THE SHORT-TERM SKELETAL AND DENTOALVEOLAR EFFECTS OF OVEREXPANSION: A RANDOMIZED CONTROLLED TRIAL

A Thesis

by

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ABSTRACT

The purpose of this study was to compare the skeletal and dentoalveolar effects of expansion in patients who are overexpanded (9-12 mm of RPE screw activation) with patients who are expanded conventionally (minimum of approximately 4 mm of RPE screw activation).

This randomized controlled trial included 23 patients (12 males, 11 females) aged 11.3 to 16.2 years (mean 13.5 years), who had RPE planned as part of their orthodontic treatment. Subjects were randomly assigned to the conventional expansion control group (n=12) or the overexpansion experimental group (n=11). CBCT scans were obtained prior to RPE delivery (T1) and after expansion was complete (T2). Linear and angular skeletal and dentoalveolar measurements were made using the CBCT images to evaluate the effects of RPE and to compare the changes between groups.

Final results were available for 21 subjects. Mean screw expansion was 5.7 ± 1.2 mm in the conventional group and 9.9 ± 0.5 mm in the overexpansion group ($p<0.001$). Overexpansion produced significantly greater amounts of skeletal expansion at the nasal cavity (p=0.002-0.004) and maxillary base (p=0.009), as well as greater increases in intermolar width ($p<0.001$) and molar inclinations (p=0.007-0.013). Skeletal expansion was moderately correlated with appliance activation (r=0.55-0.65). Dental expansion was strongly correlated with appliance activation (r=0.94) and the relationship was approximately 1:1. Expansion of the nasal cavity and maxillary base ranged from 22-32%, with slightly greater percentages observed in the overexpansion group (p=0.222-0.384). The percentages of skeletal expansion obtained were highly variable and were negatively correlated with skeletal maturity (r=-0.47 to -0.64) and skeletal age (r=-0.46 to -0.70).

Overexpansion leads to greater amounts of skeletal and dental expansion than conventional expansion. Skeletal expansion is moderately correlated with appliance activation. Dental expansion is very strongly correlated with appliance activation and increases in intermolar width are approximately equal to screw expansion. Expansion of the nasal cavity and maxillary base amount to 20-33% of screw activation. There is a large degree of individual variability in the proportion of skeletal expansion obtained, and this percentage is inversely related to skeletal maturity. The effects of RPE treatment are greater inferiorly than superiorly.

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Contributors

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The statistical analyses depicted in Section 3 were completed with the assistance of Dr. Buschang of the Department of Orthodontics.

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NOMENCLATURE

ABInc_IR	Alveolar bone inclination (inner right)
ABInc_IL	Alveolar bone inclination (inner left)
ABInc_OR	Alveolar bone inclination (outer right)
ABInc_OL	Alveolar bone inclination (outer left)
ANW	Anterior nasal width
GPFW	Greater palatine foramina width
IMW	Intermolar width
MInc_R	Molar inclination (right)
MInc_L	Molar inclination (left)
Mx_NF	Maxillary width (nasal floor)
Mx_AC	Maxillary width (alveolar crest)
PNW	Posterior nasal width
RPE	Rapid palatal expansion

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1. INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Rapid palatal expansion (RPE) has been utilized as an adjunct to traditional orthodontic treatment for over 150 years.[1] Over the course of that time, RPE has been advocated for a variety of problems, including posterior crossbites, transverse and anteroposterior maxillary deficiencies, and mild to moderate crowding.[2-10] Palatal expansion appliances exert orthopedic and orthodontic forces on the maxilla and its associated structures, resulting in both skeletal and dentoalveolar effects. Rapid expansion is often preferred to slow expansion because it is thought to maximize the skeletal correction while minimizing dental alterations.[4, 11-13] The orthopedic and orthodontic responses to RPE have been described to occur in the following order – compression of the periodontal ligament, bending of the alveolar processes and tipping of the maxillary posterior teeth, and finally separation of the midpalatal suture.[4, 5, 7, 11]

Various techniques have been employed in an attempt to calculate the orthopedic and orthodontic effects of RPE. In the past, this commonly involved the use dental casts and radiographs.[2, 3, 5-10, 13-25] These modalities pose inherent limitations and can lead to inaccurate measurements due to superimposition of objects in different planes of space and projection errors on radiographs.[26-30] The recent application of cone beam computed tomography (CBCT) in orthodontics has allowed for highly accurate three-dimensional visualization of the nasomaxillary complex with minimal distortion and relatively low radiation.[31-34] The skeletal response to RPE has been reported to typically amount to approximately 20% to 50% of the total changes, with various landmarks used for skeletal measurements.[7, 10, 15, 16, 20, 21, 24, 35-45] One method of quantifying the skeletal component of expansion is to compare it to the amount of dental expansion observed (Table 1).[10, 16, 41]

Table 1. Skeletal expansion percentages calculated as a proportion of dental expansion.

	Dental Expansion (mm)	Skeletal Location	Skeletal Expansion (mm)	Skeletal Expansion %
Cross et al, 2000	5.50	Nasal Cavity	1.06	19.3%
Cross et al, 2000	5.50	Maxillary Base	1.11	20.2%
Silva Fihlo et al, 1995	5.47	Nasal Cavity	2.08	38.0%
Kartalian et al, 2010	5.35	Maxillary Base	2.25	42.1%
Silva Fihlo et al, 1995	5.47	ANS	2.66	48.6%
Cross et al, 2000	5.50	ANS	3.19	58.0%

Another way to calculate the relative skeletal contribution of expansion is to compare it to the amount of appliance activation or screw expansion performed (Table 2).[15, 36, 38-40, 42-44]

Table 2. Skeletal expansion percentages calculated as a proportion of RPE screw expansion.

	Screw Expansion (mm)	Skeletal Location	Skeletal Expansion (mm)	Skeletal Expansion %
Pereira et al, 2017	8.00	Maxillary Base	1.76	22.0%
Podesser et al, 2007	7.00	Midpalatal Suture	1.60	22.9%
Chung et al, 2004	7.58	Nasal Cavity	1.75	23.1%
Podesser et al, 2007	7.00	Maxillary Base	1.70	24.3%
Kanomi et al, 2013	5.00	Nasal Cavity	1.28	25.6%
Chung et al, 2004	7.58	Maxillary Base	2.28	30.1%
Baratiera et al, 2014	7.00	Nasal Cavity	2.11	30.1%
Garib et al, 2005	7.00	Maxillary Base	2.60	37.1%
Garrett et al, 2008	5.08	Nasal Cavity	1.89	37.2%
Weissheimer et al, 2011	8.00	Maxillary Base	3.10	38.8%
Weissheimer et al, 2011	8.00	Midpalatal Suture	3.14	39.3%
Garrett et al, 2008	5.08	Midpalatal Suture	2.55	50.2%

Greater skeletal response to RPE is important because the dental component of expansion has been demonstrated to relapse anywhere from 17% to 56% following fixed retention.[17-19, 22, 23, 25, 46, 47] Skeletal expansion, on the other hand, has been shown to be relatively stable with minimal, if any, relapse reported in the literature.[8, 21]

The most predictable way to achieve a favorable orthopedic response is to perform expansion prior to or during the pubertal growth spurt.[3, 4, 11, 13, 21, 45, 48, 49] Given the progression of expansion events described previously, it is reasonable to hypothesize that after the force threshold required to separate the midpalatal suture is achieved, true skeletal expansion predominates and dentoalveolar effects are limited. If this is the case, continued RPE activation should translate into sustained sutural opening, and thus, a greater skeletal response.

A limited amount of overexpansion, ranging from 2 to 4 mm, has been previously recommended to account for the expected post-retention relapse.[4, 10, 13, 41, 50-53] Haas[5-8] was an advocate of even greater overexpansion. He believed that, for good orthopedic technique, the mandibular arch should be completely contained by the maxillary arch at the completion of RPE treatment, and that 10 mm should be considered minimum and 12 mm considered average expansion.[8] Despite this claim, the effects of overexpanding to this magnitude has not been evaluated. Further investigation is needed to determine whether this amount of overexpansion leads to a statistically and clinically significant increases in the absolute and relative amount of skeletal expansion following RPE treatment.

The aim of the present study is to compare the skeletal and dentoalveolar effects of expansion in patients who are overexpanded (9-12 mm of screw activation) with patients who are expanded conventionally until the lingual cusps of maxillary posterior teeth lie along the incline of the buccal cusps of the mandibular posterior teeth (minimum of approximately 4 mm of screw activation).

1.2. Problem and Significance

Rapid palatal expansion (RPE) elicits both orthopedic and orthodontic responses throughout the nasomaxillary complex. The skeletal effects of expansion have typically been reported to make up 20% to 50% of the dentoalveolar effects or RPE activation.[7, 10, 15, 16, 20, 21, 24, 35-45] Skeletal modifications are more stable than the corresponding dental component,[8, 21] which has been shown to relapse up to 56% of the initial expansion in intermolar width.[17-19, 22, 23, 25, 46, 47] Since the amount of skeletal change accompanying expansion is relatively limited compared to what is observed dentally, it is critical that clinicians are able to maximize this orthopedic expansion when performing RPE in order to achieve stable results.

Given the described progression of expansion events – compression of the periodontal ligament, bending of the alveolar processes, tipping of the anchor teeth, and finally separation of the midpalatal suture[4, 5, 7, 11] – it seems reasonable to hypothesize that once the force threshold required for orthopedic movement is surpassed, continued application of transverse forces from the RPE appliance will act to further open the midpalatal suture with limited dentoalveolar side effects. If so, this would result in a greater skeletal response than if RPE activation had been ceased shortly after sutural opening. While there have been several studies that have attempted to quantify the orthodontic and orthopedic contributions to maxillary expansion, no study in the existing literature has examined the effects of the proposed amount of expansion or compared the skeletal and dental effects of RPE in patients who underwent vastly different amounts of appliance activation.

Therefore, it would be worthwhile to investigate whether overexpansion leads to a statistically and clinically significant greater amount of orthopedic expansion when compared to conventional RPE treatment. The results of this study could give clinicians valuable information that leads to more effective expansion treatment with increased long-term stability.

1.2.1. Objectives

The purpose of this study is to evaluate the skeletal and dentoalveolar effects of expansion in patients who are overexpanded (9-12 mm of RPE screw activation) compared to the effects observed in patients wo are expanded conventionally (minimum of approximately 4 mm of RPE screw activation).

1.2.2. Hypotheses

Null Hypotheses:

1. There is no difference in the amount of skeletal expansion observed in the overexpansion group compared to the conventional expansion group.
2. This is no difference in the percentage of skeletal expansion observed in the overexpansion group compared to the conventional expansion group.

