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Skeletal Changes after Rapid Maxillary Expansion and Fixed Orthodontic Treatment: A CBCT Study

Chandler Ho

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

Skeletal Changes after RME & Fixed Orthodontic Treatment: A CBCT Study

by

Chandler Ho

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 Master of Science.

____, Chairperson

Kitichai Rungcharassaeng, Professor of Orthodontics

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Joseph M. Caruso, Professor of Orthodontics

____

V. Leroy Leggitt, Professor of Orthodontics

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This thesis is dedicated to all of my family and friends who have supported me throughout my schooling. I am grateful to my wife, Alison, and my parents, Dr. Ken and Vicki Ho, for their constant love and care. The Lord has blessed me with more than I can imagine, and I look forward to serving Him with all the knowledge, skills, and training I have received.

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ABBREVIATIONS

Act	Activation Time
AE	Appliance Expansion
App	Type of Appliance
ART	Alveolar Ridge Thickness
BMW	Buccal Maxillary Width
C1	Cuspid
CBCT	Cone Beam Computed Tomography
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
H Ret	Hyrax Retention
IA	Interdental Angle
ID	Interdental Width
Inc1	Central Incisor
M1	First Molar
MSWA	Maxillary Sinus Width Actual
MSWT	Maxillary Sinus Width Total
NFW	Nasal Floor Width
NW	Nasal Width
P1	First Premolar
P2	Second Premolar
PAA	Palatal Alveolar Angle
PC Ret	Pre-CBCT Retention

PMW	Palatal Maxillary Width
Rate	Rate of Appliance Expansion
RME	Rapid Maxillary Expansion
RPE	Rapid Palatal Expansion
SE	Sutural Expansion
T1	Pre-Rapid Maxillary Expansion
T2	Post-Rapid Maxillary Expansion
T3	Completion of Orthodontic Treatment
T Ret	Total Retention Time
TTT	Total Treatment Time

ABSTRACT OF THE THESIS

Skeletal Changes after Rapid Maxillary Expansion and Fixed
Orthodontic Treatment: A CBCT Study

by

Chandler Ho

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

Introduction: The purpose of this study was to use cone-beam computed tomography to quantitatively evaluate the skeletal effects of rapid maxillary expansion and orthodontic treatment, with a specific interest in evaluating whether the skeletal changes achieved by RME will maintain throughout orthodontic treatment. **Methods:** Thirty consecutive patients (16 boys, 14 girls; mean age, 13.9 ± 1.8 years) who required RME with Hyrax appliances as part of their comprehensive orthodontic treatment were studied. Measurements before and after RME, and after orthodontic treatment, of palatal and buccal maxillary widths, palatal alveolar angle, nasal width, nasal floor width, and maxillary sinus width at C1, P1, P2, and M1 were compared by using Wilcoxon signed rank, Kruskal-Wallis, and Wilcoxon rank sum tests. Pearson correlation analyses were also performed ($\alpha = 0.05$). **Results:** Widths measured for the maxillary buccal and palatal cortical plates post expansion and at the end of orthodontic treatment were statistically similar ($P > .05$). Nasal width and nasal floor width measured post-expansion to the end of orthodontic treatment were statistically similar ($P > .05$). Alveolar tipping statistically significantly increased ($P < .001$) with RME and then statistically significantly decreased when measured at the end of orthodontic treatment (P =.014). Increased age was significantly correlated with increased alveolar tipping (P =.002).

Conclusions: Skeletal width increases of the maxillary alveolar ridge and nasal cavity were maintained after RME.

CHAPTER ONE

REVIEW OF LITERATURE

In the field of orthodontics, rapid maxillary expansion (RME) has been shown to be effective in correcting maxillary width deficiency or posterior crossbite as well as expanding arch perimeter to help resolve dental crowding. In many cases, RME can be incorporated into treatment as an adjunct to other treatment, such as class II correction, or used to create space in a non-extraction manner.[1-5]

These RME appliances can be tooth borne, osseous borne, and can even include being partially soft tissue borne. They exert heavy forces laterally which separate the maxillary suture leading to maximum orthopedic movement and minimal dental movement; resulting from suture expansion and maxillary alveolar bone bending.[6,7] The expansion force has been shown to affect other sutures surrounding the maxilla: frontomaxillary suture, zygomaticomaxillary suture, zygomaticotemporal suture, and the pterygopalatine sutures.[8] Upon RME activation, the maxilla moves around centers of rotation at the frontonasal suture superiorly and posteriorly at the pterygoid process of the palatine bone.[1] Complementary to maxillary expansion has been an observed increase of the nasal cavity width which may lead to improved airflow and nasal breathing.[1-3]

Studies on RME to date have measured pretreatment to posttreatment skeletal and dental changes, utilizing dental casts, 2-dimensional (2D) cephalometric or occlusal radiographs, and more recently, cone-beam computed tomography (CBCT) technology.

Evaluation of RME utilizing dental casts has been explored in depth with many variations of evaluation. For example, researchers have drawn comparisons viewing casts at multiple time points: pre-expansion, post-expansion, and after years of retention - allowing for evaluation of relapse. In 1995, Moussa studied 55 patients with casts from the aforementioned time points. He noted statistically significant differences in arch length, arch perimeter, and intercanine width, when comparing values at the end of expansion and post-retention.[9] Again in 2010, Gurel had an RME study that revealed similar findings of decreased maxillary arch width at post retention with most significant relapse in the intercanine region.[10] No matter the RME study, solely relying on dental casts for quantitative data has limitations, being that only inferences can be made regarding the underlying skeletal base housing the observed dentition.

As an adjunct to using dental casts for study or even in separate studies, RME research incorporated the use of 2-dimensional (2D) cephalometric or occlusal radiographs. These provided visualization of skeletal changes occurring when using RME, offering the ability to view sutural changes as well as collect cephalometric measurements for comparison. Being able to identify skeletal landmarks radiographically allowed researchers to measure maxillary expansion and nasal width changes.[11] These radiographs were used to show that RME effectively increases transverse facial dimensions in the long term at both the skeletal and dentoalveolar levels.[12]

With technological advancement, clinicians and researchers do not have to settle for overlap and superimpositions seen in posterioranterior cephalograms and occlusograms. Via cone-beam computed tomography (CBCT) technology, it is now possible to acquire accurate radiographic images that allow clinicians and researchers to quantitatively evaluate bone changes in 3 dimensions, with minimal distortion and lower radiation doses than a traditional CT scan.[13] These volumes enable users to make cuts of the image at particular areas of evaluation, decreasing unwanted noise and overlapping structures.

Most commonly, CBCT has been used to visualize the maxillary suture in response to RME using pre-expansion and post expansion time points; showing that expansion increases along the suture anteriorly and distance between opposite alveolar ridges increases.[6,14-17] In Italy, CBCT studies evaluated RME stability using a protocol of six months post-expansion. In that time, they found that the mid-palatal suture reorganizes, resembling its initial presentation, and that expansion across the first molars did not have any significant difference (when using the apex of the palatal root as a reference point).[14,15] Comparing widths measured between the apices of the palatal root of the maxillary first molars, they found no statistical difference from the end of expansion to six months into retention. This was complemented by a similar interdental width ratio of root apex to crown for the maxillary first molars from initial to post-retention, indicating maintenance of dental inclination.[14]

CBCT studies yielded information regarding RME's effects on the maxilla, surrounding sutures, nasal cavity, maxillary sinus, tooth positioning, alveolar tipping, alveolar bone thickness and height.[6,16,18-24] In growing children, the lateral force exerted by RME was shown to displace the bones of the frontonasal suture, intermaxillary suture, zygomaticomaxillary sutures, and midpalatal suture.[24] Nasal cavity width increases and maxillary sinus width decreases have been noted with RME.[6] Increased axial inclination of the maxillary first premolar, second premolar, and first molar has been documented post-expansion.[6,19,23-25] Studies have shown that such increase in dental inclination has been complemented by alveolar tipping laterally.[6,18] In regards to changes in alveolar bone thickness, an increase in alveolar palatal bone thickness has been noted, along with either a maintenance or decrease of alveolar buccal bone thickness.[21,22]

Overall skeletal changes measured seem to reflect trends published by Garrett et al in 2008 which used CBCT to quantitatively analyze the effects of RME.[6,18,20,23] They measured sutural expansion, width changes at the level of the maxillary buccal and palatal cortical plates, as well as changes in inclination of the alveolar ridges. Analyzing this data with consideration of dental expansion observed, they inferred the contributions of orthopedic expansion, alveolar bending, and dental tipping to overall expansion.[6,16] They observed that sutural expansion in response to RME followed the triangular pattern of being greater anteriorly than posteriorly.[6,23] This orthopedic expansion accounted for 55% of the total expansion at the first premolar, 45% at the second premolar, and 38% at the first molar.[6] Of the three, alveolar bending or tipping had the least contribution to overall expansion at 6% for the first premolar, 9% for the second premolar, and 13% for the first molar.[6] It is very clear that such in depth analysis would not be possible with dental casts or two dimensional radiographs.

