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Comparison of Bone- and Tooth-Anchored, Bone-Anchored, and Surgically Assisted Bone-Anchored Rapid Palatal Expansion: a Pilot Retrospective CBCT Study

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Abstract

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Materials and Methods: Pre- (T1) and post-expansion (T2) Cone Beam Computed Tomography (CBCT) radiographs from 12 patients treated with BAME (median age = 15.5, 95% CI 14.0-18.1), 7 patients treated with BTAME (median age = 19, 95% CI 14.8-26.9), and 5 patients treated with SRBAME (median age = 38, 95% CI 21.6-56.0) were included in the study. All skeletal, alveolar, and dental changes were standardized using suture opening at first molar for intergroup comparisons. There were seven linear and two angular measurements evaluated at the first premolar, second premolar, first molar, and second molar levels for intra- and intergroup comparisons.

Results: BTAME and BAME approaches both resulted in significant changes to transverse skeletal and alveolar transverse dimension with some dental tipping. Alveolar bone tipping at the first molar level in BAME was greater than in BTAME (p0.05) while it was significantly greater in the anterior than posterior in BAME (p

Conclusions: Both BTAME and BAME result in significant transverse skeletal, alveolar, and dental expansion. BAME resulted in greater alveolar bone bending while BTAME resulted in greater dental tipping. Among the three groups, BTAME suture opening was closest to parallel from anterior to posterior. Contribution of skeletal expansion to intermolar width increase is more favorable in BAME than BTAME.

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Comparison of bone- and tooth-anchored, bone-anchored, and surgically assisted bone-anchored rapid palatal expansion: a pilot retrospective CBCT study

THESIS

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ABSTRACT

Introduction: The purpose of this retrospective pilot study is to evaluate and compare the transverse dental and skeletal changes in three different approaches to miniscrew-assisted rapid palatal expansion (MARPE) including bone- and tooth-anchored (BTAME), bone-anchored (BAME), and surgically assisted bone-anchored maxillary expansion (SRBAME) maxillary expansion. The secondary purpose is to formulate new research questions and develop methods for future MARPE studies. **Materials and Methods:** Pre- (T1) and post-expansion (T2) Cone Beam Computed Tomography (CBCT) radiographs from 12 patients treated with BAME (median age = 15.5, 95% CI 14.0-18.1), 7 patients treated with BTAME (median age = 19, 95% CI 14.8-26.9), and 5 patients treated with SRBAME (median age = 38, 95% CI 21.6-56.0) were included in the study. All skeletal, alveolar, and dental changes were standardized using suture opening at first molar for intergroup comparisons. There were seven linear and two angular measurements evaluated at the first premolar, second premolar, first molar, and second molar levels for intra- and intergroup comparisons. **Results:** BTAME and BAME approaches both resulted in significant changes to transverse skeletal and alveolar transverse dimension with some dental tipping. Alveolar bone tipping at the first molar level in BAME was greater than in BTAME ($p<0.05$). Dental tipping of first molars in BTAME was greater than in BAME ($p=0.054$). Contribution of skeletal expansion to first molar intermolar width increase was 78.6% in BAME and 61.9% in BTAME ($p<0.05$). Suture opening was closest to parallel from anterior to posterior in BTAME ($p>0.05$) while it was significantly greater in the anterior than posterior in BAME ($p<0.05$) and SRBAME ($p<0.05$). Dental tipping of right and left teeth was asymmetrical in BTAME ($p<0.05$) and BAME ($p<0.05$). **Conclusions:** Both BTAME and BAME result in significant transverse skeletal, alveolar, and dental expansion. BAME resulted in greater alveolar bone bending while BTAME resulted in greater dental tipping. Among the three groups, BTAME suture opening was closest to parallel from anterior to posterior. Contribution of skeletal expansion to intermolar width increase is more favorable in BAME than BTAME.

DEDICATION

I dedicate this thesis to my loving father, my devoted orthodontic faculty, and my amazing co-residents. The last few years have been incredibly rewarding thanks to their love and support. Words cannot describe my appreciation for them.

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Chapter 1) Introduction:

Transverse maxillary deficiency is a common orthodontic problem that is associated functional and esthetic concerns. Mild to moderate transverse problems often require treatment but are difficult to quantify so epidemiological studies often use posterior crossbites as the primary indicator. According to one study in 2007, roughly 21% of children in primary dentition present with some form of posterior crossbite.[1] Estimates of its prevalence range from 13-25%.[2,3] If mild to moderate deficiencies are included, the prevalence of transverse maxillary deficiencies would certainly increase. Orthopedic correction is recommended at an early age to correct transverse maxillary deficiencies.[4] Left untreated, the problem is likely to persist through to adulthood, increasing the risk for development of other problems including occlusal disturbances, damage to periodontal structures, changes in tongue posture, functional shifts, asymmetric growth of condyles, and temporomandibular joint (TMJ) disorders.[5,6]

Rapid maxillary expansion (RME), or rapid palatal expansion (RPE), first introduced in 1860 by Dr. Angell[7] and later popularized in the 1960s by Dr. Haas[8], is the recommended treatment modality to increase transverse maxillary dimension in growing patients.[9] This conventional expansion strategy involves the rapid application of transverse orthopedic forces to the anchor teeth, allowing midpalatal suture opening before bone remodeling for orthodontic tooth movement can occur.[4,8,10] Two of the most widely recognized conventional RPE appliances are the Hyrax, which involves banded molars (tooth-anchored), and Haas, which involves banded molars and palatal acrylic coverage (tooth- and tissue-anchored).[11]

For effective maxillary expansion, midpalatal suture and zygomatic buttresses must allow for lateral movement of the two maxillary halves. A greater response to RPE therapy has been reported in younger, growing patients than in adults who are skeletally mature.[12] In growing patients, the midpalatal suture is patent but the timing of fusion varies among individuals and studies report different results. Melsen reported that transverse growth of midpalatal suture continued to 16 years old in girls and 18 in boys.[13] Persson and Thilander reported that palatal suture may begin closure in the juvenile period but is rarely completely closed until the third decade of life.[14] Knaup et al. reported that the youngest subject with midpalatal suture ossification was 21 years old while the oldest subject without ossification was a 54 years old.[15] Interestingly, Korbmacher et al. concluded that interdigitation is, in fact, independent of age and the degree of obliteration of the suture is very low in all age groups.[16] Despite the differing reports, the authors all agree that resistance to midpalatal suture opening increases with skeletal development and age. In addition, it is widely recognized in the literature that the primary resistance to maxillary expansion is provided by the zygomatic buttresses, including the nasomaxillary, zygomaticomaxillary, and pterygomaxillary buttresses, and associated circummaxillary sutures.[5,12,17-20] Thus, in late adolescence or adulthood in which there is a rigid facial skeleton with high resistance to midpalatal suture opening, conventional RPE could lead to significant, undesired dentoalveolar and periodontal effects such as dental buccal tipping and bony dehiscence of the anchor teeth.[4,21,22] These effects occur proportional to patient age and skeletal maturation.[5] Thus, surgically assisted rapid palatal expansion (SARPE), in which osteotomies to decrease resistance to expansion are performed, is recommended in skeletally mature patients.[12,17,19,20]

With the advent of miniscrews, or temporary anchorage devices (TADs), skeletal anchorage can be used to maximize orthopedic changes and minimize undesired dental consequences without SARPE.[23] The literature has reported successful outcomes with this expansion strategy known as miniscrew-assisted rapid palatal expansion (MARPE) in late adolescence and young adulthood. Choi et al. reported that the midpalatal suture successfully opened in 86.96% of subjects with a mean age of 20.9 and results were stable in post-treatment follow up.[24] Cantarella et al reported that maxillary and zygomatic bones were significantly displaced with MARPE.[25] In a case report by Lee et al., a 20-year-old male underwent successful MARPE with minimal buccal tipping before orthognathic surgery.[26] In addition, studies have shown that bone-anchored expansion leads to greater orthopedic changes and fewer dentoalveolar side effects than tooth-anchored expansion in late adolescence.[27,28]

The MARPE approaches can be broadly categorized into bone- and tooth-anchored (BTAME) or bone-anchored (BAME) maxillary expansion. BTAME uses both palatal miniscrews and teeth, typically the first molars and in some designs, includes the first premolars, as anchors for force application. BAME uses palatal miniscrews with or without palatal acrylic coverage as anchors (Figure 1). In some literature, BAME is differentiated from MARPE because the purely skeletal anchorage allows for slow expansion, not "rapid" as the "R" suggests.[29] While successful expansion has been reported in both anchorage approaches, studies comparing the two are limited with contradictory conclusions. Oh et al reported that Maxillary Skeletal Expander (MSE), a BTAME appliance developed by Dr. W Moon[30], resulted in greater expansion of the nasal floor, maxillary base, and palatal suture than Dresden-type BAME and hyrax appliances.[31] However, another study reported that MSE and C-expander, a BAME appliance, had similar skeletal changes but MSE had increased severity of unwanted effects such as buccal tipping and loss of alveolar bone height and thickness, recommending C-expander for patients vulnerable to periodontal disease.[32] SARPE may also be prescribed in conjunction with BTAME or BAME. Successful expansion has been reported in bone-borne surgically assisted rapid palatal expansion.[33] Still, more information comparing the different MARPE approaches is needed for definitive guidance in clinical decision making.

The purpose of this study is to evaluate and compare the transverse skeletal and dentoalveolar changes of BTAME, BAME, and surgically-assisted bone-anchored maxillary expansion (SRBAME) using CBCT. Additionally, this study aims to formulate questions and establish methods for future MARPE studies that will help guide clinical decisions.

Chapter 2) Materials and Methods:

This study was approved by the Institutional Review Board of University of Pennsylvania. All CBCT images were analyzed using Dolphin Imaging 3D Software (Version 11.9, Dolphin Imaging & Management Solutions, Chatsworth, CA).

Subjects & Study Design:

De-identified CBCTs taken from 2013 to 2020 were collected from four sources: (1) the orthodontic graduate clinic at University of Pennsylvania School of Dental Medicine; and three private practices in (2) Kennett Square, PA; (3) Wayne, PA; (4) Princeton Junction, NJ. The inclusion criteria for the CBCTs were as follows: (1) diagnosis of transverse maxillary deficiency treated successfully with BAME, BTAME, or SRBAME; (2) CBCTs that were taken both prior to expansion (T1) and upon completion of expansion (T2); (3) no craniofacial syndromes or remarkable medical history. Successful expansion was defined as midpalatal suture opening observable on the T2 CBCT. 24 patients with pre- (T1) and post- (T2) expansion CBCTs were included yielding 48 CBCTs for analysis. CBCTs were grouped according to MARPE approach. 12 patients underwent bone-anchored maxillary expansion (BAME), 7 patients underwent bone- and tooth-anchored maxillary expansion (BTAME), and 5 patients underwent surgically-assisted bone-anchored maxillary expansion (SRBAME) (Table 1).

Table 1) Description of samples

	n	Male	Female	Mean age	Median	95% CI		Mean T1-T2 (days)
						Lower	Upper	
BAME	12	6	6	16.1 ± 3.2	15.5	14.0	18.1	99.1 ± 49.4
BTAME	7	5	2	20.9 ± 6.6	19	14.8	26.9	117.7 ± 72.0
SRBAME	5	4	1	38.25 ± 15.92	38	21.6	56.0	119.2 ± 156.2

BAME, BTAME, SRBAME Design:

The BAME appliance consisted of a jackscrew central body with palatal acrylic coverage anchored to four miniscrews (Figure 1A-B). The BTAME appliance consisted of a jackscrew central body anchored to four miniscrews and first molar bands (Figure 1C). In two BTAME samples, first premolars were included as anchors with palatal mesh designs (Figure 1D). Rocky Mountain Orthodontics (RMO) self-tapping miniscrews, 1.6mm in diameter and 8-13mm in length were used in all BAME and SRBAME samples, and four BTAME samples. 3M Unitek self-tapping miniscrews, 1.8mm in diameter and 11-13mm in length, were used in three BTAME samples. In the BAME and SRBAME appliances, the four miniscrews, two posterior and two anterior, were placed 5-10 mm lateral to the midpalatal suture angled so that the tapping ends were approaching the interradicular bone between the first premolar, second premolar, and first molar roots. In the BTAME appliance, four miniscrews, two posterior and two anterior, were placed close to the midpalatal suture perpendicular to the palate and parallel to the other miniscrews. Bicortical (oral and nasal) placement of miniscrews was achieved in all BTAME appliances as described in manufacturer's instructions.[30] Rapid expansion protocol was used with one to two turns per day in all groups.

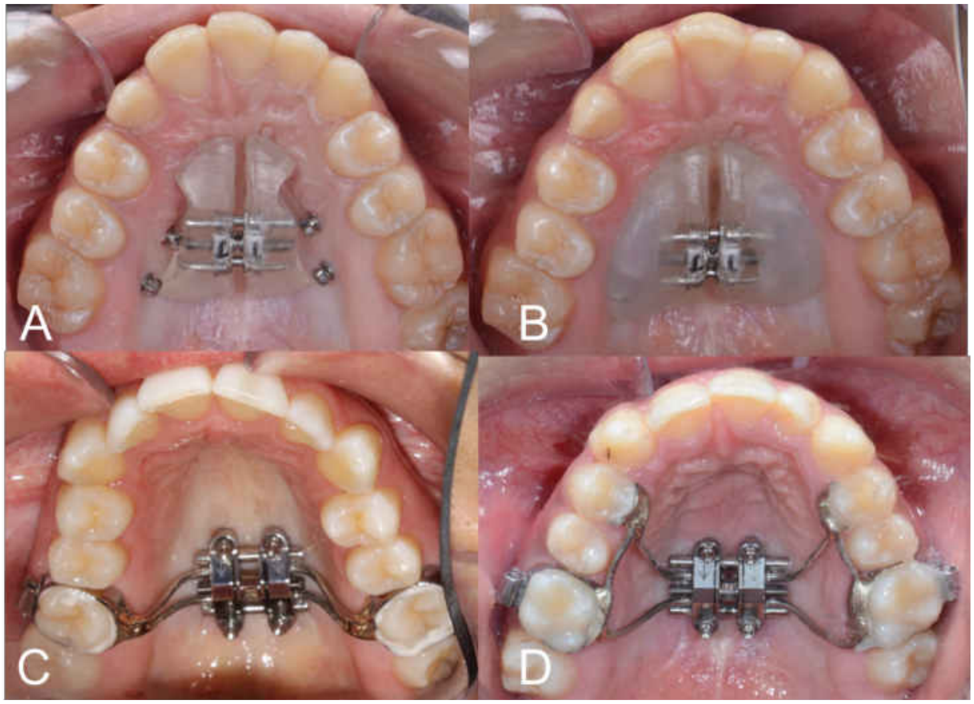


Figure 1) Expander designs included in the study. BAME appliance before (A) and after (B) coverage of miniscrews with acrylic. BTAME appliance with banded first molar and (C) with first premolar palatal mesh (D).

