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Retrospective Evaluation of Skeletal, Dentoalveolar, and Periodontal Changes of Microimplant Assisted Rapid Palatal Expansion (MARPE) In Skeletally Matured Patients

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ABSTRACT

Retrospective Evaluation of Skeletal, Dentoalveolar, and Periodontal Changes of Microimplant Assisted Rapid Palatal Expansion (MARPE) In Skeletally Matured Patients

Uyen Kelly Nguyen, D.M.D

Introduction: Microimplant-assisted rapid palatal expansion (MARPE) has recently been offered to adult patients as a treatment option for correcting maxillary transverse deficiency. However, there is a lack of information in the literature on the effects of this newer expansion technique specifically related to skeletal maturity. The purpose of this study was to investigate the immediate skeletal, dentoalveolar, and periodontal response to MARPE in skeletally matured patients, as assessed by the cervical vertebral maturation (CVM) method, using cone-beam computed tomography.

Experimental Design and Methods: Eight patients (2 females, 6 males; mean age of 21.9 ± 1.5 years) treated with the maxillary skeletal expander (MSE), a particular type of MARPE appliance, were included in the study. Measurements before and after MARPE of midpalatal suture opening, upper facial bony expansion, aveolar bone bending, dental tipping, and buccal bone thickness were compared using one-way ANOVA or matched-pair t-test ($\alpha = 0.05$).

Results: Midpalatal suture separated in 100% of subjects with no dislodged microimplants. Contribution to total expansion include 41% skeletal, 12% alveolar bone bending, and 48% dental tipping. Pattern of midpalatal suture opening was parallel in both coronal and axial view. On average, absolute dental tipping ranged from 4.17^{o} to 4.96^{o} and buccal bone thickness reduced by 0.27 mm to 0.68 mm, which may be improved overtime with orthodontic uprighting.

Conclusion: MARPE can be a clinically acceptable, nonsurgical treatment option for correcting mild to moderate maxillary transverse discrepancies, less than 7 mm, in skeletally matured adult patients with a healthy periodontium.

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"The best kind of people are the ones that come into your life, and make you see the sun where you once saw clouds. The people that believe in you so much, you start to believe in you too. The people that love you, simply for being you. The once in a lifetime kind of people."

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I dedicate this thesis to my wonderful family, particularly my parents. Thank you for giving me life and for always encouraging and supporting me to do what makes my heart smile. I also dedicate this thesis to my life-long friends. Thank you for playing a role in shaping me into the person I am today. I feel truly blessed to have been gifted with the loving family and friends that I have in this lifetime.

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CHAPTER 1: INTRODUCTION

Background

Maxillary transverse deficiency (MTD) is a common problem that is found in patients who seek orthodontic care. It has been reported that 9.4% of the whole population and nearly 30% of adult orthodontic patients have MTD related to a posterior crossbite.[69] Conventional rapid palatal expansion (RPE) have proven to be a reliable treatment method for correcting transverse skeletal jaw disharmony in prepubertal patients.[5] However, its use in adult patients has little or no skeletal effects but rather greater dental side effects that may be detrimental to periodontal support.[5, 12, 37, 64, 97] Surgically assisted rapid palatal expansion (SARPE) has been the common treatment of choice for overcoming the areas highly resistant to maxillary expansion in the adult facial skeleton.[64, 69, 97] However, the morbidity, risks, and costs related to surgery may discourage many patients from seeking correction through this procedure.[22, 26, 69] Recently in the orthodontic literature, much attention has been given to microimplant assisted rapid palatal expansion (MARPE) and its use as a nonsurgical treatment option for correcting MTD in adult patients. However, there is limited information available on the skeletal, dentoalveolar and periodontal effects produced by this novel technique specifically relating to skeletal maturity.

Generally, it is known that chronological age is not a precise index in predicting skeletal maturation[58] and there is tremendous variability in the developmental stages of the midpalatal suture relative to chronological age.[7] Skeletal maturity may be assessed by the Cervical Vertebral Maturation (CVM) method, which have been shown to be able to detect the greatest mandibular and craniofacial growth increments.[11, 12] It has been found that the period between Cvs 3 to Cvs4 correlates with the peak in statural height 93.5% of the time.[11, 12] In short, Cvs 1 through Cvs 3 represent the time before peak in skeletal maturity where Cvs 4 through Cvs 6 represent the time at or after the peak in skeletal maturity.[12] The application of the CVM method has revealed that skeletal effects of RPE are greater at prepubertal stages, while pubertal or postpubertal use of RPE produces greater dentoalveolar effects.[11]

Most published studies on RPE utilized bi-dimensional (2-D) radiographs cephalograms or occlusal x-rays. These records present diagnostic and analytical limitations because they give 2-D information of a 3-dimensional (3D) object.[81] Landmark identifications and obtaining exact measurements are difficult with the 2-D images because many structures may superimposed upon each other on multiple planes of space.[13] With cone-beam computed tomography (CBCT) technology, volumetric images may be obtained that would allow for accurate identification of landmarks and quantification of bony structural changes with minimal distortion and lower radiation dosages compared to medical computed tomography.[7] CBCT scans are valuable because they can overcome the limitations of 2D imaging as well as allow for quantitative evaluation of bony changes induced by treatment effects.[41]

Purpose and Significance of Study

The purpose of this study was to investigate the short-term skeletal, dentoalveolar and periodontal treatment effects associated with microimplant rapid palatal expansion (MARPE) in skeletally matured patients, as assessed by the cervical vertebral maturation (CVM) method, using CBCT imaging. The results of this research will reveal if MARPE can serve as a clinically safe, non-surgical option for correcting maxillary transverse deficiency in post-pubertal adult patients.

Null Hypotheses (H_0)

1. There is no midpalatal suture opening in skeletally matured patients treated with MARPE appliance
2. There is no significant difference in midpalatal suture opening in the axial plane at the canine (C), first premolar (P1), second premolar (P2), and first molar (M1).
3. There is no significant differences in midpalatal suture opening in the coronal plane at nasal and palatal floor.
4. There is no change in the transverse width of the facial skeleton at the level of the zygomatic bones.
5. There is no significant difference between the expansion at the zygomatic bones compared to the infrazygomatic crests.
6. There is no significant difference in the palatal alveolar angle between T1 and T2 measured at P1 and M1.
7. There is no significant difference in the dental tipping angle between T1 and T2 measured at P1 and M1.
8. There is no significant difference in the buccal bone thickness between T1 and T2 measured at the first premolar (P1), mesiobuccal root of the first molar (MB-M1) and distobuccal root of first the molar (DB-M1).

Assumptions

1. Pretreatment CBCT scans were taken prior to any orthodontic or orthopedic intervention and posttreatment scans were taken immediately at the end of MARPE appliance activation.
2. The CBCT scans included in this study were of diagnostic quality and were well captured with no patient movement which may introduce radiographic artifacts into the image.

3. Cone beam computed tomography with Invivo 5 3D Imaging software allows for accurate landmark identification and quantification of linear and angular measurements.
4. Using the CBCT scans, the ITK-SNAP software allows for accurate construction of 3D surface models that can be registered at the anterior cranial fossa and superimposed. Additionally, the software can create 3D graphic renderings for measurements.
5. The Slicer CMF 3.1 software allows for precise evaluation of linear measurements on the 3D superimposed models.
6. Operators of the CBCT equipment and imaging software understands how to use the technology appropriately.

Limitations

1. There was patient variability in terms of gender, ethnicity, age, skeletal maturity, craniofacial anatomy, and bone anatomy and physiology.
2. There was treatment variability in terms of the following:
    a. The amount of appliance activation needed to resolve transverse jaw disharmony
    b. The position of the appliance anteroposteriorly along the palate
    c. The number of teeth selected for appliance anchorage
    d. The number of microimplants used to fixate and anchor appliance to the palate
    e. The number of bi-cortically engaged microimplants
3. Small sample size
4. The lack of long-term follow-up of the treatment effects
5. Investigator's ability to manipulate 3D imaging software to accurately orient T1 and T2 CBCT scans, determine landmarks, and obtain linear and angular measurements for reliable comparison.

6. Resolution of CBCT in Invivo 5 imaging software and noises and scatter produced by expander and micro-implants made it difficult to precisely identify particular landmarks in some patients (i.e. buccal cortical plate and palatal shelf)

Delimitations

1. Subjects selected in postpubertal stages: cervical stage 4, 5, or 6
2. Subjects selected based on treatment with particular type of MARPE appliance, the Maxillary Skeletal Expander (MSE).
3. Subjects selected if diagnostic, full field of view (17x13 cm) baseline and immediate post-expansion CBCT records were available for evaluation
4. Subjects selected if there is no history of previous orthodontic or orthopedic treatment and no craniofacial syndrome or deformities due to abnormal development or trauma

CHAPTER 2: REVIEW OF THE LITERATURE

Transverse Growth and Development of the Maxilla

Understanding the normal transverse development and growth of the maxilla is important in the proper diagnosis and treatment planning of problems that may occur in the horizontal plane. The maxilla is comprised of two distinct bones that connect to the cranial base through circummaxillary sutures including frontomaxillary, zygomaticomaxillary, zygomaticotemporal, and pterygoplataine sutures.[16, 18, 45, 95] The two halves of the maxilla articulate at the midline through the median palatal suture.[16] Abnormalities in transverse growth may result in dentofacial asymmetries, expanded or constricted jaws, and dental crossbites.[84]

The maxilla undergoes a period of accelerated growth followed by constant growth in the transverse dimension. Nanda and colleagues[84] showed that the maxilla grows rapid laterally from 8 to 12 years old and increases steadily until full width is achieved at 15 and 16 years in males and females respectively. Maxillary width was observed to be 95-98% complete at age 12 while the mandible continued to show small increase in lateral growth at 18 years of age.[84] Transverse widening of the maxillary basal bone and alveolar process has been attributed to appositional growth at the maxillary tuberosity and lateral posterior region of the maxilla along with active growth at the median palatal suture.[52] Bjork and Skieller[19] metallic implant studies revealed that sutural separation of the two maxillae was greater posteriorly than anteriorly by 3 folds, which consequently cause the two parts to rotate in the transverse plane relative to each other. Interestingly in the coronal plane, the average lateral growth at the maxillary base is greater than the growth that occurs at the maxillary first molars, resulting in an inverted triangle[52, 59] The reported average maxillary intermolar width at age 18 was 55.7 mm for females and 59.5 mm for males.[84] With respect to the dentition, as maxillary and mandibular intermolar widths increases, maxillary molars erupt with buccal crown torque while mandibular molars erupt with lingual crown torque, both upright with age. [62, 74]

Postnatal morphological midpalatal suture changes have been described. During the first infantile stage, Melsen[16, 78] reported that the suture is broad and Y shaped, with the placement of the vomerine bone in a V-shaped groove between the two halves of the maxilla. Overtime, the median palatal suture appears wavier and more tortuous due to the development of bony interdigitations across the suture.[78] The ossification process in the median palatal suture begins with formation of bone spicules in the sutural gap along with masses of acellular and inconsistently calcified tissues, referred to as “islands”.[28, 63, 89] Sutural interdigitation increases with maturation and eventually intensify until the right and left maxillary bones fuse together, with ossification progressing from the posterior to anterior end.[16, 62, 89]

Fusion of the median palatal suture vary with sex and age. Previous implant studies of Bjork and Skieller[19] showed the peak rate of maxillary transverse sutural growth occurred during pubertal growth spurt and does not complete, on average, until 17 years of age. Melson[78] observed growth activity in the midpalatal suture continued beyond age 13 to 14 years old, up to age 16 and 18 in girls and boys respectively. Similarly, Persson and Thilander[89] noted fusion of the midpalatal suture in patients 15 to 19 years old. However, the lack of fusion of this suture has been reported in patients at ages 32,[89] 54,[62] and 71[63]. The inconsistent findings show there is tremendous intrasutural and interindividual variability in the developmental stages of the midpalatal suture, which also does not directly relate to chronologic age.[7, 62, 89, 103] Despite the conflicting literature, it is a widespread belief that the midpaltal suture is patent through early mid-teens years and ossify or heavily interdigitate at late teens and adulthood.[59]

Maxillary Transverse Deficiency: Description, Prevalence, and Etiology

Maxillary transverse deficiency (MTD) commonly contributes to the malocclusion of patients seeking orthodontic treatment. It is a skeletal condition that is characterized by a constricted maxilla relative to the surrounding structures of the craniofacial complex in the horizontal dimension.[16] Clinically, it may be distinguished by a narrow palatal vault and is commonly associated with problems such as dental crowding, protrusion of teeth, and unilateral or bilateral posterior crossbite.[23, 30, 75] The literature has reported 8-23% of children and less than 10% of adults have a transverse discrepancy between the maxillary and mandibular arch.[29, 55] However, considering the adult orthodontic population, it has been reported that 30% of adult patients have MTD related to a posterior crossbite.[69] Belluzo et al[16] showed that 32.3% of patients diagnosed with MTD present with greater constriction in the anterior region compared to the posterior region.