CHAPTER TWO

SKELETAL CHANGES AFTER RAPID MAXILLARY EXPANSION AND FIXED ORTHODONTIC TREATMENT: A CBCT STUDY

Abstract

Introduction: The purpose of this study was to use cone-beam computed tomography to quantitatively evaluate the skeletal effects of rapid maxillary expansion and orthodontic treatment, with a specific interest in evaluating whether the skeletal changes achieved by RME will maintain throughout orthodontic treatment. **Methods:** Thirty consecutive patients (16 boys, 14 girls; mean age, 13.9 ± 1.8 years) who required RME with Hyrax appliances as part of their comprehensive orthodontic treatment were studied. Measurements before and after RME, and after orthodontic treatment, of palatal and buccal maxillary widths, palatal alveolar angle, nasal width, nasal floor width, and maxillary sinus width at C1, P1, P2, and M1 were compared by using Wilcoxon signed rank, Kruskal-Wallis, and Wilcoxon rank sum tests. Pearson correlation analyses were also performed ($\alpha = 0.05$). **Results:** Widths measured for the maxillary buccal and palatal cortical plates post expansion and at the end of orthodontic treatment were statistically similar ($P > .05$). Nasal width and nasal floor width measured post-expansion to the end of orthodontic treatment were statistically similar ($P > .05$). Alveolar tipping statistically significantly increased ($P < .001$) with RME and then statistically significantly decreased when measured at the end of orthodontic treatment ($P = .014$). Increased age was significantly correlated with increased alveolar tipping ($P = .002$).

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The purpose of this study was to evaluate whether post-RME skeletal changes can be expected to maintain throughout fixed orthodontic treatment. Using CBCT, we evaluated the effects of RME on the alveolar arch, nasal width, and other skeletal parameters and then compared these changes to the end of fixed orthodontic treatment.

Materials and Methods

Patient Selection

This retrospective study was approved by the Institutional Review Board of Loma Linda University, California, USA. Thirty consecutive patients who had been treated at the Graduate Orthodontic Clinic, Loma Linda University School of Dentistry, and required Rapid Maxillary Expansion (RME) using Hyrax appliances as part of their comprehensive orthodontic treatment were included. These patients had CBCT images taken before RME (T1), after RME (T2) and at orthodontic treatment completion (T3). T1 images were obtained prior to orthodontic treatment, T2 images were obtained with the appliances still in place within three months after the activation had been finalized, T3 images were taken within two months of removal of orthodontic appliances. Five patients had first premolar extraction during their treatment time.

Patient scans were taken in a standardized fashion having the patient in a supine position with chin and shoulder supports; a vertical sighting beam was also used to ensure their position was accurate and repeated for all three scans. Scans lasted 36 seconds and were performed at 110kV. Newton 3G Smart-Beam technology was used and based on the patient's anatomic density, milliampere values fluctuated with a maximum of 15mA delivered. Data was recorded with .2mm voxel size and was reconstructed with 0.5 mm slice thickness. The DICOM (Digital Imaging and Communications in Medicine) images were assessed through OsiriX Medical Imaging software (v. 2.4) Expansion appliances for the sample were either two or four-Band Hyrax expanders (Fig 1 and Fig 2).

Figure 1. Four-Banded Hyrax Rapid Maxillary Expansion Appliance

Figure 2. Two-Banded Hyrax Rapid Maxillary Expansion Appliance

Data Collection

The following parameters were under evaluation: nasal width (NW), maxillary sinus width (MSW), nasal floor width (NFW), palatal alveolar angle (PAA), palatal maxillary width (PMW), buccal maxillary width (BMW), alveolar ridge thickness (ART) at the canine (C1), first premolar (P1), second premolar (P2) and first molar (M1) for T1, T2 and T3. Amount of appliance expansion (AE) was measured from T2, which included the expander. For each patient, age, activation time (amount of time which expansion occurred), pre-CBCT retention (amount of time from end of expansion to T2), hyrax retention time (total amount of time hyrax was in place as a retainer), and total treatment time (total amount of treatment time from expansion through the end of orthodontic treatment), were recorded. All measurements were performed by one examiner. Linear and angular measurements were made to the nearest 0.01mm and 0.01 degree respectively.

The following measurements were made according to definitions in a previous study conducted by Garrett et al[6]:

1. PMW and BMW. Using three orthogonal slices (coronal, sagittal, and axial), C1 and P2 apices and P1 and M1 furca were located. Figure 3 illustrates the method using the maxillary first molar furcation as an example. A line was then drawn between these points that corresponded to the position of C1, P1, P2, or M1 and the contralateral tooth. From an axial section of the T1 CBCT image, at the level of the furcation of the M1, a line was drawn between the right and left furcations. The palatal maxillary width of the first molar (PMW M1) was the interalveolar distance between the palatal surface of the cortical plates along this line (Fig 4). The respective PMW measurements were taken as the interalveolar distance between the palatal surface of the palatal alveolar cortical plates along this line (Fig 4). The lines connecting the C1 and P2 apices and P1 and M1 furca were then extended to the external surface of the buccal cortical plates. The BMW is the interalveolar distance between the buccal surface of the buccal cortical plates along each line (C1, P1, P2, or M1) (Fig 4). The procedure was repeated for the T2 and T3 measurements. The amount of buccal and

palatal maxillary expansion was according to time points T1, T2, and T3. Positive ΔPMW and ΔBMW values will indicated expansion, negative values indicated relapse.

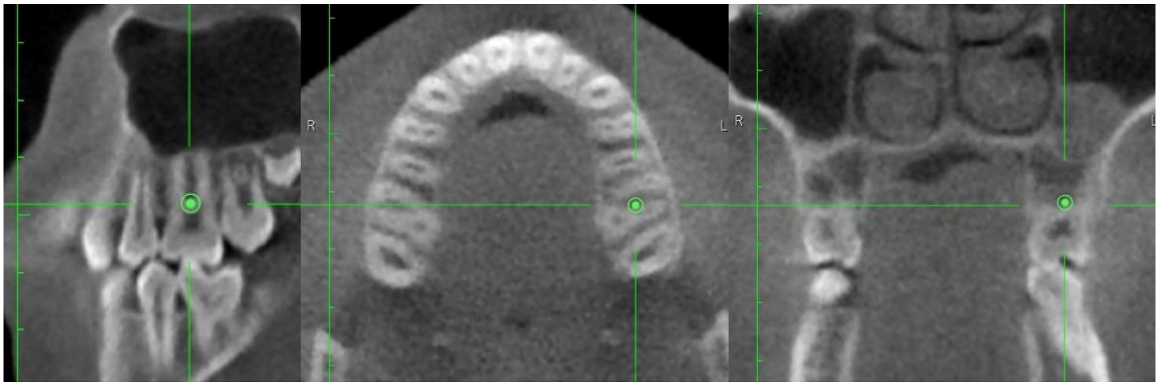

Figure 3. Three orthogonal views showing identification of the M1 furcation.

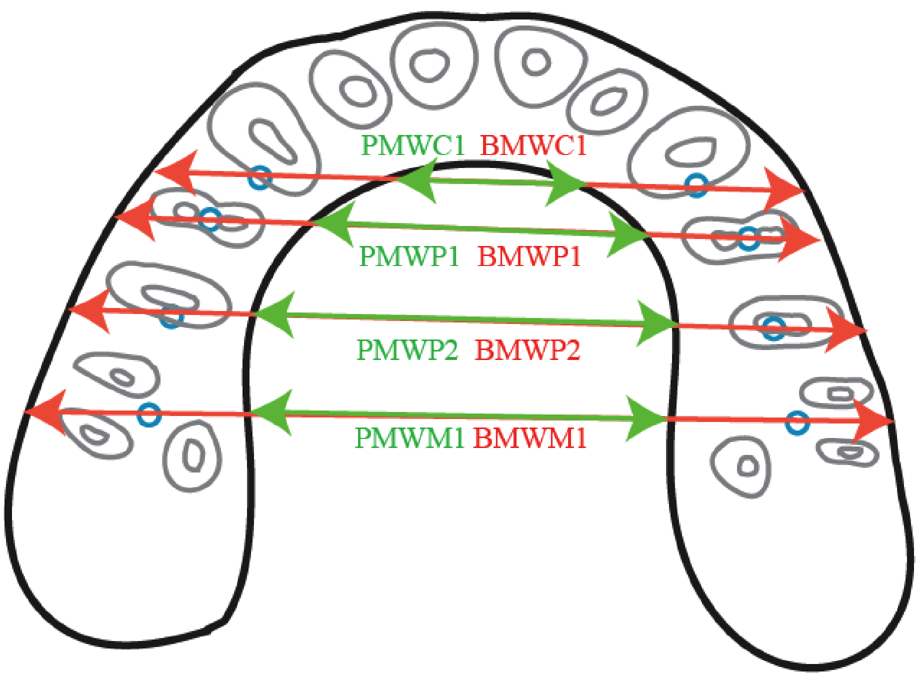

Figure 4. Diagram Showing M1 furca and P1 furca, and respective C1 and P2 apex reference points with measurement lines connecting contralateral sides.

2. NW, NFW, and MSWA. From an axial section of the T1 images, at the level of furcation of M1, an opened-polygon cut (tool used in OsiriX to create dissection lines through points of interest to obtain orthogonal image slices) was made buccolingually so that it intersected the maxillary first molar furcation bilaterally. On the coronal image derived from the opened-polygon cut, NW was obtained by measuring the distance between the widest transverse portion of the nasal aperture judged by the outer surface of the cortical bone (Fig 5). MSWA was then obtained by first extending through the NW line to the lateral maxillary sinus borders and measuring the total distance, maxillary sinus nasal width (SNW). The NW dimension was then be subtracted from this SNW distance to get MSWA, which is the sum of the right and left maxillary sinus widths at that level (Fig 5). NFW was obtained on the same coronal slice by measuring the distance between the widest transverse portion of the nasal floor at the most inferior border of the nasal aperture (Fig 5). The procedure was repeated for the T2 and T3 measurements. The changes in NW (ΔNW), NFW (ΔNFW), and MSWA (ΔMSWA) were calculated based on time points T1, T2, and T3. Positive ΔNW and ΔNFW values indicated expansion, and negative ΔMSWA values would indicate narrowing of the maxillary sinus.