CBCT Protocol and Measurements:

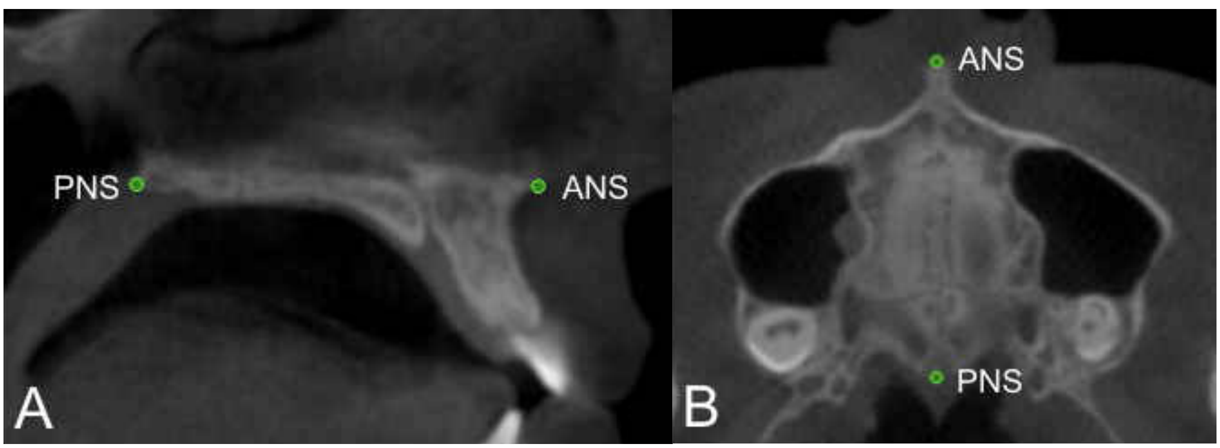
CBCT scans were taken with 0.3mm voxel size with iCAT FlexV10 at 120 kVp, 3 mA, and 10mm filtration or Planmeca ProMax 3D at 84 kVp, 14 mA, and 3mm filtration. Field of view varied from 8x8cm to 16x13cm depending on the source. CBCT images were converted to DICOM format and rendered into volumetric images for measurements using Dolphin Imaging 3D software.

The landmarks used for orientation and measurements included ANS, PNS, apices of premolars and molars, and centers of pulp chamber of premolars and molars (Table 2, Figure 2). Sagittal, axial, and coronal volumetric slices were all used to accurately determine landmark positions. The more prominent root apex that was clearly and consistently identifiable in both T1 and T2 CBCTs was used if premolars had buccal and palatal roots. The palatal root apex was used for molars. The level of the osseous crest as viewed on the sagittal volumetric slice was used as the vertical center of pulp chamber for the premolars (Figure 2C). The pulpal floor was used as reference to identify the vertical center of pulp chambers in molars (Figure 2D).

Table 2) Landmarks used for CBCT measurements

Landmark	Description
ANS	Anterior nasal spine
PNS	Posterior nasal spine
PCR, PCL*	Center of pulp chamber of right (R) and left (L) sides
AR, AL*	Apices of right (R) and left (L) sides

*identified at first premolars, second premolars, first molars, and second molars



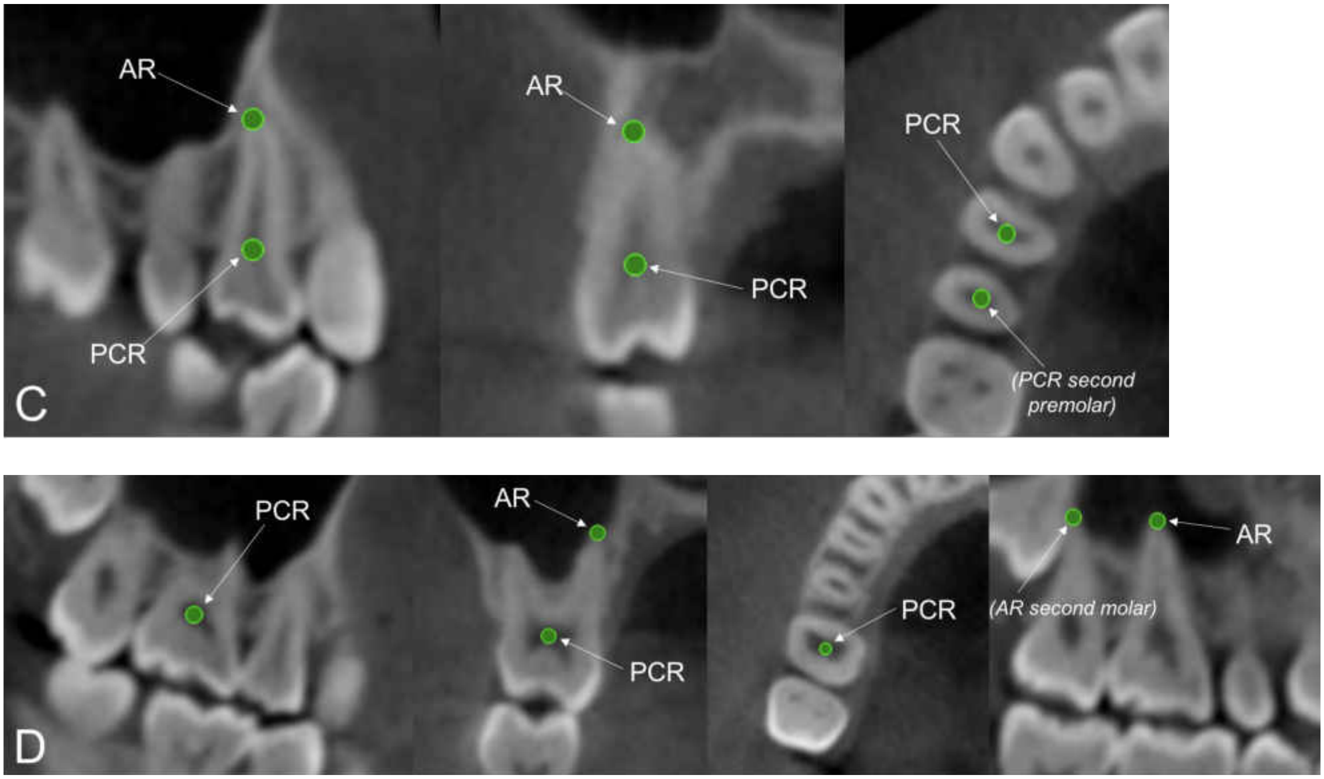


Figure 2) Landmarks used for orientation and measurement of CBCTs. ANS and PNS in sagittal (A) and axial (B) planes; center of pulp chamber (PCR) and apex (AR) of right first premolar in three planes (C); center of pulp chamber (PC6R) and apex (A6R) of right first molar in three planes (D).

Nasal cavity width, suture opening, alveolar width, dental linear, and dental inclination measurements were made in T1 and T2 CBCT images (Table 3).[27,34] For nasal cavity, suture opening, and alveolar measurements, CBCTs were oriented in the sagittal plane using the palatal plane (ANS-PNS), and in the coronal and axial planes using the left and right apices (Figure 3). Nasal cavity (NC) was measured as the length between the most lateral aspects of the nasal cavities on left and right sides (Figure 4A). The suture was measured at the vertical center of the maxillary palatal bone (Figure 4B). Alveolar widths were measured at the level of the apices (A), 5mm above the apices (A+5), and 5mm below the apices (A-5) (Figure 4A). *Ectoprämolare apical* and *ectoemolare apical*, the point on the outer surface of the alveolar ridge corresponding to the apex of the first premolar and first molar has been used in a previous study.[21] Dental linear measurements were defined as the distance between right (R) and left (L) apices (AR-AL) and between centers of pulp chambers (PCR-PCL) of the right and left teeth (Figure 5A). Dental inclination measurements were defined as the angle formed by center of pulp chamber of one side to apex of same side to apex of contralateral side (Figure 5B). All measurements were completed at the four sagittal tooth levels of the first premolar (4), second premolar (5), first molar (6), and second molar (7) for the BTAME and BAME groups. Several modifications were made in SRBAME group measurements: 1) first premolar level measurements were not included because three out of five samples were missing premolars, 2) Nasal Cavity measurements were only included in the second molar level because of limited T2 CBCT field of view in three samples out of five samples, 3) A+5 measurement was not included because location of surgical osteotomy varied in each sample, 4) Dental measurements were not completed because pre- and post-surgical orthodontic treatment affected results.

Table 3) Definitions of parameters measured

Parameter	Description
Nasal Cavity (NC)	Linear distance (mm) between the most lateral aspects of the nasal cavity on the right and left sides
Suture Opening (S)	Linear distance (mm) of suture opening
Alveolar Bone (A+5)	Linear width (mm) of the alveolar bone 5mm above the level of the right and left apices
Alveolar Bone (A)	Linear width (mm) of the alveolar bone at the level of the right and left apices
Alveolar Bone (A-5)	Linear width (mm) of the alveolar bone 5mm below the level of the right and left apices
Dental Linear, Apices (AR-AL)	Linear distance (mm) between the right and left apices
Dental Linear, Pulp Chamber (PCR-PCL)	Linear distance (mm) between the right and left pulp chamber centers
Dental Inclination, Right Side (PCR-AR-AL)	Angle (degrees) formed by the right pulp chamber center to right apex to the left apex
Dental Inclination, Left Side (AR-AL-PCL)	Angle (degrees) formed by the left pulp chamber center to left apex to the right apex

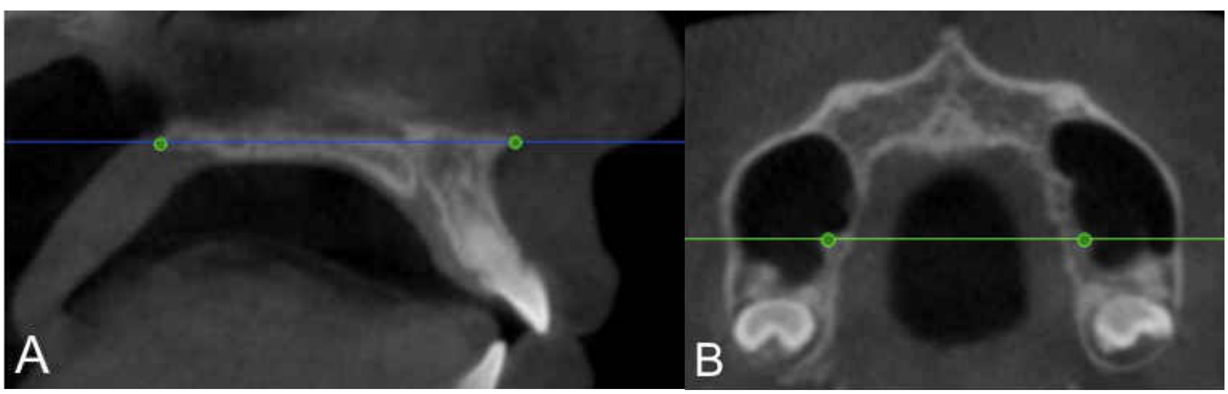


Figure 3) Orientation in sagittal plane according to ANS-PNS (A) and axial plane according to left and right apices (B).

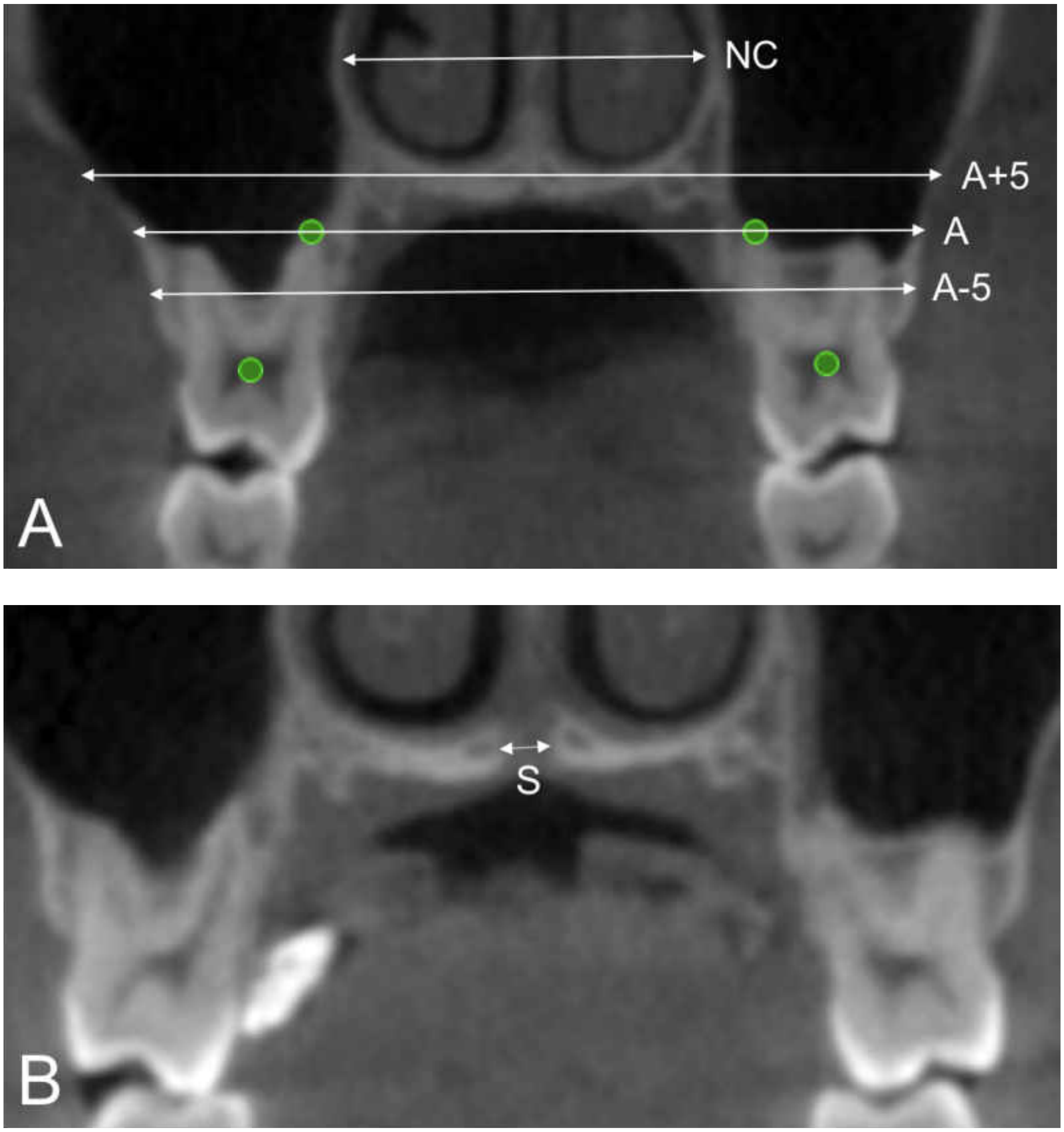


Figure 4) Orientation in coronal plane according to left and right apices and measurements of nasal cavity and alveolar bone width at vertical levels (A) and suture opening (B).