1.3. Literature Review

Expansion of the midpalatal suture is one of the oldest and most widely used adjuncts to orthodontic treatment. The procedure was first reported in 1860 by Angell,[1] who simply fabricated a jackscrew across the roof of a patient's mouth with its ends abutting against the premolars. After losing favor in the United States for a period in the late 19th century, the technique regained popularity in the mid 20th century and has been commonly used since. Palatal expansion has been indicated for a variety of conditions in the orthodontic literature, including real or relative maxillary deficiencies, unilateral or bilateral posterior crossbites, Class II cases, Class III cases, mild to moderate tooth size-arch length discrepancies, cleft palate patients, and cases of nasal stenosis.[2-10]

Two opposing ideologies eventually emerged with regard to the rate of palatal expansion. Slow expansion techniques utilize low continuous forces ranging from several ounces to 2 pounds[4, 11, 50, 54, 55] to achieve approximately 0.5 to 1.0 mm of expansion per week.[11, 53, 55-57] These lighter forces do not have the power to overwhelm the tensile strength of the sutural elements and result in an increased percentage of orthodontic movements.[11, 55, 57] Skeletal changes are reported to be between 16% and 30% of total changes and vary with age.[4, 11, 55, 56]

With rapid expansion, orthopedic and orthodontic forces are distributed throughout the nasomaxillary complex. Proponents of rapid expansion contend that it maximizes skeletal effects and minimizes dentoalveolar effects.[4, 11-13] Expansion typically occurs at a rate of about 0.2 to 0.5 mm per day during active treatment.[4, 11] Isaacson and Ingram[12] reported that single activations of RPE appliances transmit forces ranging from 3 to 10 pounds, and that multiple daily activations can result in cumulative loads of 20 pounds or greater. Maxillary expansion occurs as the force delivered from the appliance progressively increases through the range causing orthodontic movement of the teeth and alveolar processes before ultimately exceeding the threshold required to act as an orthopedic force to separate the midpalatal suture.[4]

Upon application of the transverse biomechanical force from the RPE appliance, the initial response of the maxillary complex involves compression of the periodontal ligament, lateral bending of the alveolar processes, and buccal tipping of the posterior maxillary teeth.[4, 5, 7, 11, 57-61] This early orthodontic response appears to be essentially completed within the first week of appliance activation.[11, 57, 60] Subsequent orthodontic movements take place in the form of bodily translation as the buccal alveolar plate resorbs with continued force application.[11, 57, 59, 62] If this force reaches sufficient magnitude to overcome the bioelastic strength of the midpalatal suture, separation of the palatal segments is observed.[4, 11, 12, 57-61, 63] This orthopedic expansion will continue until the distribution of forces is reduced below the tensile strength of the sutural elements.[11, 12, 57, 63] Following the cumulative application of this high magnitude force, it is important to leave the RPE appliance in place in order to initially allow the residual load within the maxillary complex to dissipate,[8, 11, 64] and eventually reorganization and remodeling of the connective and skeletal tissues to occur.[11, 51, 57, 58, 65] A fixed retention period of 3 to 6 months has been recommended in order to achieve stabilization of the expanded maxillary complex.[4, 7, 11, 51, 57]

Various techniques have been employed in an attempt to quantify the orthopedic and orthodontic effects of RPE. Several studies used dental casts to make pre- and post-expansion measurements.[2, 5-9, 13, 17-25, 47] This method poses the obvious limitation of only allowing visualization and measurement of external structures, namely the crowns of the teeth and their supporting soft tissues. Radiography allows the additional benefit of assessing skeletal structures in addition to making dentoalveolar measurements. When analyzing the effects of expansion in the transverse dimension, posteroanterior (PA) cephalograms and occlusal radiographs have been utilized.[3, 5, 6, 10, 13, 14, 16, 24, 28] However, these 2-dimensional radiographs can lead to inaccurate landmark identification and measurements due to the superimposition of structures in different planes of space and projection errors inherent to radiography.[26-30] The more recent advent of cone beam computed tomography (CBCT) in orthodontics has allowed for three-dimensional visualization of the maxillofacial hard tissues with minimal distortion and relatively low radiation. The high accuracy of CBCT for quantitative analyses has been demonstrated.[31-34]

In an early attempt to compare the dental and skeletal effects of RPE, Krebs[20, 21] placed metal implants in the hard palates and zygomatic processes of patients and analyzed the changes in distance between the implants before and after expansion using PA cephalograms. The mean expansion in the maxillary base of 2.3 mm made up 38.3% of the expansion observed dentally (6.0 mm). Krebs[21] also noted a decreasing percentage of maxillary base expansion with increasing age and skeletal maturity.

These findings have been validated by subsequent studies. The reported skeletal response to RPE typically accounts for 20% to 50% of total changes, with various landmarks used for skeletal measurements.[7, 10, 15, 16, 20, 21, 24, 35-45] Percentages of skeletal expansion can be calculated either as a proportion of dental expansion[10, 16, 41] or as a proportion of screw expansion.[15, 36, 38-40, 42-44]

In addition to the relatively limited skeletal contribution when compared the overall effects, another area of concern for clinicians when performing expansion is relapse, which has been demonstrated to occur following palatal expansion. This inevitable reduction in the maxillary transverse dimension initially obtained must be accounted for by the clinician when planning for the long-term stability of the expansion performed. In a seven-year follow-up to his implant study, Krebs[21] found that once retention was discontinued following expansion, there was a reduction in dental arch width that often continued for up to 5 years. In subsequent studies, this dental relapse has been calculated to amount to a 17% to 56% reduction in intermolar width from post-treatment to long-term retention.[17-19, 22, 23, 25, 46, 47] On the other hand, Krebs[21] found that the skeletal maxillary base experienced minor relapse of about 0.5 mm in the first 3 to 4 months during retention, but stabilized thereafter or actually increased with growth. Haas[8] also reported no reduction in apical base width at long-term post-retention.

The relative stability of skeletal, compared to dentoalveolar, expansion is the reason it is considered ideal to maximize this component during RPE treatment. It has been reported that the most predictable way to achieve a favorable orthopedic response is to perform maxillary expansion prior to or during the pubertal growth spurt.[3, 4, 11, 13, 21, 45, 49] Revelo and Fishman[49] reported that the ideal time to begin orthopedic expansion is during early maturation stages, SMI 1 to 4. The authors also recommended that if separation of the midpalatal suture is desired, it should be accomplished by SMI 9, as the suture is only 26.5% fused at this point, but increases sharply to 45.1% fused at SMI 10. Baccetti et al[3] concluded that patients treated with RPE prior to the pubertal growth peak (CVM stages 1-3) demonstrate more significant and effective long-term skeletal changes than those treated afterwards (CVM stages 4-6). Unfortunately, this is not always possible, as some patients present to the clinician for treatment after this stage. Since it has been noted that the bending of the alveolar processes and tipping of the posterior teeth occur early during expansion treatment,[4, 5, 11, 57-61] it is reasonable to hypothesize that after the initial force required to separate the midpalatal suture is achieved, true skeletal expansion predominates with limited dentoalveolar effects. If this is the case, continued application of transverse forces from the RPE will translate into sustained sutural opening, and thus a greater orthopedic response.

The existing RPE literature utilizing 3-dimensional CT and CBCT technology was analyzed to evaluate the skeletal and dentoalveolar effects of RPE and to attempt to determine if a relationship exists between the amount of skeletal expansion achieved and the amount of appliance expansion performed.

Garrett et al[39] reported 38% orthopedic expansion, 49% orthodontic tooth movement, and 13% alveolar bending at the first molar level following an average appliance expansion of 5.08 mm. Additionally, the study found significant positive correlations of the amount of sutural expansion ($r = 0.64$) and increase in palatal maxillary width ($r = 0.72$) at the first molar level with the amount of appliance expansion, suggesting the possibility of increased skeletal expansion with greater appliance activation. The authors also demonstrated a general trend of greater sutural expansion and increase in palatal maxillary width anteriorly than posteriorly, supporting previous claims.

Although it is difficult to directly compare studies due to differences among the parameters measured, the most common landmarks used to measure orthopedic expansion were found to be the midpalatal suture, maxillary base, and nasal cavity. The relevant data was organized and grouped based on these three measurements for more comprehensive analysis.

When evaluating opening of the midpalatal suture at the level of the maxillary first molars, Garrett et al[39] reported a mean increase of 2.55 mm (52.9%) following a mean screw expansion of 5.08 mm. Podesser et al[35] reported an average opening of 1.6 mm (22.9%) following 7 mm of RPE activation. Weissheimer et al[37] found a mean increase of 3.14 mm (39.3%) after 8 mm of hyrax expander screw activation.

When measuring maxillary base width at the level of the maxillary first molars, Podesser et al,[43] Garib et al,[38] and Baratiera et al[36] all reported 7 mm of screw expansion, with a corresponding 1.7 mm (24.3%), 2.6 mm (37.1%), and 2.65 mm (37.9%) of skeletal expansion, respectively. Pereira et al[42] and Weissheimer et al[44] both conducted 8 mm of screw activation, resulting in 1.76 mm (22.0%) and 3.1 mm (38.8%) increases in maxillary base width, respectively.

Finally, when measuring nasal cavity width, Kanomi et al[40] reported a 1.28 mm (25.6%) increase following 5 mm of RPE activation. Garrett al[39] reported a mean increase in nasal width of 1.89 mm (37.2%) with a mean screw expansion of 5.08 mm. Baratiera et al[36] expanded all patients 7 mm and found a resulting mean increase in nasal width of (30.1%).

After analyzing the relevant CT and CBCT literature relating to RPE, a few noteworthy conclusions can be made. First, the reported orthopedic contribution following expansion in the studies evaluated ranges from 22% to 53%,[36, 38-40, 42-44] with various landmarks used to make the skeletal measurements. In general, the current literature also supported previous claims of the non-parallel nature of expansion, with greater skeletal expansion demonstrated anteriorly than posteriorly and inferiorly than superiorly. No consistent pattern is evident between the amount of appliance activation and subsequent skeletal expansion for any of the parameters evaluated. However, the range of RPE screw activation reported in the existing literature is fairly limited, ranging from 5 to 8 mm. Thus, even if a relationship exists, it would be difficult to detect. Garrett et al[39] found positive correlations between sutural expansion and appliance expansion (r=0.64) and between buccal maxillary width and appliance expansion (r=0.63) at the level of the first molars. This provides a basis for the idea that increased total expansion may lead to increased skeletal expansion.

Several authors in the past have recommended a limited amount of overexpansion, typically ranging from 2 to 4 mm, to account for the expected post-retention relapse.[4, 10, 13, 41, 50-53] Haas,[5-8] considered by most in the field of orthodontics to be one of the pioneers of and authorities on maxillary expansion, was one of the earliest and most outspoken proponents of even greater overexpansion. In 1980,[8] he wrote, "I wish to emphasize that good orthopedic technique demands that most, if not all, of the rapid palatal expansion cases should have the mandibular arch completely contained by the maxillary arch at the conclusion of the procedure. One of the greatest errors made is that too often clinicians do not carry the expansion far enough. Ten millimeters should be considered minimum and 12 millimeters should be considered average expansion, as that increment of expansion due to alveolar bending, periodontal membrane compression, lateral tooth displacement, and tooth extrusion will most assuredly be lost." In this same publication, Haas[8] reports 10 cases with average increases of 9 mm in apical base width and 4.5 mm in nasal cavity width that remained completely stable after 6 to 14 years without upper retention. Additionally, Dr. Phillip Campbell, former Chair of the Department of Orthodontics at Texas A&M College of Dentistry, routinely conducted expansion of 12 mm or greater on patients throughout his 32 years in private practice. Dr. Campbell remains a staunch advocate of the procedure and reports stable long-term results with no deleterious effects.

After examining the current orthodontic literature, it is apparent that no well controlled studies exist that evaluate the relationship between RPE screw expansion and skeletal expansion. Additionally, no studies have examined the skeletal and dentoalveolar effects of the magnitude of overexpansion proposed in the present study. Therefore, it would be worthwhile to investigate whether this proposed overexpansion leads to a statistically and clinically significant increased amount of skeletal expansion following RPE treatment.

2. MATERIALS AND METHODS

A randomized controlled trial was designed to evaluate the effects of overexpansion in orthodontic patients. The study included patients recruited at the Graduate Orthodontic Clinic at Texas A&M College of Dentistry, who had rapid palatal expansion planned as part of their orthodontic treatment.

To be eligible for inclusion in the study, patients had to be 16 years old or younger, in the late mixed or early permanent dentition, and require a minimum of approximately 4 mm of palatal expansion. Patients were excluded from participation if they had pre-treatment hypodontia, if they presented with cleft palate or any other craniofacial anomaly, or if their treatment plan involved the use of an additional appliance, such as a Herbst, in conjunction with RPE.

Subjects in the control group were to be expanded conventionally until the palatal cusps of maxillary posterior teeth lie along the lingual incline of the buccal cusps of the mandibular posterior teeth. Subjects in the experimental group were to be overexpanded until the RPE screw could longer be activated.