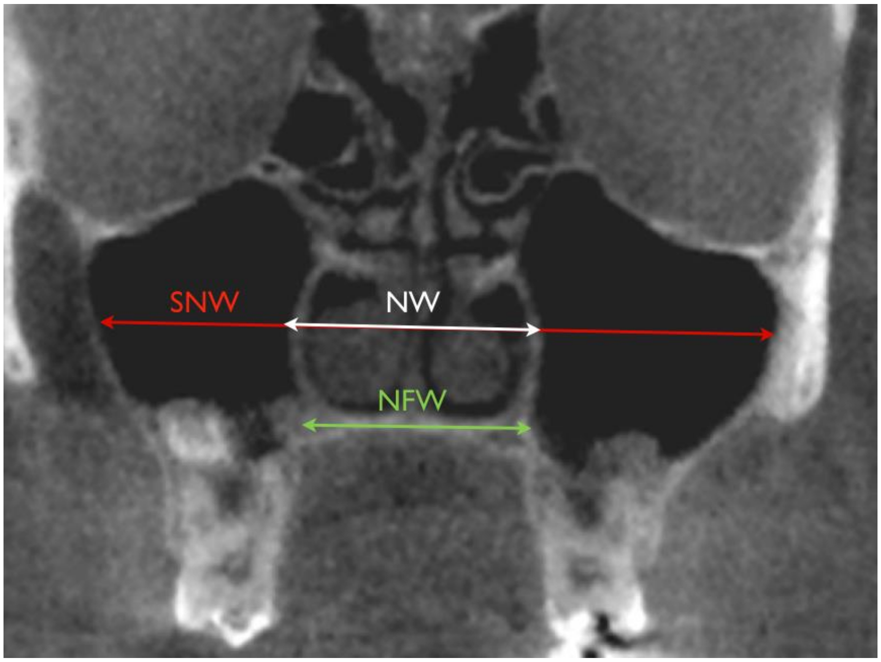

Figure 5: T1 coronal image derived from the open-polygon cut. SNW – NW = MSWA

3. PAA. From an axial section of the T1, T2, and T3 images, at the level of the furcation of M1, the opened-polygon cut tool was used to make an orthogonal cut in the coronal plane that intersected maxillary first molar furcation points. From this coronal image, best-fit lines were constructed through the palatal surfaces of the right and left palatal cortical plates, and the PAA was measured as the angle between the two cortical plate lines (Fig 6). The amount of palatal alveolar tipping (ΔPAA) was the difference when comparing the T1 PAA, T2 PAA, and T3 PAA. A positive ΔPAA indicated alveolar tipping or bending in the buccal direction, whereas a negative value after expansion could indicate relapse.

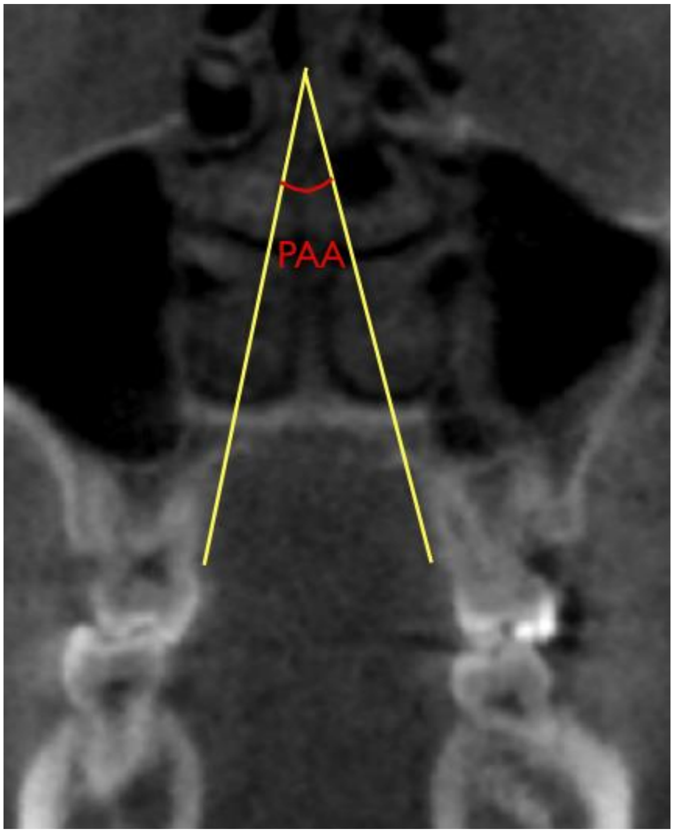

Figure 6: Coronal image illustrating how PAA was measured.

4. SE. On a thick cut of the T2 image that shows the entire thickness of the expanded maxillary suture, the root apex points used for PMW and BMW were reproduced. Reference lines connecting M1 furcations, central incisor (Inc1), C1, P1, and P2 root apices were drawn and the amount of SE was measured along these reference lines (Fig 7). SE was the distance measured between right and left maxillary bones.

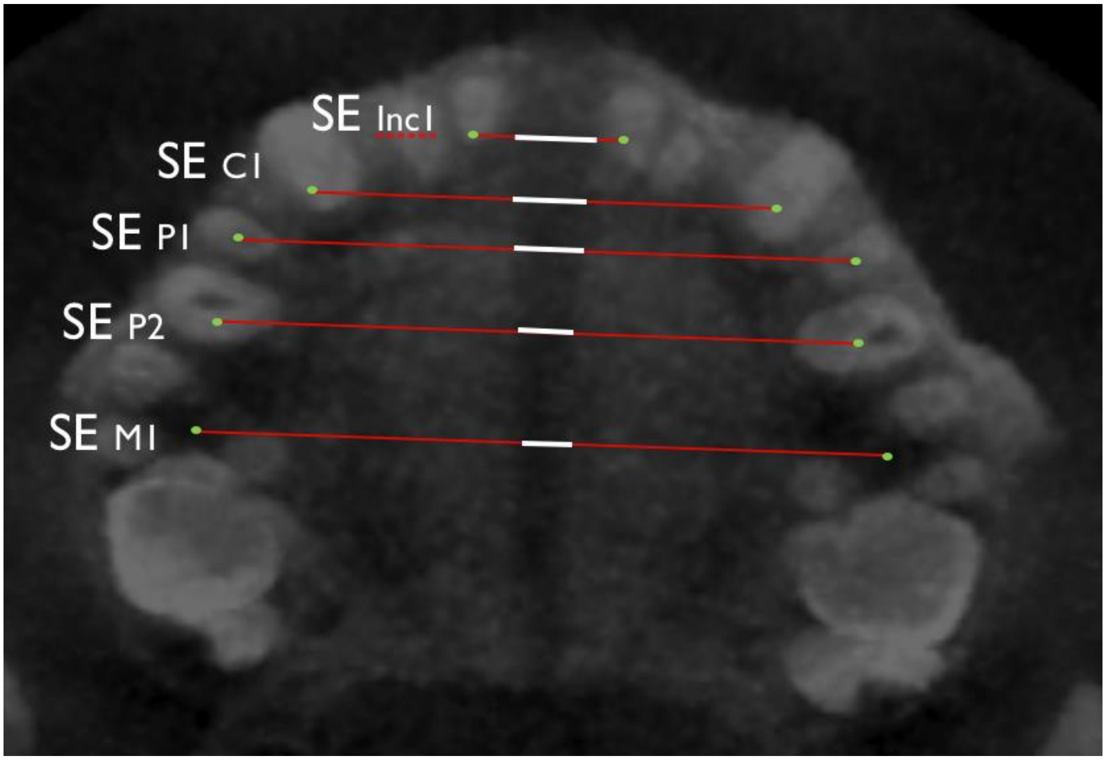

Figure 7. Thick slice axial image showing maxillary SE (White).

5. AE. From the axial section of the T2 images, at the level of Hyrax appliance, an open polygon cut was made bisecting the appliance transversely. On the coronal image derived from the opened-polygon cut, the separation distances and the thickness of the middle portion of the appliance were measured (Fig 8). Their difference represented the AE.

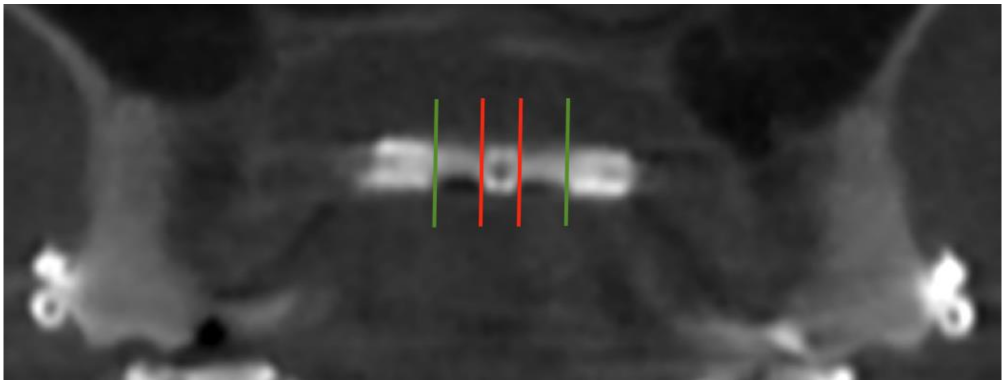

Figure 8. Coronal image illustrating how AE was measured. The appliance expansion is the difference between the separation distance of the appliance (green lines) and the thickness of the middle portion of the appliance (red lines).