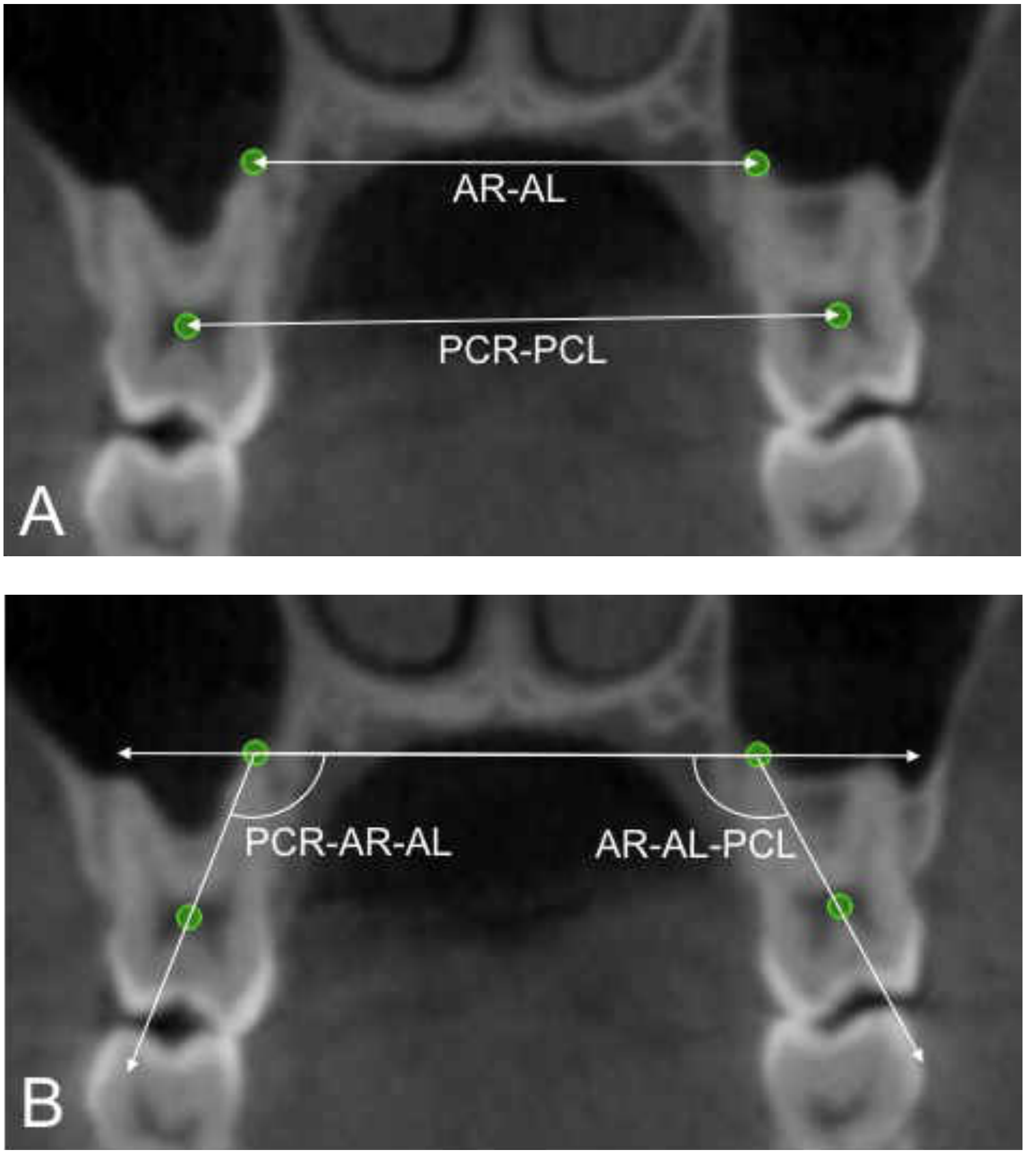


Figure 5) Definition of dental linear (A) and dental inclination (B) measurements.

Statistical Analysis

Statistical analyses were performed on IBM SPSS software, version 26 (IBM SPSS Inc., Chicago, IL). All measurements were repeated by the same operator after at least two weeks. Intraexaminer reliability was determined with the intraclass correlation coefficient (ICC). The mean of the two measurements was used for analysis. Normality of data was tested using Shapiro-

Wilk test. Descriptive statistics including means, standard deviations, and standard error were calculated for the measurements at T1 and T2. A paired t test was used to evaluate whether changes from T1 to T2 were statistically significant. All other two-sample comparisons were completed with paired t-test or independent t-test if data was normally distributed, and Wilcoxon signed rank test or Mann-Whitney rank sum test if data was not normally distributed. In order to test for symmetry of inclination changes on the right and left sides, the side with greater inclination change was compared with the contralateral side with smaller inclination change. All multiple group comparisons were completed with one-way analysis of variance (ANOVA) and Scheffe post hoc analysis if data was normally distributed, and Kruskall-Wallis test and Mann-Whitney U for post-hoc testing with Bonferroni correction if data was not normally distributed. For intergroup comparisons, data was standardized according to the skeletal expansion (suture opening) at the level of the first molar to adjust for differences in expansion completed between the groups. All intragroup and intergroup comparisons are outlined in Table 4. Because of the low sample size, there was low power to detect small but significant differences using multiple group comparisons with post-hoc testing so a predetermined two-group equivalent for each multiple group comparison was included (Table 5).

Table 4) Intragroup and intergroup comparisons. Multiple group comparisons had a two-group equivalent described in Table 5.

Intragroup Comparisons	Intergroup Comparisons
T1 vs. T2	BTAME vs. BAME vs. SRBAME for all mean changes
PCR-AR-AL vs AR-AL-PCL	BTAME vs. BAME for [PCR-PCL]-[AR-AL]
PCR-PCL vs AR-AL	BTAME vs. BAME vs. SRBAME for [A-5]-[A]
4 vs 5 vs 6 vs 7* for [PCR-PCL]-[AR-AL]	BTAME vs. BAME for S/[PC-PC]
NC vs A+5 vs A vs A-5	
4 vs 5 vs 6 vs 7* for [A-5]-[A]	
4 vs 5 vs 6 vs 7* for S	

*4 = first premolar, 5 = second premolar, 6 = first molar, 7 = second molar

Table 5) Multiple group comparisons and two group equivalents

Multiple Group Comparison	Two Group Equivalent	Rationale
BTAME vs. BAME vs. SRBAME	BTAME vs. BAME	Different anchorage approaches
	BAME vs. SRBAME	Nonsurgical vs. surgically-assisted changes with same appliance design
NC vs. A+5 vs. A vs. A-5	A vs. A-5	On alveolar bone
Changes at 4 vs. 5 vs. 6 vs. 7*	4 vs. 7*	Anterior-most vs. posterior-most

*4 = first premolar, 5 = second premolar, 6 = first molar, 7 = second molar

Chapter 3) Results

<u>Intraexaminer Reliability</u>

Intraclass correlation (ICC) for all linear measurements was greater than 0.99 (95% CI 0.99-1.00). The mean absolute difference in linear measurements was 0.21 ± 0.27mm. ICC for all angular measurements were also greater than 0.99 (95% CI 0.99-1.00). The mean absolute difference in angular measurements was 0.43 ± 0.35º.

<u>T1-T2 Changes in BTAME, BAME, and SRBAME (Tables 6,7, Figures 6-8)</u>

All skeletal, alveolar, and dental linear measurements in the three groups had statistically significant mean increases from T1 to T2. Only 5 out of 16 angular measurements in BTAME and BAME groups had statistically significant mean increases from T1 to T2. In BTAME, the mean buccal inclination of left second premolar ($p<0.05$), and left first molar ($p<0.05$) increased significantly from T1 to T2. In BAME, the mean buccal inclination of right second premolar ($p<0.05$), left first premolar ($p<0.05$), and left second premolar ($p<0.05$) increased significantly from T1 to T2. The remaining 11 out of 16 angular measurements in BTAME and BAME showed mean increases in buccal inclination but were not statistically significant ($p>0.05$)

Table 6) Mean changes from T1 to T2 after maxillary expansion with BTAME, BAME

			BTAME				BAME			
			First Premolar	Second Premolar	First Molar	Second Molar	First Premolar	Second Premolar	First Molar	Second Molar
SKELETAL	NC (mm)	n	6	6	6	6	12	12	12	10
		Mean Change	1.37	1.24	1.62	1.68	4.21	3.97	3.88	3.03
		SD	1.20	1.20	1.34	1.16	1.90	1.92	2.00	1.24
		p-value	0.038*	0.028*	0.043*	0.017*	<0.005*	<0.005*	<0.005*	<0.005*
	Suture (mm)	n	7	7	7	7	12	12	12	10
		Mean Change	3.01	2.59	2.80	2.46	5.88	5.48	4.89	3.77
		SD	1.65	1.35	1.40	1.41	2.72	2.63	2.29	1.38
		p-value	0.018*	0.018*	0.018*	0.018*	0.002*	0.002*	0.002*	0.005*
ALVEOLAR	A+5 (mm)	n	7	6	6	6	12	12	11	10
		Mean Change	1.70	1.53	1.74	1.79	3.37	2.66	2.70	3.14
		SD	1.37	1.20	0.99	1.09	2.00	1.64	1.59	1.59
		p-value	0.017*	0.026*	0.008*	0.027*	0.004*	<0.005*	0.004*	<0.005*
	A (mm)	n	7	7	7	7	12	12	12	10
		Mean Change	2.87	2.28	2.29	2.20	5.03	4.50	4.06	3.65
		SD	1.75	1.39	1.40	1.25	2.17	2.33	2.11	1.96
		p-value	0.005*	0.005*	0.005*	0.003*	<0.005*	<0.005*	0.002*	<0.005*
	A-5 (mm)	n	7	7	7	7	12	12	12	10
		Mean Change	3.09	2.46	2.61	2.42	6.03	5.79	5.22	4.41
		SD	1.94	1.78	1.61	1.65	2.44	2.84	2.54	2.06
		p-value	0.018*	0.018*	0.005*	0.008*	<0.005*	<0.005*	<0.005*	<0.005*
DENTAL	A-A (mm)	n	7	7	7	7	12	12	12	10
		Mean Change	2.49	1.96	2.92	2.16	5.94	5.64	5.42	4.53
		SD	1.80	1.70	1.74	1.30	2.83	2.67	2.52	2.21
		p-value	0.011*	0.022*	0.004*	0.005*	<0.005*	0.002*	<0.005*	<0.005*
	PC-PC (mm)	n	7	7	7	7	12	12	12	10
		Mean Change	3.49	3.54	4.61	3.05	6.93	6.88	6.18	4.85
		SD	2.52	2.53	2.53	1.72	2.90	2.94	2.71	2.48
		p-value	0.01*	0.01*	0.003*	0.003*	<0.005*	<0.005*	<0.005*	<0.005*
	R Inc (°)	n	7	7	7	7	12	12	12	10
		Mean Change	1.19	2.45	2.13	1.22	2.02	2.48	2.14	0.99
		SD	1.95	3.10	2.87	2.41	3.48	2.69	4.10	3.43
		p-value	0.158	0.081	0.097	0.228	0.069	0.009*	0.098	0.386
	L Inc (°)	n	7	7	7	7	12	12	12	10
		Mean Change	3.29	3.79	5.76	3.08	2.53	3.15	1.71	0.96
		SD	4.51	3.96	3.15	3.50	3.26	3.61	3.82	2.98
		p-value	0.102	0.045*	0.018*	0.059	0.021*	0.012*	0.149	0.334

*$p<0.05$

Table 7) Mean changes from T1 to T2 after maxillary expansion with SRBAME

			SRBAME		
			Second Premolar	First Molar	Second Molar
SKELETAL	NC (mm)	n			5
		Mean Change			1.74
		SD			1.05
		p-value			0.021*
	Suture (mm)	n	5	5	5
		Mean Change	4.48	3.28	2.46
		SD	1.73	1.09	0.98
		p-value	0.043*	0.043*	0.043*
ALVEOLAR	A (mm)	n	5	5	5
		Mean Change	4.71	3.39	2.79
		SD	1.14	0.84	0.84
		p-value	0.001*	0.001*	0.002*
	A-5 (mm)	n	5	5	5
		Mean Change	5.38	4.14	3.73
		SD	1.11	0.64	1.02
		p-value	<0.005*	<0.005*	0.001*

*p<0.05

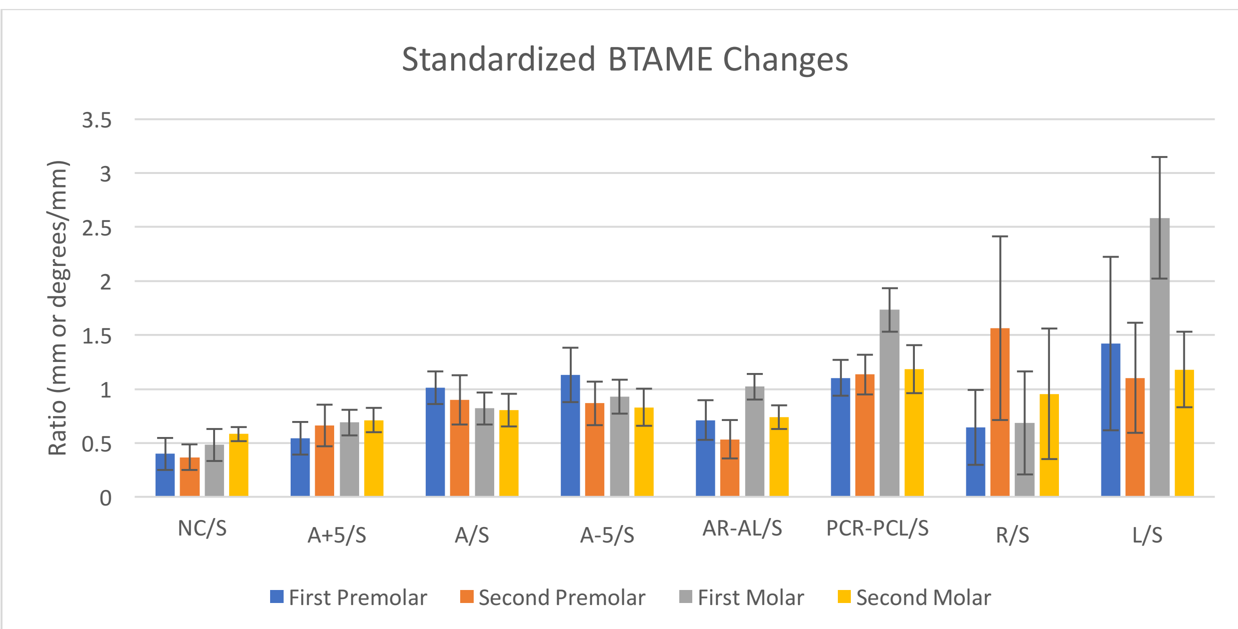


Figure 6) Mean T1 to T2 changes standardized by suture opening at first molar level (S) in BTAME; R, angle formed by PCR-AR-AL; L, angle formed by AR-AL-PCL; Error bar, SEM.

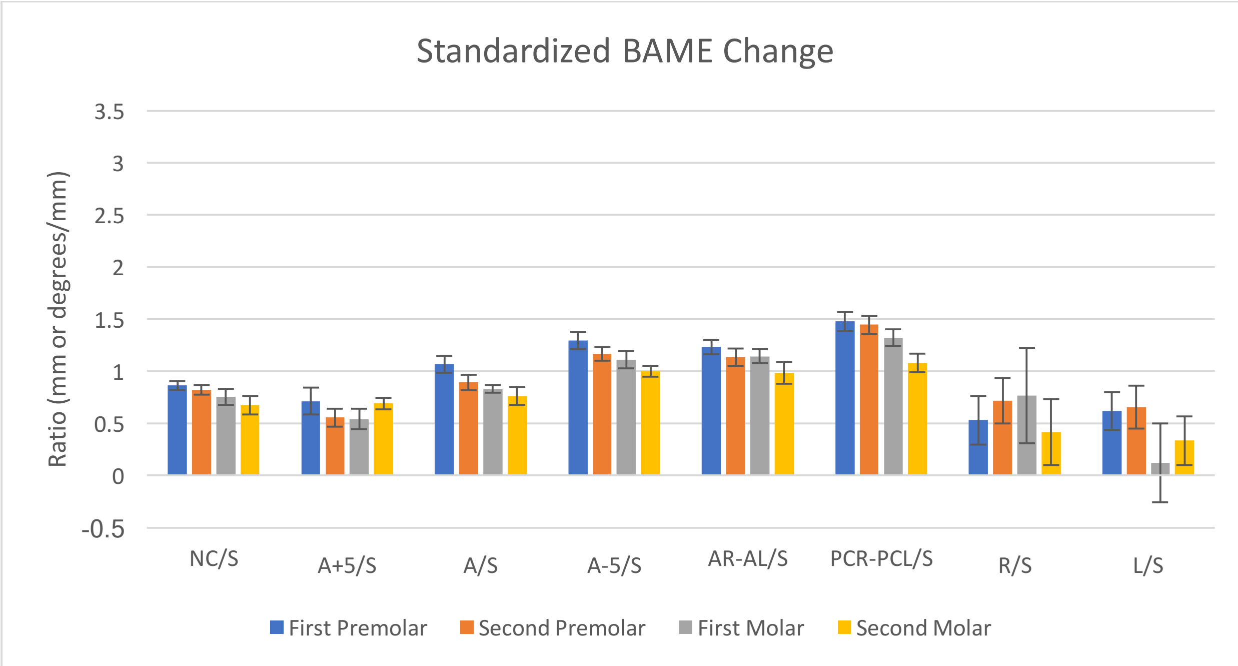


Figure 7) Mean T1 to T2 changes standardized by suture opening at first molar level (S) in BAME; R, angle formed by PCR-AR-AL; L, angle formed by AR-AL-PCL; Error bar, SEM.