Multiple etiological factors have been described for maxillary transverse deficiency. Causes of the condition may include developmental disturbances, such as clefts in the lip and palate, mouth breathing, parafunctional habits like thumb sucking, atypical phonation and swallowing. [5, 17, 55, 73, 84, 93] Poor tongue posture, an imbalance of perioral muscles, a lack of lip seal along with labial hypotonicity may also contribute to maxillary constriction.[84] Malocclusion, such as open bite[54], Class II Division I[100], or Class III[16], have also been found to influence the transverse development of the jaws. Tollaro et al.[100] have shown that a Class II patient usually has a 3 to 5 mm transverse discrepancy between the maxilla and mandible even when it appears that bucco-lingual relationship in the posterior dentition is normal.

It has been well documented that correction of MTD facilitates other orthodontic/orthopedic mechanics and enhances dental and facial esthetics, oral function, nasal mucociliary clearance, and nasal respiration.[9, 33, 43, 87] Therefore, continuous research has been performed to improve MTD treatment modalities while reducing associated negative side effects.

History of Rapid Palatal Expansion (RPE)

Rapid palatal expansion (RPE) is a common procedure that is used to correct maxillary transverse deficiency. The basis of this treatment method relies on palatal devices that can generate considerable orthopedic forces to separate the maxilla at the midpalatal suture and increase its width laterally.[35, 36] Maxillary expansion is achieved when the force applied to the teeth and maxillary alveolar processes exceeds the threshold required for orthodontic tooth movement.[18] RPE remains well recognized in the orthodontic profession and the treatment modality has evolved greatly since it's early use in the 1800s.

RPE was initially proposed by Emerson C. Angell[8] in 1860 but did not gain popularity until Andrew Haas reintroduced the technique in the 1900s known as the "maxillary expansion years". [104] Haas[5, 46, 48] presented a fixed tooth-tissue-borne expander that consisted of a rigid metal frame work anchored off the maxillary first premolars and molars, a centered expansion screw and lateral palatal acrylic pads. Advocates of the tissue-borne fixed appliance believe the split palatal acrylic design can distribute the expansive force more evenly between the posterior teeth and the palatal vault, thereby producing less tooth movement and more orthopedic displacement of the maxillae. [5, 44] Since the introduction of the Haas expander, various RPE designs have been developed. One widely recognized expander appliance is the Hyrax device.

The Hyrax appliance is a tooth-borne expansion device.[35] It consists of a metal framework with a center nonspring-loaded jackscrew supported by posterior teeth and no acrylic pads.[35] This appliance is believed to be more hygienic, provide greater comfort, and reduce irritation of the palatal mucosa[18] compared to the Haas expander.[35, 47] Although the Hyrax appliance presumably deliver lateral forces to the maxilla only through the anchored teeth, studies have reported that both tooth-borne and tooth tissue-borne expanders tended to produce similar expansion effects.[35]

Indications and Contraindications of RPE

Although RPE is an effective method in facilitating orthodontic correction in the transverse plane, not all patients are good candidates for this treatment modality. Patients who have moderate upper arch crowding or unilateral or bilateral posterior crossbites as a result of maxillary constriction may particularly benefit from RPE treatment.[5, 42, 104] Individuals with anteroposterior discrepancies with a narrow upper jaw such as skeletal Class II, Division 1 or Class III malocclusion with borderline skeletal and pseudo Class III problems are also suitable candidates for treatment with an expander device.[18, 43, 48, 104] Cleft lip and palate patients with collapsed maxillae are also RPE candidates.[18]

The literature lists several contraindications for RPE treatment. Patients who have a single tooth in crossbite, anterior open bites, steep mandibular planes, and convex profiles are generally not good candidates for RPE[4, 104] Patients who have marked skeletal problems including maxillo-mandibular asymmetries and severe anteroposterior or vertical skeletal discrepancies are also not well-suited for RPE.[18] However, if orthognathic surgery is a part of the treatment plan, RPE may be used to facilitate the surgical treatment if transverse discrepancy exist between the maxilla and mandible.[18]

Skeletal and Dentoalveolar Effects of Conventional RPE

RPE produces a combination of skeletal and dental transverse changes and the effects of conventional RPE appliances have been most widely investigated. During the expansion process, lateral forces from the appliance compresses the periodontal ligament, bends the alveolar processes and tips the anchor teeth before the midpalatal suture is opened gradually.[44] From an occlusal view, the midpalatal suture have been observed to separate in a nonparallel, wedge-shaped manner where the apex is towards the posterior nasal spine and the wider base is towards the anterior nasal spine.[36, 56, 104] In the frontal plane, the maxillary suture was also found to separate in a nonparallel pattern superioinferiorly, producing a pyramidal shape where the apex is in the nasal cavity and the base is towards the oral cavity.[5, 18, 104] In a study by Garrett et al.[36], it was reported that midpalatal suture separation (skeletal expansion) accounted for 38% of total expansion at the first molar.

Individual variability exists with the magnitude of midpalatal suture opening following RPE treatment.[5, 18] Clinically, separation of the median suture can be confirmed with the appearance of a midline diastema between the central incisors.[18, 47, 76] Adkins et al[1]demonstrated that approximately 0.7 mm of arch perimeter may be achieved with every 1 mm of first premolar expansion produced by the Hyrax appliance. The space gained from RPE may be helpful in alleviating crowding in the maxillary dental arch, partially if not completely.[36, 76] During active suture opening, it has been estimated that the incisors separate approximately half the distance of the expansion screw opening;[44] however, authors have cautioned against using the width of the diastema as a measurement of suture separation.[104]

RPE have been reported to change the position of the maxillary halves in the frontal and sagittal plane. Haas[47], Wertz[104] and Chung[27] found the maxilla moves forward and downward with RPE, an effect similar to the normal physiological growth of the maxilla. The change in the maxilla position invariably causes a downward and backward rotation of the mandible, decreasing the effective length of the mandible and increasing the lower face vertically.[18, 47] This may particularly be useful in correction of anterior crossbites in skeletal Class III patients.[45, 47] However, the final position of the maxilla at the end of treatment is unpredictable and have been reported to return partially[47] or completely[104] to its original position. In the frontal plane, the two parts of the maxilla tip laterally with the fulcrum of rotation approximately at the frontomaxillary suture.[44, 46, 104] Implant studies[53] have shown the maxillae to tip between -1 to +8 degrees, which reduces the lateral widening at the sutural level compare to the dental level. After stabilization is terminated, residual forces in displaced tissues are said to act on the alveolar process, causing them to rebound.[57] Furthermore, RPE have been reported to transversely widen the base of the nasal cavity, which may lead to decreased nasal air resistance and improve nasal breathing.[27, 33, 48, 76]

With conventional RPE, expansive forces are transmitted to the anchoring teeth before reaching the bony maxillae, rendering dentoalveolar effects unavoidable. Buccal dental tipping and translation as well as lateral maxillary alveolar bone bending have been observed.[18, 36, 47, 61] Lateral dental tipping have been reported to account for 49% of total expansion at the first molar.[36] Hicks[53] observed the angulation between the supporting first molars increased from 1-24 degrees during expansion. It has been shown that maxillary alveolar bone bent buccally 4.75[36] to 5.6[62] degrees and accounted for 13% of total expansion at the first molar.[36] Due to potential buccal dental tipping, the initial angulation of the molars and premolars should be kept in mind when considering RPE. When teeth used for appliance anchorage are buccally inclined, conventional expansion will tip them further into the buccal musculature.[18]

Dental buccal movement caused by RPE is a relevant orthodontic concern due to the possible related periodontal consequences. It has been reported that RPE may reduce the buccal bone plate thickness of the supporting teeth by 30-60% while proportionally increasing the palatal alveolar bone thickness. [13, 34, 37] This effect is due to the response of the periodontal ligament and bone to sustained force, where bone resorption occurs on the pressure side and apposition on the tension side.[18, 59] A decrease in buccal alveolar bone width and height may increase the risk for gingival recession especially in the presence of buccal dehiscence or fenestrations.[13, 104] However, both buccal and lingual bone thickness have been observed to recover after a retention period of 6 months but the magnitude and duration of recovery was not reported[13, 59]

Maxilllary expansion through conventional means is most predictable and successful in adolescents; however, achieving adequate expansion in non-growing individuals may be difficult or impossible without surgical assistance.[6, 18, 64] As previously mentioned, contiguous bones become more rigid, especially at the zygomaticofrontal buttress over time.[47, 78] The zygomatic and sphenoid bones are said to be main areas that resist expansion and not the midplatal suture.[18] Haas reported that it is frequently impossible to achieve maxillary expansion entirely with a tooth-supported expander after the age of 18 years old.[47] Bishara et al.[18] recognized that although it may be possible to accomplish expansion in adults, the results are neither as predictable nor as stable compared to RPE in adolescents. However, there are a few reports in the literature that state maxillary expansion by non-surgical, traditional means is as successful in adults as it is in children.[49, 50]

Unsuccessful expansion in skeletally matured patients by utilizing conventional modes may lead to detrimental effects. Baccetti et al.[10] demonstrated that patients treated after the pubertal growth spurt with traditional RPE exhibited more dentoalveolar rather than skeletal changes. These unwanted effects may include but are not limited to lateral tipping of posterior teeth, extrusion, buccal root resorption, alveolar bone bending, and palatal tissue necrosis.[97] With greater dental displacement, there is an increased risk for periodontal complications.[34, 64, 97] The more teeth move buccally, the thinner the buccal alveolar bone and gingiva becomes, which predisposes the teeth to a greater chance for bony dehiscence, fenestrations and gingival recession.[37] Other unwanted effects that Haas[47] explained failure to open the midpalatal suture during RPE could result in extreme dental pain, teeth perforating through the buccal alveolar plate and potentially unstable buccolingual angulations of supporting teeth.

Surgically Assisted Rapid Palatal Expansion (SARPE)

Surgically assisted rapid palatal expansion (SARPE) has been advocated to correct maxillary transverse deficiency of greater than 5[97] to 7[91] mm in skeletally mature patients. It has been said that once skeletal maturity has been reached, orthodontic treatment alone cannot provide stable widening of the maxilla for deficiencies greater than 5mm.[64] The technique traditionally involves several corticotomies to release areas resistant to expansion followed by activation of a tooth-borne expander to distract the two halves of the maxilla.[64] The areas resistant to lateral forces in the midface include the piriform aperture (anterior), the ossified midpalatal suture (median), the zygomatic buttress (lateral), and the pterygoid junction (posterior).[64] Studies have shown that the major resistant sites for achieving parallel maxillary expansion is not the median palatal suture, but rather, it is the facial sutures including the zygomaticotemporal, zygomaticofrontal and zygomaticomaxillary sutures.[15, 72, 104] Although segmental LeFort I osteotomy may also facilitate the surgical correction of maxillary transverse discrepancy[97], only SARPE is able to provide dental arch space for alignment of crowded teeth by means of a diastema.[64] Chamberlain and Proffit reported achieving about 46% of skeletal expansion immediately after SARPE.[24]

Many orthodontists consider the patient age as an important factor for choosing between a nonsurgical or surgical approach to maxillary expansion. However, the literature presents conflicting views regarding at what age is surgical assistance required for correcting a narrow maxilla. Surgical assistance for maxillary expansion have been recommended for patients over the age of 14[79], 16[32], and 25 years. Alpern and Yurosko more specifically suggested SARPE for men over age 25 and women over age 20 for the correction of maxillary transverse deficiency. Adding to the confusion is the reported success in achieving maxillary expansion in older adults.[3, 21, 50, 56, 69]