2.1. Appliance Design and Expansion Protocol

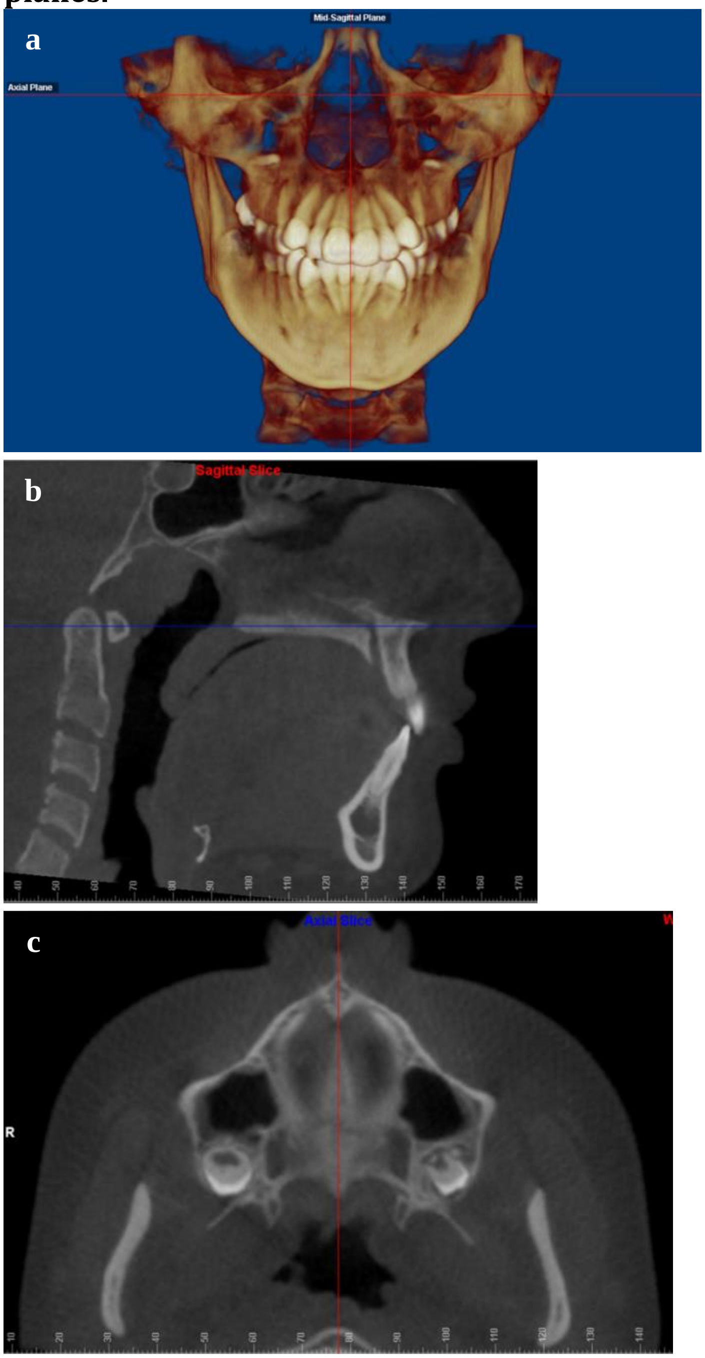
The RPE appliances used in the present study were hyrax expanders, with bands on the maxillary first molars and metal arms extending anteriorly to the second and first premolars, or deciduous molars, if applicable. The appliances were all fabricated by the same laboratory technician, and utilized 10 or 12 mm expansion screws. The expanders were cemented by the resident treating the case, under supervision of the attending faculty member. Subjects were instructed to turn the expansion screw one time per day (0.25 mm activation) for the specified interval. Study participants were also provided with a checklist to track of each turn of their expander daily (Appendix A). Expansion was monitored by the treating resident, attending faculty, and study operator at each scheduled orthodontic appointment. When expansion was determined to be complete, screw expansion was measured intraorally to the nearest hundredth of a millimeter using digital calipers. All screw expansion measurements were taken twice and the average of the two measurements was used for the purposes of the study.

2.2. CBCT Methodology

In order to quantify the skeletal and dental effects of expansion, 11 cm CBCT scans were obtained prior to RPE delivery (T1) and after expansion was complete (T2). The CBCT scans were taken at Texas A&M College of Dentistry's Oral and Maxillofacial Imaging Center using an i-CAT FLX unit (Imaging Sciences International, Hatfield, PA) at 0.3 mm^3 voxel size with a pulsed scan time of 8.9 seconds. Image volumes generated by the scans were saved in the Digital Imaging and Communications in Medicine (DICOM) format and imported into Dolphin 3D software (version 11.9, Dolphin Imaging & Management Solutions, Chatsworth, CA).

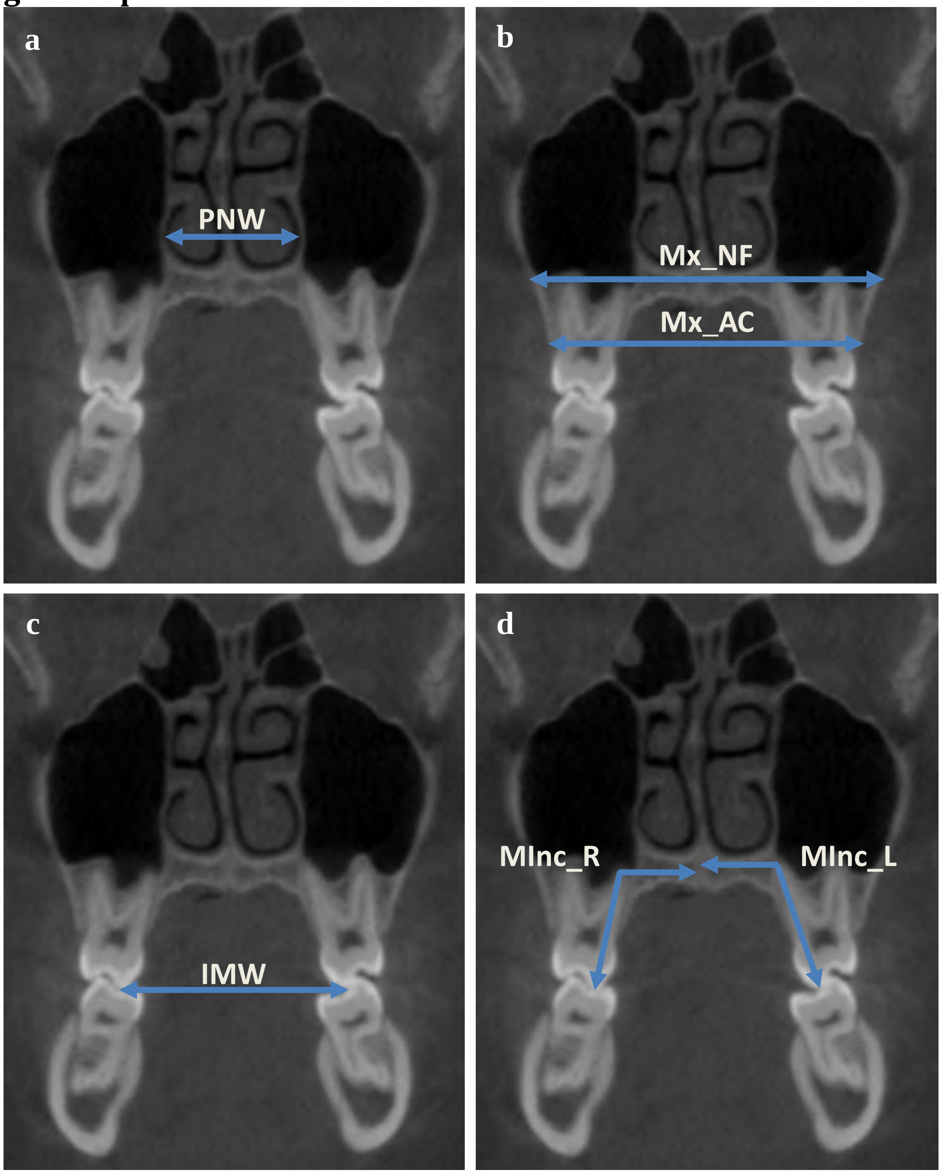
The CBCT scans were oriented systematically in all three planes for consistency of measurements as follows. In the coronal view, the floors of the right and left orbits were oriented along the true horizontal (Figure 1a). In the sagittal plane, ANS and PNS were oriented along the true horizontal (Figure 1b). In the axial plane, the midpalatal suture was oriented along the true vertical (Figure 1c).

Figure 1. Orientation of CBCT scans in the a) coronal, b) sagittal, and c) axial planes.



After orientation, the coronal slice passing through the center of the palatal root of the maxillary first molars was identified for both the right and left sides and linear and angular skeletal and dentoalveolar measurements were made.[38, 41, 43] Posterior nasal width (PNW) was measured as the width at the widest portion of the nasal aperture at the level of the first molars (Figure 2a).[36, 39] Maxillary basal width was measured as the distance between the cortical plates of the maxilla at the levels of the nasal floor (Mx_NF) and the buccal alveolar crest (Mx_AC) (Figure 2b).[36, 38, 41-44] Maxillary intermolar width (IMW) was measured as the distance between the palatal cusp tips of the maxillary first molars (Figure 2c).[38, 41] Maxillary molar inclination (MInc_R and MInc_L) was measured as the angle formed by the intersection of the line connecting the palatal cusp tip and root apex of the maxillary first molars and the true horizontal (Figure 2d).[41, 66] Alveolar bone inclination was measured as the angle formed by the intersection of the line approximating the outer cortical plate of alveolar bone and the true horizontal.[41, 66] This angle was measured for both the inner (ABInc_IR and ABInc_IL) and outer (ABInc_OR and ABInc_OL) alveolar bone (Figures 2e and 2f). In order to measure skeletal expansion at a level anterior to the first molars, anterior nasal width (ANW) was measured on a coronal slice through the center of the incisive foramen (Figure 2g).[67] Alternately, to measure skeletal expansion posterior to the first molars, greater palatine foramina width (GPFW) was measured as the distance between the lateral margins of the greater palatine foramina on an axial slice through the center of the hard palate (Figure 2h).[67]

Figure 2. a) posterior nasal width, b) maxillary width at nasal floor, alveolar crest, c) intermolar width, d) molar inclination, e) inner alveolar bone inclination, f) outer alveolar bone inclination, g) anterior nasal width, h) greater palatine foramina width.



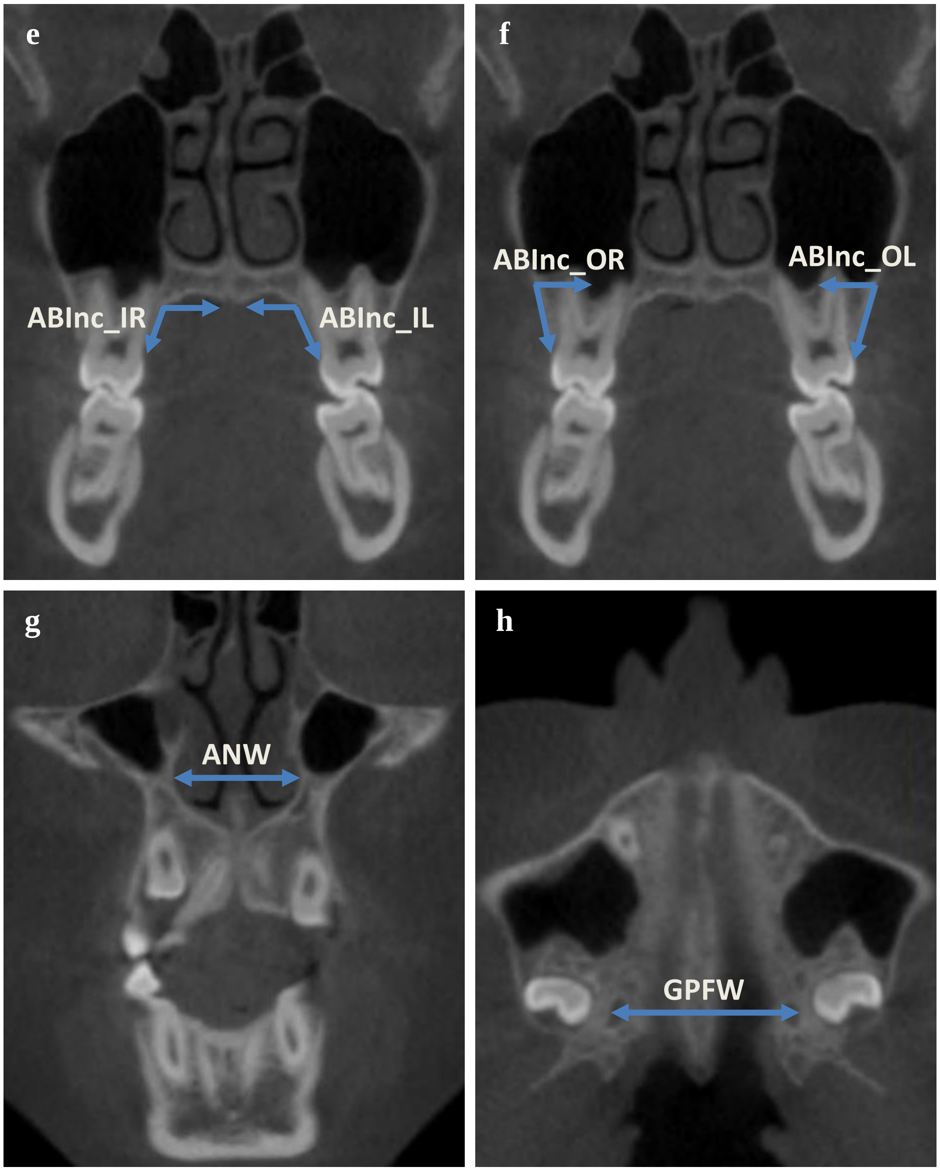


Figure 2. Continued.