From the recorded values, calculated values were also evaluated:

1. Rate. Rate of appliance expansion was defined as the amount of appliance expansion divided by the activation time (mm/wk).
2. ART. The difference of Buccal Maxillary Width (BMW) and Palatal Maxillary Width (PMW) was defined as the Alveolar Ridge Thickness (ART). These values were calculated at T1, T2, and T3 for the C1, P1, P2, and M1.

Statistical Analysis

The intra-examiner reliability of the measurements were determined by using triple assessments on measurements taken at least two weeks apart. Means, standard deviations and ranges were calculated for each parameter. Measurements were assessed with Friedman, Kruskal-Wallis and Mann-Whitney U-tests. Pairwise comparisons were performed with Wilcoxon Signed Rank Tests. To determine which variables were associated, Kendall's Tau correlation analyses were performed. Statistical significance was denoted when $P < .05$.

Results

This study included 30 patients (16 males and 14 females) with a mean age of 13.9 (range 10.3-17.7) years old. Of these 30 patients, 13 had two-banded and 17 had four-banded appliances. The mean appliance expansion, activation time, rate of appliance expansion, pre-CBCT retention time, Hyrax retention time, and total treatment time were 5.24 mm, 6.47 weeks, 1.11 mm/week, 3.93 weeks, 21 weeks, and 146.63 weeks, respectively (Table 1).

Table 1. Means, standard deviations, and ranges.

	Mean ± SD	**Range**
Age (yr)	13.88 ± 1.83	10.25 – 17.67
AE (mm)	5.24 ± 1.69	2.20 – 10.00
Activation Time (wk)	6.47 ± 4.16	2 – 18
Rate of Appliance Expansion (mm/wk)	1.11 ± 0.68	0.18 – 3.00
Pre-CBCT Retention (wk)	3.93 ± 4.25	0 – 12
Hyrax Retention Time (wk)	21.00 ± 7.29	4 – 46
Total Treatment Time (wk)	146.63 ± 52.91	70 – 270

Measurements for the study proved to be highly reliable and reproducible based on intraclass correlation coefficients for all variables being above 0.99 (Table 2).

Table 2. Intraclass Correlation Coefficients (ICC)

Variable	ICC
Appliance Activation (AE)	1.000
Buccal Maxillary Width at 1st Molar (BMW M1)	0.999
Buccal Maxillary Width at 1st Premolar (BMW P1)	0.998
Buccal Maxillary Width at 2nd Premolar (BMW P2)	0.997
Buccal Maxillary Width at Canine (BMW C1)	0.996
Maxillary Sinus Width (MSW)	0.998
Nasal Floor Width (NFW)	0.993
Nasal Width (NW)	0.998
Palatal Alveolar Angle (PAA)	0.995
Palatal Maxillary Width at 1st Molar (PMW M1)	0.995
Palatal Maxillary Width at 1st Premolar (PMW P1)	0.995
Palatal Maxillary Width at 2nd Premolar (PMW P2)	0.996
Palatal Maxillary Width at Canine (PMW C1)	0.998
Sutural Expansion at 1st Molar (SE M1)	1.000

Table 3 includes the means and standard deviations of all measured parameters at T1, T2 and T3. Friedman tests with pairwise Wilcoxon Signed Rank Tests were used for statistical analysis. No statistically significant differences among all time points were found in MSWA, ART P1, ART P2, and ART M1 ($P > .05$; Table 3). For PAA, statistically significant differences were found among all time points ($P < .001$). For the rest of the parameters, no significant differences were found between T2 and T3 values ($P > .05$), but they were different from T1 value ($P < .05$).

Table 3. Comparison of all parameters among different time intervals (T1, T2 and T3) using Friedman test.

	T1 (Mean ± SD)	T2 (Mean ± SD)	T3 (Mean ± SD)	P value
NW (mm)	30.49 ± 3.06[a]	32.37 ± 3.63[b]	32.39 ± 3.30[b]	<.001
NFW (mm)	27.09 ± 3.26[a]	28.95 ± 3.57[b]	29.35 ± 3.34[b]	<.001
MSWA (mm)	42.50 ± 7.08	42.25 ± 6.94	43.39 ± 6.81	.131
PAA (degrees)	30.16 ± 5.16[a]	36.60 ± 6.12[b]	33.67 ± 5.26[c]	<.001
BMW C1 (mm)	41.51 ± 4.52[a]	45.52 ± 4.58[b]	44.73 ± 4.12[b]	<.001
BMW P1 (mm)	45.32 ± 3.82[a]	49.13 ± 3.61[b]	48.81 ± 2.49[b]	<.001
BMW P2 (mm)	50.95 ± 3.80[a]	54.41 ± 3.68[b]	53.89 ± 4.25[b]	<.001
BMW M1 (mm)	56.90 ± 3.61[a]	60.22 ± 3.88[b]	60.42 ± 4.02[b]	<.001
PMW C1 (mm)	18.03 ± 4.24[a]	21.41 ± 4.12[b]	21.35 ± 3.78[b]	<.001
PMW P1 (mm)	21.76 ± 2.61[a]	25.54 ± 2.74[b]	25.60 ± 2.82[b]	<.001
PMW P2 (mm)	25.22 ± 2.88[a]	28.97 ± 3.15[b]	29.02 ± 3.25[b]	<.001
PMW M1 (mm)	27.32 ± 2.93[a]	30.61 ± 2.92[b]	31.05 ± 2.89[b]	<.001
ART C1 (mm)	23.48 ± 2.58	24.10 ± 2.63	23.38 ± 2.93	.056
ART P1 (mm)	23.55 ± 2.39	23.59 ± 2.26	23.21 ± 2.03	.852
ART P2 (mm)	25.73 ± 2.88	25.44 ± 2.39	24.87 ± 2.05	.239
ART M1 (mm)	29.58 ± 2.31[a]	29.61 ± 2.23[a]	29.37 ± 2.33[a]	.792

[a,b,c] : different letters denote statistically significant difference between time intervals (Pairwise Wilcoxon Signed Rank Test at $\alpha = 0.05$)

Table 4 shows the means and standard deviations of the amount of changes of each parameter among different time intervals (Δ_1 = initial change, Δ_2 = relapse, and Δ_3 = overall change). Kruskal-Wallis ranks test with pairwise Wilcoxon Signed Rank Tests were used to compare changes among different teeth. Measured sutural expansion for Inc1 and C1 were statistically different than measured at P1, P2, and M1 ($P < .001$). Mean values for these parameters were 3.77 mm, 3.37 mm, 3.00 mm, 2.70 mm, and 2.54 mm for Inc 1, C1, P1, P2, and M1. There were no statistically significant differences when separately comparing initial changes (Δ_1) and relapse (Δ_2) at the level of each tooth (C1, P1, P2, and M1) for both the buccal and palatal aspects of the maxillary alveolus. There was also no statistically significant difference when comparing overall change (Δ_3)

at the level of each tooth (C1, P1, P2, and M1) for both the buccal and palatal aspects of the maxillary alveolus.

Table 4. Comparison of changes in parameters at different time intervals (Δ_1, Δ_2, Δ_3) among all the teeth (Inc1, C1, P1, P2 and M1) using Kruskal-Wallis ranks test.

	Mean ± SD					P value
	Inc1	C1	P1	P2	M1	
AE (mm)	5.24±.29					
SE (mm)	3.77 ± 1.29[a]	3.37 ± 1.13[b]	3.00 ± 1.21[c]	2.70 ± 1.07[c]	2.54 ± 1.09[c]	< .001
Δ_1 NW					1.88 ± 1.52	
Δ_2 NW					0.01 ± 1.50	
Δ_3 NW					1.89 ± 1.83	
Δ_1 NFW					1.86 ± 1.51	
Δ_2 NFW					0.39 ± 0.97	
Δ_3 NFW					2.26 ± 1.66	
Δ_1 MSWA					-0.25 ± 2.87	
Δ_2 MSWA					1.14 ± 2.44	
Δ_3 MSWA					0.89 ± 3.22	
Δ_1 PAA					6.44 ± 4.85	
Δ_2 PAA					-2.93 ± 5.21	
Δ_3 PAA					3.51 ± 18.03	
Δ_1 BMW		4.00 ± 2.12	3.81 ± 2.49	3.46 ± 1.80	3.32 ± 1.45	.102
Δ_2 BMW		-0.79 ± 2.54	-0.33 ± 2.16	-0.51 ± 1.95	0.21 ± 1.23	.084
Δ_3 BMW		3.21 ± 2.09	3.49 ± 1.96	2.94 ± 2.20	3.52 ± 1.69	.938
Δ_1 PMW		3.38 ± 2.28	3.78 ± 2.08	3.75 ± 1.65	3.29 ± 1.43	.160
Δ_2 PMW		-0.06 ± 2.91	0.06 ± 2.39	0.05 ± 2.09	0.45 ± 1.56	.438
Δ_3 PMW		3.32 ± 3.06	3.84 ± 1.91	3.80 ± 2.17	3.74 ± 1.91	.145

[a,b,c,d,e] : different letters denote statistically significant difference between teeth (Pairwise Wilcoxon Signed Rank Test at $\alpha = 0.05$)

Tables 5 displays a comparison of all parameters for two-banded versus four-banded appliances, using Mann-Whitney U-tests for C1, P1, P2 and M1, respectively. Initial change (Δ_1) for PAA showed a statistically significant larger angle for the four-banded appliances relative to the two-banded (Δ_1 PAA; P =.043; Table 5). For C1 and P1, there were no parameters with significant differences between the four-banded and two-banded appliances. For P2, use of four-banded appliance resulted in statistically significant more overall expansion measured at the buccal aspect of the alveolus (Δ_3 BMW P2; P =.014; Table 5). For M1, use of two-banded appliance resulted in statistically significant greater relapse compared to the four-banded when measured at the palatal aspect of the alveolus (Δ_2 PMW M1; P =.025; Table 5). Overall change for BMW at M1 showed significantly greater change with four-banded appliances relative to two-banded (ΔBMW M1; P =.035; Table 5).