Compared to non-surgical, conventional RPE, SARPE is believed to reduce dentoalveolar effects and periodontal complications.[64, 97] However, with the combined use of a tooth-borne expander, lateral forces are still delivered to the anchored teeth which inevitably compress the periodontal ligament and may lead to alveolar bone resorption, higher incidence of cortical fenestration and buccal root resorption.[79, 97] Sygouros et al.[98] evaluated the effects of surgically assisted rapid maxillary expansion with cone-beam computed tomography imaging and found there was significant buccal alveolar bending as well as posterior teeth buccal tipping and buccal alveolar bone loss, especially when there was a lack of surgical disjunction of the pterygoid plates. Some studies indicated that expansion effects of SARPE are similar to those obtained with RME alone, even though the palate and alveolar base are separated surgically from the maxillary complex prior to appliance activation.[67, 92, 101] To reduce the unwanted dentoalveolar effects and potential anchorage loss and relapse, authors have recommended the use of a bone-borne titatinum device in combination with surgical assistance.[79]

Although SARPE increases the predictability and success of maxillary expansion in non-growing patients, the procedure is invasive and associated with various complications. Serious surgical risks may include but is not limited to life-threatening epistaxis, cerebrovascular accident, skull-base fracture with reversible oculomotor nerve pareses and orbital compartment syndrome.[65, 90] Other complications such as postoperative hemorrhage, pain, sinusitis, palatal tissue irritation or ulceration, asymmetrical expansion, nasal septum deviation, and relapse may also be experienced by a patient undergoing SARPE.[77] Some unusual complications that have also been reported include orbital compartment syndrome resulting in blindness, bilateral lingual anesthesia, and a nasopalatine canal cyst.[97] Treatment with SARPE may also be costly and require a long recovery time for some patients. Nevertheless, in cases of extreme transverse maxillary hypoplasia and where orthodontic maxillary expansion has failed due to sutural resistance, SARPE remains the most commonly recommended treatment for patients.[64]

Micro-implant Assisted Rapid Palatal Expansion (MARPE)

In recent years, micro-implant assisted rapid palatal expansion (MARPE) has been utilized to maximize the orthopedic separation of the maxilla and overcome the disadvantages presented by tooth-borne and tooth-tissue borne expansion appliances. The technique involves using a hyrax jackscrew that is anchored to posterior teeth and fixated to the palate with miniscrews.[41, 81, 98] The tooth-bone-borne appliance provides several advantages including the lack of need for invasive surgery, cost-effective, and can be used in patients with inadequate dental anchorage.[105] This newer approach has been under investigation and its effects have been evaluated and compared to conventional rapid palatal expansion.

MARPE have shown to be effective at orthopedically expanding the maxilla with a clinically detectable diastema in young adolescents.[41, 81] The dentoalveolar effects associated with this novel technique have been reported to be minimal or nonsignificant compared to conventional RPE.[41] In a comparative study between tooth-borne and bone-borne devices, Mosleh et al. [82] observed significant increases in transverse dentolinear measurements in both groups; however, the tooth-borne expansion group showed greater increases in the tested variables. Lin et al.[70] also concluded that bone-borne expanders produce greater orthopedic changes and fewer dentoalveolar tipping than the Hyrax expander. The microimplants incorporated in the MARPE technique enable greater expansive forces to be distributed towards the rigid midpalatal suture and away from the teeth supporting the appliance, which leads to a decrease in adverse dentoalveolar changes and periodontal effects.[22]

The pattern of expansion resulting from MARPE have shown to differ from conventional RPE. Toklu et al.[41] observed a reverse “V” expansion pattern with increase in intermolar distances almost 3 times greater than the increase in the distance between the first premolars. In contrast, Wilmes et al.[105] reported a V-shaped expansion pattern with the wider base towards the anterior area in patients treated with the tooth-bone-borne expanders. Lin et al.[71] found the skeletal expansion pattern in the hyrax group was triangular, with a wider base at the anterior portion of the maxilla, whereas the pattern was parallel in the bone-borne expander group. In the front perspective, Lin et al.[71] observed a triangular pattern for both groups, with the least increase at the nasal floor and the greatest increased at the hard palate. The variation in sutural opening pattern may be due to difference in appliance fabrication utilizing zero, two, or four posterior teeth for appliance support and/ or the location of expander and TADs placement. The observed dental effects were consistent with those noted by Lin et al.[71] Nonetheless, bone-borne expanders was shown to produced greater statistically significant increases in suture expansion than did the hyrax group.[71]

CHAPTER 3: EXPERIMENTAL MATERIALS AND METHODS

Sample Description and Collection

This study has been approved by the Institutional Review Board of West Virginia University (see *Appendix C*) and serves as a retrospective, non-randomized pilot investigation. Fifteen patients from the archives of West Virginia University Orthodontic Department, who were treated with micro-implant assisted rapid palatal expansion (MARPE), were selected for this study.

Inclusion Criteria

Subjects were selected based on the following criteria:

1. Treatment with MARPE, particularly with the use of Maxillary Skeletal Expander (MSE), to correct maxillary transverse deficiency

2. Full field of view (17x13 cm) CBCT scans of diagnostic quality, including all pertinent anatomy, captured before and immediately after expansion treatment.
3. Presented with a cervical vertebral maturation (CVM) stage of 4 or greater based on the method published by Baccetti[11] et al.
4. No history of previous orthodontic or orthopedic treatment
5. No craniofacial syndrome or deformities due to abnormal development or trauma

Exclusion Criteria

Subjects were excluded base on the following criteria:

1. Lack of full field of view CBCT scans at baseline or immediate post-expansion.
2. Lack of skeletal maturity due to a cervical vertebral maturation (CVM) stage of 3 or below based on the method published by Baccetti[11] et al.

Pretreatment (T1) and an immediate post-expansion (T2) CBCT scans were collected for each patient. The scanned tomographic images were de-identified and coded with numbers to protect patient privacy. All CBCT images were required by the clinicians for diagnosis and treatment of these patients. The CBCT scan images were obtained with the Gendex GX-DP-700 cone-beam 3-dimensional imaging scanner. The chosen field of view was 17x13 cm with a 300 voxel size and 16 bit gray scale. Exposure components were pre-adjusted to the selected field of view: 11.30 seconds scan time, 85 KV, and 4.0 mA. All subjects were scanned in supine position, upright head posture and in maximum intercuspation (MICP). The data of each patient were reconstructed with 0.0 mm slice thickness, and the DICOM (digital imaging and communications in medicine) images were assessed by using Invivo 5 advance 3D imaging software (Anatomage, San Jose, CA).

Individual skeletal maturity was assessed for the sample using the cervical vertebral maturation (CVM) method published by Baccetti[11] et al (Figure 1). Patients presented with cervical stage (CS) 4 or greater were categorized as skeletally matured and included in the study. Two evaluators (P.N. and K.U.N.) were employed to judge the skeletal maturation. The judges were calibrated and the sample was included in the study if both judges agreed on the same CVM stage. Seven patients were excluded from the original sample due to inadequate tomograms or lack of skeletal maturity. The remaining 8 subjects (2 females, 6 males) were skeletally matured with a mean age: 21.9 years. None of the subjects possessed craniofacial abnormalities nor a history of previous orthodontic or orthopedic therapy.

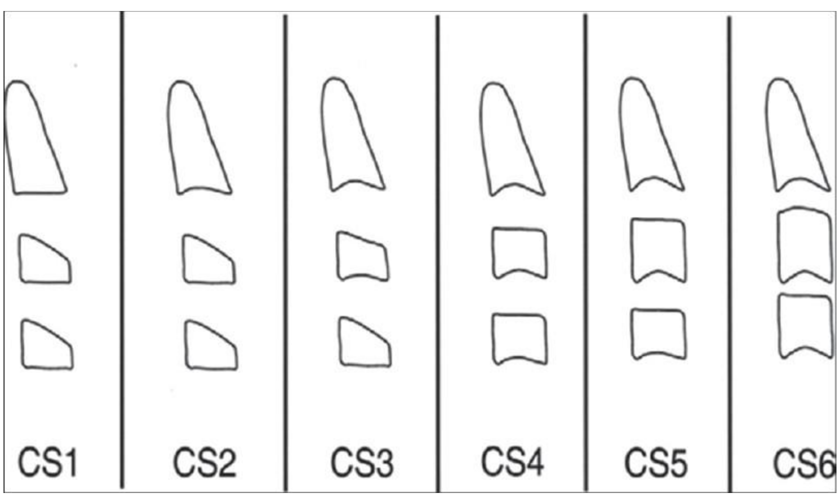

Figure 1. Cervical Vertebral Maturation assessment diagram

The amount of expansion each subject received varied with the magnitude of transverse discrepancy between their upper and lower jaw. Cast analysis measuring cusp tip-fossa relationship was used to quantify the maxillary transverse discrepancy for each patient at the canine, first premolar, and first molar area as described in Table 1 and shown in Figure 2. All measurements were adjusted for the uprighting of posterior teeth.

Table 1. Description of maxillary transverse discrepancy assessment

Area of Maxillary Transverse Discrepancy Assessment	Equation for Maxillary Transverse Discrepancy Calculation
Canine	[width between distofacial surfaces of mandibular canines] - [width between mesiolingual surfaces of maxillary canines]
First premolar	[width between central fossae of mandibular first premolars] - [width between palatal cusp tip of maxillary first premolars]
First molar	[width between central fossae of mandibular first molars] - [width between palatal cusp tip of maxillary first molars]

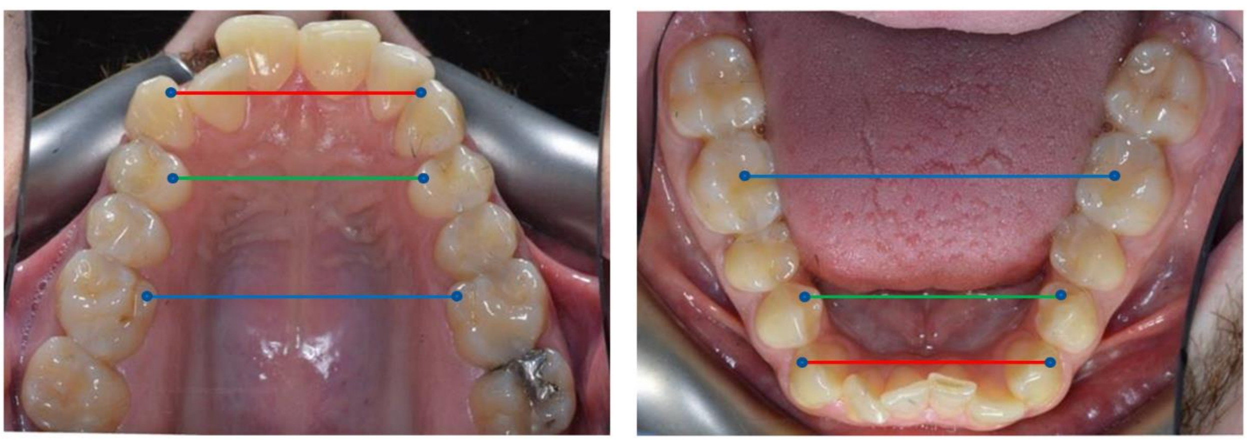

Figure 2. Landmark illustration for maxillary transverse discrepancy assessment

Appliance Description

The patients included in this study were treated with the maxillary skeletal expander (MSE), a specific type of microimplant assisted rapid palatal expansion appliance manufactured by BioMaterials Korea, Inc (Figure 3). The appliance consists of a central expansion screw and four attached arms that may be soldered to orthodontic bands, pre-fitted around anchored teeth to facilitate the placement of the appliance along the palate. Welded to the central expansion screw are four tubes that serve as guides for the placement of four microimplants. The microimplants allow for fixation of the expander flushed to the palate and are 1.5-1.8 mm in diameter and 11 mm in length. The microimplant length allows for bi-cortical engagement of the palatal and nasal floor, while the diameter allows for a secure fit within the tubes, reducing the magnitude of lateral force transfer to anchored teeth during appliance activation.

Figure 3. Maxillary Skeletal Expander (MSE) fabrication

Although the same expander appliance was used for all patients in the study sample, there were variations relating to the following:

1. **Number of teeth selected for appliance anchorage.** The expander was either banded to four teeth (first premolars and first molars) or two teeth (first molars only) (Figure 3).
2. **Appliance position.** The expander appliance was place in one of three locations along the palate:
    a. On the inclines of the anterior palate distal to the second or third rugae (anterior position).
    b. On the flat surface of the palate around the level of the permanent second premolar (middle position).

c. On the flat surface of the palate 1 mm anterior to the soft palate around the level of the permanent first molar (posterior position).

3. **Appliance activation.** The amount of appliance activation each patient received varied with the magnitude of transverse discrepancy between the upper and lower jaw. When the palatal cusp tips of the maxillary first molars were in contact with the corresponding buccal cusp tips of the mandibular first molars, expansion was considered complete and appliance activation was stopped.
4. **Number of microimplants used to secure appliance to the palate.** Two or four microimplants were selected to fixate the expander to the palate.