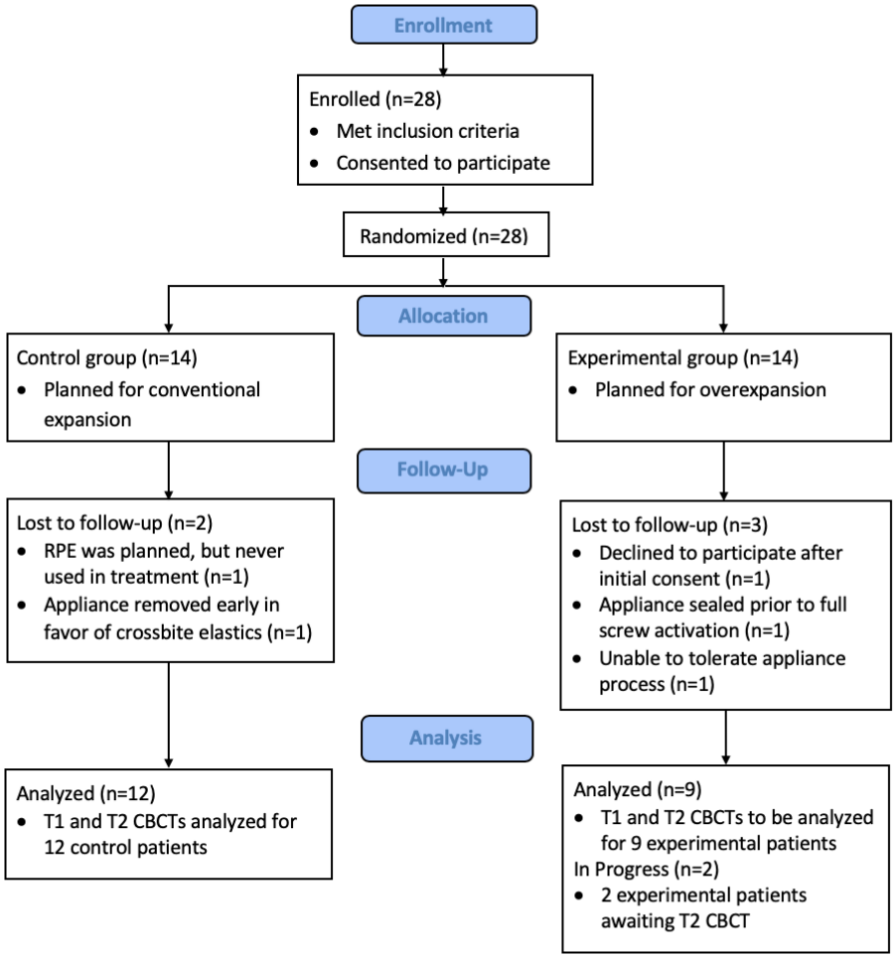
All measurements were made by the study operator. Blinding was not possible, as the amount of expansion performed could be visualized on the CBCT images. In order to evaluate reliability, 10 subjects were randomly selected and their CBCTs were re-oriented and re-measured. No statistically significant differences were found between measurements made at either timepoint for any of the described parameters. Method error ranged from 0.19 to 0.37 mm for linear measurements and from 0.20 to 1.24 degrees for angular measurements.

2.3. Patient Flow

To determine sample size, a power analysis was conducted, assuming a power of 90% and a type I error of 5%. The analysis yielded a desired sample size of 12 patients per group. It was determined that a total of 28 patients would be recruited to participate in the study in order to account for dropouts.

The study was approved by the Institutional Review Board at Texas A&M University (2017-0585-CD-FB). Twenty-eight patients and one of their parents or guardians consented to participate in the study. Subjects were randomly assigned to the conventional expansion control group (n=14) or the overexpansion experimental group (n=14) using the randomization function on Microsoft Excel software (version 16.0, Microsoft Corporation, Redmond, WA). Five patients dropped out during the course of the study, leaving a total 23 subjects (12 males, 11 females) for evaluation. Final results were available for 21 subjects (10 males, 11 females) for statistical analysis, with 2 subjects in the experimental group undergoing ongoing expansion. Patient flow through the study is shown in Figure 3.

Figure 3. Patient flow through study.



2.4. Group Distribution

The control group was composed of 12 subjects (5 males and 7 females), while the analyzed experimental group was composed of 9 subjects (5 males and 4 females). A Pearson chi-squared test indicated that there were no significant differences between groups with regard to sex distribution (χ^2=0.368).

The mean age of the conventional expansion group was 13.2 years (range 11.3-16.2 years), while the mean age of the overexpansion group was 13.9 (range 11.3 to 15.3 years). A hand-wrist radiograph taken at initial records was used to determine each participant's Fishman skeletal maturity indicator (SMI) and its associated skeletal age.[48] Independent t-tests indicated that there were no significant pre-treatment differences between the experimental and control groups with respect to age (p=0.287), SMI (p=0.241), or skeletal age (p=0.116).

2.5. Statistical Analysis

All statistical analysis was performed using IBM SPSS Statistics software (version 25.0, IBM Corporation, Armonk, NY). The significance level was set at 0.05 ($p<0.05$). Pearson chi-squared tests were used to determine group differences with respect to sex and age distribution. Descriptive statistics were calculated for all variables. Independent samples t-tests were used to compare the experimental and control groups at T1 and T2, as well as the changes from T1 to T2. Bonferroni corrections were used reduce the likelihood of making Type I errors. Pearson correlations were calculated to evaluate relationships between variables.

3. RESULTS

The mean amount of appliance activation performed in the conventional group during expansion was 5.7 ± 1.2 mm, while the mean screw expansion performed during treatment in the overexpansion group was 9.9 ± 0.5 mm. This difference was highly significant ($p<0.001$).

Independent t-tests demonstrated that there were no statistically significant between-group differences with respect to any of the variables at T1 (Table 3). At T2, there were statistically significant different between-group differences in anterior nasal width (ANW), maxillary width at the alveolar crest (Mx_AC), intermolar width (IMW), and right molar inclination (MInc_R) (Table2). After Bonferroni corrections, only the differences in ANW and IMW were significant.

Table 3. Comparison of the conventional expansion and overexpansion groups at T1.

	Units	Conventional Expansion		Overexpansion		Probability
		Mean	SD	Mean	SD	
ANW	**mm**	21.8	1.7	22.9	1.8	0.167
PNW	**mm**	27.6	3.5	27.1	1.1	0.647
Mx_NF	**mm**	63.6	4.7	64.0	2.8	0.841
Mx_AC	**mm**	57.7	3.5	59.5	2.8	0.204
GPFW	**mm**	30.3	2.5	30.5	1.8	0.873
IMW	**mm**	39.7	3.1	39.8	1.7	0.928
MInc_R	°	101.69	4.67	101.66	2.85	0.984
MInc_L	°	103.24	5.01	100.37	3.15	0.148
ABInc_IR	°	106.39	5.83	104.76	2.38	0.393
ABInc_IL	°	107.64	4.89	104.22	2.88	0.078
ABInc_OR	°	87.56	11.62	91.40	5.87	0.336
ABInc_OL	°	88.59	11.24	94.09	5.88	0.165

Table 4. Comparison of the conventional expansion and overexpansion groups at T2.

	Units	Conventional Expansion		Overexpansion		Probability
		Mean	SD	Mean	SD	
ANW	**mm**	23.3	1.3	26.0	1.3	< 0.001
PNW	**mm**	28.9	3.0	30.1	1.2	0.235
Mx_NF	**mm**	64.9	4.7	66.9	2.4	0.236
Mx_AC	**mm**	61.0	3.1	64.2	2.6	0.020
GPFW	**mm**	31.8	2.1	33.1	1.8	0.156
IMW	**mm**	45.4	3.0	50.1	2.4	0.001
MInc_R	°	105.2	4.3	110.8	6.6	0.027
MInc_L	°	105.4	4.9	107.1	5.1	0.456
ABInc_IR	°	109.6	7.7	110.7	5.0	0.717
ABInc_IL	°	112.8	6.6	112.1	5.4	0.791
ABInc_OR	°	93.7	9.8	97.1	5.4	0.358
ABInc_OL	°	93.1	8.6	100.4	6.8	0.051

The changes that occurred between T1 to T2 showed several statistically significant differences between the experimental and control groups (Table 5). Anterior nasal width (ΔANW), posterior nasal width (ΔPNW), maxillary width at the nasal floor, and intermolar width (ΔIMW) all increased significantly more in the overexpansion group. Between-group differences in greater palatine foramina width (ΔGPFW) were not statistically significant after Bonferroni adjustment. Changes in molar inclination (ΔMInc_R and ΔMInc_L) were also significantly greater in the overexpansion group. Outer and inner alveolar bone inclinations (ΔABInc_IR, ΔABInc_IL, ΔABI_OR, and ΔABI_OL) showed no statistically significant between-group differences.

Table 5. Comparison of changes from T1 to T2 for the conventional expansion and overexpansion groups.

	Units	Conventional Expansion		Overexpansion		Probability
		Mean	SD	Mean	SD	
ΔANW	**mm**	1.5	0.9	3.1	1.4	0.004
ΔPNW	**mm**	1.3	0.9	3.0	1.3	0.002
ΔMx_NF	**mm**	1.3	1.1	2.9	1.4	0.009
ΔMx_AC	**mm**	3.4	1.5	4.7	1.7	0.067
ΔGPFW	**mm**	1.5	0.9	2.6	1.2	0.022
ΔIMW	**mm**	5.7	1.4	10.3	1.1	< 0.001
ΔMInc_R	°	3.5	4.2	9.1	5.3	0.013
ΔMInc_L	°	2.2	3.1	6.7	3.8	0.007
ΔABInc_IR	°	3.2	5.5	5.9	5.7	0.285
ΔABInc_IL	°	5.2	3.1	7.9	4.8	0.136
ΔABInc_OR	°	6.2	6.4	5.7	4.7	0.869
ΔABInc_OL	°	4.5	6.1	6.3	3.5	0.449

When the five skeletal transverse measurements were evaluated as a proportion of screw expansion, there were no statistically significant between-group differences (Figure 4). However, there was a consistent pattern of between-group differences. Overexpansion led to a 5.1% greater increase in ANW, a 7.3% greater increase in PNW, and a 6.5% greater increase in Mx_NF. Conventional expansion led to a 9.9% greater increase in Mx_AC than overexpansion. Both groups exhibited about the same relative changes in GPFW, increasing approximately 26% of screw expansion. When evaluated as a proportion of dental expansion, between-group differences were very similar, but none were statistically significant (Figure 5).

Figure 4. Comparison of skeletal expansion percentages (measured as proportion of screw expansion) between the conventional expansion and overexpansion groups.