Table 5. Comparison of two-banded versus four-banded appliances for C1, P1, P2, and M1 using Mann-Whitney U-test.

	(Mean ± SD)		P value
	2-Banded	4-Banded	
AE (mm)	4.93 ± 1.78	5.47 ± 1.88	.245
Δ1 NW	1.62 ± 1.21	2.08 ± 1.73	.592
Δ2 NW	-0.02 ±1.53	0.04 ± 1.52	.967
Δ3 NW	1.59 ± 1.97	2.13 ± 1.73	.300
Δ1 NFW	1.71 ± 1.52	1.98 ± 1.53	.650
Δ2 NFW	0.18 ± 1.03	0.55 ± 0.93	.229
Δ3 NFW	1.89 ± 1.56	2.53 ± 1.70	.509
Δ1 MSWA	0.27 ± 3.54	-0.65 ± 2.27	.837
Δ2 MSWA	1.68 ± 2.99	0.73 ± 1.91	.432
Δ3 MSWA	1.95 ± 3.49	0.08 ± 2.82	.113
Δ1 PAA	4.48 ± 5.04	7.93 ± 4.27	.043*
Δ2 PAA	-2.52 ± 7.05	-3.24 ± 3.40	.837
Δ3 PAA	1.96 ± 5.35	4.69 ± 4.58	.157
SE C1 (mm)	3.19 ± 1.16	3.50 ± 1.12	.646
Δ1 BMW C1	3.48 ± 1.46	4.47 ± .57	.457
Δ2 BMW C1	-0.83 ± 2.74	-.80 ± .57	1.000

Δ3 BMW C1	2.66 ± 1.85	3.66 ± .51	.300
Δ1 PMW C1	3.59 ± 1.71	3.22 ± 2.67	.363
Δ2 PMW C1	-0.32 ± 3 .13	0.14 ± 2.82	.483
Δ3 PMW C1	3.26 ± 3.25	3.35 ± 3.00	.457
SE P1 (mm)	2.38 ± 0.85	3.31 ± 1.26	.093
Δ1 BMW P1	3.37 ± 1.63	4.02 ± 2.83	.588
Δ2 BMW P1	-0.69 ± 1.79	-0.15 ± 2.35	.754
Δ3 BMW P1	2.67 ± 0.64	3.87 ± 2.26	.194
Δ1 PMW P1	3.28 ± 1.73	4.01 ± 2.24	.344
Δ2 PMW P1	-0.39 ± 2.06	0.27 ± 2.57	.588
Δ3 PMW P1	2.89 ± 1.82	4.28 ± 1.83	.262
SE P2 (mm)	2.43 ± 0.97	2.92 ± 1.13	.249
Δ1 BMW P2	3.06 ± 1.21	4.02 ± 2.83	.408
Δ2 BMW P2	-1.23 ± 1.91	0.04 ± 1.84	.133
Δ3 BMW P2	1.83 ± 1.84	3.80 ± 2.12	.014*
Δ1 PMW P2	3.88 ± 1.33	3.65 ± 1.90	.902
Δ2 PMW P2	-0.83 ± 2.02	0.72 ± 1.93	.053
Δ3 PMW P2	3.06 ± 2.16	4.36 ± 2.07	.133
SE M1 (mm)	2.37 ± 0.99	2.67 ± 1.18	.475
Δ1 BMW M1	2.97 ± 1.17	3.58 ± 1.62	.183
Δ2 BMW M1	-0.11 ± 0.97	0.45 ± 1.38	.281
Δ3 BMW M1	2.86 ± 0.89	4.03 ± 1.98	.035*
Δ1 PMW M1	3.36 ± 1.63	4.02 ± 2.83	.742
Δ2 PMW M1	-0.69 ± 1.79	-0.15 ± 2.35	.025*
Δ3 PMW M1	2.67 ± 0.64	3.87 ± 2.26	.103

* Statistically significant at $\alpha = 0.05$

Tables 6, 7, 8, 9 and 10 demonstrate Kendall's Tau (τ) correlation coefficients and respective P values for changes in C1, P1, P2 and M1. For all teeth, with the exception of palatal of P2, there was positive significant correlation ($P < .05$) between appliance expansion and initial (Δ_1) expansion at the buccal and palatal aspects of the alveolus.

Age, total treatment time (TTT), and rate of expansion (Rate) did not demonstrate any significant correlation to the relapse (Δ_2) of expansion for any teeth. Hyrax retention showed to be significantly correlated with overall change (Δ_3) at the palatal aspect of P1 (r = 0.476, P =.016; Table 8) and P2 (r = 0.483, P =.007; Table 9) with no significant correlation with the other teeth. Age correlated strongly with Δ_1 PAA (r = 0.531, P =.003; Table 7).

Table 6. Matrix of Kendall's Tau correlation coefficients for changes in nasomaxillary structures

	Age	Act T	Rate	PC Ret	H Ret	TTT	AE	Δ1NW	Δ2NW	Δ3NW	Δ1NFW	Δ2NFW	Δ3NFW	Δ1MSWA	Δ3MSWA	Δ3MSWA
Age	1															
Act T	-.207 .273	1														
Rate	.410 .024*	-.770 .000*	1													
PC Ret	.011 .954	-.387 .035*	.131 .489	1												
H Ret	.206 .274	.035 .856	.090 .635	.217 .249	1											
TTT	-.225 .231	.626 .000*	-.452 .012*	-.453 .012*	-.054 .777	1										
AE	.457 .011*	.271 .147	.344 .063	-.430 .018*	.143 .452	.228 .225	1									
Δ1NW	.154 .415	.267 .154	-.027 .887	-.368 .046*	-.108 .570	.305 .102	.469 .009*	1								
Δ2NW	-.178 .346	-.287 .124	.223 .235	.261 .164	.015 .938	.220 .244	-.226 .229	-.286 .125	1							
Δ3NW	-.077 .684	-.054 .778	.209 .268	.006 .977	-.096 .616	.364 .048*	.219 .244	.598 .001*	.532 .002*	1						
Δ1NFW	-.140 .461	.235 .211	.015 .939	-.382 .037*	-.018 .924	.347 .060	.405 .026*	.298 .110	.120 .529	.410 .024*	1					
Δ2NFW	-.043 .823	.269 .150	-.123 .516	-.072 .706	.289 .122	.291 .119	.254 .176	.326 .079	-.202 .284	.116 .542	-.132 .486	1				
Δ3NFW	-.155 .412	.352 .057	-.042 .827	-.401 .028*	.101 .596	.455 .012*	.535 .002*	.442 .014*	-.068 .722	.412 .024*	.804 .000*	.409 .025*	1			
Δ1MSWA	-.169 .371	-.255 .174	.157 .408	.381 .038*	.164 .388	-.212 .260	-.186 .324	-.421 .020*	.267 .153	-.131 .490	-.111 .558	-.193 .307	-.246 .190	1		
Δ2MSWA	-.014 .941	.489 .006*	-.420 .021*	-.357 .053	.000 .998	.174 .358	.165 .384	.143 .452	-.656 .000*	-.405 .027*	.023 .902	-.038 .844	.015 .936	-.342 .064	1	
Δ3MSWA	-.349 .059	.160 .398	-.254 .176	-.012 .949	.127 .504	.002 .992	-.186 .325	-.297 .111	-.275 .141	-.463 .010	-.097 .612	-.212 .260	-.212 .262	.583 .001*	.496 .005*	1

Table 7. Matrix of Kendall's Tau correlation coefficient for changes in maxillary canine (C1)