CBCT Image Analysis

A. Measurement Error Analysis

The same examiner took all measurements for the tested variables at least two weeks apart. Matched-paired t-tests were used to assess intra-examiner reliability. Respective measurements were averaged to adjust for measurement error and used for further statistical analysis.

B. CBCT Image Volume Reorientation

For purposes of standardizing the image analysis procedure and setting an identical reference plane for the T1 and T2 stages, all CBCT volumes were adjusted in three planes of space (coronal, sagittal, and axial). The image volume reorientation process was adopted from Molen, A[59] and performed within the render volume section of the Invivo5 imaging software (Figure 4).

The coronal view (frontal perspective) of the 3-D image volume was oriented parallel to software's horizontal position indicator line that connected the left and right medial termini of the zygomaticofrontal (ZF) sutures. The ZF line served as a stable reference because its location is in the superior third of the craniofacial complex, which has been described to be adequately distant from the sources of most facial asymmetries. [88]

The sagittal view (right lateral perspective) of the 3-D image volume was re-oriented parallel to the software's horizontal line that connected the right porion (Po), superior point of the external auditory meatus, and orbitale (Or), the inferior margin of the orbit. These same landmarks are used to establish the Frankfort plane as described by the World Congress on Anthropology in Frankfurt am Main, Germany in 1884.[51] A study by Daboul et al. revealed excellent intra-examiner reproducibility and inter-examiner reliability of Frankfort Horizontal plane through 3D landmark identification in MRI images and have suggested that the FH plane is

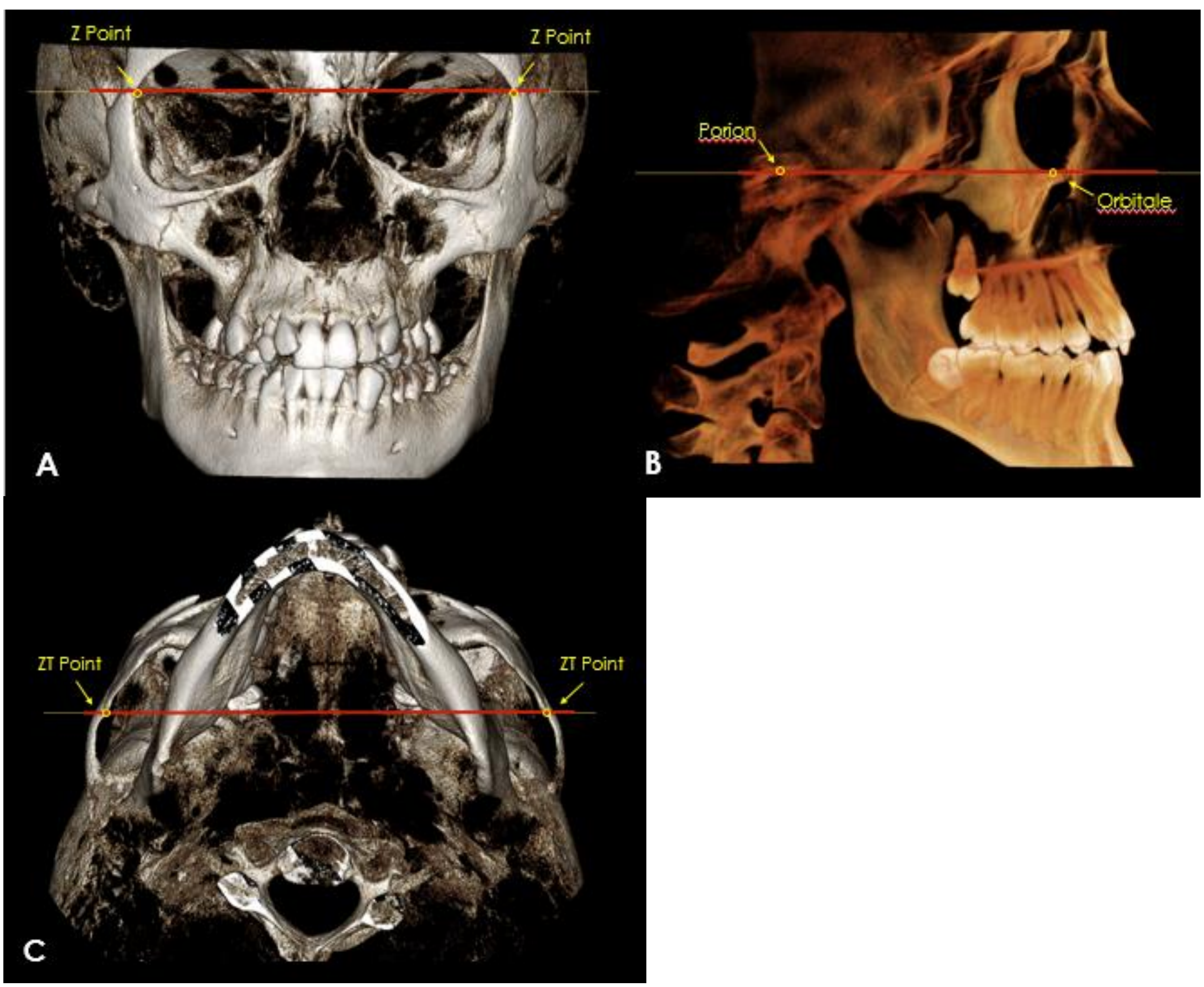

Figure 4. CBCT head orientation in three planes of space

a sufficiently stable landmark-based reference plane for craniofacial structures and treatment analysis.[31]

The axial view (inferior perspective) of the 3-D image volume was oriented parallel to the software's horizontal line that connected the left and right medial termini of the zygomaticotemporal (ZT) sutures. As described by Molen,[59] the ZT line facilitate the reorientation of the volume's yaw.

C. Midpalatal Suture Maturation Assessment

Individual midpalatal suture maturation was evaluated for the sample by one expert examiner (F.A.) using a novel classification method proposed by Angelieri[6] et al. The visual analysis system is the first to evaluate overall midpalatal suture morphology using CBCT and involves radiographic interpretation of all palate axial cross-sections for adequate staging. Five maturational stages (A-E) were developed to describe the degree of midpalatal suture fusion (Table 2, Figure 5). Patients in stages D and E are considered to have partially or completely fused midpalatal sutures.

Table 2. Description of individual midpalatal suture maturation assessment

Maturational Stages of Midpalatal Suture	Definition of Midpalatal Suture Maturational Stage
A	Straight high-density sutural line with no or little interdigitation
B	Scalloped appearance of the high-density sutural line
C	Two parallel, scalloped high-density lines that were close to each other, separated in some areas by small low-density spaces
D	Fusion completed in the palatine bone, with no evidence of a suture
E	Fusion anteriorly in the maxilla

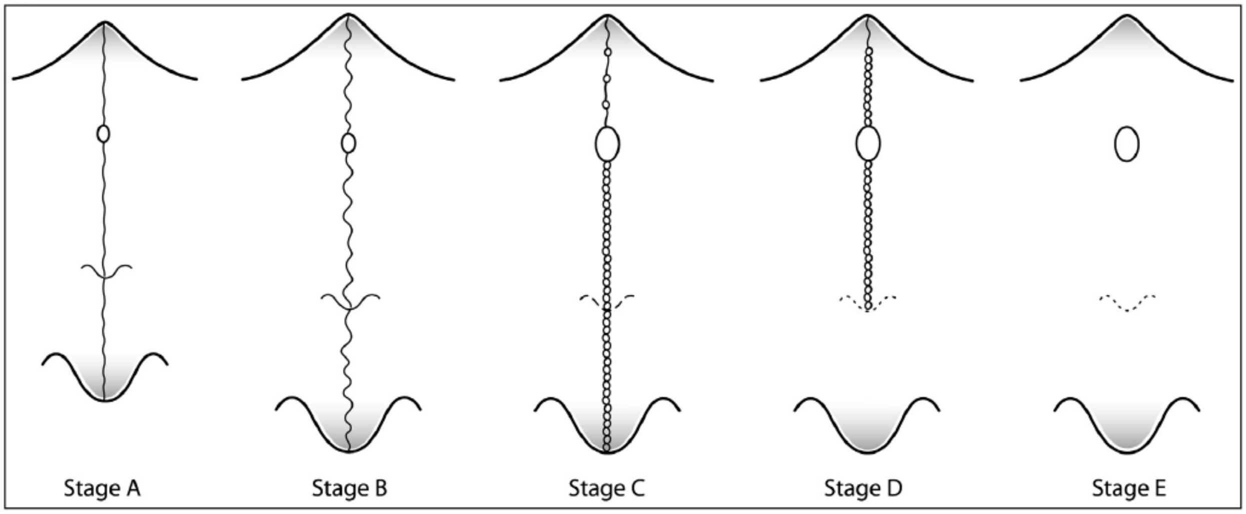

Figure 5. Schematic diagram of individual midpalatal suture maturational stages

D. Total Expansion

Total expansion achieved with RPE appliances includes the direct separation of the maxillary halves at the midpalatal suture (skeletal expansion) along with alveolar bone bending and dental tipping (dentoalveolar expansion). The following equation shows the components of total expansion:

[Total Expansion] = [Midpalatal Sutural Separation] + [Alveolar Bone Bending] + [Dental Tipping]

Skeletal (Orthopedic) Expansion (= [Midpalatal Sutural Separation]) **Dentoalveolar (Orthodontic) Expansion** (= [Alveolar Bone Bending] + [Dental Tipping])

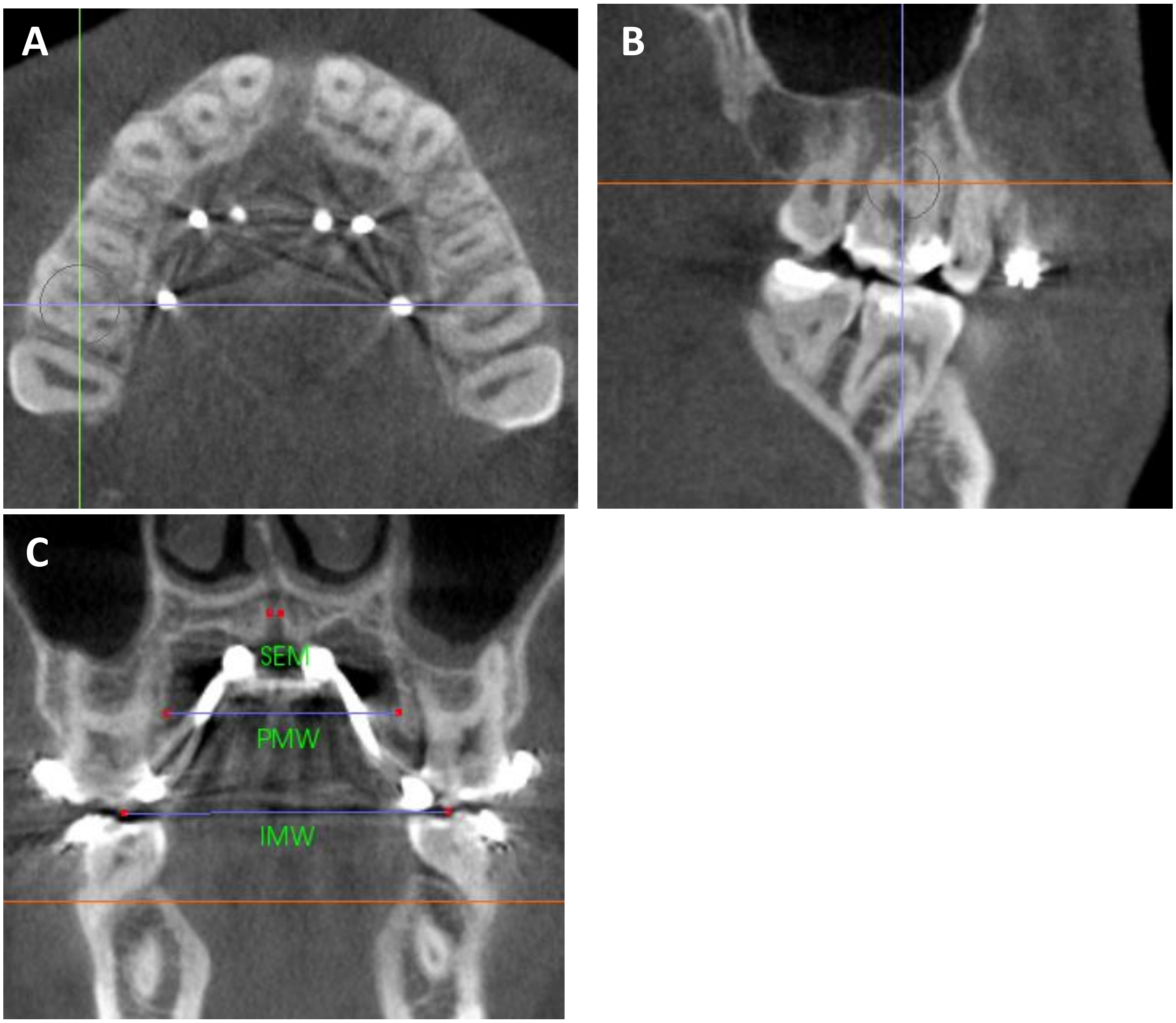

Figure 6. Measurement of sutural expansion (SEM), palatal maxillary width (PMW) and intermolar width (IMW) on a coronal cross-sectional slice through the midportion of M1.