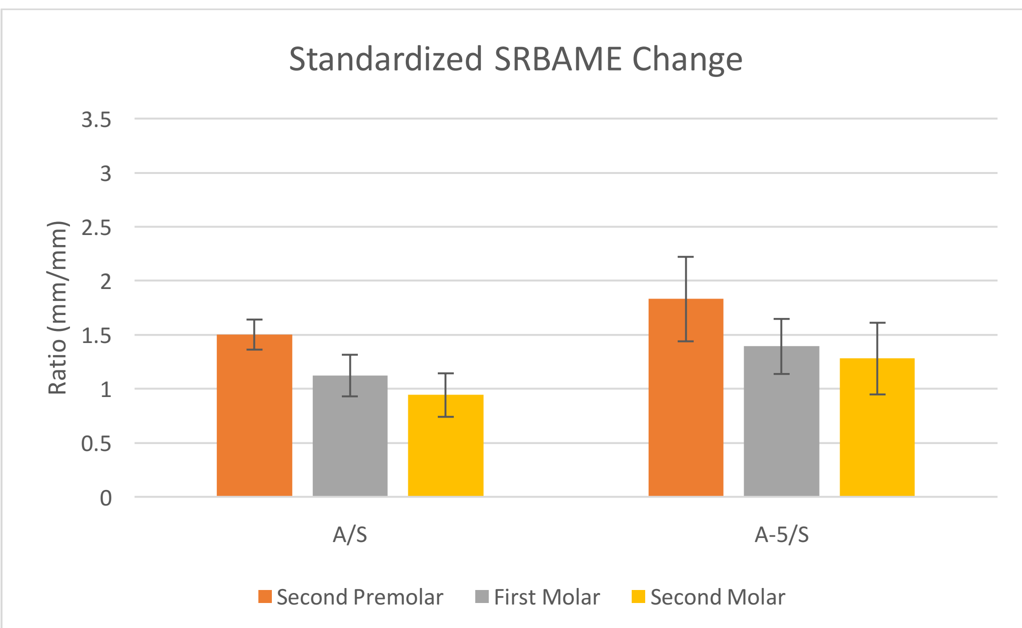


Figure 8) Mean T1 to T2 changes standardized by suture opening at first molar level (S) in BAME; Error bar, SEM.

Intragroup Dental Comparisons

Intragroup Dental Comparison 1: PCR-AR-AL vs. AR-AL-PCL in BTAME and BAME (Figures 9,10)

Mean buccal inclination change was significantly different between the two sides at all tooth levels in BTAME ($p<0.05$) and BAME ($p<0.05$). The mean of the greater inclination changes was compared with the mean of the contralateral smaller inclination changes rather than comparing the means of the right and left side changes. The difference was greatest at the second premolar level in the BTAME group and at the first molar level in the BAME group.

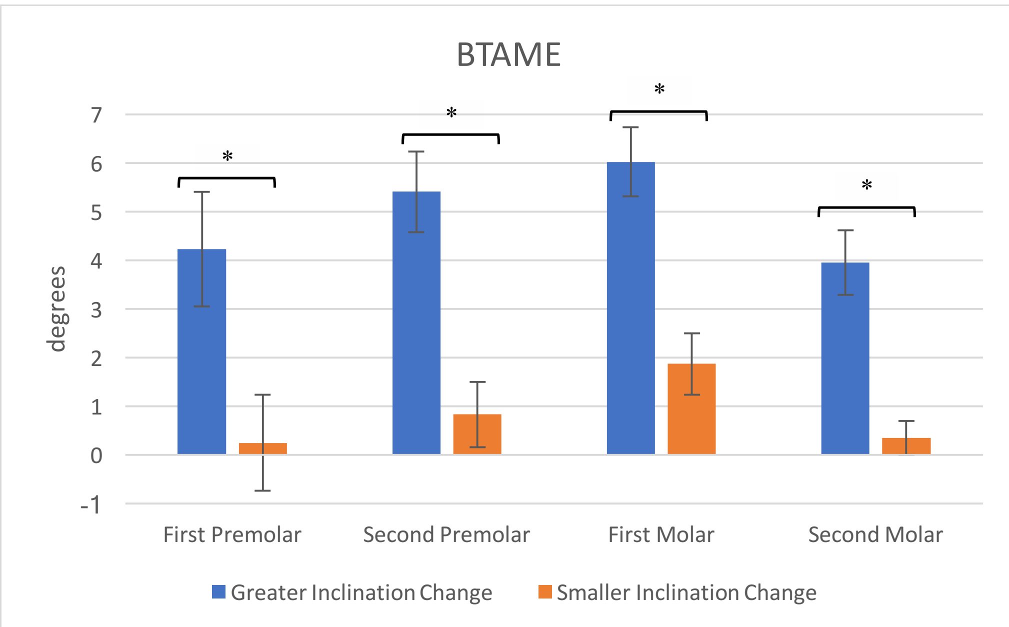


Figure 9) Comparison of mean greater inclination change versus contralateral smaller inclination change in BTAME group; Error bar, SEM; *$p<0.05$

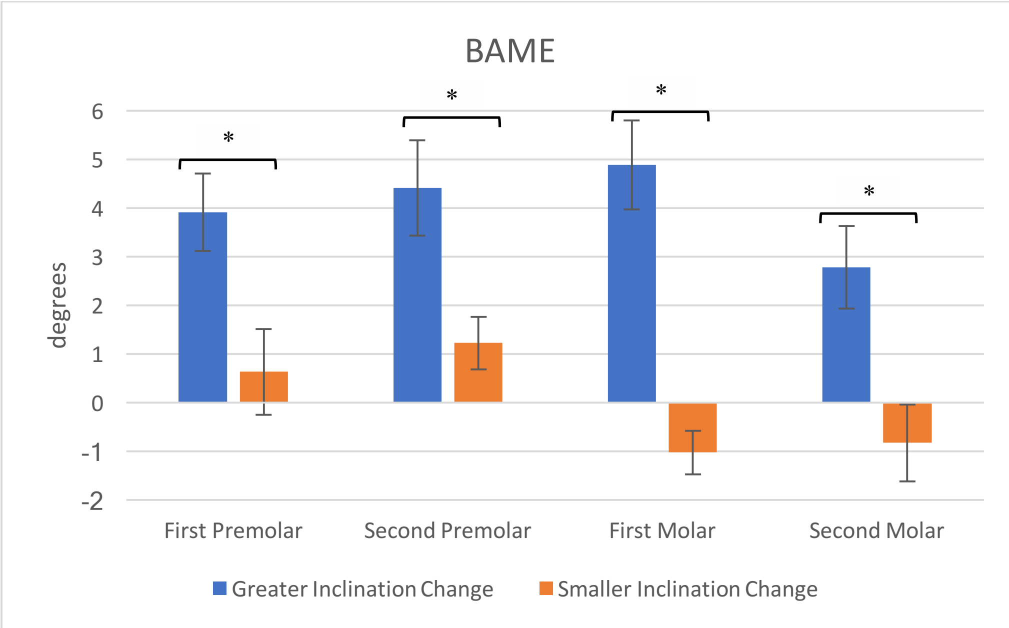


Figure 10) Comparison of mean greater inclination change versus contralateral smaller inclination change in BAME group; Error bar, SEM; *p<0.05

Intragroup Dental Comparison 2: PCR-PCL vs. AR-AL in BTAME and BAME (Table 8)

Expansion of crowns (PCR-PCL) was significantly greater than expansion of apices (AR-AL) at the second premolar ($p<0.05$) and first molar ($p<0.05$) in BTAME and at the first premolar ($p<0.05$), second premolar ($p<0.05$), and first molar ($p<0.05$) in BAME. PCR-PCL was greater than AR-AL for the remaining teeth in both groups but there was no statistical significance ($p>0.05$).

Table 8) Comparison of PCR-PCL vs. AR-AL in BTAME and BAME at each tooth level

	BTAME				BAME			
	First Premolar	Second Premolar	First Molar	Second Molar	First Premolar	Second Premolar	First Molar	Second Molar
Mean diff. PCR-PCL vs. AR-AL (mm)	1.00	1.58	1.69	0.89	0.99	1.25	0.76	0.32
SD	1.13	1.12	1.15	0.97	1.32	1.31	0.61	0.92
p-value	0.057	0.01*	0.008*	0.052	0.025*	0.007*	0.001*	0.301

*p<0.05

Intragroup Dental Comparison 3: First premolar vs. second premolar vs. first molar vs. second molar in BTAME and BAME for [PCR-PCL]-[AR-AL] (Figure 11,12)

[PCR-PCL]-[AR-AL] represented the difference in crown expansion and apical expansion. There were no significant differences in mean [PCR-PCL]-[AR-AL] between any of the teeth (six possible comparisons in each group) in both BTAME ($p>0.05$) and BAME ($p>0.05$). The greatest mean [PCR-PCL]-[AR-AL] occurred at the first molar in BTAME and second premolar in BAME. In both groups, the smallest mean [PCR-PCL]-[AR-AL] occurred at the second molar. Means of [PCR-PCL]-[AR-AL] are summarized in Table 8.

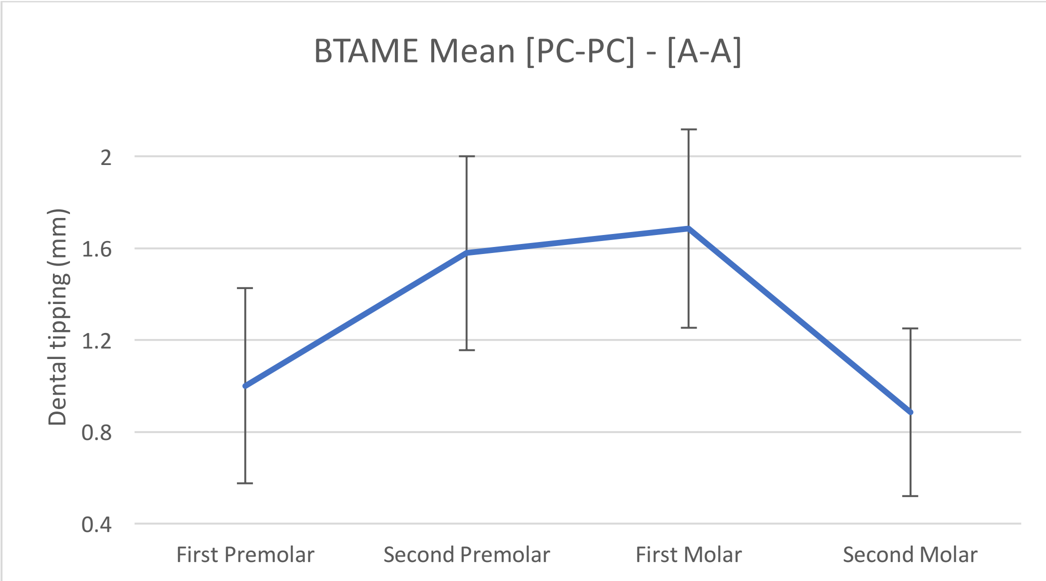


Figure 11) Mean difference between crown expansion (PCR-PCL) and apical expansion (AR-AL) at each tooth level in BTAME; Error bar, SEM.

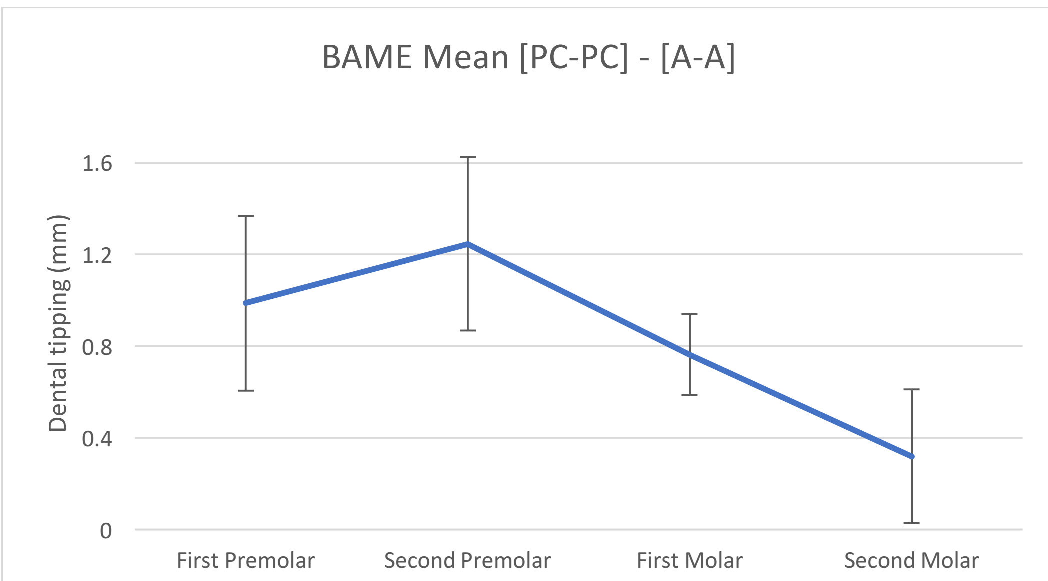


Figure 12) Mean difference between crown expansion (PCR-PCL) and apical expansion (AR-AL) at each tooth level in BAME; Error bar, SEM.

Intragroup Dental Comparison 4: First premolar vs. second molar in BTAME and BAME for [PCR-PCL]-[AR-AL]

This comparison was the two-group equivalent of *Intragroup Dental Comparison 3*. There was no statistically significant difference in mean [PCR-PCL]-[AR-AL] between first premolar and second molar in BTAME ($p>0.05$) and BAME ($p>0.05$). Means of [PCR-PCL]-[AR-AL] are summarized in Table 8.

Intergroup Dental Comparisons

Intergroup Dental Comparison 1: BTAME vs. BAME for Dental Changes (Table 9)

Standardized mean expansion of the apices (AR-AL) was significantly greater in BAME than BTAME at the first premolar ($p<0.05$) and second premolar ($p<0.05$) levels. Standardized mean expansion of the crowns (PCR-PCL) was significantly greater in BAME than BTAME at the first premolar level ($p<0.05$). Standardized mean left side inclination change was significantly greater in BTAME than BAME at the first molar level ($p<0.05$). There were no other significant differences in dental expansion between the two groups ($p>0.05$)

Table 9) Comparison of BTAME vs. BAME for standardized mean dental changes at each tooth level

		BTAME (n=7)		BAME (n=12)		Comparison	
	Parameter	Mean	SD	Mean	SD	Mean Difference	P-value
First Premolar	AR-AL†	0.71	0.48	1.23	0.24	0.51	0.002*
	PCR-PCL†	1.1	0.44	1.48	0.32	0.37	0.047*
	R Inc. Change††	0.65	0.92	0.53	0.81	-0.11	0.78
	L Inc. Change††	1.42	2.12	0.62	0.63	-0.8	0.366
Second Premolar	AR-AL†	0.53	0.47	1.13	0.29	0.6	0.003*
	PCR-PCL†	1.14	0.49	1.45	0.31	0.31	0.104
	R Inc. Change††	1.56	2.24	0.72	0.76	-0.84	0.242
	L Inc. Change††	1.1	1.35	0.66	0.71	-0.45	0.355
First Molar	AR-AL†	1.02	0.31	1.14	0.23	0.12	0.35
	PCR-PCL†	1.73	0.53	1.32	0.28	-0.41	0.063
	R Inc. Change††	0.68	1.26	0.77	1.59	0.08	0.673
	L Inc. Change††	2.58	1.49	0.12	1.31	-2.46	0.002*
Second Molar	AR-AL†	0.74	0.3	0.98	0.33	0.25	0.135
	PCR-PCL†	1.18	0.59	1.08	0.28	-0.1	0.922
	R Inc. Change††	0.95	1.6	0.41	1	-0.54	0.403
	L Inc. Change††	1.18	0.93	0.33	0.73	-0.84	0.053

*$p<0.05$
†Standardized (mm change per mm suture opening at first molar level)
††Standardized (° change per mm suture opening at first molar level)

Intergroup Dental Comparison 2: BTAME vs. BAME for [PCR-PCL]-[AR-AL] (Table 10, Figure 13)

There was no statistically significant difference in standardized mean [PCR-PCL]-[AR-AL] between BTAME and BAME at any of the four tooth levels ($p>0.05$). However, standardized mean [PCR-PCL]-[AR-AL] was greater in BTAME than BAME at all four tooth levels with greatest significance ($p=0.054$) at the first molar level.