	Age	Act T	Rate	PC Ret	H Ret	TTT	AE	SE C1	Δ1PAA	Δ2PAA	Δ3PAA	Δ1BMW C1	Δ2BMW C1	Δ3BM W C1	Δ1PM W C1	Δ2PM W C1	Δ3PM W C1
Age	1																
Act T	-.207 .273	1															
Rate	.410 .024*	-.770 .000*	1														
PC Ret	.011 .954	-.387 .035*	.131 .489	1													
H Ret	.206 .274	.035 .856	.090 .635	.217 .249	1												
TTT	-.225 .231	.626 .000*	-.452 .012*	-.453 .012*	-.054 .777	1											
AE	.457 .011*	.271 .147	.344 .063	-.430 .018*	.143 .452	.228 .225	1										
SE C1	.057 .782	.273 .177	.083 .686	-.067 .743	.014 .947	.246 .226	.650 .000*	1									
Δ1PAA	.531 .003*	.085 .655	.065 .734	-.066 .730	-.083 .661	.018 .925	.342 .064	.312 .121	1								
Δ2PAA	-.163 .390	-.151 .425	.088 .642	.193 .307	.048 .800	-.239 .203	-.144 .449	-.239 .239	-.490 .006*	1							
Δ3PAA	.345 .062	-.114 .547	.234 .212	.167 .377	-.043 .822	-.256 .172	.211 .264	.157 .443	.469 .009*	.487 .006*	1						
Δ1BMW C1	.085 .653	.220 .243	.174 .358	-.441 .015*	.161 .396	.076 .689	.612 .000*	.246 .227	.254 .175	-.344 .063	-.140 .461	1					
Δ2BMW C1	-.084 .658	-.216 .252	-.096 .613	.449 .013*	.080 .673	-.099 .601	-.454 .012*	-.264 .192	-.146 .441	.497 .005*	.401 .028*	-.620 .000*	1				
Δ3BMW C1	.116 .542	-.038 .842	.027 .889	.134 .481	.193 .306	-.062 .745	.077 .684	-.213 .295	.116 .543	.279 .136	.368 .045*	.218 .248	.559 .001	1			
Δ1PMW C1	.022 .284	.140 .460	.143 .452	-.457 .011*	.261 .164	.150 .430	.429 .018*	.370 .063	.131 .491	-.174 .358	.012 .952	.682 .000*	-.301 .106	.203 .281	1		
Δ2PMW C1	-.202 .284	.082 .668	-.190 .313	.363 .049*	.110 .564	.081 .672	-.167 .377	-.101 .625	-.084 .658	.170 .369	.094 .621	-.283 .130	.410 .024*	.301 .106	-.558 .001*	1	
Δ3PMW C1	-.197 .297	.202 .285	-.007 .969	-.022 .908	.261 .164	.337 .068	.218 .246	.185 .366	-.044 .817	.120 .528	.131 .491	.262 .163	.254 .176	.549 .002*	.352 .056	.506 .004*	1

Table 8. Matrix of Kendall's Tau correlation coefficient for changes in maxillary 1st premolar (P1)

	Age	Act T	Rate	PC Ret	H Ret	TTT	AE	SE P1	Δ1PAA	Δ2PAA	Δ3PAA	Δ1BMW P1	Δ2BMW P1	Δ3BMW P1	Δ1PMW P1	Δ2PMW P1	Δ3PMW P1
Age	1																
Act T	-.207 .273	1															
Rate	.410 .024*	-.770 .000*	1														
PC Ret	.011 .954	-.387 .035*	.131 .489	1													
H Ret	.206 .274	.035 .856	.090 .635	.217 .249	1												
TTT	-.225 .231	.626 .000*	-.452 .012*	-.453 .012*	-.054 .777	1											
AE	.457 .011*	.271 .147	.344 .063	-.430 .018*	.143 .452	.228 .225	1										
SE P1	.173 .378	.358 .062	.178 .366	-.232 .235	.248 .204	.239 .220	.809 .000*	1									
Δ1PAA	.531 .003*	.085 .655	.065 .734	-.066 .730	-.083 .661	.018 .925	.342 .064	.291 .133	1								
Δ2PAA	-.163 .390	-.151 .425	.088 .642	.193 .307	.048 .800	-.239 .203	-.144 .449	-.170 .388	-.490 .006*	1							
Δ3PAA	.345 .062	-.114 .547	.234 .212	.167 .377	-.043 .822	-.256 .172	.211 .264	.192 .328	.469 .009*	.487 .006*	1						
Δ1BMW P1	-.065 .759	.219 .292	.135 .520	-.430 .032*	.012 .953	.090 .670	.641 .001*	.608 .002*	..051 .808	-.187 .370	-.141 .502	1					
Δ2BMW P1	-.006 .977	-.143 .494	-.185 .376	.425 .034*	.149 .477	.013 .952	-.479 .015*	-.293 .174	.151 .472	.335 .102	.436 .029*	-.677 .000*	1				
Δ3BMW P1	-.048 .821	.126 .550	-.140 .506	.060 .775	.170 .417	-.013 .949	.137 .514	.317 .140	.264 .203	.254 .220	.413 .040*	.410 .042*	.277 .180	1			
Δ1PMW P1	-.057 .788	.188 .369	.042 .841	-.294 .154	.363 .075	.139 .509	.443 .027*	.549 .007*	-.113 .591	-.002 .992	-.085 .686	..739 .000*	-.450 .024*	.444 .026*	1		
Δ2PMW P1	-.128 .542	-.051 .809	-.149 .478	.503 .010*	.096 .649	.085 .687	-.351 .085	-.246 .258	.170 .415	.066 .755	.176 .401	-.559 .004*	.589 .002*	.001 .997	-.602 .001*	1	
Δ3PMW P1	-.105 .619	.228 .273	-.150 .475	.100 .633	.476 .016*	.328 .109	.165 .430	.359 .093	.108 .607	.196 .349	.230 .268	.038 .858	.344 .092	.511 .997	.209 .315	.566 .003*	1

Table 9. Matrix of Kendall's Tau correlation coefficient for changes in maxillary 2nd premolar (P2)

	Age	Act T	Rate	PC Ret	H Ret	TTT	AE	SE P2	Δ1PAA	Δ2PAA	Δ3PAA	Δ1BMW P2	Δ2BMW P2	Δ3BMW P2	Δ1PMW P2	Δ2PMW P2	Δ3PMW P2
Age	1																
Act T	-.207 .273	1															
Rate	.410 .024*	-.770 .000*	1														
PC Ret	.011 .954	-.387 .035*	.131 .489	1													
H Ret	.206 .274	.035 .856	.090 .635	.217 .249	1												
TTT	-.225 .231	.626 .000*	-.452 .012*	-.453 .012*	-.054 .777	1											
AE	.457 .011*	.271 .147	.344 .063	-.430 .018*	.143 .452	.228 .225	1										
SE P2	.168 .385	.327 .084	.211 .272	-.129 .504	.046 .813	.212 .270	.797 .000*	1									
Δ1PAA	.531 .003*	.085 .655	.065 .734	-.066 .730	-.083 .661	.018 .925	.342 .064	.153 .428	1								
Δ2PAA	-.163 .390	-.151 .425	.088 .642	.193 .307	.048 .800	-.239 .203	-.144 .449	.081 .678	-.490 .006*	1							
Δ3PAA	.345 .062	-.114 .547	.234 .212	.167 .377	-.043 .822	-.256 .172	.211 .264	..276 .147	.469 .009*	.487 .006*	1						
Δ1BMW P2	.165 .385	.289 .121	.156 .410	-.289 .122	.063 .740	.081 .671	.613 .000*	.613 .000*	.174 .357	.023 .905	.222 .239	1					
Δ2BMW P2	.195 .301	-.167 .377	-.096 .615	.349 .058	.293 .116	-.009 .964	-.235 .219	-.235 .219*	.205 .278	-.037 .848	.117 .539	-.364 .048*	1				
Δ3BMW P2	.326 .079	.103 .588	.023 .905	.074 .699	.393 .032*	-.010 .957	.203 .291	.203 .291	.316 .089	.012 .948	.265 .157	.557 .001*	.472 .009*	1			
Δ1PMW P2	-.046 .811	.315 .090	.093 .626	-.602 .000*	.177 .351	.419 .021*	.309 .103	.309 .103	.150 .430	-.280 .133	-.102 .590	.590 .001*	-.272 .145	.310 .096	1		
Δ2PMW P2	-.154 .418	-.006 .976	-.160 .400	.390 .033*	.338 .068	-.067 .723	-.249 .193	-.249 .193	-.014 .940	.011 .954	-.089 .639	-.389 .034*	.463 .010*	.074 .696	-.349 .058	1	
Δ3PMW P2	-.176 .353	.237 .206	-.107 .574	-.137 .470	.483 .007*	.261 .164	-.047 .807	-.047 .807	.029 .879	-.084 .660	-.161 .395	.082 .668	.226 .229	.382 .037*	.446 .014*	.611 .000*	1

Table 10. Matrix of Kendall’s Tau correlation coefficient for changes in maxillary 1st molar (M1)