In this study, total expansion (TE) was defined as the change (T2-T1) in the intermolar width (IMW), the distance between the palatal cusp tip of the right and left first molars (M1) measured in a coronal cross-sectional slice through the center of M1 (Figure 6). The sutural expansion in the middle of the palate (SEM) and the palatal maxillary width (PMW) measured at M1 furcation was quantified on the same coronal cross-sectional slice (Figure 6). Alveolar bone bending, defined as any additional palatal alveolar expansion beyond that of sutural separation, was determined by subtracting SEM from the change (T2-T1) in PMW. Dental tipping was calculated by subtracting SEM and the change in PMW from TE.

E. Midpalatal Suture Expansion Pattern

Axial View

Successful midpalatal suture separation was defined as complete opening of the suture anteroposteriorly. Measurements were made at the canine (C), first premolar (P1), second premolar (P2), and first molar (M1) position. The landmarks were identified and recorded with a small dot on an axial cross-sectional slice through the furcation of M1 (Figure 7). Suture width opening was measured between the right and left external edges of the suture on an axial cross-sectional slice through the center of the palate by using the Invivo5 distance measuring tool (Figure 8A-C). The suture external edges were verified in the coronal cross-sectional slice for each tested position (Figure 8D). A one-way ANOVA-Tukey's HSD test was used to compare the mean values of midpalatal suture expansion among C, P1, P2, and M1.

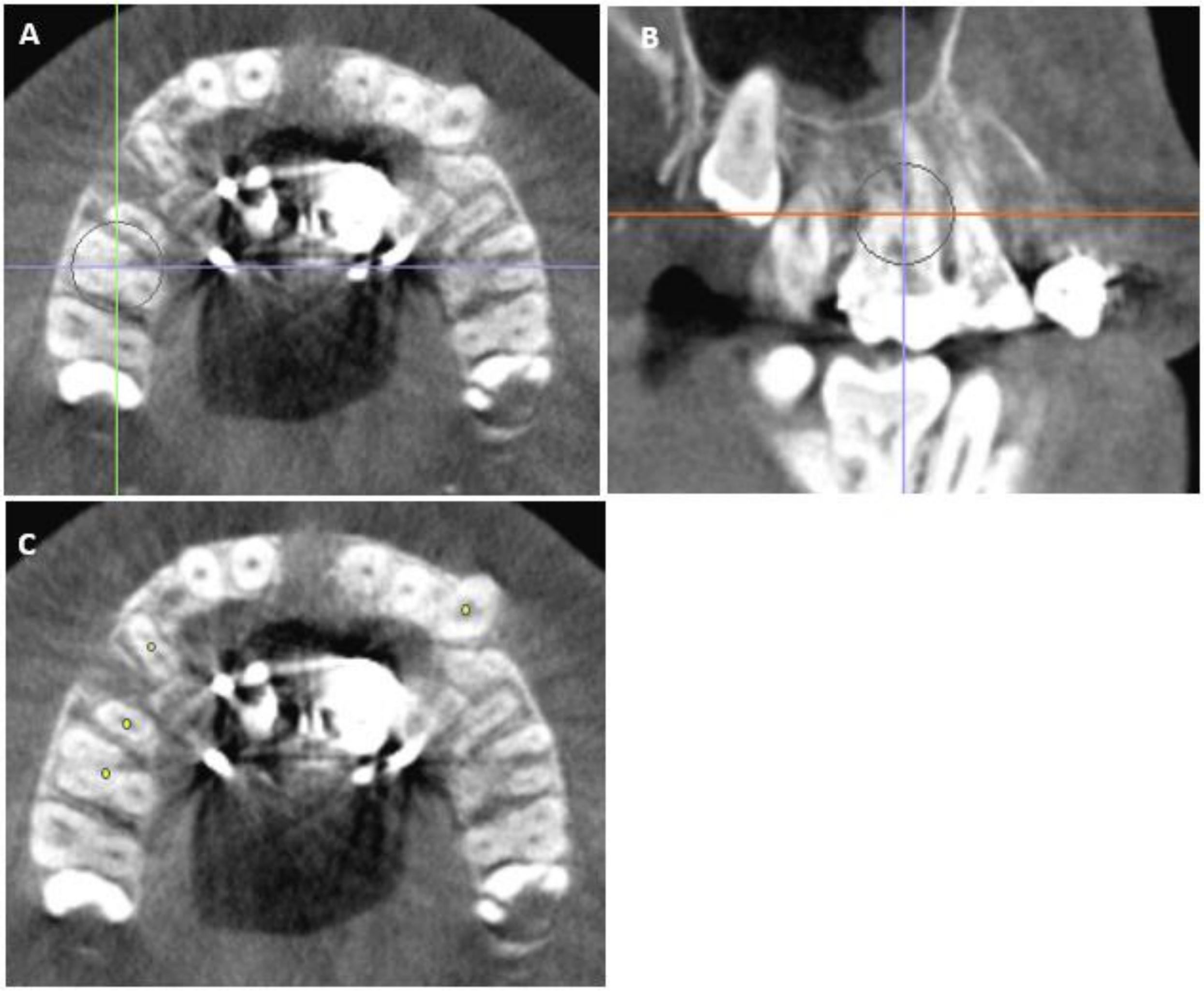

Figure 7. Identification of canine (C), first premolar (P1), second premolar (P2) and first molar (M1) on an axial cross-sectional slice through M1 furcation.

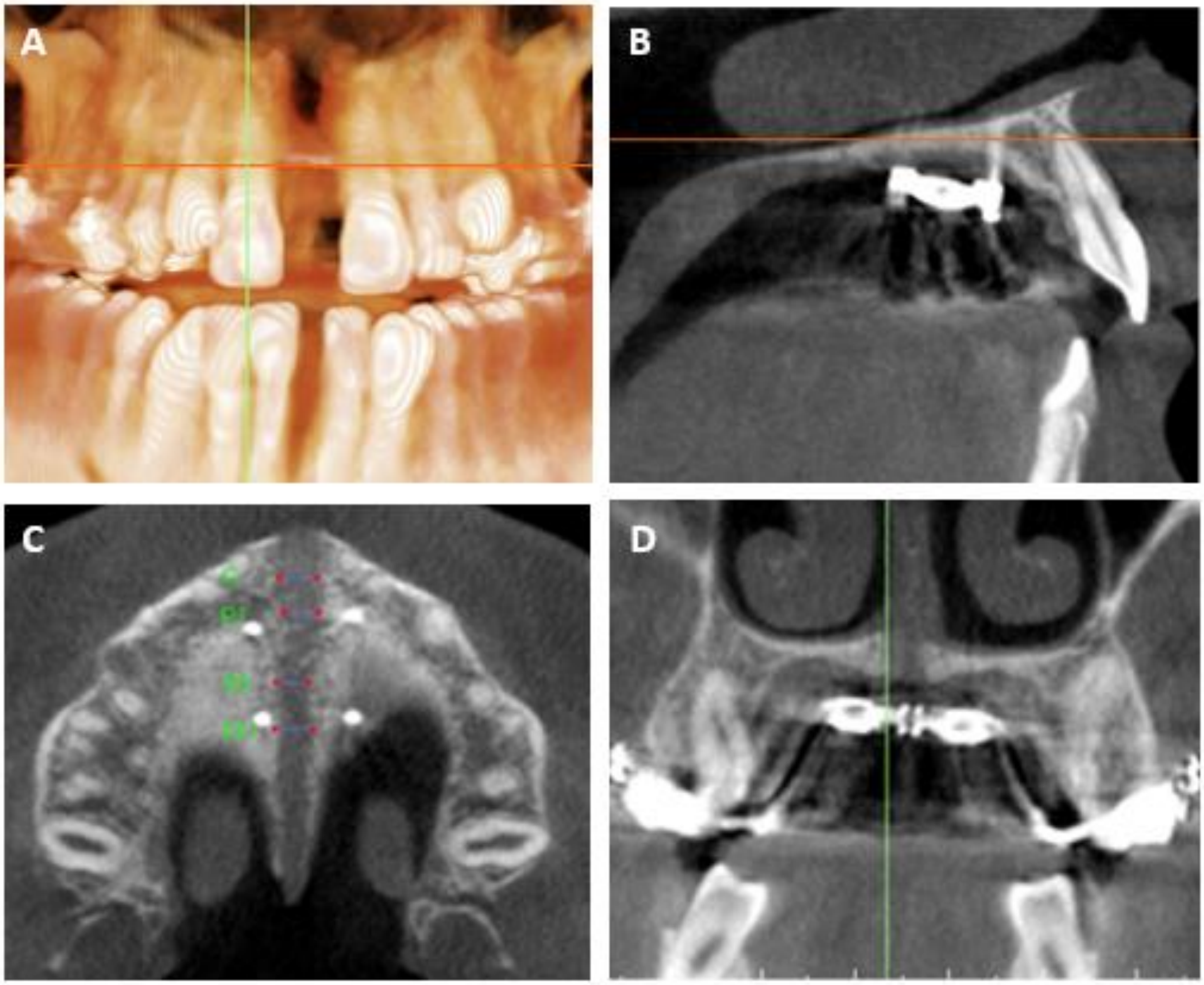

Figure 8. Measurement of sutural expansion on an axial cross-sectional slice through the midpalate at C, P1, P2, and M1.

Coronal View

Midpalatal suture expansion in the coronal view was measured at the nasal and palatal floor on a coronal cross-sectional slice through the center of M1 by connecting the right and left external edges of the suture (Figure 9A). The suture external edges were verified in the axial cross-sectional slice for each tested position (Figure 9B). A Matched-paired t-test was used to compare the suture opening at the nasal and palatal floor.

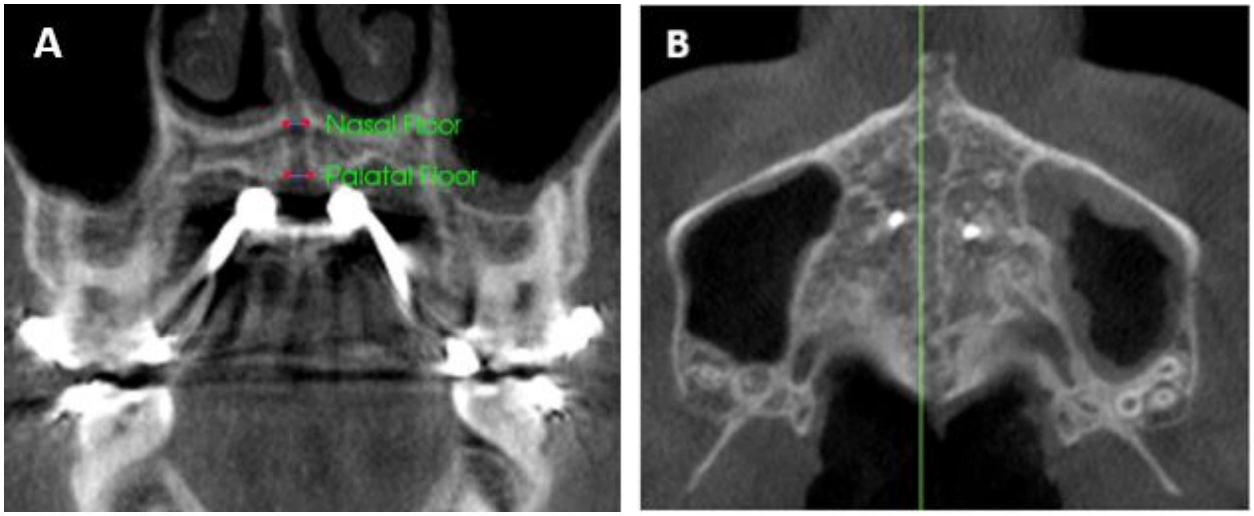

Figure 9. Measurement of sutural expansion at the nasal and palatal floor on a coronal cross-sectional slice through the midportion of M1.