Table 10) Comparison of BTAME vs. BAME for standardized mean [PCR-PCL]-[AR-AL] at each tooth level

	BTAME (n=7)		BAME (n=12)		Comparison	
	Mean†	SD	Mean†	SD	Mean Difference†	P-value
First Premolar	0.39	0.42	0.25	0.28	-0.145	0.31
Second Premolar	0.60	0.45	0.31	0.31	-0.29	0.11
First Molar	0.71	0.59	0.18	0.13	-0.53	0.054
Second Molar	0.44	0.47	0.10	0.22	-0.348	0.107

†Standardized (mm change per mm suture opening at first molar level)

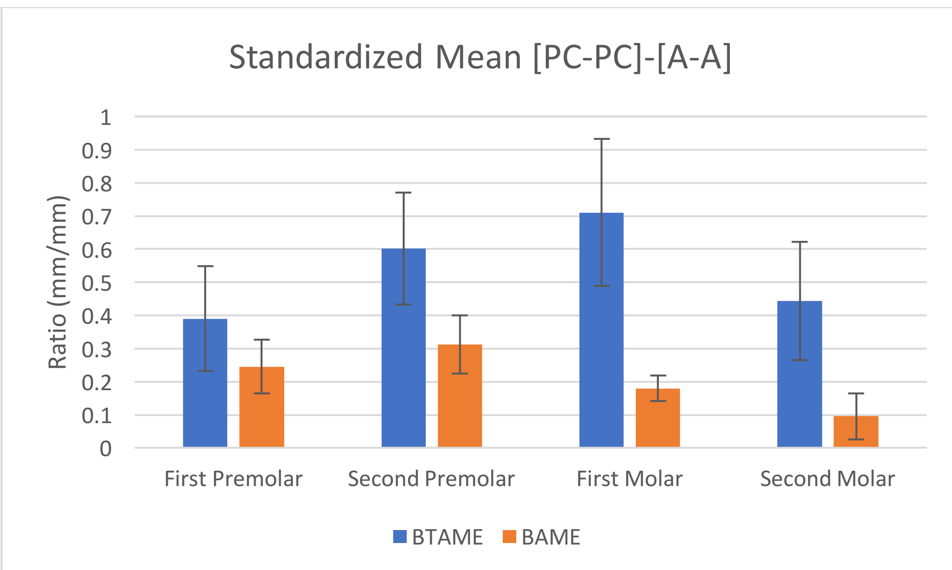


Figure 13) Standardized mean [PCR-PCL]-[AR-AL] at each tooth level in BTAME and BAME; Error bar, SEM.

Intragroup Skeletal and Alveolar Changes

Intragroup Skeletal/Alveolar Comparison 1: NC vs. A+5 vs. A vs. A-5 in BTAME and BAME (Tables 11,12, Figures 14,15)

In BAME, mean expansion 5mm below the level of apices (A-5) was significantly greater than 5mm above the level of apices (A+5) at the first premolar ($p<0.05$) and second premolar ($p<0.05$) levels. There were no other significant differences in mean expansion between any vertical levels NC, A+5, A, and A-5 (six possible comparisons) in BAME and BTAME. Alveolar expansion increased from A+5 to A-5 in all tooth levels in both groups.

Table 11) Comparisons of expansion at NC vs. A+5 vs. A vs. A-5 in BTAME

	First Premolar	Second Premolar	First Molar	Second Molar
NC (mm)	1.3667	1.2417	1.6167	1.675
A+5 (mm)	1.7	1.525	1.7417	1.7917
A (mm)	2.8714	2.2786	2.2857	2.2
A-5 (mm)	3.0929	2.4643	2.6071	2.4214
P-Value (Multiple Groups)	0.165	0.374	0.532	0.718
Post-Hoc Test	N/A	N/A	N/A	N/A

Table 12) Comparisons of expansion at NC vs. A+5 vs. A vs. A-5 in BAME

	First Premolar	Second Premolar	First Molar	Second Molar
NC (mm)	4.21	3.97	3.88	3.03
A+5 (mm)	3.37	2.66	2.70	3.14
A (mm)	5.03	4.50	4.06	3.65
A-5 (mm)	6.03	5.79	5.22	4.41
P-Value (Multiple Groups)	0.025*	0.012*	0.053	0.288
Post-Hoc Test	p = 0.036* A-5 > A+5**	p = 0.014* A-5 > A+5**	N/A	N/A

*p<0.05

**Comparisons with significant differences

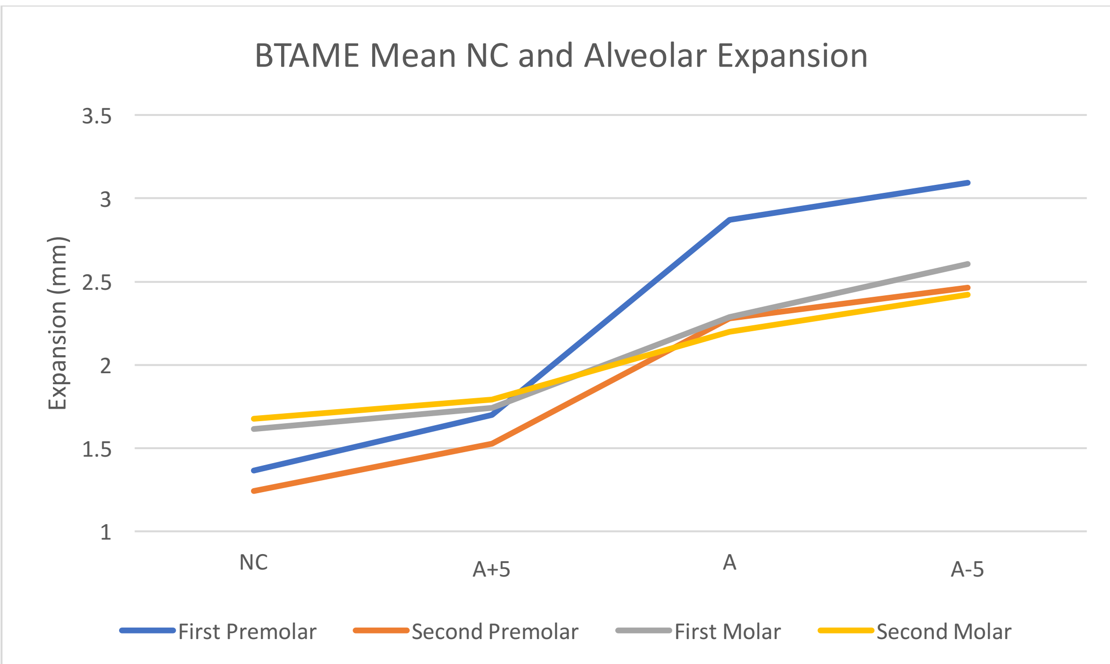


Figure 14) Nasal cavity (NC) and alveolar expansion at each tooth level in BTAME.

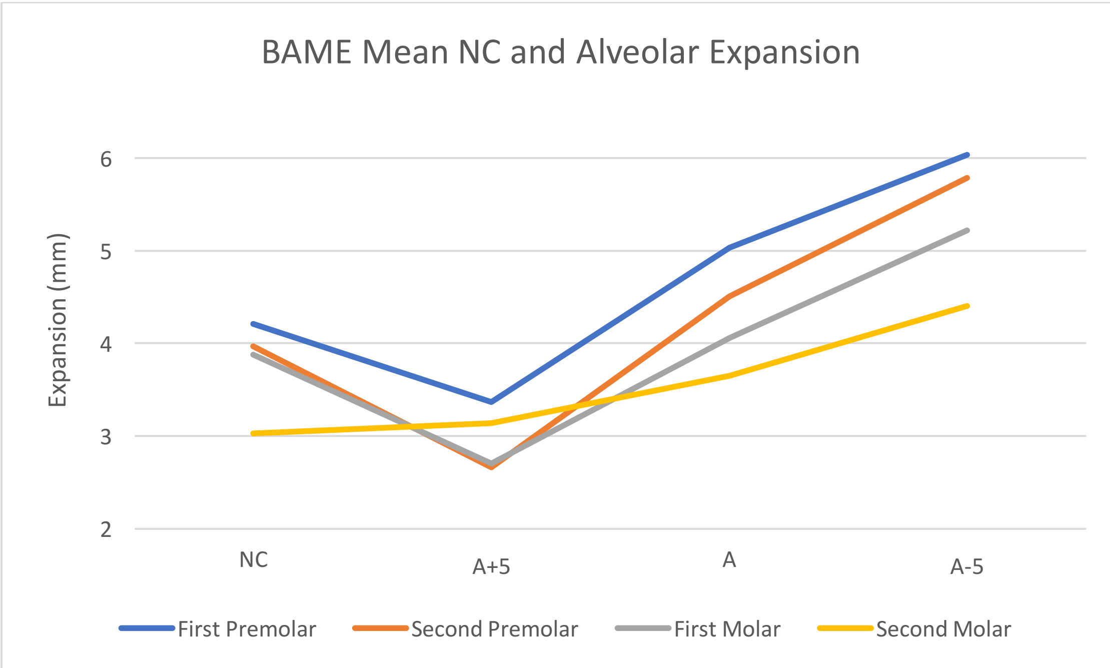


Figure 15) Nasal cavity (NC) and alveolar expansion at each tooth level in the BAME.

Intragroup Skeletal/Alveolar Comparison 2: NC vs. A vs. A-5 in SRBAME at the second molar level (Table 13, Figure 16)

In SRBAME, mean expansion 5mm below the level of apices (A-5) was significantly greater than at nasal cavity (NC) at the second molar level ($p<0.05$). There were no significant differences in mean expansion between the other two comparisons (NC vs. A and A vs. A-5) at the second molar level.

Table 13) Comparisons of expansion at NC vs. A vs. A-5 in SRBAME

	Second Molar
NC (mm) A (mm) A-5 (mm)	1.74 2.79 3.73
P-Value (Multiple Groups)	0.024*
Post-Hoc Test	p = 0.024* A-5 > N**

*p<0.05
**Groups with significant differences

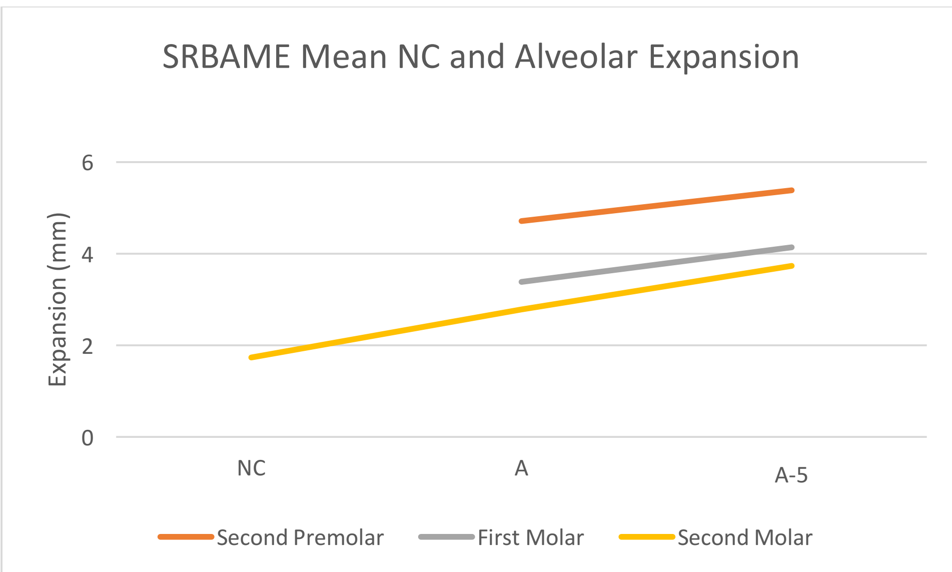


Figure 16) Nasal cavity (NC) and alveolar expansion at each tooth level in SRBAME (NC not available for second premolar and first molar).

Intragroup Skeletal/Alveolar Comparison 3: A vs. A-5 for BTAME, BAME, and SRBAME (Tables 14-16)

This comparison was the two-group equivalent of *Intragroup Skeletal/Alveolar Comparisons 1 and 2*. Mean expansion 5mm below the level of apices (A-5) was significantly greater than that at the level of apices (A) at the first molar level ($p<0.05$) in BTAME and at all four tooth levels ($p<0.05$) in BAME. Mean expansion at A-5 was greater than at A at the first premolar, second premolar, and second molar levels in BTAME and at the second premolar, first molar, and second molar levels in SRBAME but there was no statistical significance ($p>0.05$).

Table 14) Comparison of expansion at A-5 vs. A at each tooth level in BTAME

BTAME				
	First Premolar	Second Premolar	First Molar	Second Molar
Mean diff. A-5 vs. A (mm)	0.22	0.19	0.32	0.22
SD	0.40	0.72	0.34	0.59
p-value	0.195	0.518	0.047*	0.359

*p<0.05

Table 15) Comparison of expansion at A-5 vs. A at each tooth level in BAME

BAME				
	First Premolar	Second Premolar	First Molar	Second Molar
Mean diff. A-5 vs. A (mm)	1.00	1.28	1.16	0.76
SD	0.76	0.80	0.76	0.32
p-value	0.001*	<0.001*	<0.001*	<0.001*

*p<0.05

Table 16) Comparison of expansion at A-5 vs. A at each tooth level in SRAME

	SRBAME		
	Second Premolar	First Molar	Second Molar
Mean diff. A-5 vs. A (mm)	0.67	0.75	0.94
SD	1.06	0.84	1.03
p-value	0.232	0.118	0.111

Intragroup Skeletal/Alveolar Comparison 4: First premolar vs. second premolar vs. first molar vs. second molar levels in BTAME, BAME and second premolar vs. first molar vs. second molar levels in SRBAME for [A-5]-[A] (Figures 17-19)

[A-5]-[A] represented the difference in expansion 5mm below apices and at level of apices. There were no significant differences in mean [A-5]-[A] between any of the tooth levels (six possible comparisons in each group) in BTAME ($p>0.05$), and BAME ($p>0.05$), and any of the tooth levels (three possible comparisons) in SRBAME ($p>0.05$). The greatest mean [A-5]-[A] occurred at the first molar in BTAME, second premolar in BAME, and second molar in SRBAME. Means of [A-5]-[A] are summarized in Tables 14-16.