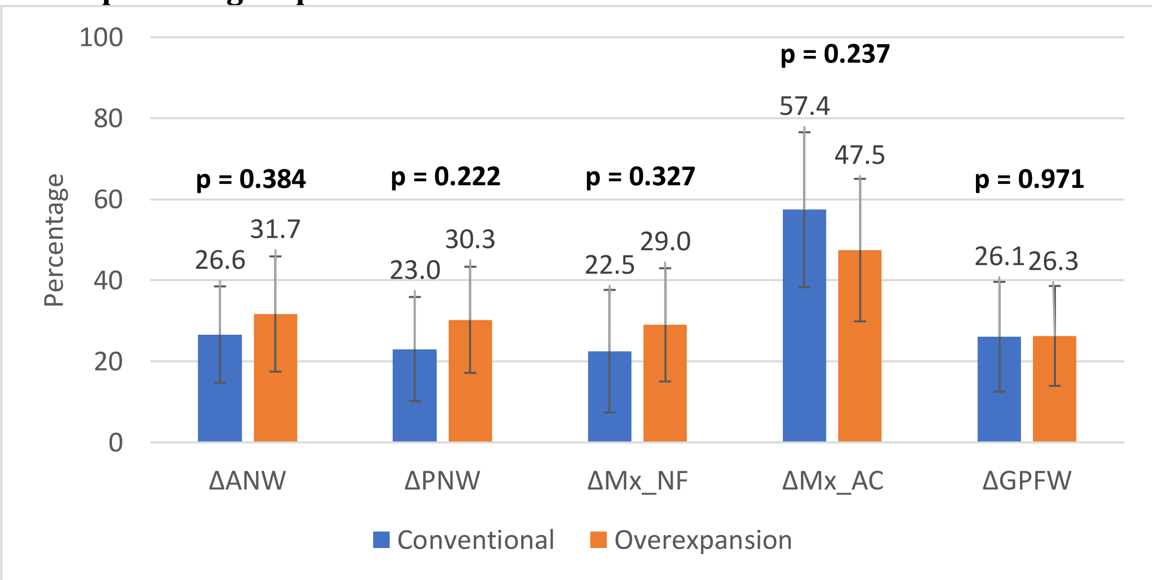
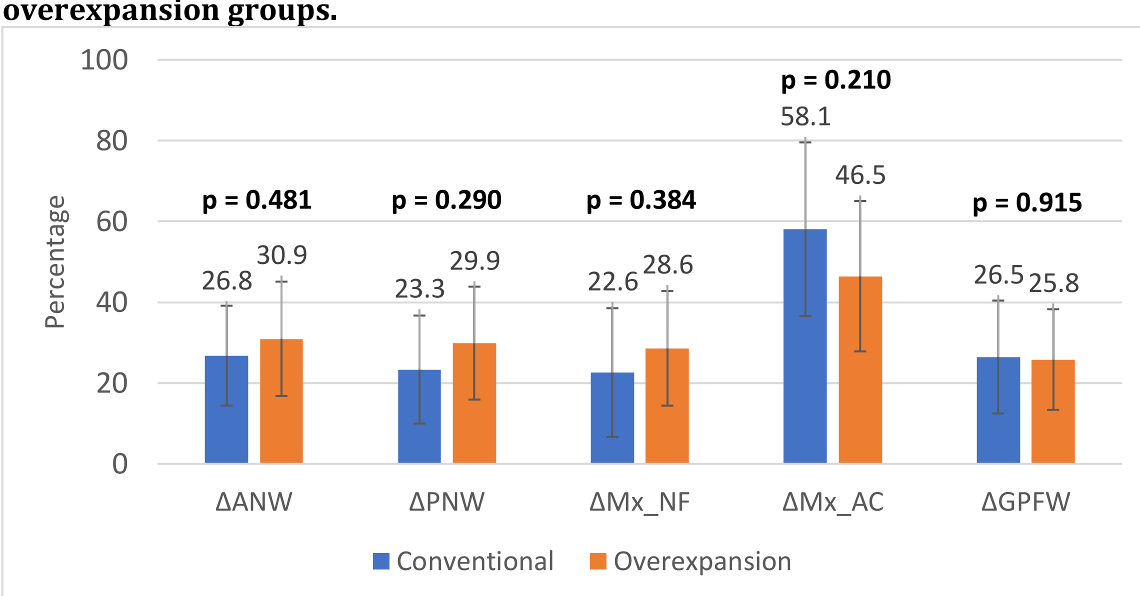
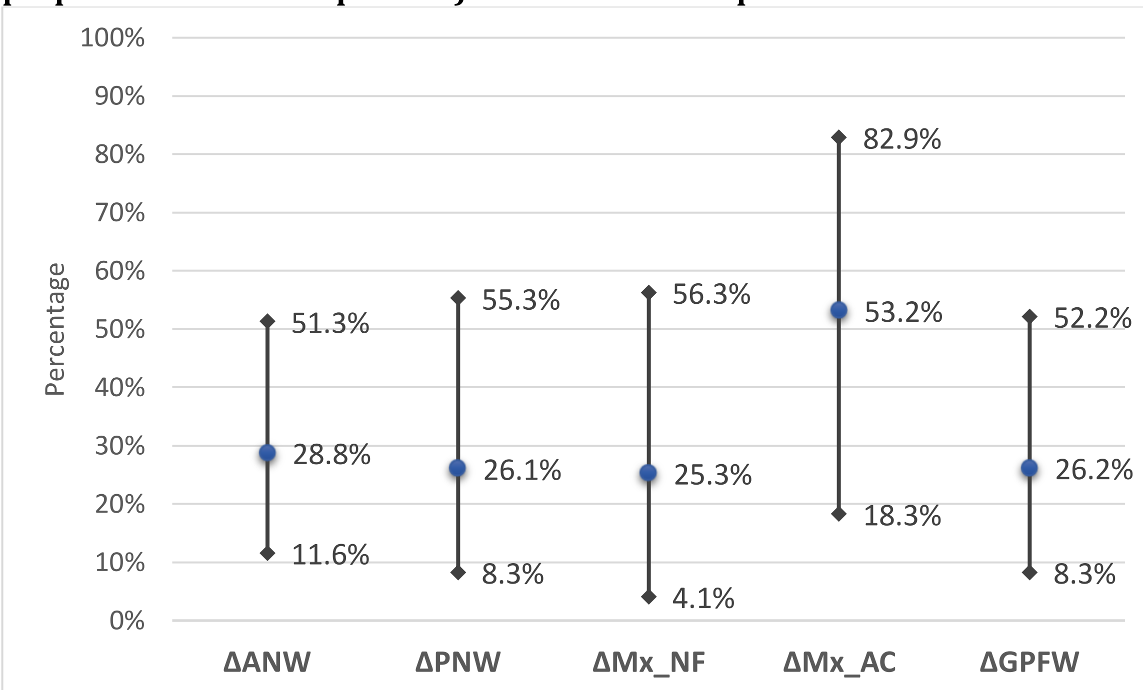


Figure 5. Comparison of skeletal expansion percentages (measured as proportion of dental expansion) between the conventional expansion and overexpansion groups.



Importantly, there were large amounts of individual variation in the percentages of orthopedic expansion obtained (Figure 6). ΔANW, as a percentage of screw expansion, ranged from 11.6% to 51.3%, ΔPNW ranged from 8.3% to 55.3%.,ΔMx_NF ranged from 4.1% to 56.3%, ΔMx_AC ranged from 18.3% to 82.9%, and ΔGPFW ranged from 8.3% to 52.2%.

Figure 6. Ranges and means of skeletal expansion percentages (measured as proportion of screw expansion) for the entire sample.



While the percentages of skeletal expansion were negatively correlated with patient age, the correlations were relatively low (r<-0.4), and none were statistically significant (Table 6). However, there were statistically significant negative correlations between the percentages of skeletal expansion and patient's skeletal maturity indicator (SMI), as well as between percentages of skeletal expansion and skeletal age, for all skeletal transverse measurements (Table 6).

Table 6. Correlations of chronological age, SMI, and skeletal age with skeletal expansion percentages (measured as proportion of screw expansion).

	Chronological Age		SMI		Skeletal Age	
	r	Sig.	r	Sig.	r	Sig.
ΔANW %	-0.390	0.080	-0.547	0.010	-0.491	0.024
ΔPNW %	-0.172	0.456	-0.548	0.010	-0.495	0.023
ΔMx_NF %	-0.266	0.244	-0.514	0.017	-0.459	0.037
ΔMx_AC %	-0.169	0.463	-0.467	0.033	-0.506	0.019
ΔGPFW %	-0.393	0.078	-0.635	0.002	-0.697	<0.001

There also were statistically significant correlations between the amount of RPE activation and changes in skeletal transverse measurements, intermolar width, and molar inclinations (Table 7, Figures 7-14). The only variables that were not significantly correlated with screw expansion were the alveolar bone inclinations. After Bonferroni adjustments, the increases in ANW, PNW, Mx_NF, IMW were all positively related to screw expansion. There was a very high correlation between ΔIMW and amount of screw expansion (r=0.941), as well as a nearly perfectly 1:1 relationship between the two variables (Figure 12). The mean increase in IMW (7.7 mm) was slightly greater than the 7.5 mm mean screw expansion that occurred. Amount of screw expansion explained 88.5% of the changes in IMW.

Table 7. Correlations between amount of screw expansion performed and changes in all skeletal and dentoalveolar measurements.

	r	Significance
ΔANW	0.637	0.002
ΔPNW	0.648	0.001
ΔMx_NF	0.608	0.003
ΔMx_AC	0.556	0.009
ΔGPFW	0.549	0.010
ΔIMW	0.941	< 0.001
ΔMInc_R	0.583	0.006
ΔMInc_L	0.562	0.008
ΔABInc_IR	0.374	0.094
ΔABInc_IL	0.381	0.089
ΔABInc_OR	0.065	0.780
ΔABInc_OL	0.360	0.109

Figure 7. Scatterplot depicting correlation between amount of screw expansion performed and change in ANW.

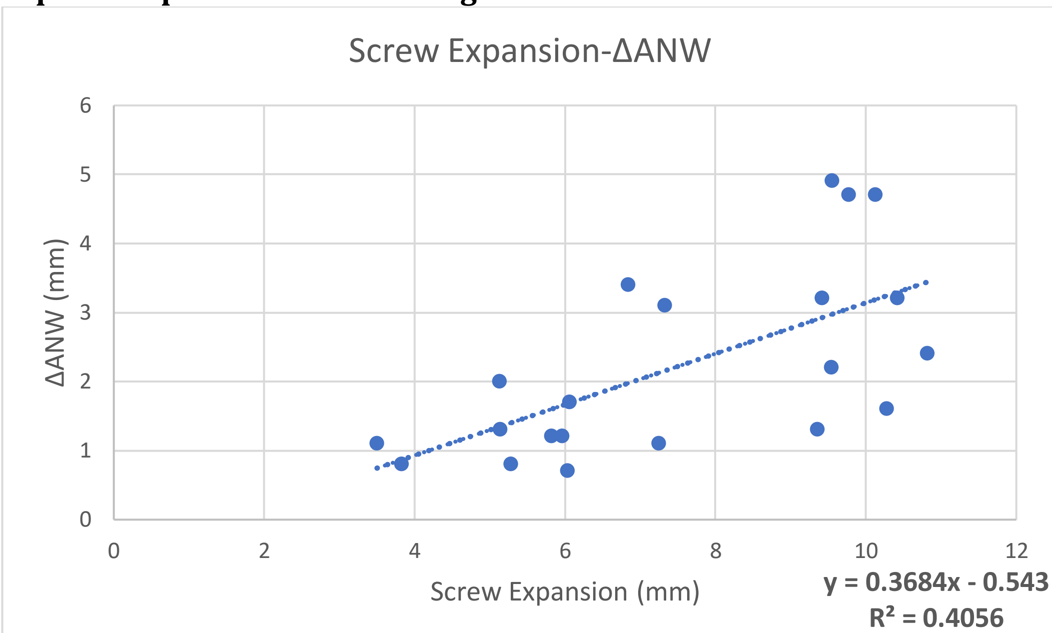


Figure 8. Scatterplot depicting correlation between amount of screw expansion performed and change in PNW.

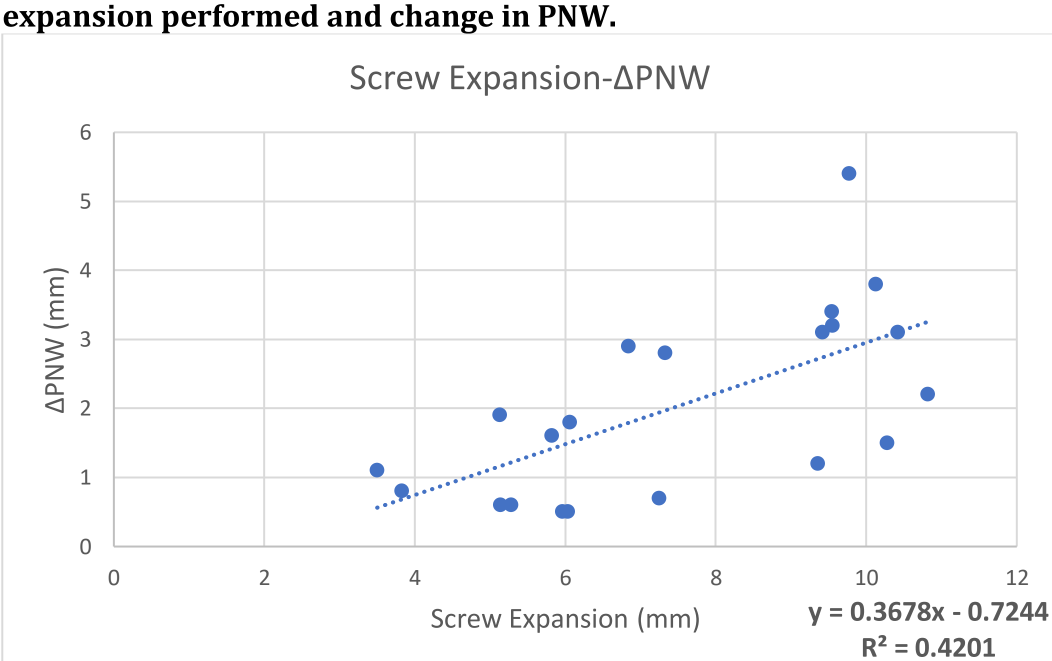


Figure 9. Scatterplot depicting correlation between amount of screw expansion performed and change in Mx_NF.