F. Alveolar Bone Bending

Alveolar bone bending was defined as the degree difference (T2-T1) between the palatal alveolar angle (PAA) measured for the anchored teeth, P1, M1 or both, on a coronal cross-sectional slice through the midportion of the teeth. Figure 10 shows the PAA value obtained for M1 by measuring the intersecting angle formed by a best fit line through the palatal cortical plate and the software's horizontal indicator line that transverse the middle of the palate. A positive change in PAA indicated alveolar bone bending in the buccal direction. A Matched-paired t-test was used to compare T1 and T2 PAA values for each tested variable.

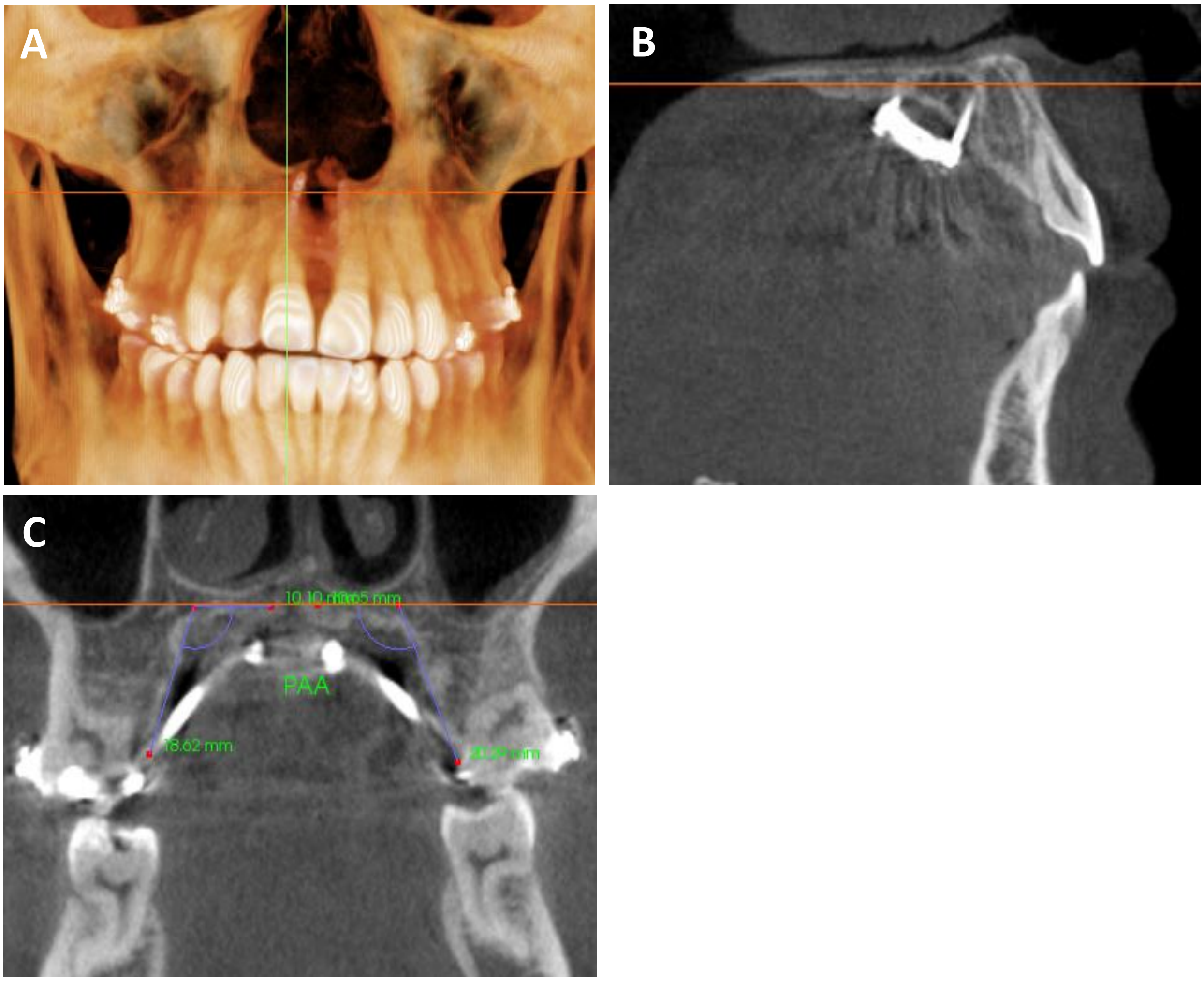

Figure 10. Measurement of palatal alveolar angle (PAA) for M1 on a coronal cross-sectional slice through the midportion of the tooth.

E. Dental Tipping

Dental tipping was defined as the degree difference (T2-T1) between the dental tipping angle (DTA) measured for the anchored teeth, P1, M1 or both, on a coronal cross-sectional slice through the midportion of the teeth. Figure 11 shows the DTA value obtained for M1 by measuring the intersecting angle formed by a best fit line through the long axis of the tooth and the software's horizontal indicator line that transverse the middle of the palate. A positive change in DTA indicated dental tipping in the buccal direction. A Matched-paired t-test was used to compare T1 and T2 DTA values for each tested variable.

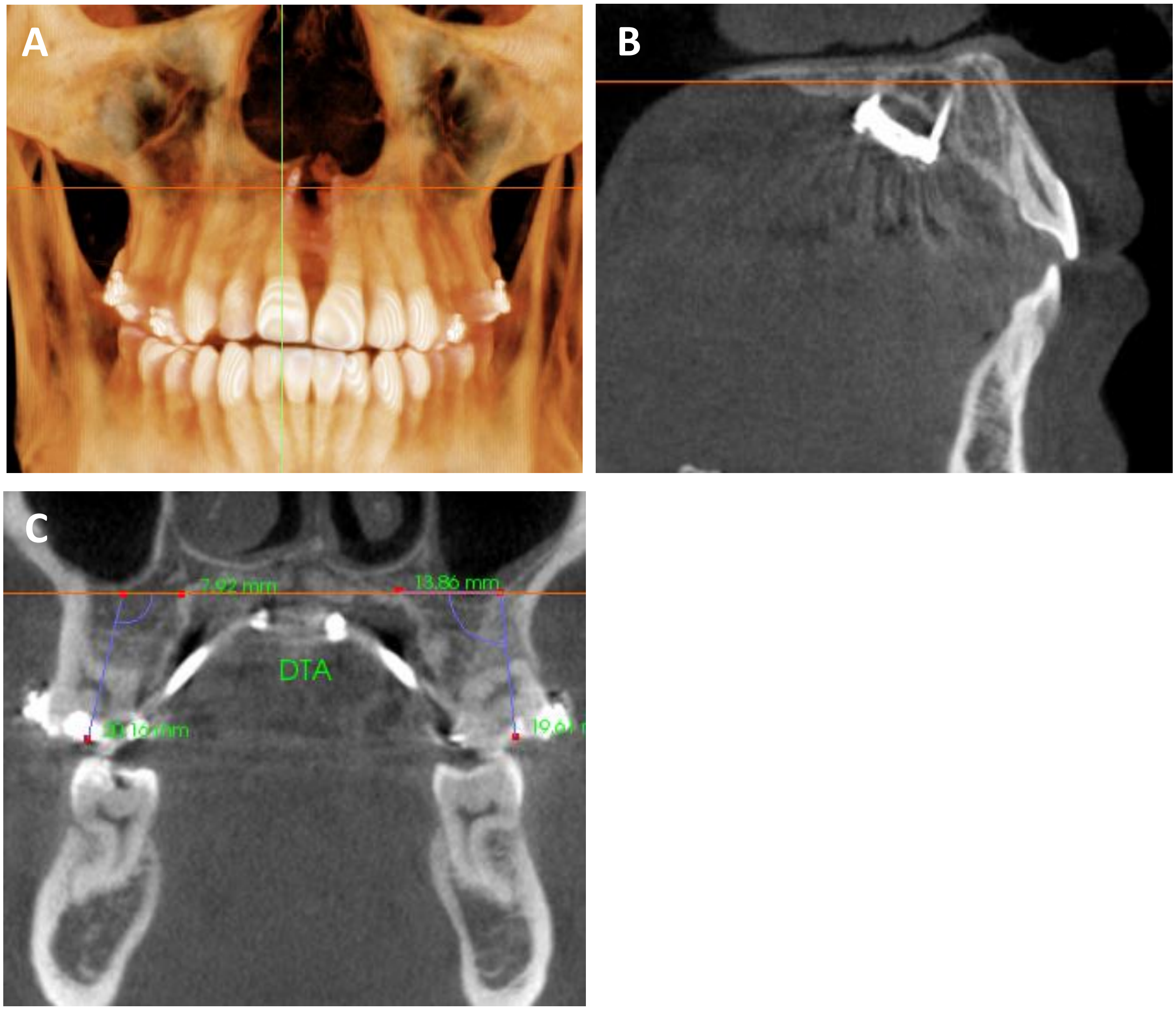

Figure 11. Measurement of dental tipping angle (DTA) for M1 on a coronal cross-sectional slice through the midportion of the tooth.

G. Buccal Bone Thickness Analysis

Buccal bone thickness (BBT) was measured for P1, the mesiobuccal root of M1, and the distobuccal root of M1 when P1, M1 or both was used for appliance anchorage on an axial cross-sectional slice through the furcation of M1 (Figure 12). BTT was defined as the perpendicular distance between the most facial surface of the tested tooth and the external aspect of the maxillary buccal cortical plate. A Matched-paired t-test was used to compare T1 and T2 BBT values for each tested variable.

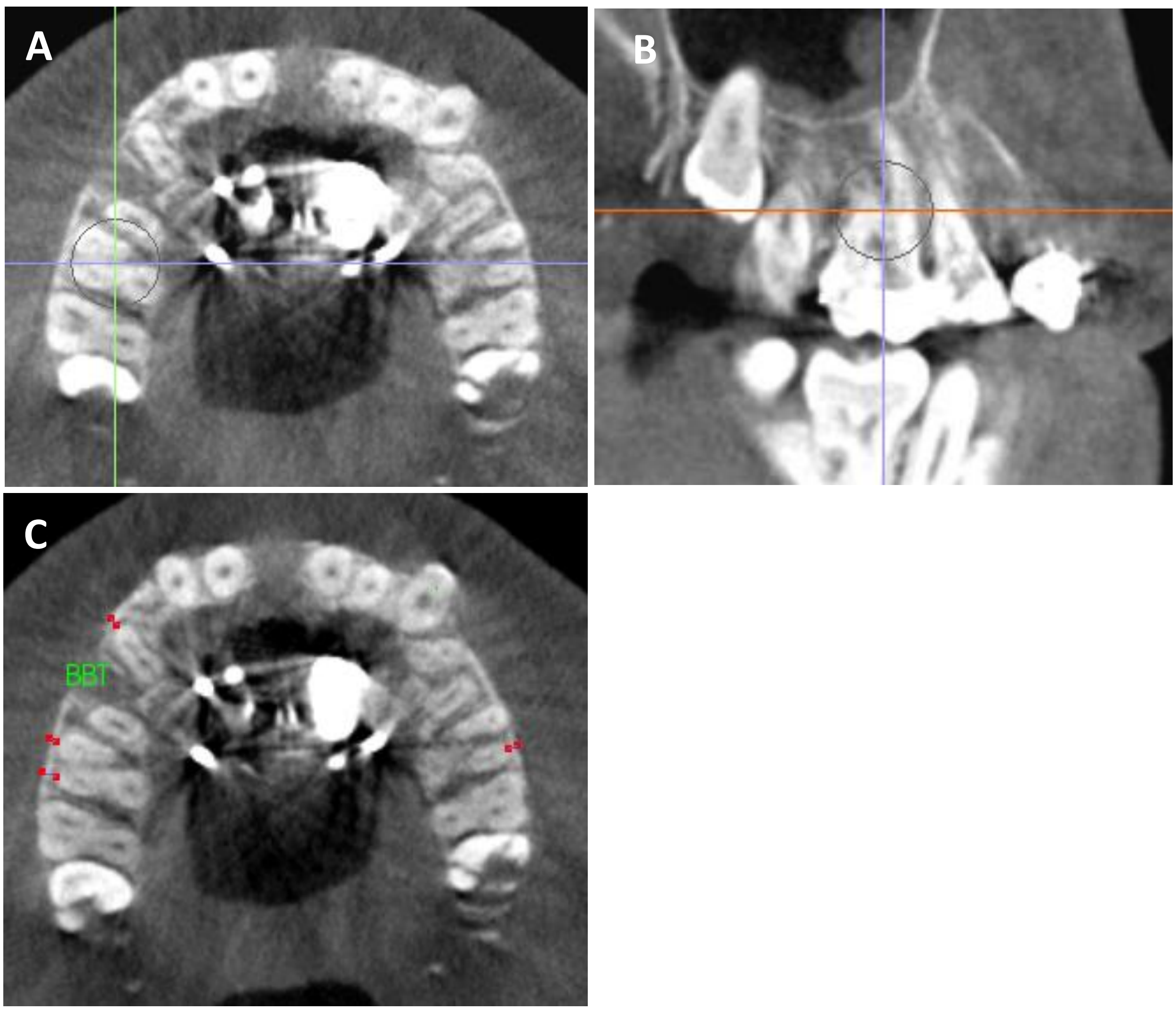

Figure 12. Measurement of buccal bone thickness (BTT) for P1 and mesiobuccal and distobuccal root of M1 on an axial cross-sectional slice through the furcation of M1.