	Age	Act T	Rate	PC Ret	H Ret	TTT	AE	SE M1	Δ1PAA	Δ2PAA	Δ3PAA	Δ1BM W M1	Δ2BM W M1	Δ3BM W M1	Δ1PM W M1	Δ2PM W M1	Δ3PM W M1
Age	1																
Act T	-.207 .273	1															
Rate	.410 .024*	-.770 .000*	1														
PC Ret	.011 .954	-.387 .035*	.131 .489	1													
H Ret	.206 .274	.035 .856	.090 .635	.217 .249	1												
TTT	-.225 .231	.626 .000*	-.452 .012*	-.453 .012*	-.054 .777	1											
AE	.457 .011*	.271 .147	.344 .063	-.430 .018*	.143 .452	.228 .225	1										
SE M1	.087 .653	.247 .196	.256 .179	-.145 .452	.076 .695	.256 .181	.809 .000*	1									
Δ1PAA	.531 .003*	.085 .655	.065 .734	-.066 .730	-.083 .661	.018 .925	.342 .064	.291 .133	1								
Δ2PAA	-.163 .390	-.151 .425	.088 .642	.193 .307	.048 .800	-.239 .203	-.144 .449	-.170 .388	-.490 .006*	1							
Δ3PAA	.345 .062	-.114 .547	.234 .212	.167 .377	-.043 .822	-.256 .172	.211 .264	.192 .328	.469 .009*	.487 .006*	1						
Δ1BMW M1	.286 .125	.256 .171	.121 .522	-.040 .832	.085 .654	.038 .843	.654 .000*	.662 .000*	.306 .100	-.047 .807	.175 .356	1					
Δ2BMW M1	-.051 .787	-.168 .374	-.094 .622	.162 .393	-.145 .445	-.020 .916	-.317 .088	-.224 .251	.236 .210	.134 .482	.281 .132	-.299 .108	1				
Δ3BMW M1	.234 .213	.138 .467	.061 .751	.017 .928	.002 .993	-.009 .964	.437 .016*	.477 .010*	.411 .024*	.075 .692	.351 .057	.798 .000*	.281 .132	1			
Δ1PMW M1	-.032 .865	.271 .148	.045 .814	-.500 .005*	-.039 .836	.236 .210	.474 .008*	.621 .000*	.030 .877	-.096 .615	-.015 .938	.354 .055	-.115 .545	.232 .218	1		
Δ2PMW M1	-.150 .427	-.032 .867	-.004 .981	.307 .099	.138 .466	-.170 .368	.005 .980	.003 .987	.139 .463	.120 .526	.214 .257	.022 .907	.318 .087	.322 .083	-.317 .088	1	
Δ3PMW M1	-.152 .424	.155 .412	.153 .419	-.181 .338	-.044 .819	.016 .933	.492 .006	.584 .001*	.122 .520	.047 .805	.186 .324	.385 .036*	.071 .709	.476 .008*	.560 .001*	.500 .005*	1

Discussion

The objective of this study was to evaluate the skeletal responses observed in the transverse plane, immediately after rapid maxillary expansion and at the completion of orthodontic treatment. Other studies have been structured similarly, with the goal of analyzing the effects of rapid maxillary expansion.[9,10,12,14] However, most have used 2D x-rays or model analysis, this study utilized CBCT with the intent of better visualization of the underlying skeletal structures.

Expansion effects from RME consist of 3 components: the orthopedic expansion (skeletal/sutural separation), alveolar bending, and orthodontic expansion (dental tipping) (Figure 9).[6,26]

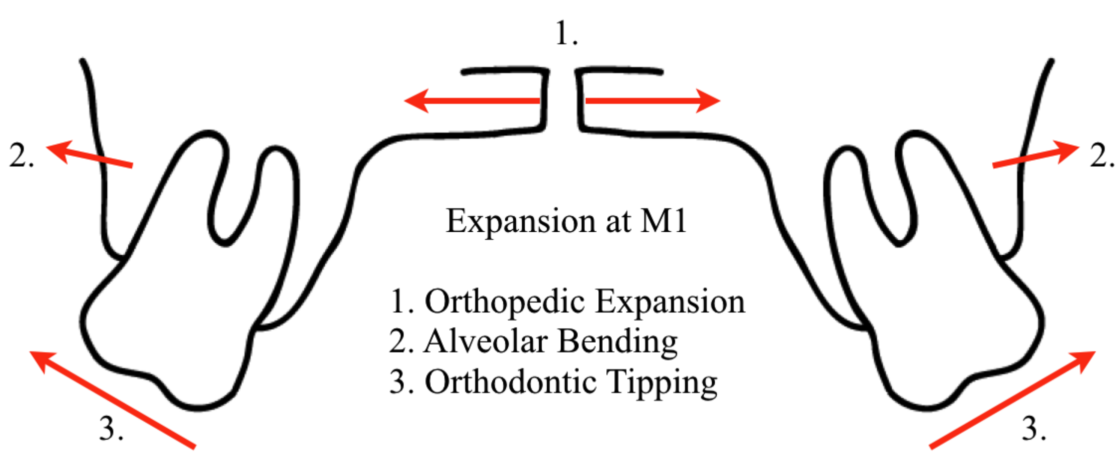

Figure 9. Diagram depicting three components of expansion[6]

The total expansion can be calculated from the change in interdental width (ΔID). The total expansion (ΔID) of the patient population in this study has been previously analyzed and these values were used in conjunction with the findings in this study to assess the contribution of each component.[27] We followed a previous method characterizing SE as orthopedic expansion, the difference of ΔBMW and SE as alveolar bending, and the difference of ΔID and ΔBMW as orthodontic expansion.[6] Using ΔID as the total amount of expansion; we identified the percentage contribution of orthopedic expansion, alveolar bending/tipping, and orthodontic expansion to total expansion. The means and standard deviations of these values are shown in Table 11 and their percentage contribution to expansion at T2 and T3 in Table 12 and 13.

Table 11. Comparison of SE, ΔBMW, and ΔID.

	P1	P2	M1
SE (mm)	3.00 ± 1.21	2.70 ± 1.07	2.54 ± 1.09
Δ_1 BMW	3.81 ± 2.49	3.46 ± 1.80	3.32 ± 1.45
Δ_1 ID	7.08 ± 2.85*	6.19 ± 2.28*	6.83 ± 2.73*
Δ_1 BMW - SE	0.81	0.76	0.78
Δ_1 ID - Δ_1 BMW	3.27	2.73	3.51
Δ_2 BMW	-0.33 ± 2.16	-0.51 ± 1.95	0.21 ± 1.23
Δ_2 ID	-1.36 ± 2.99*	-1.08 ± 2.41*	-2.77 ± 2.49*
Δ_2 ID – Δ_2 BMW	-1.03	-0.57	-2.98
Δ_3 BMW	3.49 ± 1.96	2.94 ± 2.20	3.52 ± 1.69
Δ_3 ID	5.71 ± 1.97*	5.11 ± 1.75*	4.06 ± 2.55*
Δ_3 BMW - SE	0.49	0.24	0.98
Δ_3 ID – Δ_3 BMW	2.22	2.17	0.54

* values drawn from previous study by Milliner et al.[27]

Table 12. Summary of orthopedic, alveolar bending, and orthodontic contributions to total expansion at T2. Orthopedic = SE/ ΔID, Alveolar bending = (ΔBMW-SE)/ ΔID, Orthodontic = (ΔID- ΔBMW)/ ΔID

At T2	Orthopedic	Alveolar bending	Orthodontic	Total
P1	42%	12%	46%	100%
P2	44%	12%	44%	100%
M1	37%	11%	52%	100%

Table 13. Summary of orthopedic, alveolar bending, and orthodontic contributions to total expansion at T3. Orthopedic = SE/ ΔID, Alveolar bending = (ΔBMW-SE)/ ΔID, Orthodontic = (ΔID- ΔBMW)/ ΔID

At T3	Orthopedic	Alveolar bending	Orthodontic	Total
P1	52%	9%	39%	100%
P2	53%	5%	42%	100%
M1	63%	24%	13%	100%

Skeletal Expansion

Evaluation of the maxillary suture revealed transverse expansion that decreased from anterior to posterior: 3.77 (Inc1), 3.37 (C1), 3.00 (P1), 2.70 (P2), and 2.54 mm (M1) (P <.001; Table 4). This data affirms previous studies that noted the triangular geometry of expansion observed at the maxillary suture, with the wider portion located anteriorly.[6,14-17] Due to the interlocking of the pyramidal processes with the medial and lateral pterygoid plates of the sphenoid bone, anatomy at the posterior portion of the maxillary suture directly contributes to this observed pattern of expansion where the posterior expansion is less than the anterior.[1,28]

Since it is impossible to evaluate the change in suture expansion as the bone has filled in the suture/expansion space, the stability of the orthopedic expansion may be assessed through interpretation of the perceived changes of PAA and PMW. The hyrax retention time observed in this study seems adequate to maintain the skeletal effect of the RME. From T2 to T3, PAA decreased by 2.93° (Table 4) whereas PMW at all posterior teeth did not change significantly (P > .05). These indicate that the width at the maxillary base has been maintained, and hence the orthopedic expansion. At T3, sutural orthopedic expansions accounted for 52%, 53%, and 63% of total expansion at P1, P2 and M1

(Table 13), which were all higher values than at T2 (42%, 44%, and 37%, respectively; Table 12). These noted changes were largely a result of orthodontic relapse between T2 and T3, where values were -1.03, -0.57, and -2.98 mm for P1, P2, and M1 (Table 11). For this study, the amount of hyrax retention time and archwire retention time seemed adequate to maintain the skeletal effect of RME.

Dentoalveolar Expansion or Tipping

Changes in BMW relate to alveolar expansion resulting from RME, and the amount of BMW change greater than the sutural expansion was attributed to tipping/bending of the alveolar ridges. A comparison of T2 and T3 measurements for BMW revealed no statistical difference at any of the tooth locations ($P > .05$; Table 4). It is interesting to note that while C1, P1 and P2 experienced some relapse (Δ_2 BMW ranged from -0.79 to -0.33 mm), there was no relapse observed on M1 at the end of treatment (Δ_2 BMW = 0.21 mm). However, Δ_2 BMW values were not significantly different among all teeth ($P = .081$). Studies have shown that an expected 0.6 mm maxillary width increase can be expected every year during growth.[29] For the members of the sample who were growth still growing, natural growth could contribute to the maxillary width changes observed in this study, and possibly compensate for relapse of maxillary width.