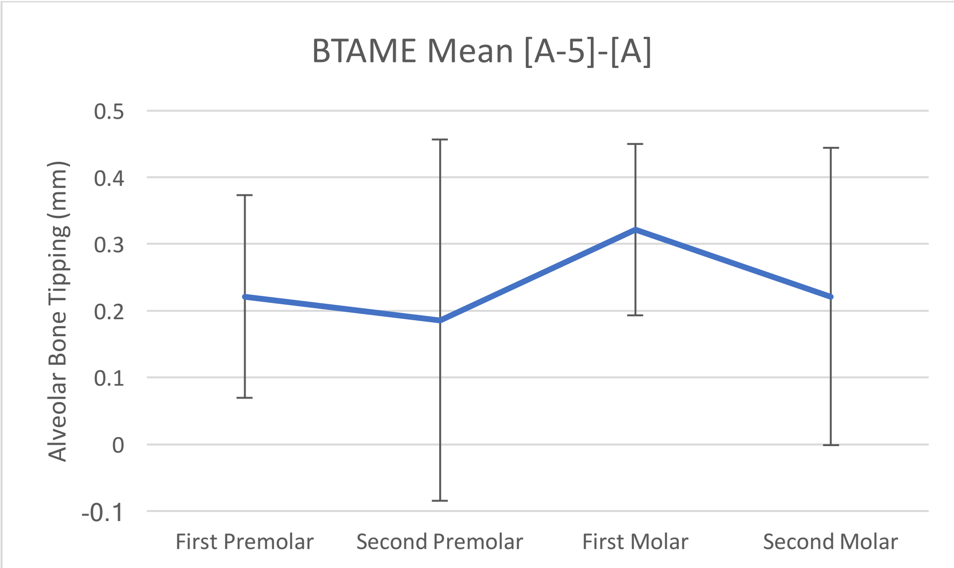


Figure 17) Mean [A-5]-[A] at each tooth level in the BTAME; Error bar, SEM.

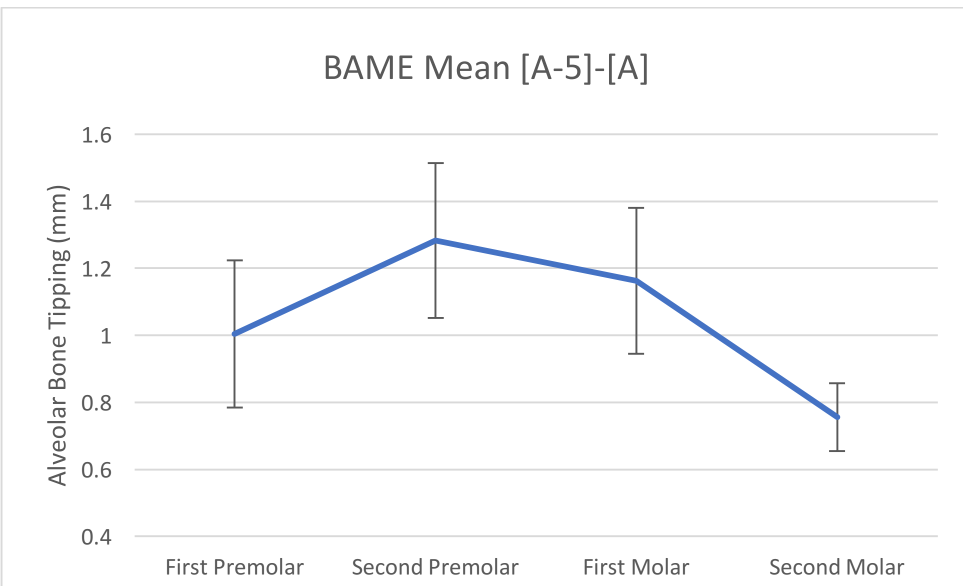


Figure 18) Mean [A-5]-[A] at each tooth level in BAME; Error bar, SEM.

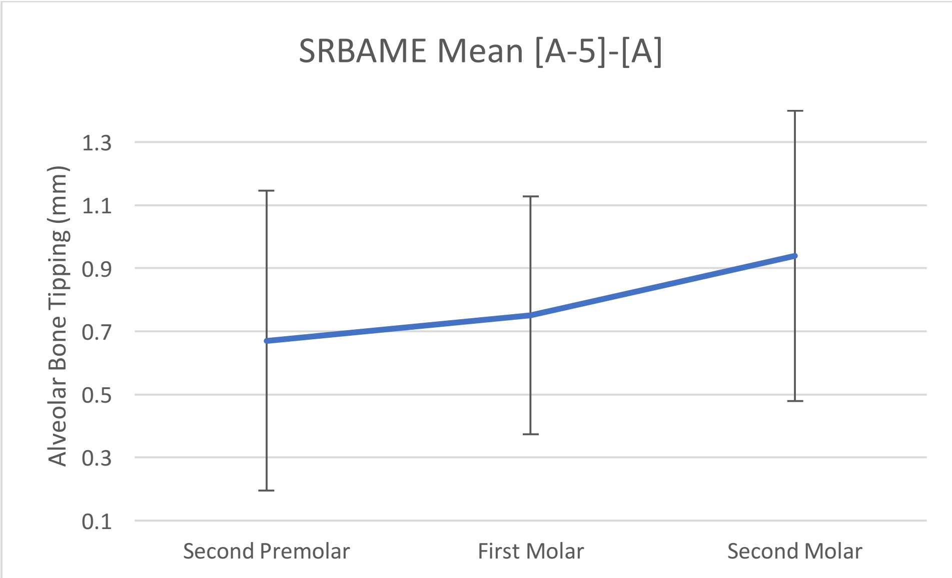


Figure 19) Mean [A-5]-[A] at each tooth level in SRBAME; Error bar, SEM.

<u>Intragroup Skeletal/Alveolar Comparison 5: First premolar vs. second molar levels in BTAME, BAME and second premolar vs. second molar levels in SRBAME for [A-5]-[A]</u>

These comparisons were the two-group equivalents of *Intragroup Skeletal/Alveolar Comparison 4*. There was no statistically significant difference in mean [A-5]-[A] between first premolar and second molar in BAME ($p>0.05$) or between second premolar and second molar in SRBAME ($p>0.05$). Mean [A-5]-[A] was the same first premolar and second molar in BTAME. Means of [A-5]-[A] are summarized in Tables 14-16.

Intragroup Skeletal/alveolar Comparison 6: First premolar vs. second premolar vs. first molar vs. second molar levels in BTAME, BAME and second premolar vs. first molar vs. second molar levels in SRBAME for Suture Opening (S) (Tables 17-19, Figures 20-22)

There were no statistically significant differences in mean suture opening between any of the tooth levels (six possible comparisons in each group) in BTAME ($p>0.05$), and BAME ($p>0.05$). There were no significant differences in mean suture opening between any of the teeth (three possible comparisons) in SRBAME ($p>0.05$). The greatest suture opening occurred at the first premolar level in both BTAME and BAME, and at the second premolar level in SRBAME. The smallest suture opening occurred at the second molar level in all three groups.

Table 17) Comparisons of suture opening at first premolar vs. second premolar vs. first molar vs. second molar in BTAME

	First Premolar	Second Premolar	First Molar	Second Molar	p-value (Multiple Groups)
Mean S (mm)	3.01	2.59	2.80	2.46	0.898
SD	1.65	1.35	1.40	1.41	

Table 18) Comparisons of suture opening at first premolar vs. second premolar vs. first molar vs. second molar in BAME

	First Premolar	Second Premolar	First Molar	Second Molar	p-value (Multiple Groups)
Mean S (mm)	5.8792	5.475	4.8875	3.77	0.196
SD	2.7164	2.63305	2.29061	1.37663	

Table 19) Comparisons of suture opening at second premolar vs. first molar vs. second molar in SRBAME

	Second Premolar	First Molar	Second Molar	p-value (Multiple Groups)
Mean S (mm)	4.48	3.28	2.46	0.088
SD	1.73082	1.09236	0.98323	

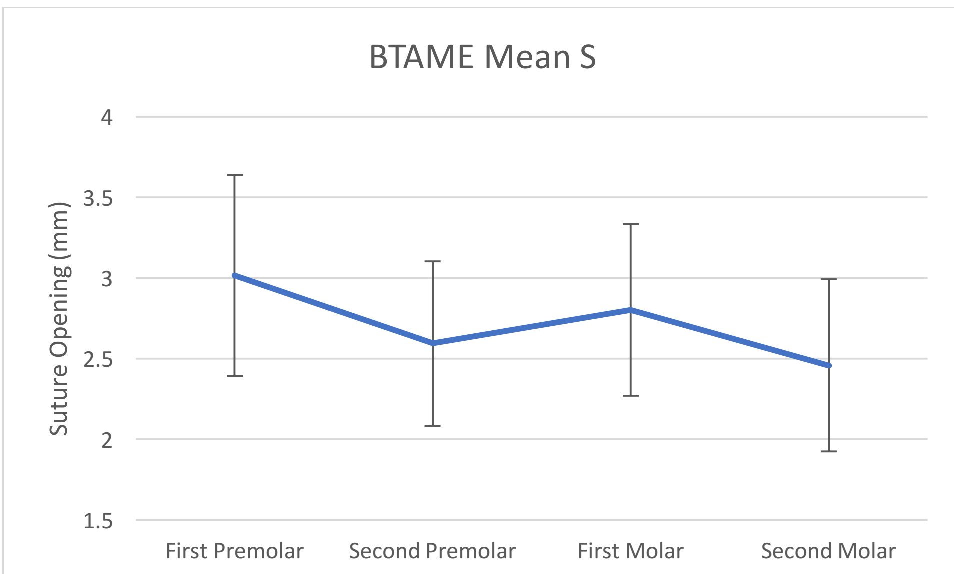


Figure 20) Mean suture opening (S) at each tooth level BTAME; Error bar, SEM.

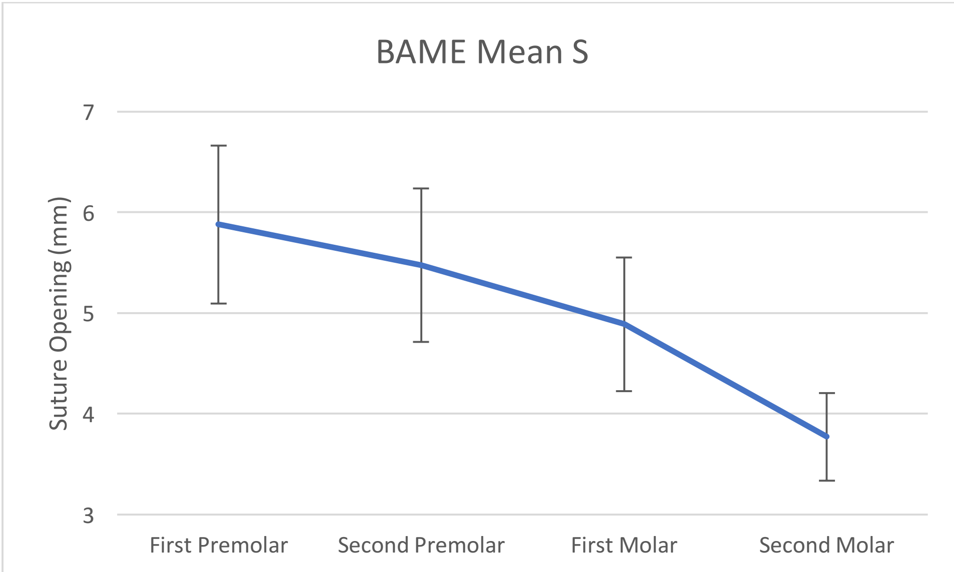


Figure 21) Mean suture opening (S) at each tooth level BAME; Error bar, SEM.

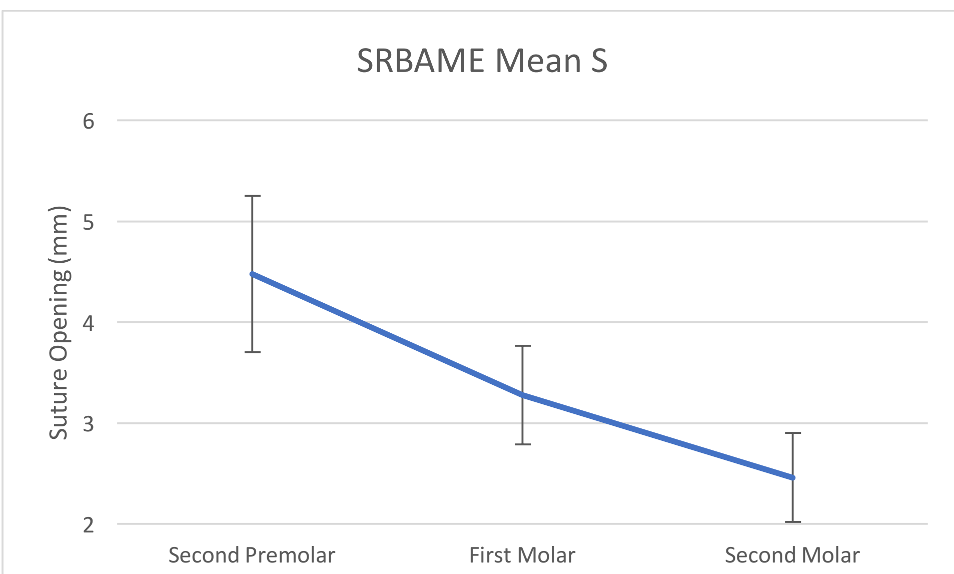


Figure 22) Mean suture opening (S) at each tooth level SRBAME; Error bar, SEM.

Intragroup Skeletal/Alveolar Comparison 7: First premolar vs. second molar levels in BTAME, BAME and second premolar vs. second molar levels in SRBAME for Suture Opening (S)

These comparisons were the two-group equivalents of *Intragroup Skeletal/Alveolar Comparison 6*. Suture opening was significantly greater at the first premolar level than at the second molar level in BAME ($p<0.05$) and significantly greater at the second premolar level than at the second molar level in SRBAME ($p<0.05$). There was no significant difference in suture opening at the first premolar and second molar levels in BTAME ($p>0.05$). Means of S are summarized in Tables 17-19.

Intergroup Skeletal and Alveolar Comparisons

Intergroup Skeletal/Alveolar Comparison 1: BTAME vs. BAME vs. SRBAME for NC, A, A-5 (Table 20,21, Figure 23-25)

There was no significant difference in standardized mean nasal cavity expansion (NC) at the second molar level among the three groups. Standardized mean apical expansion (A) was significantly greater in SRAME than in BAME at the second premolar level ($p<0.05$). Standardized mean expansion 5mm below the apices (A-5) was significantly greater in SRBAME than in BTAME at the second premolar level ($p<0.05$). There were no significant differences in standardized mean alveolar expansion between the groups (three possible comparisons) at the first and second molar levels ($p>0.05$). Overall, standardized mean NC expansion was greatest in BAME while standardized mean alveolar expansion was greatest in SRBAME.

Table 20) Comparisons of BTAME vs. BAME vs. SRBAME for standardized mean NC expansion at second molar level

		BTAME			BAME			SRBAME			Comparison
	Parameter†	n	Mean	SD	n	Mean	SD	n	Mean	SD	P-Value (Multiple Groups)
Second Molar	NC	6	0.59	0.16	10	0.67	0.28	5	0.50	0.25	0.419

†Standardized (mm change per mm suture opening at first molar level)

Table 21) Comparisons of BTAME vs. BAME vs. SRBAME for standardized mean expansion at A and A-5

		BTAME			BAME			SRBAME			Comparison	
	Parameter†	n	Mean	SD	n	Mean	SD	n	Mean	SD	P-Value (Multiple Groups)	Post-Hoc Test
Second Premolar	A	7	0.90	0.60	12	0.89**	0.25	5	1.50**	0.31	0.021*	0.029*
	A-5	7	0.87**	0.53	12	1.17	0.22	5	1.83**	0.88	0.012*	0.013*
First Molar	A	7	0.82	0.39	12	0.83	0.13	5	1.12	0.43	0.161	N/A
	A-5	7	0.93	0.41	12	1.11	0.29	5	1.39	0.57	0.155	N/A
Second Molar	A	7	0.81	0.40	10	0.76	0.27	5	0.94	0.44	0.757	N/A
	A-5	7	0.83	0.45	10	1.00	0.16	5	1.28	0.74	0.504	N/A

*p<0.05
**Means with statistically significant differences
†Standardized (mm change per mm suture opening at first molar level)

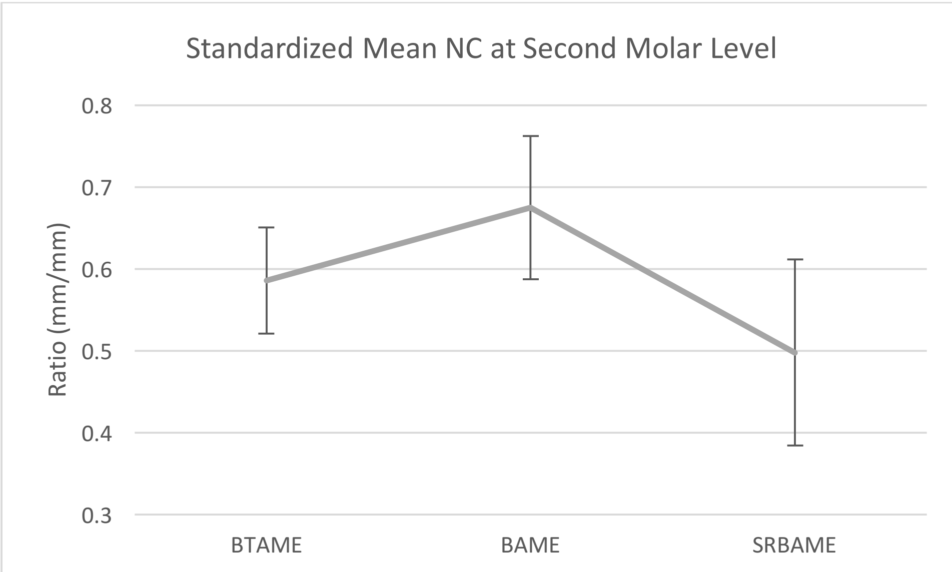


Figure 23) Standardized mean NC expansion in the three groups; Error bar, SEM.

