dimensions and the voxel resolution of the DICOM files used in this study ranged from 0.36 x 0.36 x 0.30 mm to 0.42 x 0.42 x 0.40 mm. The most effective way to increase the resolution is to decrease the voxel size, the trade off is that the radiation dose increases with smaller voxel sizes.[37, 38]

High resolution CBCT machines are relatively new and finding patients that met the inclusion criteria for this paper required looking 10 years into past records. The difference in image resolution made an accurate 1:1 measurement between T1 and T2 scans more difficult. While the results are accurate down to less than 0.5 mm many of the data parameters were less than 0.5 mm. Once our library of higher resolution 0.2 mm voxel scans grow revisiting this study with higher resolution images will be extremely useful.

Another factor to consider with respect to accuracy of buccal bone measurements in this study was recent orthodontic tooth movement. It has been shown that as force is applied to a tooth to induce orthodontic movement, the resulting osteoclastic activity and bone turnover causes a decrease in bone density.[39] Since a CBCT scan distinguishes different matters through their difference in density, it is difficult to identify the less dense immature bone on the CBCT image.[40] Therefore, waiting at least one year before taking a final scan has been recommended for buccal bone measurement.[40]

There have been various studies conducted in the past that look at the effect orthodontic tooth movement has on alveolar bone adaptation. Initially they were performed on casts and radiographs, but now a few studies have been conducted with CBCT. However, there are still very few studies that have examined the adaptation of the alveolar process in three dimensions with CBCT. Because this study is one of the first of its kind, future studies with larger sample sizes, and higher resolution CBCT scans will be needed to truly determine the alveolar process's response to orthodontic tooth movement.

Study Improvements and Future Directions

As with any new study there are always areas that could have been changed, the following are five areas where the study could have been improved. The first would be to increase the sample size, this would help increase the power and clinical significance of the study. The second is due to the fact that the inclusion criteria only looked at lower incisor inclination many of the patients showed little change in the canine region and therefore including the canine in data collection may have not been necessary. The third was that most of the T1 CBCT images were taken on the Newtom 3g machine that had a lower resolution when compared to the Newtom 5g. Having higher resolution images would help with measurement accuracy. The fourth would involve looking at incisor intrusion vs extrusion, that may change the way the alveolar process adapts and including a parameter to track that movement would help strengthen the study. The fifth would involve looking into methods to superimpose the T1 and T2 images based on pixels rather than surface superimposition methods.

As for future research once the resolution of CBCT images is high enough to accurately separate the teeth from the alveolar process, a measurement of pure bony change could be achieved. Another idea would involve looking at the adaptation of alveolar bone in incisor retraction vs incisor proclination cases. And finally looking at patients two years into retention and examining areas of bone loss to see if these areas regain their former shape and mineral density.

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