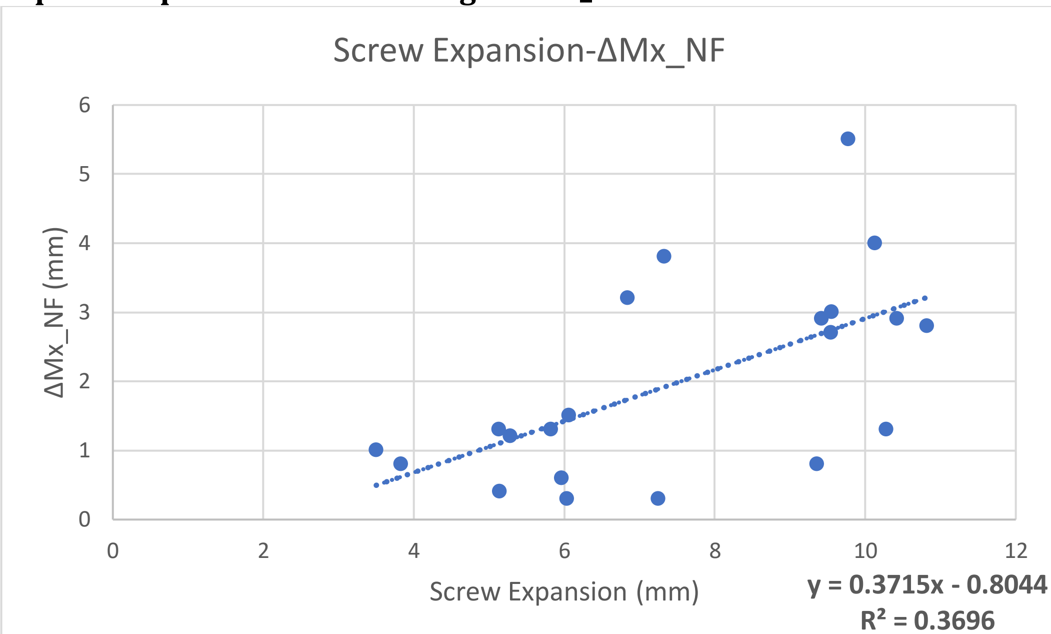


Figure 10. Scatterplot depicting correlation between amount of screw expansion performed and change in Mx_AC.

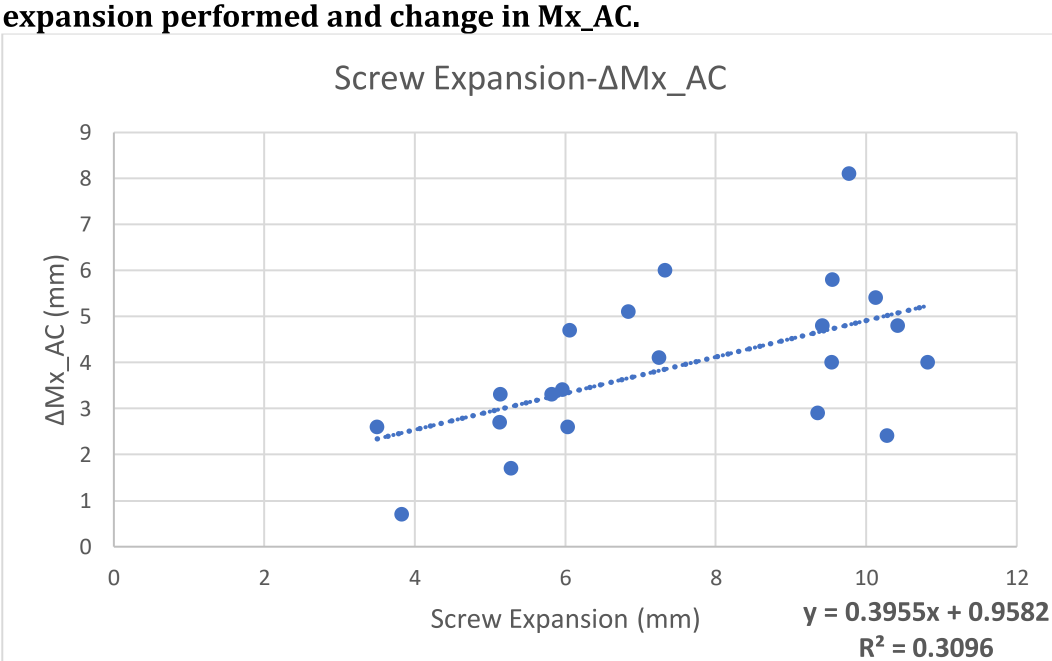


Figure 11. Scatterplot depicting correlation between amount of screw expansion performed and change in GPFW.

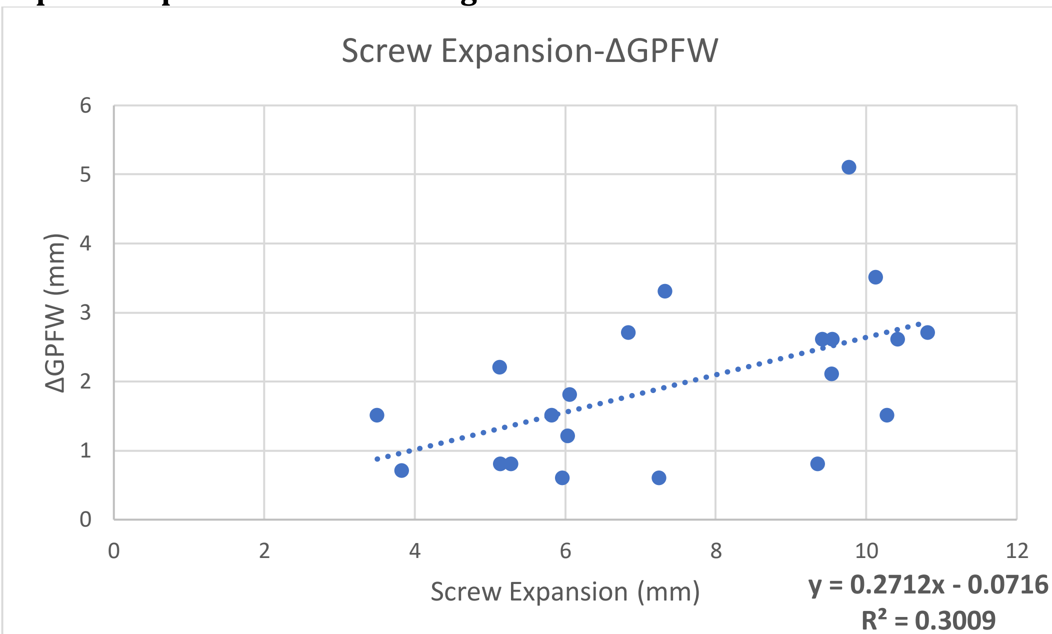


Figure 12. Scatterplot depicting correlation between amount of screw expansion performed and change in IMW.

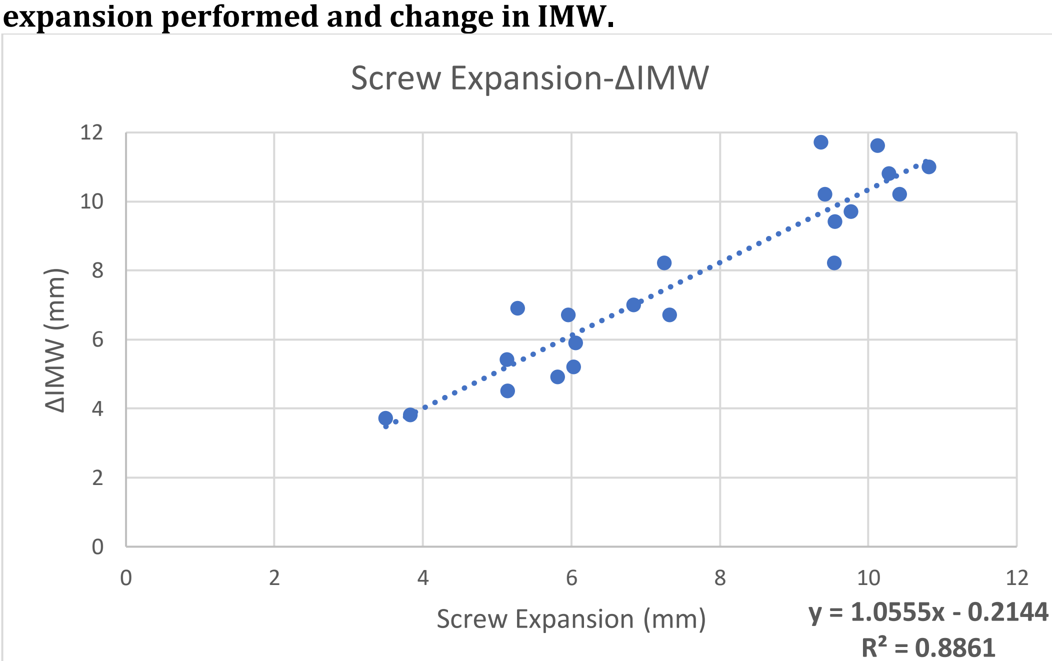


Figure 13. Scatterplot depicting correlation between amount of screw expansion performed and change in MInc_R.