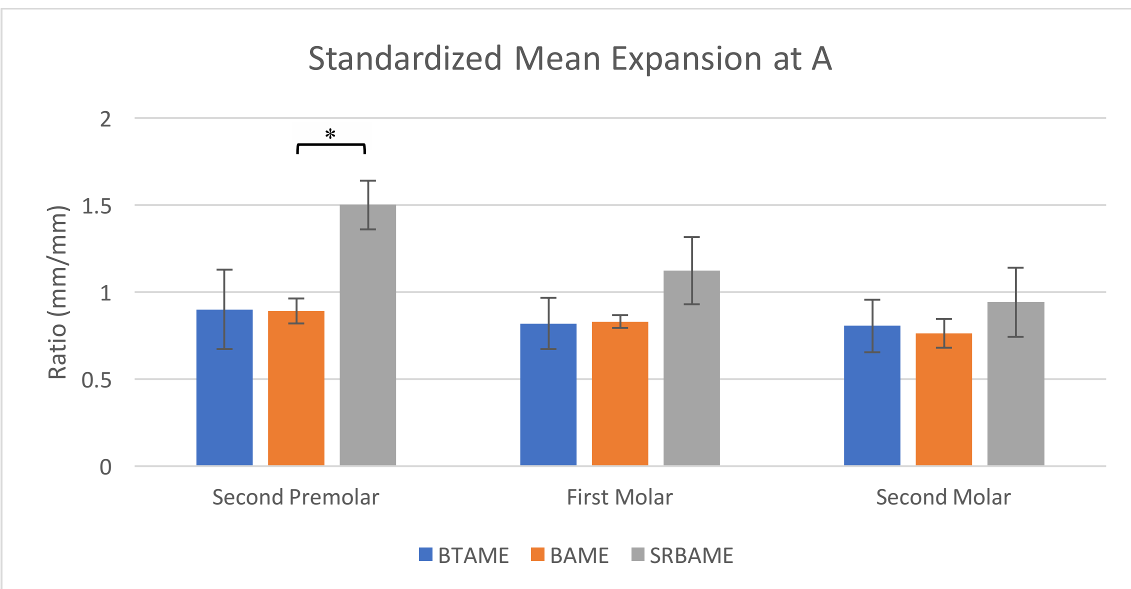


Figure 24) Standardized mean expansion at A in the three groups; Error bar, SEM.

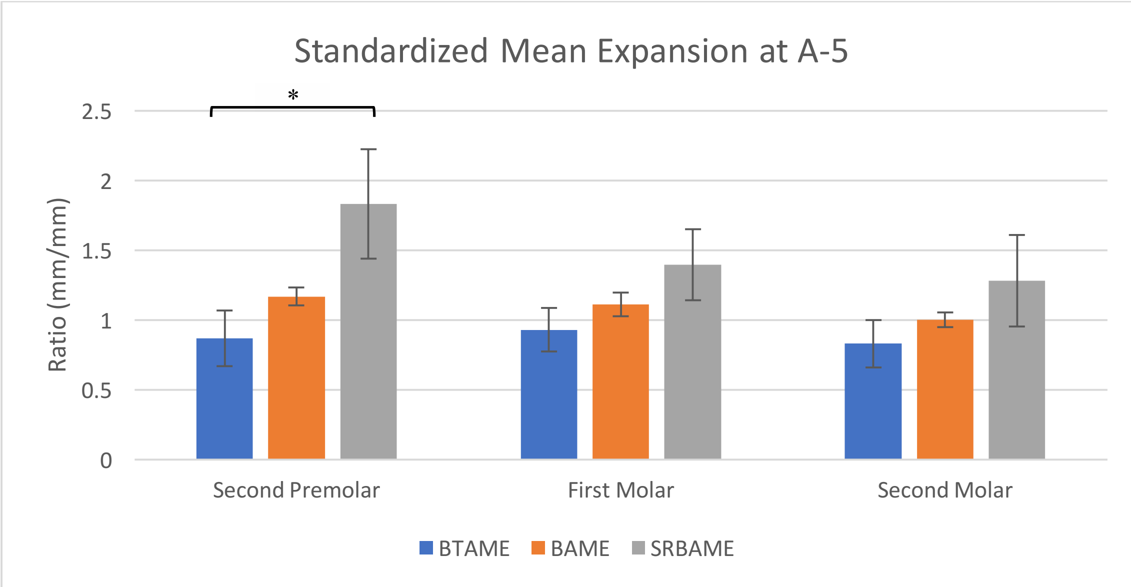


Figure 25) Standardized mean expansion at A-5 in the three groups; Error bar, SEM.

<u>Intergroup Skeletal/Alveolar Comparison 2: BTAME vs. BAME for NC, A+5, A, A-5 (Table 22)</u>

This comparison was a two-group equivalent of *Intergroup Skeletal/Alveolar Comparison 1*. Standardized mean expansion of the nasal cavity (NC) was significantly greater in BAME than in BTAME at the first premolar ($p<0.05$) and second premolar ($p<0.05$) levels. There were no other significant differences in NC or alveolar expansion between the two groups.

Table 22) Comparison of BTAME vs. BAME for standardized mean expansion at NC, A+5, A, A-5

		BTAME			BAME			Comparison	
	Parameter†	n	Mean	SD	n	Mean	SD	Mean Diff.	P-value
First Premolar	NC	6	0.40	0.36	12	0.86	0.14	0.46	0.025*
	A+5	7	0.54	0.40	12	0.71	0.45	0.17	0.42
	A	7	1.01	0.40	12	1.06	0.28	0.05	0.743
	A-5	7	1.13	0.67	12	1.30	0.28	0.17	0.455
Second Premolar	NC	6	0.37	0.29	12	0.82	0.16	0.45	0.01*
	A+5	6	0.66	0.47	12	0.56	0.30	-0.11	0.567
	A	7	0.90	0.60	12	0.89	0.25	-0.01	0.977
	A-5	7	0.87	0.53	12	1.17	0.22	0.30	0.197
First Molar	NC	6	0.48	0.36	12	0.75	0.26	0.27	0.075
	A+5	6	0.69	0.29	11	0.54	0.33	-0.15	0.363
	A	7	0.82	0.39	12	0.83	0.13	0.01	0.947
	A-5	7	0.93	0.41	12	1.11	0.29	0.18	0.273
Second Molar	NC	6	0.59	0.16	10	0.67	0.28	0.09	0.485
	A+5	6	0.71	0.28	10	0.69	0.17	-0.02	0.867
	A	7	0.81	0.40	10	0.76	0.27	-0.04	1
	A-5	7	0.83	0.45	10	1.00	0.16	0.17	0.37

*p<0.05
†Standardized (mm change per mm suture opening at first molar level)

Intergroup Skeletal/Alveolar Comparison 3: BAME vs. SRBAME for NC, A, A-5 (Table 23)

This comparison was the other two-group equivalent of *Intergroup Skeletal/Alveolar Comparison 1*. Standardized mean expansion at the level of apices (A) was significantly greater in SRBAME than in BAME at the second premolar ($p<0.05$) and first molar ($p<0.05$) levels. There was no statistically significant difference in standardized mean expansion 5mm below apices (A-5) between the two groups at any of the three tooth levels ($p>0.05$). There was also no statistically significant difference in standardized mean NC expansion between the two groups at the second molar level.

Table 23) Comparison of BAME vs. SRBAME for standardized mean expansion at NC vs. A vs. A-5

		BAME			SRBAME			Comparison	
	Parameter†	n	Mean	SD	n	Mean	SD	Mean Diff.	P-value
Second Premolar	A	12	0.89	0.25	5	1.50	0.31	0.61	0.001*
	A-5	12	1.17	0.22	5	1.83	0.88	0.66	0.167
First Molar	A	12	0.83	0.13	5	1.12	0.43	0.29	0.043*
	A-5	12	1.11	0.29	5	1.39	0.57	0.28	0.188
Second Molar	A	10	0.76	0.27	5	0.94	0.44	0.18	0.54
	A-5	10	1.00	0.16	5	1.28	0.74	0.28	0.854
	NC	10	0.67	0.28	5	0.50	0.25	-0.18	0.251

$p<0.05$
†Standardized (mm change per mm suture opening at first molar level)

Intergroup Skeletal/Alveolar Comparison 4: BTAME vs. BAME vs. SRBAME for [A-5]-[A] (Table 24, Figure 26)

There were no statistically significant differences in standardized mean [A-5]-[A] between the three groups (three possible comparisons) at the first molar ($p>0.05$), or second molar ($p>0.05$). After post hoc test with Bonferroni correction, there were no significant differences between the three groups at the second premolar level ($p>0.015$).

Table 24) Comparison of BTAME vs. BAME vs. SRBAME for standardized mean [A-5]-[A]

	BTAME			BAME			SRBAME			Comparison	
	n	Mean†	SD	n	Mean†	SD	n	Mean†	SD	P-Value (Multiple Groups)	Post-Hoc Test
Second Premolar	7	-0.03	0.26	12	0.27	0.13	5	0.33	0.60	0.038*	BTAME vs. BAME P=0.018** BTAME vs. SRBAME P=0.291 BAME vs. SRBAME P = 0.14
First Molar	7	0.11	0.09	12	0.28	0.21	5	0.27	0.31	0.165	N/A
Second Molar	7	0.02	0.20	10	0.24	0.24	5	0.34	0.41	0.056	N/A

*p<0.05
**p>0.015 (Bonferroni correction to adjust for type 1 errors)
†Standardized (mm change per mm suture opening at first molar level)

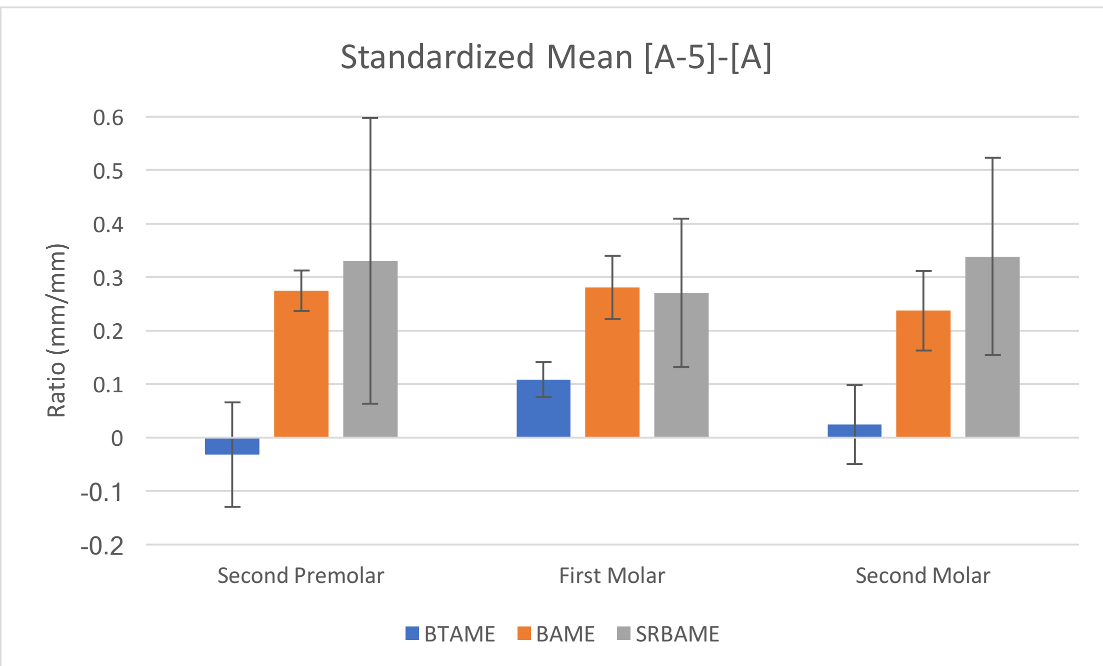


Figure 26) Standardized mean [A-5]-[A] in the three groups; Error bar, SEM.

Intergroup Skeletal/Alveolar Comparison 5: BTAME vs. BAME and BAME vs. SRBAME for [A-5]-[A] (Table 25,26)

These comparisons were the two-group equivalents of *Intergroup Skeletal/Alveolar Comparison 4*. Standardized mean [A-5]-[A] was significantly greater in BAME than in BTAME at the second premolar, first molar, and second molar levels ($p<0.05$). The difference was not statistically significant at the first premolar level. There was no statistically significant difference in standardized mean [A-5]-[A] between BAME and SRBAME at any of the three tooth levels ($p>0.05$).

Table 25) Comparison of BTAME vs. BAME for standardized mean [A-5]-[A]

	[A-5]-[A]† Mean Diff. BTAME vs. BAME	P-value
First Premolar	0.11	0.308
Second Premolar	0.31	0.019*
First Molar	0.17	0.035*
Second Molar	0.21	0.015*

*p<0.05
†Standardized (mm change per mm suture opening at first molar level)

Table 26) Comparison of BAME versus SRBAME for standardized mean [A-5]-[A]

	[A-5]-[A]† Mean Diff. BAME vs. SRBAME	P-value
Second Premolar	0.06	0.14
First Molar	-0.01	1
Second Molar	0.10	0.327

†Standardized (mm change per mm suture opening at first molar level)

BTAME vs. BAME for Contribution of Skeletal Expansion to Crown Expansion (Table 27)

Percent contribution of skeletal expansion (S) to expansion of the crowns (PCR-PCL) was significantly greater in BAME (78.5%) than BTAME (61.9%) ($p<0.05$).

Table 27) Comparison of BTAME vs. BAME for percent contribution of skeletal expansion to crown expansion.

	BTAME			BAME			Comparison	
	n	Mean	SD	n	Mean	SD	Mean Diff.	P-value
First Premolar	7	1.21	0.81	12	0.85	0.12	-0.36	0.272
Second Premolar	7	1.11	0.92	12	0.80	0.13	-0.30	0.933
First Molar	7	0.62	0.16	12	0.79	0.15	0.17	0.037*
Second Molar	7	0.84	0.30	10	0.84	0.23	0.00	0.991

*p<0.05

Chapter 4) Discussion

Using CBCT, the present study demonstrates that BTAME, BAME, and SRBAME can be effective in expanding the maxilla orthopedically in the transverse direction. Despite skeletal anchorage using miniscrews, some dental tipping is unavoidable. Dental tipping was greater in BTAME than in BAME, with greatest significance at the first molar, which served as the anchor tooth in BTAME. The right and left first molars had a combined buccal tipping of 0.71±0.59mm and 0.18±0.13mm for every mm of suture opening, in BTAME and BAME respectively. Contribution of skeletal expansion to first molar intermolar width increase was more favorable in BAME (78.6%) than in BTAME (61.9%). However, there was greater alveolar bone tipping in BAME than in BTAME. Suture opening was closest to parallel from anterior to posterior in the BTAME group while anterior was significantly greater than posterior suture opening in BAME and SRBAME.