H. Craniofacial Expansion Assessment

Individual facial skeletal changes due to expansion treatment were evaluated at the zygomatic and infrazygomatic areas from superimposed three-dimensional skeletal color maps of T1 and T2 by one expert examiner (T.N.) using protocols developed by Nguyen[85] et al (Figure 13). Pre-treatment and immediate post-expansion CBCT images were downsized to an isotropic voxel dimension of 0.5 X 0.5 X 0.5 mm to decrease computer processing. CBCT images taken at T1 and T2 were registered using the anterior cranial fossa as reference, an area that is completed growth at 7 years of age.[85] After the registration procedure, ITK-SNAP, an open-source software, was used to construct 3D surface models of the anatomic structures of interest and to create 3D graphic renderings for measurements. The registered models were evaluated for the greatest surface displacement/ expansion at the zygomatic bone and infrazygomatic crest areas

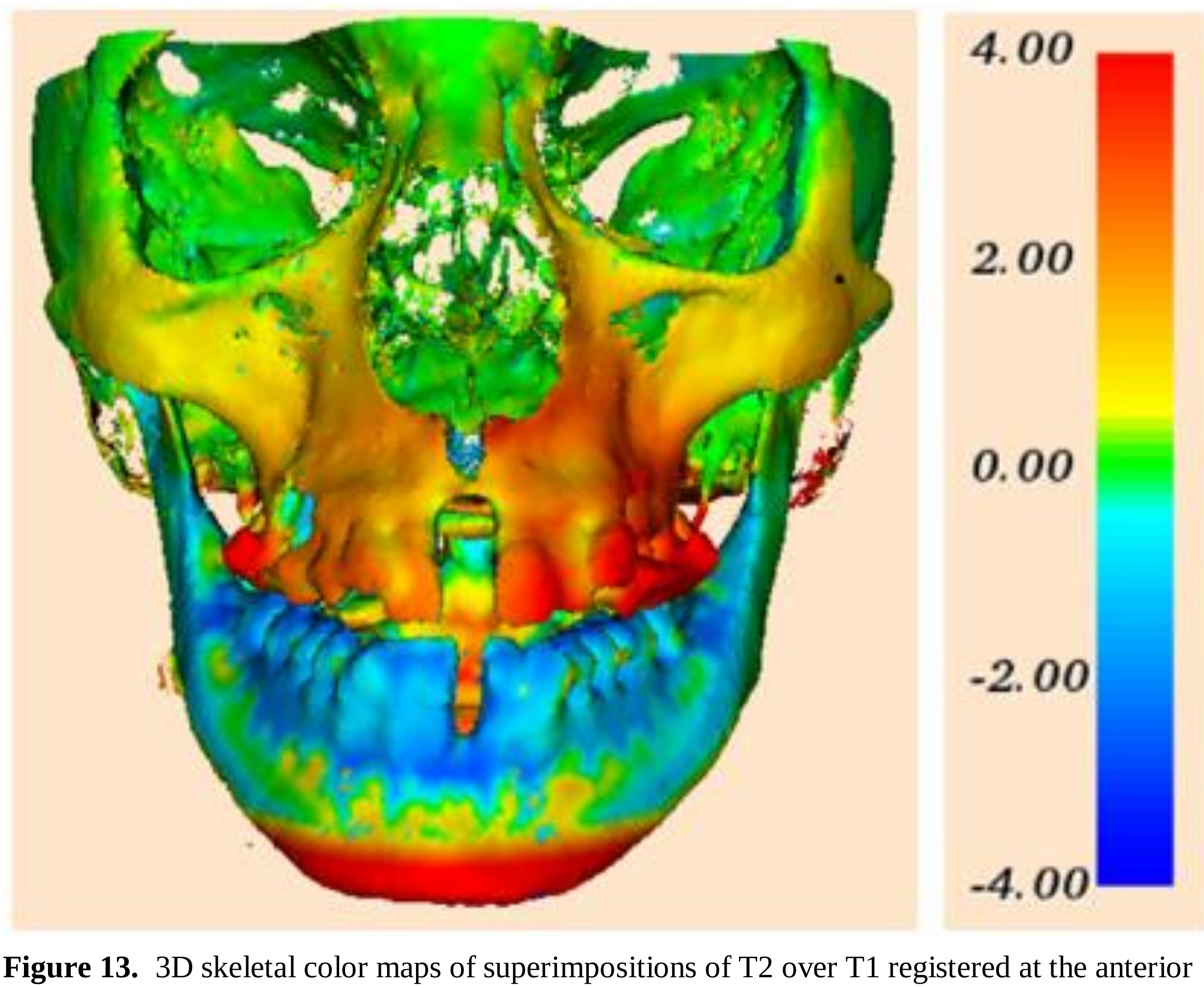

Figure 13. 3D skeletal color maps of superimpositions of T2 over T1 registered at the anterior cranial base with a scale of -4 to +4 mm. Red represents outward displacement of T2 relative to T1. Blue represents inward displacement

using Slicer CMF 3.1 (Slicer.org). A Matched-paired t-test was used to compare the expansion changes (T2-T1) of the zygomatic and infrazygomatic area on the same side.

CHAPTER 4: RESULTS

Sample Analysis

The final sample consisted of 8 subjects (2 females, 6 males) with a mean age of 21.9 ± 9.73 years. All subjects had a CVM of at least 4 and were considered skeletally matured. Individual midpalatal suture assessment showed 2 patients in stage C, 3 patients in stage D, and 3 patients in stage E (Figure 15). No differentiation was made for medical history or ethnicity. The average appliance activation was 5.61 ± 1.19 mm with mean treatment time of 7.64 ± 5.66 weeks. The appliance was placed in the anterior palate (palatal inclines distal to the second or third rugae) in 4 patients and in the middle of the palate (flat surface around the level of the second premolar) in 4 patients. None of the patients had the expander posteriorly positioned. The number of teeth used for appliance anchorage ranged from 2 to 4 (mean: 3.63). The appliance was secured to the palate with 4 micro-implants, except one patient with 2 micro-implants. Table 3 lists the details for the 8 patients included in this study.

Table 3. Description of sample study.

Subject	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		**Mean ± SD**
Age	45	19	21	19	17	17	23	14		21.9 ± 9.73
Sex	F	M	M	M	M	M	F	M		
CVM	5-6	5	4	5	5	5	5	5-6		
Number of Teeth Used for Appliance Anchorage	3	4	4	4	2	4	4	4		3.63
Appliance Position: A (Anterior) M (Middle)	M	A	A	M	M	A	M	A		
Appliance Activation (mm)	6.7	6.24	5.5	5.76	6.5	6.0	5.28	2.93		5.61 ± 1.19
Treatment time (weeks)	5	12.86	12.14	17	6.86	2.71	2.57	2		7.64 ± 5.66

Number of Inserted Micro-implants	4	2	4	4	4	4	4	4		
Midpalatal Suture Maturation Assessment	C	D	D	E	E	D	E	C		

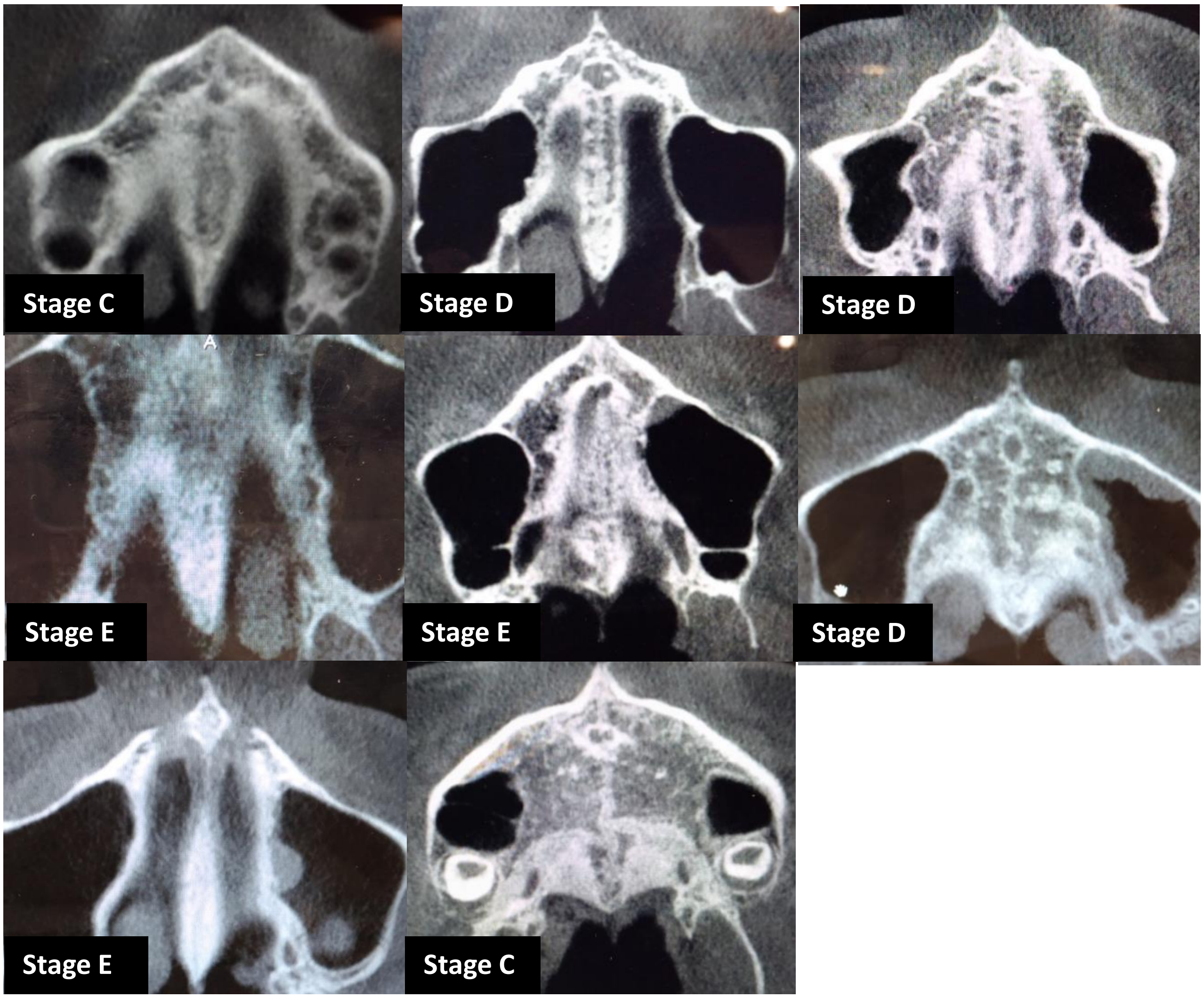

Figure 14. Individual midpalatal suture assessment images.