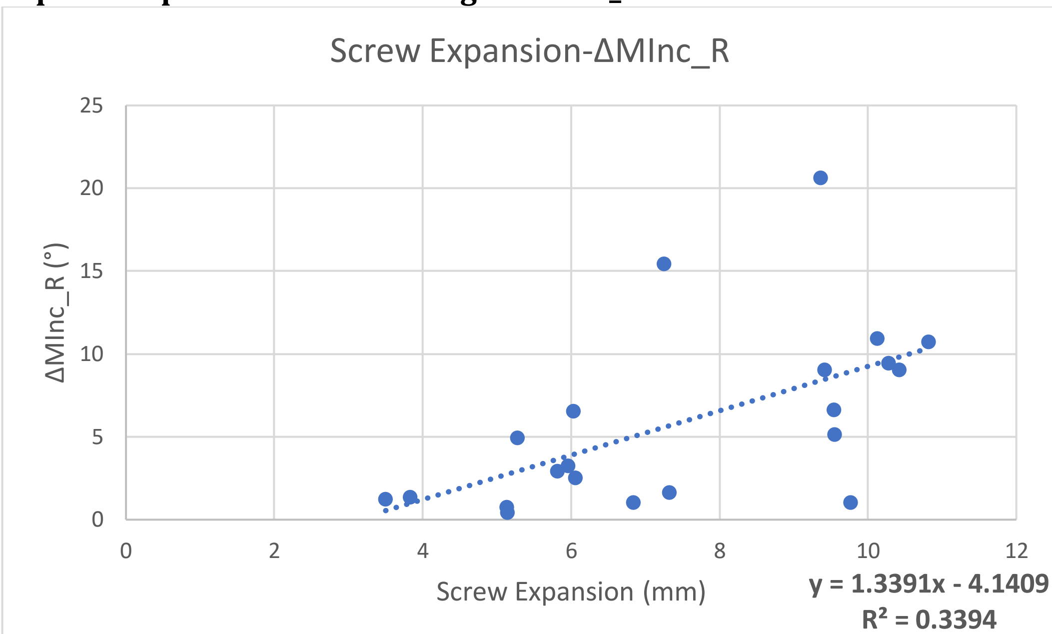
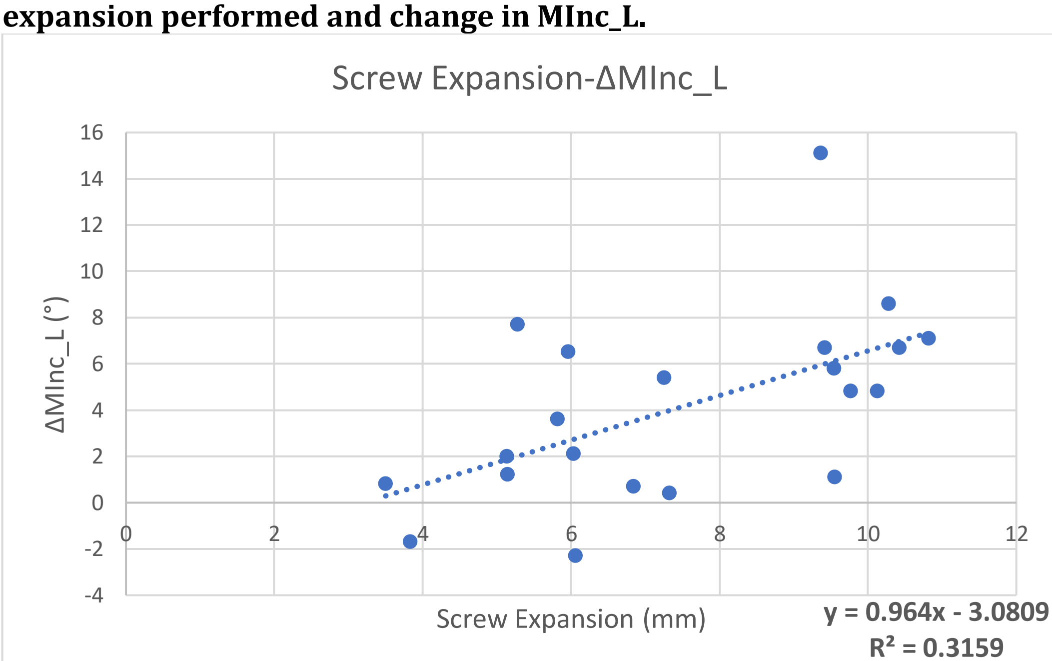


Figure 14. Scatterplot depicting correlation between amount of screw expansion performed and change in MInc_L.



4. DISCUSSION

During RPE treatment, continued activation of the appliance leads to continued increases in skeletal and dentoalveolar dimensions. The current study demonstrated that overexpansion leads to significantly greater increases in anterior nasal width (ANW), posterior nasal width (PNW), maxillary width at the nasal floor (Mx_NF), greater palatine foramina width (GPFW), intermolar width (IMW), and molar inclinations (ΔMInc_R, ΔMInc_L) than conventional expansion. For the conventional expansion group, increases in transverse skeletal dimensions ranged from 1.3 mm to 1.5 mm. Overexpansion led to approximately double the amount of skeletal expansion, ranging from 2.6 mm to 3.1 mm. No study has previously been conducted to statistically compare groups designed to have differing amounts of expansion. However, several studies have reported results with screw expansion ranging from 5 mm to just over 8 mm.[36-38, 42-44, 68] With respect to posterior nasal width and maxillary base measurements, the present results, in conjunction with those previously reported, support the notion that skeletal changes are typically greater with greater amounts of screw activation. (Figures 15 and 16). A relationship is to be expected because increased amounts of screw expansion indicate prolonged application of transverse forces to the nasomaxillary complex, resulting in greater overall effects.

Figure 15. Comparison of present results with previous studies in terms of relationship between screw expansion and posterior nasal width expansion.

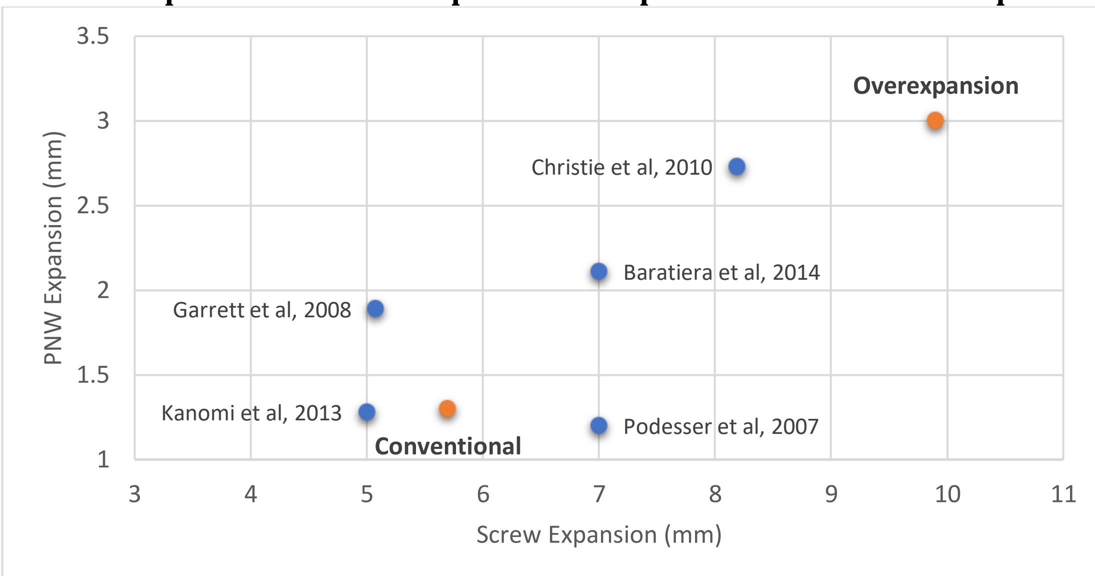
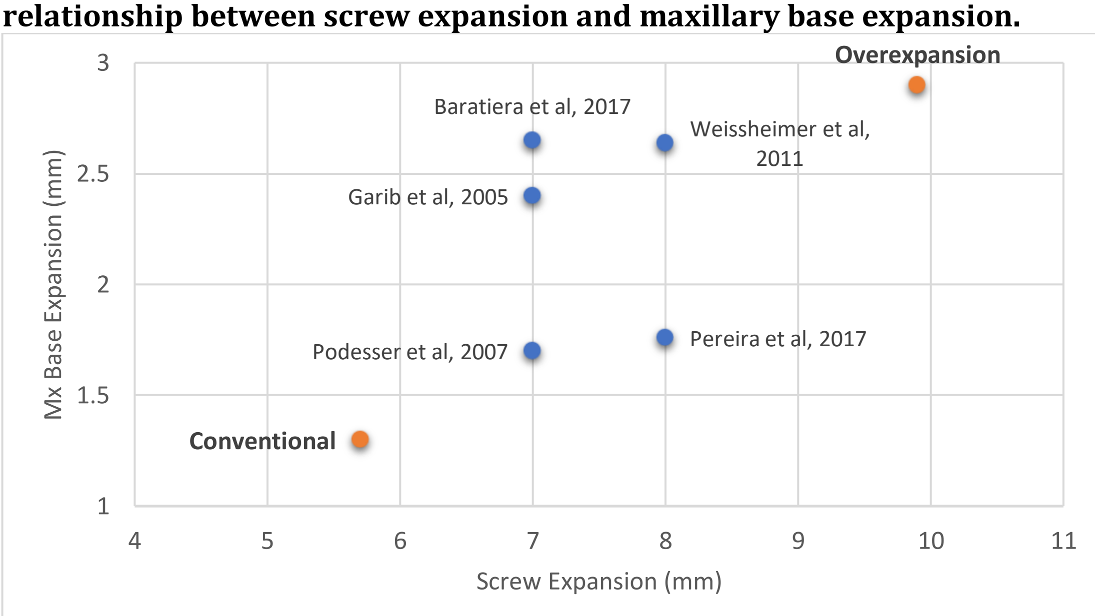


Figure 16. Comparison of present results with previous studies in terms of relationship between screw expansion and maxillary base expansion.



The amounts of skeletal expansion achieved with RPE treatment are significantly correlated with the amount of appliance activation performed. Correlation coefficients in the present study ranged from 0.55 to 0.65, indicating that approximately 30% to 42% of variation in skeletal expansion can be explained by the amount of screw expansion. Similar correlations to what was found for ∆Mx_NF (r=0.61) and ∆PNW (r=0.65) have been reported previously.[39] Grunheid et al[67] found a correlation of 0.14 between expansion at the greater palatine foramina and screw expansion, which was substantially weaker than the corresponding correlation calculated in the present study (r=0.55). However, their study measured expansion after all orthodontic treatment was complete, making it is impossible to assess the effects of expansion alone, without the confounding effects of orthodontic treatment and growth. Additionally, post-expansion retention in their study ranged from 2 to 77 weeks (mean 15 weeks), indicating that several subjects likely did not have the appliance retained for a sufficient amount of time to maintain the expansion initially gained. Relapse has been reported to occur without adequate retentions.[4, 21, 55, 57] While the results of the present and previous studies show that there is an association between screw activation and skeletal expansion, the reported correlations indicate that this association is moderate, implicating the involvement of additional factors.

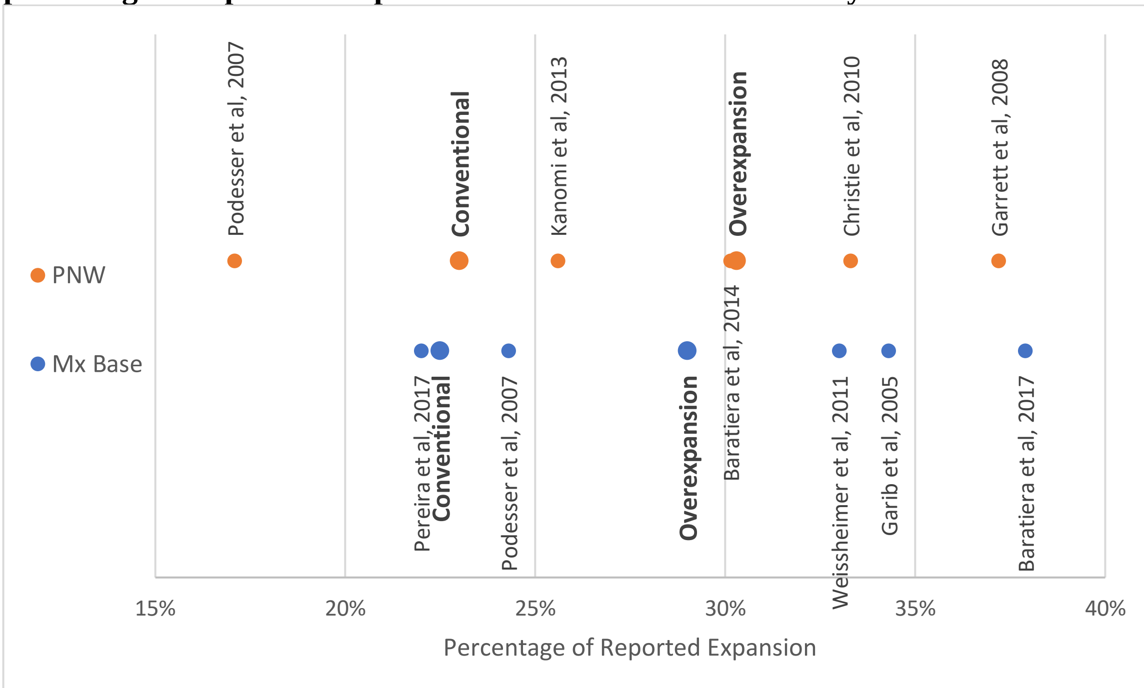
Dental expansion during RPE treatment is approximately equivalent to the amount of appliance activation. The current results demonstrate that increases in IMW were very highly correlated with RPE screw expansion (r=0.94). The relationship is essentially 1:1. There was a slightly greater mean increase in IMW (7.7 mm) than mean screw expansion (7.5 mm), due to the combination of tipping and bodily movement of the molars. While correlations between the amount of screw expansion and dental expansion have not been previously reported, the approximate 1:1 relationship is supported by averages previously reported. For example, Weissheimer et al[44] reported a 7.8 mm increase in IMW with 8.0 mm of appliance expansion, Garib et al[38] described a 7.3 mm increase in IMW with 7.0 mm of screw activation, and Chung and Font[15] found a 7.9 mm increase in IMW on PA cephalograms following 7.6 mm mean screw expansion. A strong correlation and 1:1 relationship is to be expected because forces from the appliance during RPE treatment are applied directly to the maxillary first molars.