Both BTAME and BAME approaches resulted in significant orthopedic expansion with some dental tipping. For T1 to T2 changes in the two groups, all linear measurements increased significantly at all sagittal tooth levels while some angular dental changes at individual teeth were not significant. The nonsignificant angular dental changes may be explained by the use of skeletal anchorage for maxillary expansion to distribute forces directly to the palate in order to minimize effects on the teeth. These findings are in accordance with previous studies that report reduction in dental sequelae with MARPE.[21,28,31,32] Similarly, in a comparison of bone-borne versus tooth-borne expanders, Lin et al concluded that bone-borne expanders produced greater orthopedic effects and fewer dentoalveolar side effects than the tooth-borne expander.[27] The SRBAME approach also resulted in significant orthopedic expansion but dental measurements could not be reported.

The present study clearly demonstrates that dental buccal tipping occurs in BTAME and BAME. Crown expansion was greater than apical expansion in both groups although the difference was not statistically significant in some teeth. Within both groups, there were no significant differences in dental tipping between the teeth. However, in the BTAME group, the greatest buccal tipping occurred in the first molars, which were anchor teeth in all samples. The buccal tipping of first molars in BTAME may be explained by deformation and movement of miniscrews within bone resulting in application of forces directly on first molar anchor teeth. An *in vitro* study on force transmission in BTAME reported that miniscrews with shaft diameter of 1.36mm were deformed and recommended thicker diameters of 2.5-3mm to improve bony anchorage and stability.[35] Barthelemi et al demonstrated TAD movement during en masse retraction of anterior teeth.[36] The authors reported that TADs on the palatal side had double the movement of the buccal side because palatal mucosa is thicker, increasing the lever arm. If lever arm is increased, bone-TAD contact ratio decreases with time.[37] In addition, Moon et al reported that some tipping of anchor teeth can be attributed to the difference in diameter of the TAD (1.6-1.8mm) and the expander hole (2mm).[32] This would allow for loading primarily on the anchor teeth during initial activation.[38]

In BTAME and BAME, there was also significant tipping of nonanchor teeth. In BTAME, increased tension of transeptal fibers between anchor and nonanchor teeth may contribute to movement of nonanchor teeth.[39,40] In addition, dental tipping of nonanchor teeth can be attributed to alveolar bone tipping. Previous studies have demonstrated minimal changes in dental inclination within the alveolar housing in bone-anchored MARPE.[21,27,32] In the present study, angular assessment of dental tipping relative to alveolar bone tipping was not completed because stable skeletal references for reliable measurement of angular alveolar changes were not accessible in our limited field of view. However, in BAME, trends of alveolar bone tipping closely matched that of dental tipping.

Dental tipping was greater in BTAME than BAME at all four tooth levels although none were statistically significant. The most significant difference between the two groups was observed at the first molars, which were anchor teeth in BTAME. With a larger sample size, this finding may be statistically significant and can be explained by the previously discussed deformation and movement of TADs, and discrepancy of TAD and expander hole diameters placing forces directly on anchor teeth.[36-38] Greater apical expansion in BAME than in BTAME confirms the difference in dental tipping since apical expansion requires buccal root movement, which decreases dental tipping. Because teeth were not banded for anchorage in BAME, the apical expansion can be attributed mostly to alveolar expansion. This agrees with a previous study demonstrating that much of the dentoalveolar expansion is contributed by alveolar changes in BAME and by dental changes in BTAME.[32] However, BAME's lower mean age and skeletal maturity may have played a role in allowing less resistance to expansion, resulting in an increased dentoalveolar expansion.

The right and left side dental inclination changes in BTAME and BAME groups were not symmetrical. Because an asymmetry can occur on either right or left side, the side with the greater inclination change was compared with the side with the smaller inclination change. Asymmetrical dental tipping observed in the present study goes against findings from other studies which report minimal differences between the right and left sides when using a MARPE approach.[27,34] Christie et al, in a study evaluating a tooth-borne bonded expander, reported a mean difference of 0.62° between the right and left first molars.[41] However, these studies did not use the method of comparing greater change with smaller change. In the present study, the use of dental reference, AR-AL, to measure angles may have affected results. Another possible explanation is that the miniscrews of one side deformed more than the contralateral. Deformation of miniscrews is possible especially in monocortical engagement.[42] Asymmetrical deformation may be prevented by ensuring that conditions of miniscrews are the same on both sides. Lagravere et al reported that a Dresden bone-anchored expander, which uses a temporary anchorage device (TAD) on one side and a mini-implant on the other side resulted in asymmetrical expansion in which crown expansion was greater on the TAD side.[43] These papers may suggest that type, number, and engagement objectives of miniscrews should stay the same on both sides if symmetrical expansion is desired. Cantarella et al was the first to report asymmetry of midpalatal split in which ANS on one half moved more than the contralateral by 1.1mm.[44] They hypothesized that asymmetry is explained by external forces such as crossbite that may hamper movement of one half of the maxilla, circummaxillary sutures that may not open proportionally on either side, and discrepancies in zygomatic buttress density and morphology.[44] Further studies evaluating the effects of discrepancies of skeletal characteristics between right and left sides on expansion are recommended.

Alveolar bone expansion increased from superior (A) to inferior (A-5) in all three MARPE approaches with statistical significance at all sagittal tooth levels in BAME and at first molar level in BTAME. Maxillary expansion can be divided into naso-maxillary complex (NMC) rotation, alveolar bone bending, and tooth tipping.[32] In the present study, NMC rotation could not be quantified due to limited field of view of CBCTs but alveolar expansion findings demonstrate that alveolar tipping occurred in all three groups. BAME exhibited significantly greater alveolar tipping compared with BTAME, which had the least tipping of the three groups. These findings are in accordance with previous studies in which bone-anchored expansion resulted in significant alveolar bending.[21,27,32] Garrett et al also reported that alveolar bending accounted for at least 6-13% of total expansion in conventional RPE.[45] The significant alveolar tipping in BAME can be explained by TAD placement farther inferiorly on the palatal slope than in BTAME. This may also explain why there was significant alveolar tipping at the first molar level in BTAME, where inferior force was applied rapidly at the bands. Many previous studies have confirmed triangular expansion with widest expansion at the maxillary dentition converging superiorly in conventional RPE.[10,18,46] Similarly, other studies have concluded that the center of rotation of maxillary expansion in coronal plane falls on the frontonasal suture.[21,32,47] This is valid anatomically because the frontal bone is a single structure whereas the nasal bone is separated by the internasal suture. The center of resistance of the dentomaxillary complex from the sagittal view occurs above the molar apices and below orbitale.[35,48] As force is applied farther from the center of resistance, a greater moment is created resulting in rotation and tipping of bone as observed in the BAME group.[49] In contrast, miniscrews in BTAME were placed deeper in the palatal vault, closer to the center of resistance. Also, the BTAME miniscrews were bicortically engaged, potentially allowing more parallel expansion in the coronal plane.[42]

Alveolar bone tipping occurred in SRBAME but changes were not statistically significant likely as a result of small sample size. A previous study evaluating outcomes of combining Dresden Distractor, a bone-borne expander, with surgical osteotomy of the lateral maxilla without midpalatal suture split,[12] found that there was 8-9.8° of alveolar tipping.[50]

Among the three groups, BTAME suture opening from anterior to posterior in axial plane was closest to parallel with no significant differences between the four sagittal tooth levels. Still, suture opening at the second molar level was 82% that of first premolar level. In a previous study, Cantarella et al reported suture opening at PNS was 90% that of ANS, which was nearly parallel, in Maxillary Skeletal Expander (MSE), a BTAME appliance.[44] On the other hand, Oh et al reported the percentage was 72% in MSE.[31] Cantarella et al[44] attributed parallel suture opening to favorable biomechanics in which separation force could be distributed along the entire suture length as a result of bicortical engagement of miniscrews in the posterior part of the palate where resistance is greatest.[5,42,51] This may explain why suture opening was more parallel in BTAME than in BAME or SRBAME in the present study. In BTAME, miniscrews were placed in a posterior position independent of tooth root positions. In contrast, the placement of miniscrews in BAME and SRBAME depended on position of the premolars and first molar, resulting in more anterior placement than in BTAME. Anterior suture opening was significantly greater than posterior suture opening in BAME and SRBAME. Some studies on bone-anchored expanders reported wider suture opening anteriorly[21,31] while others reported near parallel suture opening.[27,28] Although conclusions were different, these studies agreed that anterior suture opening is greater, to variable degree, than posterior suture opening. This pattern of suture opening is also well-reported in conventional, tooth-borne RPE in growing patients.[18,52,53] Results in SRBAME may depend on the surgical technique and osteotomies completed. Loddi et al[54] reported parallel opening in Haas and hyrax expanders with SARPE while Goldenberg et al[55] reported nonuniform expansion with greater expansion in the anterior portion of maxilla using hyrax expander with SARPE. Pterygomaxillary separation was not performed in the latter study.

There was significant expansion of the Nasal Cavity (NC) in BTAME and BAME. Previous studies have reported significant increases in nasal cavity width after bone-anchored expansion[28] and conventional tooth-anchored RPE.[10,45,56] A case report found an apnea/hypopnea index (AHI) decrease from 7.9 to 1.5 after MSE, a BTAME appliance.[5] Nasal cavity expansion was greater in BAME than in BTAME with significance at the first and second premolar levels.

This was an unexpected finding because of biomechanical considerations in BTAME regarding bicortical engagement of miniscrews reported by Lee et al.[42] This finding may be attributed to the younger age in BAME because nasal changes are more likely to occur in younger patients. Baccetti et al reported that patients treated with RPE before pubertal peak showed significantly greater short-term and long-term increases in width of nasal cavities compared with patients during or slightly after pubertal peak.[57] In SRBAME, NC expansion could only be evaluated at the second molar level, in which there was a significant increase. Previous studies have confirmed increase in nasal cavity width after bone-borne surgically assisted rapid palatal expansion.[33] Location of osteotomy may affect the degree and location of nasal cavity expansion.

Contribution of skeletal expansion (S) to dental crown expansion (PCR-PCL) was significantly greater in the BAME (78.6%) than BTAME (61.9%) group at the first molar level. This may be attributed to differences in age and anchorage approaches between the two groups. BTAME's higher mean age suggested that the group had greater skeletal maturity with higher resistance to orthopedic expansion with midpalatal suture opening.[10,12] In addition, risk for dental consequences was greater with anchor teeth.[32,38] Previous studies have reported more favorable skeletal contribution in bone-anchored expansion than in expansion involving tooth anchorage in adolescence. Oh et al reported that contribution of skeletal expansion to intermolar width increase was 81% and 73% in BAME and BTAME equivalents respectively.[31] Celenk-koca et al reported that the percentage was 26% and 68% in hyrax and bone-borne expander, respectively.[28] Further studies comparing the dental relative to skeletal changes in BAME and BTAME approaches used in late adolescence and young adulthood are recommended.

Cone beam computed tomography (CBCT) is the most common method used in studies regarding maxillary expansion because of its many advantages. Unlike previously used methods such as dental casts, posterior-anterior cephalograms, or lateral cephalographs, CBCTs allow for three-dimensional manipulation to quantify structural changes and offer high dimensional accuracy, improving reproducibility and reliability of measured skeletal and dental changes.[58] In addition, advances in CBCT technology allow for imaging with lower radiation exposure to the patients.[59] Thus, the present study used pre- (T1) and post-expansion (T2) CBCTs to evaluate transverse changes in three different approaches of miniscrew assisted rapid palatal expansion (MARPE).

The retrospective design of the present study posed several limitations. First, as discussed previously, mean age in the BAME group was lower than in the BTAME group. The difference in age was significant because patients in the BAME group were more likely to be skeletally immature while those in the BTAME group were more likely to have completed growth. Although many studies show that obliteration of midpalatal suture in radiographs do not correlate with chronologic age[14,16] and histology of the suture is similar in individuals aged 10 to 30 years,[15] it is well-understood in the literature that resistance to expansion occurs largely from the influence of the zygomatic buttress and pterygopalatine junction.[5,20] Thus, results may have been affected in two ways: 1) growth may have played a minor role in T1-T2 changes in younger samples and 2) there may be less resistance to skeletal expansion in younger patients. Second, there were limitations to the field of view that would offer skeletal measurements and stable structures for reference. In order to account for this limitation, the present study did not evaluate expansion of structures superior to the widest portion of the nasal cavity and used dental references utilized in similar, previous studies.[21,27,34] Third, there was no control over amount of completed expansion in the groups. In order to account for this limitation, the data was standardized to reflect change per mm of suture opening at the first molar level for intergroup comparisons. Fourth, there were slight variations in design and miniscrew placement in the BTAME group. Two of the BTAME samples used the first premolars (palatal mesh) and first molars (bands) as anchor teeth while the others only used the first molars. Expander body, and vertical and coronal placement of miniscrews were consistent in BTAME samples. The slight variation in appliance design may have affected results but still provided valuable information regarding effects of combining skeletal and dental anchorage in MARPE. Lastly, information on surgical techniques in the SRBAME group was limited. Number and location of osteotomies may have affected results.[54,55] Given the limitations, the present study presents preliminary results to guide future studies on this topic. Better controlled, prospective studies are recommended to guide clinical decision making.

Small sample sizes resulted in low power to detect small but significant differences especially in multiple group comparisons involving post-hoc testing. A two-group equivalent was predetermined for each multiple group comparison. In the comparison of expansion at NC vs. A+5 vs. A vs. A-5, a two-group equivalent of A vs. A-5 was selected because these measurements consistently represented dentoalveolar changes. The A+5 measurement fell close to the zygomatic bone in some samples depending on the height of the alveolar process. In the comparison of expansion or tipping at first premolar vs. second premolar vs. first molar vs. second molar, first premolar vs. second molar was selected because these measurements represented the anterior-most vs. posterior-most sagittal levels, respectively. In the comparison of BTAME vs. BAME vs. SRBAME, BTAME vs. BAME was selected because it represented two different anchorage approaches to MARPE. BAME vs. SRBAME was also selected because it represented BAME appliance with and without surgical intervention, respectively. These two-group comparisons could provide more meaningful information to guide future studies. Future studies should include more samples in each group.

Chapter 5) Conclusion

Dental Changes:

- Apical expansion was greater in BAME than BTAME even without tooth anchorage.
- Both BTAME and BAME exhibited asymmetrical dental inclination changes on right and left sides.
- Both BTAME and BAME exhibited significant dental buccal tipping. The greatest dental tipping occurred in BTAME first molars, which were anchor teeth.
- Contribution of skeletal expansion to intermolar width increase of the first molar was more favorable in BAME (78.6%) than in BTAME (61.9%).

Nasal Cavity, Suture, and Alveolar Changes:

- Nasal Cavity expansion was greater in BAME than in BTAME.
- Among the three groups, BTAME suture opening was closest to parallel but still, suture opening at second molar level was 82% that of first premolar.
- All three groups exhibited buccal alveolar tipping. BAME resulted in greater alveolar tipping than BTAME. Anterior and posterior alveolar tipping did not differ significantly in BTAME, BAME, or SRBAME.

Overall

- BTAME, BAME, SRBAME are all effective in providing significant orthopedic transverse expansion but there are some dentoalveolar effects. BTAME resulted in greater buccal dental tipping while BAME resulted in greater buccal alveolar tipping.
- The present study's preliminary results show no apparent benefit of including tooth anchorage in MARPE.
- Future studies should include greater sample size with same age among groups.

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