Using change in BMW and sutural expansion (Δ_1 BMW – SE) to evaluate the amount of dentoalvolar expansion/tipping resulting from RME showed that alveolar tipping for our sample ranged from 0.76-0.81 mm (Table 11). At the level of each tooth measured, the amount of expansion noted at the buccal aspect of the alveolar ridge (Δ_1

BMW) was greater than the expansion noted at the suture (SE) (Table 11), indicating alveolar bending. At T2, alveolar bending contributed to expansion by about 12% for all locations whereas the orthodontic contribution was much higher, at close to 40% (Table 12). The proportions of expansion greatly changed after orthodontic treatment mainly because of the dental relapse that ranged from 0.57 to 2.98 mm (Table 11). Majority of the resultant expansion (Δ3) of M1 was attributed to orthopedic and alveolar components, while those of P1 and P2 were mostly due to orthopedic and dental components (Table 13).

The posterior tooth inclination after RME is usually unfavorable (flaring buccally due to dental tipping), and needs to be compensated during fixed orthodontic treatment. Decrease of dental expansion is a controlled relapse achieved via fixed orthodontic treatment. Alveolar bone remodeling usually occurs following tooth movement and likely contributes to the minor relapse of the alveolar bone bending. Therefore, overexpansion during RME is a common practice, with the expectation of some relapse. Long-term follow-up after completion of fixed orthodontic treatment is warranted to assess the stability of the dentoalveolar component of the RME.

Alveolar tipping was directly measured (PAA) for the sample. Measurements were made at the position of the maxillary first molar furcation with the following measurements for T1, T2, and T3: 30.16, 36.60, and 33.67 degrees (Table 3). The measurements were statistically different ($P < .001$), indicating 6.44 degrees of alveolar tipping immediately after RME which then decreases by 2.93 degrees when measured after orthodontic treatment. The average amount of alveolar tipping measured in this study approximated Kartalian’s CBCT study which measured buccal alveolar tipping to be 5.6 degrees.[18] These values indicate remodeling of the alveolus to accommodate expansion changes. Initial alveolar tipping (Δ_1 PAA) was shown to be closely correlated with age, with increased age leading to more alveolar tipping (r = 0.531, P = .003).

Alveolar ridge thickness measured at separate tooth locations (C1, P1, P2, and M1 and did not show changes throughout treatment. Alveolar ridge thickness measured at C1, P1, P2, and M1 maintained their thickness from T1, T2, to T3 (Table 3). This indicates that RME has no negative effects on the thickness of the alveolar ridge, even though the placement of the tooth within the alveolar ridge likely changes.

When comparing two-banded with four-banded appliances, all measures were statistically similar except for Δ_1 PAA, Δ_3 BMW at P2, Δ_3 BMW at M1, and Δ_2 PMW at M1. For each of the aforementioned values, the four-banded design had larger values than the two-banded, indicating more initial alveolar bending, greater expansion, and less relapse. Amount of appliance expansion for those two samples was comparable (AE; P =.245; Table 7). The four-banded design utilizes an arm connected between the banded first molar and first premolar. It is possible that this arm expressed expansion force on the second premolar more effectively than the expansion arms for two-banded appliances, leading to a larger Δ_3 BMW at P2. An appliance that is secured to four bands may also ensure a consistent location of force, whereas a two-banded system could possibly lead to occlusal movement of the expansion arm and less expressed force on the dentition. However, further exploration of this effect would be needed for explanation and to establish clinical significance, especially since the expansion differences were not consistent nor observed on complementary BMW and PMW locations. For M1, use of two-banded appliance resulted in statistically significant more relapse compared to the four-banded which recorded no relapse in that area (Δ_2 PMW M1; P = .025; Table 5). A four-banded appliance may result in more rigid retention to maintain width changes, however, relapse differences were not noted at any other locations therefore it would be difficult to make any certain conclusions. The amount of difference between the two samples for relapse in at PMW M1 was only 0.54 mm and not clinically significant.

Nasal Changes

Both nasal width (NW) and nasal floor width (NFW) showed statistically significant increases between T1 and T2 followed by maintenance of this change when compared to T3 (Table 3). This indicates that any nasal skeletal changes achieved by RME will maintain through the end of orthodontic treatment. NW and NFW showed increases of 1.88 and 1.86 mm post expansion (Δ_1). When compared to the mean appliance expansion (5.24 mm), initial changes in NW and NFW were 35.9% and 35.5%, values that are slightly higher than other studies.[6,7,11] On average, the total treatment time for the sample was over two and a half years and, on average, two years of time elapsed between the end of activation and the completion of orthodontic treatment (Table 1). Studies have shown that an expected 0.7 mm nasal width increase can be expected every year during growth.[29] For the members of the sample who were growth still growing, natural growth could contribute to the nasal width changes observed in this study, and possibly compensate for relapse of nasal width. Using the Friedman test, comparison of the maxillary sinus widths measured between T1, T2, and T3 showed to be similar in spite of RME (P = .131; Table 3). Changes in width only give information regarding that particular portion of the nasal apparatus or maxillary sinus. Volumetric analysis would be beneficial to determine widespread changes.

Conclusions

The following conclusions can be made from this study:

1. In the axial plane, sutural expansion is triangular in form with greater expansion anteriorly than posteriorly.
2. RME does not change the buccal to palatal alveolar ridge thickness at C1, P1, P2, and M1.
3. Orthopedic expansion resulting from RME does not relapse, when comparing expansion achieved at the end of activation to the end orthodontic treatment. However, natural growth may contribute to masking relapse.
4. At the maxillary first molar, the majority of expansion relapse comes in the form of orthodontic relapse. However, natural growth may contribute to masking relapse.
5. Expansion between contralateral buccal and palatal cortical plates of the maxillary alveolus resulting from RME can be maintained throughout orthodontic treatment.
6. Increases in nasal width and nasal floor width due to RME can be maintained throughout orthodontic treatment. However, natural growth may contribute to masking relapse.
7. Alveolar tipping increases with RME but there will be significant relapse throughout orthodontic treatment.
8. Taking relapse of orthodontic expansion into consideration, the contribution of orthopedic expansion comprises over 50% of total expansion at the end of

orthodontic treatment. However, natural growth may contribute to masking relapse.

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CHAPTER THREE

EXTENDED DISCUSSION

Study Improvements and Future Directions

Many improvements could be made to the study. Stricter inclusion criteria for the sample could have been implemented regarding age, whether extractions were incorporated in treatment, and how close in time the T2 CBCT was taken relative to the end of RME. Time elapsed between end of expansion and the T2 CBCT had a range of 0 – 12 weeks, which may allow sutural remodeling to occur, therefore affecting any measurement of sutural expansion. Introducing an angular measurement for the position of the palatal root of the maxillary first molars similar to Kartilian et al. would give more information on the actual amount of alveolar bending relative to dental inclination change.[18] A larger sample size would be beneficial, especially when comparing expander designs. This study did not address the question of long term stability of expansion being that the final time point was at the end of orthodontic treatment. Addition of a later time point would be beneficial.

For the future, there are several studies that can be explored. Simply measuring transverse changes in the nasal aperture does not fully explain the improvement of nasal respiration because of the complex anatomy within the nasal cavity. CBCT would be useful in measuring the actual nasal volume changes associated with RME, taking all anatomy (ie. nasal turbinates) into consideration. A CBCT sudy comparing Haas with

Hyrax expanders would be useful to evaluate RME effects on the alveolar ridge depending on appliance. This would especially be applicable being that Hyrax expansion caused PAA to increase significantly after expansion but then decrease throughout orthodontic treatment.

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APPENDIX

PAIRWISE FRIEDMAN COMPARISONS

Table 1. Comparison between time points: Friedman's Two-Way Analysis of Variance by Ranks

	p-value (T1 vs. T2)	**p-value (T2 vs. T3)**	**p-value (T1 vs. T3)**	**p-value (T1 vs. T2 vs. T3)**
NW (mm)	< .001	1.000	< .001	<.001
NFW (mm)	< .001	1.000	< .001	<.001
MSWA (mm)	-	-	-	.131
PAA (degrees)	< .001	.014	.043	<.001
BMW C1 (mm)	< .001	.467	< .001	<.001
PMW C1 (mm)	< .001	1.000	< .001	<.001
ART C1 (mm)	-	-	-	.056
BMW P1 (mm)	< .001	1.000	< .001	<.001
PMW P1 (mm)	< .001	1.000	< .001	<.001
ART P1 (mm)	-	-	-	.239
BMW P2 (mm)	< .001	1.000	< .001	<.001
PMW P2 (mm)	< .001	1.000	< .001	<.001
ART P2 (mm)	-	-	-	.154
BMW M1 (mm)	< .001	1.000	< .001	<.001
PMW M1 (mm)	< .001	1.000	< .001	<.001
ART M1 (mm)	-	-	-	.792

Table 2. Comparison between tooth locations: Friedman's Two-Way Analysis of Variance by Ranks

	p- value M1 vs. C1	**p- value M1 vs. P2**	**p- value M1 vs. P1**	**p- value C1 vs. P2**	**p- value C1 vs. P1**	**p- value P1 vs. P2**	**p- value (M1 vs. P2 vs. P1 vs. C1)**
SE (mm)	< .001	1.000	.318	< .001	.025	1.000	<.001
Δ1 BMW	-	-	-	-	-	-	.102
Δ2 BMW	-	-	-	-	-	-	.084
Δ3 BMW	-	-	-	-	-	-	.938
Δ1 PMW	-	-	-	-	-	-	.160
Δ2 PMW	-	-	-	-	-	-	.438
Δ3 PMW	-	-	-	-	-	-	.145