Sustained RPE screw activation leads to increased tipping of the maxillary first molars. The present study found significantly greater increases in molar inclination in the overexpansion group (7.9°) than the conventional expansion group (2.9°). The present results also demonstrated significant positive correlations between screw expansion and molar inclinations (r=0.56-0.58), indicating that 31% to 34% of the variation in molar angulation observed during RPE treatment can be explained by the amount of appliance activation. The association between changes in molar angulation and the amount appliance expansion has not been previously reported. Christie et al[37] reported a 6.22° increase in right molar inclination and a 5.60° increase in left molar inclination with 8.19 mm of screw expansion. Weissheimer et al[44] found a 7.53° increase in right molar angulation and a 6.17° increase in left molar angulation with 8 mm of appliance expansion. These previously reported inclination changes compare well with the 5.9° increase in right molar inclination and 4.1° increase in left molar inclination with 7.5 mm of mean screw activation observed in the present study. Greater molar inclination changes with greater screw expansion might be expected as a dental compensation due to the proportionally limited skeletal response.

Alveolar bone bending, on the other hand, is not related to RPE activation. In the present study, mean increases in inclination were 5.4° for the inner alveolar bone and 5.6° for the outer alveolar bone. Kartalian et al[41] reported a mean increase of 5.6° for inner alveolar bone angulation. Alveolar bone inclination changes did not show statistically significant between-group differences or correlations with screw expansion. It has been suggested that bending of the alveolar bone is one of the initial responses to the transverse force delivered by the RPE appliance,[4, 5, 7, 11] and that this response is essentially complete within the first week of screw activation.[57, 60] With that being the case, the present results suggest that once separation of the midpalatal suture occurs, continued increases in alveolar bone inclination are relatively limited compared to the ongoing skeletal and dental changes. The lack of significant continued alveolar bone bending with increased screw activation may also be related to the appliance design used in the present study. Hyrax RPE appliances apply forces solely to the dentition without exerting pressure on the alveolus, as is the case with other designs.

Expansion of the nasal cavity and maxillary base typically amount to only 20% ($^1/_5$) to 33% ($^1/_3$) of screw activation. The relative amounts of nasal cavity expansion obtained in the present study fell just above the values previously reported for ANW [36, 68] and within the reported range for PNW (Figure 8).[36, 37, 39, 40, 43]. Podesser et al[43] reported 17.1% expansion of PNW in 9 subjects. Garrett et al[39] reported 37.2% expansion of PNW, but they measured screw expansion using coronal slices from CBCT scans, as opposed to measuring the appliances directly. Metal artifacts present on CBCT images have been shown to lead to underestimated linear measurements.[69] The relative expansion of Mx_NF – 22.5% for the conventional expansion group and 29.0% for the overexpansion group – also fell within the 22.0% to 37.9% range reported previously (Figure 17).[36, 38, 42-44] It should be noted that all previous studies reporting greater percentages of maxillary base expansion than the overexpansion group of the present study used younger patient samples.[36, 38, 44] It is important to consider age when evaluating expansion, as it has been reported that RPE treatment prior to or during the pubertal growth spurt leads to more significant skeletal expansion.[3, 4, 11, 13, 21, 45]

Figure 17. Comparison of present results with previous studies in terms of percentage of expansion of posterior nasal width and maxillary base.



It is possible that overexpansion leads to a greater proportion of skeletal changes than conventional expansion. Although not statistically significant, the present results indicate a consistent pattern showing a greater percentage of skeletal expansion in the overexpansion group than the conventional expansion group. Overexpansion led to a 5.1% greater increase in ANW, a 7.3% greater increase in PNW, and a 6.5% greater increase in Mx_NF when compared to conventional expansion. As stated above, no previous study has compared amounts or proportions of expansion in groups with differing amounts of RPE screw activation. A greater relative orthopedic response with increasing amounts of expansion would support the notion that dentoalveolar changes are the primary consequence early in the course of RPE treatment,[4, 5, 7, 11] while skeletal effects predominate after adequate force is reached to separate the midpalatal suture.

If a lesser proportion of skeletal expansion is to be expected with conventional expansion, it is reasonable to assume there would be a greater dentoalveolar contribution. Although overexpansion (4.7 mm) led to greater absolute increases in Mx_AC than conventional expansion (3.4 mm) in the present study, conventional expansion produced relatively greater increases at the level of the alveolar crest. Neither the absolute nor relative between-group differences were statistically significant. The percentages of alveolar expansion found in the present study – 47.5% in the overexpansion group and 57.4% in the conventional expansion group – fall within the 37.1% to 81.4% range reported previously.[36, 38, 42-44] Podesser et al[43] was the only study reporting a lesser percentage of alveolar crest expansion than the current study, but it included the youngest subjects (mean 8.1 years) of any study evaluated. Younger patients may require less force to separate the midpalatal suture, which might be expected to result in a reduced amount of alveolar bending. On the other hand, studies that report greater percentages of expansion at the alveolar crest all used Haas-type RPE appliances, which utilize acrylic pads to exert force directly on the palatal alveolar mucosa, for either a portion of or their entire samples.[36, 38, 42, 44]

The percentage of skeletal expansion obtained following RPE is highly variable among individuals and is likely related to several factors in addition to screw activation. A range of 8% to 55% was found for ΔPNW in the present study.

This large variation is consistent with previously reported ranges.[43, 67] Chung and Font[15] found a slightly narrower range of nasal cavity expansion, but they used PA cephalograms, which makes direct comparisons of percentages difficult. For ∆Mx_NF, expansion ranged from 4% to 56% in the present study, which is a wider range than previously reported.[15, 43] The disparity can, in part, be attributed to the small sample size[43] and PA cephalograms[15] used in previous studies. The current study also found a wide range – 18.3% to 82.9% – for expansion at the alveolar crest, which was supported by the existing literature.[43] Lastly, a range of 8.3% to 52.2% was found for ∆GPFW. Grunheid et al[67] previously reported a 0% to 36% range of expansion for this parameter. However, expansion was measured after all orthodontic treatment was complete. The wide range of expansion percentages reported for the various skeletal parameters is likely due to differences in inherent patient characteristics, such as skeletal maturity and sutural complexity, which have been shown to alter the orthopedic response to RPE treatment.[3, 4, 11, 13, 20, 45, 49, 70-77] Variation is also to be expected as a result of individual morphological differences of the maxillary complex and palatal vault, which would alter the biomechanics of force application from the RPE appliance.

The proportion of orthopedic expansion obtained is inversely related to the patient's skeletal maturity. Skeletal expansion percentages calculated in the present study were significantly and negatively correlated with the patient's SMI stage and its associated skeletal age. It has long been reported that a patient's maturity is negatively associated with skeletal expansion.[11, 13, 20] This association is due to the increased complexity and interdigitation of the midpalatal suture that have been shown to accompany skeletal maturation.[72-77] Revelo and Fishman[49] concluded that an ideal time to begin expansion is during early maturational stages – SMI 1 to 4. They also noted that if separation of the midpalatal suture is desired, it should be accomplished by SMI 9. Baccetti et al[3] concluded that patients treated prior to the pubertal growth peak (CVM stages 1-3) demonstrate more significant and effective long-term skeletal changes than those treated afterwards (CVM stages 4-6). More recently, Angelieri et al[71] demonstrated that skeletal maturity was strongly correlated with midpalatal suture maturation assessed on CBCT scans.

From a coronal perspective, RPE treatment produces greater inferior than superior expansion. The results of the present study support the idea that the nasomaxillary complex expands in a non-parallel fashion vertically. In both groups, expansion effects increased moving inferiorly from the nasal cavity to the alveolar crest. This pattern of expansion has been previously reported.[10, 11, 13, 15, 16, 41] The triangular pattern of expansion in the coronal plane is noteworthy because it reinforces the concept that both the amount and proportion of expansion achieved decreases as the measurement progresses superiorly from the level of the dentition, to the alveolus, to the maxillary base, to the nasal cavity. This pattern may also provide the false impression that a significant amount of skeletal expansion has taken place if only evaluating dentoalveolar landmarks, when in reality, true skeletal expansion of the maxillary base and nasal cavity may be minimal. The greater amount of expansion obtained inferiorly is a result of increased resistance to the applied force superiorly, due to the presence of numerous circummaxillary sutures and bony articulations.[4]

Anteroposterior differences in expansion may not exist at more superior levels of the nasomaxillary complex. The present results indicate an almost parallel form of expansion of the nasomaxillary complex from an anteroposterior perspective. In both groups, the effects produced by expansion were only 0.1 to 0.2 mm less in the posterior than anterior aspects of the nasal cavity, moving from ANW to PNW. It should be noted that the non-parallel nature of expansion anteroposteriorly, with greater anterior expansion, has been previously described primarily at the level of the midpalatal suture.[10, 11, 13, 39, 44] Given the increased resistance superiorly due to circummaxillary articulations,[4] the absolute effects of expansion are diminished. Therefore, it is logical that anteroposterior differences would be more difficult to distinguish at more superior planes. Since CBCT scans in the current study were taken at least 3 months apart, it was impossible to directly measure midpalatal suture opening, as osteogenesis within the suture had begun to take place by time the T2 scans were taken.[4, 51, 78] Consequently, evaluation of anteroposterior expansion at the level of the midpalatal suture was not possible in the present study.

The results of this study suggest a few important clinical takeaways for the practitioner. First. clinicians should be aware that absolute increases in skeletal parameters with conventional expansion are small, typically ranging from 1 to 2 mm. Therefore, for cases with true skeletal transverse discrepancies in which orthopedic correction is required, overexpansion in the range of 9 to 12 mm of screw expansion, or more, should be considered to achieve more appreciable and stable results.

Additionally, practitioners should be cognizant of the limited proportion of skeletal expansion typically obtained, as well the considerable amount of individual variation observed. This variation and its related factors are important to understand in order to accurately plan for and predict the amount of expansion required from case to case. Additional records may be needed to verify the amounts of skeletal expansion obtained.

Lastly, the present study underscores the importance of expanding during early stages of skeletal maturity, whenever possible, in order to maximize the amount of skeletal expansion obtained. Clinicians should use available indicators of skeletal maturity, such as CVM stage using lateral cephalograms and Fishman SMI stage using hand-wrist radiographs, to inform their decisions when planning RPE treatment.

5. CONCLUSIONS

1. Overexpansion leads to significantly greater amounts of skeletal and dental expansion than conventional expansion.
2. Skeletal expansion is moderately correlated with screw expansion (r=0.55-0.65).
3. Dental expansion is very strongly correlated with appliance activation (r=0.94) and increases in intermolar width are approximately equal to screw expansion.
4. Expansion of the nasal cavity and maxillary base typically amount to 20-33% of screw activation. Skeletal expansion percentages were slightly greater in the overexpansion group, but the differences were not statistically significant.
5. There is a large degree of individual variability in the proportion of skeletal expansion obtained (4%-56%), and this percentage is inversely related to skeletal maturity (r=-0.46 to -0.70).
6. The effects of RPE treatment are triangular from a coronal perspective, greater inferiorly than superiorly.

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APPENDIX A

RPE CHECKLIST

Patient Name: ___________________________________

Texas A&M University College of Dentistry
Department of Orthodontics

Thank you for your participation in this study on rapid palatal expansion. For the purposes of the study, it is important that you follow the included instructions and track each turn of the RPE as accurately as possible.

RPE Instructions:

1) Turn the RPE 1 times per day until you have completed the required number of days/turns prescribed by your doctor.

2) Record each completed turn in the table provided below. (Please record this information honestly and accurately to ensure reliable data for the study.)

RPE Tracker:

Please record each turn of the RPE in the table below (✓ Yes or ✗ No).

My RPE was delivered on ___________________________.

Day	Turn (✓ *or* ✗)	Day	Turn (✓ *or* ✗)	Day	Turn (✓ *or* ✗)
1.		17.		33.	
2.		18.		34.	
3.		19.		35.	
4.		20.		36.	
5.		21.		37.	
6.		22.		38.	
7.		23.		39.	
8.		24.		40.	
9.		25.		41.	
10.		26.		42.	
11.		27.		43.	
12.		28.		44.	
13.		29.		45.	
14.		30.		46.	
15.		31.		47.	
16.		32.		48.	