Intra-rater reliability Analysis

To improve the accuracy of measurement and minimize error measurement, each tested variable was measured twice one week apart and the average of the two measurements was used for statistical analysis (Table 4). Matched-paired t-test was used to evaluate the intra-rater reliability of the measurements for the tested variables (Tables 5 and 6). No significant differences were found for all the variables tested except for the T2 measurement of the right palatal alveolar angle at the first molar, indicating high level of accuracy in recording these landmarks and measurements. A significant difference was observed for the T2 palatal alveolar angle (degree) measured at the right first molar only ($p < 0.05$).

Table 4. Mean values of T1, T2 and (T2-T1) for the tested variables

(C) canine; (P1) first premolar; (P2) second premolar; (M1) first molar, (MB-M1) mesial buccal root of first molar; (DB-M1) distal buccal root of first molar

Table 5. Matched-paired t-test comparing T1 values taken at least 2 weeks apart for tested variables

		Variable	Mean 1	Mean 2	Mean Diff	P- value	Sig Diff
Inter-molar Width (mm)		M1	42.59	42.65	0.06	0.72	NS

			T1 ± SD	T2 ± SD	(T2-T1) ± SD
Inter-molar Width (mm)		M1	42.62 ± 0.59	48.88 ± 2.78	6.26 ±1.31
Palatal Maxillary Width (mm)		M1	31.66 ± 2.36	34.94 ± 2.15	3.28 ± 0.75
Midpalatal Suture Expansion in Coronal View (mm)		Nasal	0	2.53 ± 0.53	2.53 ± 0.53
		Middle	0	2.55 ± 0.71	2.55 ± 0.71
		Palatal	0	2.92 ± 0.59	2.92 ± 0.59
Midpalatal Suture Expansion in Axial View (mm)		C	0	3.53 ± 0.80	3.53 ± 0.80
		P1	0	3.74 ± 0.63	3.74 ± 0.63
		P2	0	3.59 ± 0.67	3.59 ± 0.67
		M1	0	3.27 ± 0.46	3.27 ± 0.46
Buccal Bone Thickness (mm)	Right	P1	1.05 ± 0.60	0.51 ± 0.74	-0.54 ± 0.53
		MB-M1	1.14 ± 0.69	0.54 ± 0.83	-0.60 ± 0.46
		DB-M1	1.88 ± 0.83	1.39 ± 0.96	-0.49 ± 0.27
	Left	P1	1.29 ± 1.06	0.61 ± 0.71	-0.68 ± 0.70
		MB-M1	1.06 ± 0.92	0.67 ± 0.89	-0.39 ± 0.50
		DB-M1	2.00 ± 0.98	1.73 ± 0.87	-0.27 ± 0.25
Palatal Alveolar Angle (degree)	Right	P1	111.12 ± 8.96	119.41 ± 15.97	8.29 ± 13.22
		M1	104.45 ± 8.76	107.51 ± 8.66	3.06 ± 4.87
	Left	P1	110.94 ± 10.65	108.61 ± 6.89	-2.34 ± 10.67
		M1	105.16 ± 6.04	106.61 ± 5.55	1.46 ± 5.55
Dental Tipping Angle (degree)	Right	P1	87.55 ± 3.40	90.11 ± 4.37	2.56 ± 5.39
		M1	94.82 ± 5.94	102.94 ± 7.40	8.01 ± 4.82
	Left	P1	90.21 ± 5.47	99.38 ± 3.83	9.17 ± 6.03
		M1	98.21 ± 3.86	103.84 ± 6.16	5.63 ± 2.77

Palatal Maxillary Width (mm)		M1	31.67	31.64	-0.03	0.87	NS
Buccal Bone Thickness (mm)	Right	P1	1.03	1.06	0.03	0.78	NS
		MB-M1	1.12	1.16	0.04	0.60	NS
		DB-M1	1.90	1.86	-0.04	0.75	NS
	Left	P1	1.30	1.28	-0.02	0.89	NS
		MB-M1	1.06	1.05	-0.01	0.98	NS
		DB-M1	2.12	1.88	-0.24	0.05	NS
Palatal Alveolar Angle (degree)	Right	P1	113.27	108.97	-4.30	0.35	NS
		M1	105.01	103.89	-1.13	0.36	NS
	Left	P1	112.37	110.26	-2.11	0.36	NS
		M1	105.09	105.23	0.14	0.34	NS
Dental Tipping Angle (degree)	Right	P1	87.51	87.59	0.08	0.96	NS
		M1	95.64	94.00	-1.64	0.12	NS
	Left	P1	88.96	91.46	2.50	0.20	NS
		M1	98.81	97.61	-1.20	0.20	NS

(C) canine; (P1) first premolar; (P2) second premolar; (M1) first molar, (MB-M1) mesial buccal root of first molar; (DB-M1) distal buccal root of first molar

Table 6. Matched-paired t-test comparing T2 values taken at least 2 weeks apart for tested variables

		Variable	Mean 1	Mean 2	Mean Diff	P- value	Sig Diff
Inter-molar Width (mm)		M1	48.83	48.92	0.09	0.62	NS
Palatal Maxillary Width (mm)		M1	34.83	35.04	0.21	0.13	NS
Midpalatal Suture Expansion in Coronal View (mm)		Nasal	2.45	2.61	0.15	0.11	NS
		Middle	2.49	2.61	0.12	0.42	NS
		Palatal	2.82	3.01	0.19	0.19	NS
Midpalatal Suture Expansion in Axial View (mm)		C	3.69	3.37	-0.31	0.19	NS
		P1	3.71	3.76	0.05	0.78	NS
		P2	3.56	3.62	0.06	0.84	NS
		M1	3.28	3.26	-0.02	0.93	NS
Buccal Bone Thickness (mm)	Right	P1	0.50	0.52	0.02	0.87	NS
		MB-M1	0.48	0.61	0.12	0.23	NS
		DB-M1	1.35	1.43	0.08	0.34	NS

	Left	P1	0.67	0.55	-0.12	0.45	NS
		MB-M1	0.77	0.57	-0.20	0.27	NS
		DB-M1	1.70	1.76	0.06	0.58	NS
Palatal Alveolar Angle (degree)	Right	P1	119.53	119.29	-0.24	0.95	NS
		M1	108.84	106.17	-2.67	0.015	*
	Left	P1	110.71	106.50	-4.21	0.32	NS
		M1	107.74	105.49	-2.25	0.34	NS
Dental Tipping Angle (degree)	Right	P1	90.54	89.67	-0.87	0.75	NS
		M1	102.77	102.90	0.13	0.93	NS
	Left	P1	99.17	99.59	0.41	0.90	NS
		M1	102.15	105.54	3.39	0.32	NS

(C) canine; (P1) first premolar; (P2) second premolar; (M1) first molar, (MB-M1) mesial buccal root of first molar; (DB-M1) distal buccal root of first molar

* $p < 0.05$

Total Expansion

Total expansion achieved from MARPE treatment was 6.26 ± 1.31 mm, defined as the change in the intermolar width (IMW) of M1. The amount of skeletal expansion that accounted for total expansion was 41%, which was determined by using the mean midpalatal suture expansion (2.55 ± 0.71 mm) measured in the middle of the palate at M1 (Table 7). This meant the remaining 59% that contributed to total expansion was from dentoalveolar expansion.

Table 7. Average widths (mm) at various anatomic sites on a coronal cross-sectional slice through the center of M1 for T1, T2 and (T2-T1).

		N	Mean ± SD	Max	Min
Inter-molar width (IMW)	**T1**	7	42.62 ± 0.59	45.71	38.91
	T2	7	48.88 ± 2.78	52.20	44.15
	T2-T1	7	6.26 ±1.31	8.75	4.60
Midpalatal suture expansion at the middle of the palate	**T1**	7	0	0	0
	T2	7	2.55 ± 0.71	4.06	2.03
	T2-T1	77	2.55 ± 0.71	4.06	2.03
Palatal maxillary width (PMW)	**T1**	7	31.66 ± 2.36	34.94	27.74
	T2	7	34.94 ± 2.15	37.77	31.77

	T2-T1	7	3.28 ± 0.75	4.66	2.23

Alveolar bone bending and dental tipping are components of dentoalveolar expansion. Alveolar bone bending, calculated by subtracting the mean midpalatal suture separation (2.55 ± 0.71 mm) measured in the middle of the palate from the change in palatal maxillary width (3.28 ± 0.75 mm), was 0.73 ± 0.04 mm. This indicated that alveolar bone bending accounted for 12% of total expansion. The remaining fraction of total expansion derived from dental tipping, which was 47% at the first molar (2.98 ± 0.56 mm).

Midpalatal Suture Expansion

Axial View

The midpalatal suture was successfully opened in all subjects. Mean midpalatal suture expansion (mm) at C, P1, P2 and M1 ranged from 2.71-4.70 mm, 2.52-4.77 mm, 2.79-4.55 mm, and 2.56-4.05 mm respectively (Table 8). One-way ANOVA combined with a Tukey's HSD (honest significance difference) test showed no significant differences among any two tested variables ($p > 0.05$) (Appendix B, Table 31). This indicated parallel expansion along the length of the midpalatal suture

Table 8. Average midpalatal suture expansion (mm) measured at canine (C), first premolar (P1), second premolar (P2) and first molar (M1)

Position		N	Mean ± SD	Max	Min
C	**T1**	8	0	0	0
	T2	8	3.53 ± 0.80	4.70	2.71
	T2-T1	8	3.53 ± 0.80	4.70	2.71
P1	**T1**	8	0	0	0
	T2	8	3.74 ± 0.63	4.77	2.52
	T2-T1	8	3.74 ± 0.63	4.77	2.52
P2	**T1**	8	0	0	0
	T2	8	3.59 ± 0.67	4.55	2.79
	T2-T1	8	3.59 ± 0.67	4.55	2.79

M1	T1	8	0	0	0
	T2	8	3.27 $\pm$ 0.46	4.05	2.56
	T2-T1	8	3.27 $\pm$ 0.46	4.05	2.56

Coronal View

Mean midpalatal suture separation (mm) at the nasal and palatal floor ranged from 1.81-3.26 mm, 2.03-4.06 mm, and 2.03-3.99 mm respectively (Table 9). A Matched-paired t-test showed no significant differences between the suture opening at the nasal and palatal floor ($p > 0.05$) (Table 10). This indicated the separation of the midpalatal suture in the coronal view was parallel.

Table 9. Average midpalatal suture expansion (mm) measured at the nasal and palatal floor

Position		N	Mean $\pm$ SD	Max	Min
Nasal	**T1**	8	0	0	0
	T2	8	2.53 $\pm$ 0.53	3.26	1.81
	T2-T1	8	2.53 $\pm$ 0.53	3.26	1.81
Palatal	**T1**	8	0	0	0
	T2	8	2.92 $\pm$ 0.59	3.99	2.03
	T2-T1	8	2.92 $\pm$ 0.59	3.99	2.03

Table 10. Matched-paired t- test comparing midpalatal suture separation (mm) measured at the nasal and palatal floor

	N	Mean $\pm$ SD	Mean Diff $\pm$ SD	P-value	Sig Diff
Nasal	8	2.53 $\pm$ 0.53	0.39 $\pm$ 0.06	0.09	NS
Palatal	8	2.92 $\pm$ 0.59			

Alveolar Bone Bending

Alveolar bone bending was defined as the difference between the palatal alveolar angle (PAA) measured at T1 and T2 for the anchored teeth. Mean PAA (^{o}) at P1 and M1 on the right ranged from 99.65-125.75^o and 92.85-116.90^o respectively for T1 and 100.75-146.05^o and 94.90-116.40^o respectively for T2 (Table 11). Mean PAA^o at P1 and M1 on the left ranged from

94.75-127.50 ^{o} and 97.45-112.95 ^{o} respectively for T1 and 100.45-115.75 ^{o} and 98.50-116.00 ^{o} respectively for T2 (Table 11). Note that P1 and M1 PAA on the right and P1 PAA on the left was measured for 7 patients while M1 PAA on the left was measured for 8 patients. A Matched-paired t-test showed no significant difference was found between the T1 and T2 PAA values for any of the tested variables ($p > 0.05$) (Table 12).

Table 11. Average palatal alveolar angle (o) measured at P1 and M1 on the right and left sides.

	Position		**N**	**Mean ± SD**	**Max**	**Min**
Right	**P1**	**T1**	7	111.12 ± 8.96	125.75	99.65
		T2	7	119.41 ± 15.97	146.05	100.75
		T2-T1	7	8.29 ± 13.22	30.9	-5.75
	M1	**T1**	7	104.45 ± 8.76	116.9	92.85
		T2	7	107.51 ± 8.66	116.4	94.9
		T2-T1	7	3.06 ± 4.87	11.75	-1.90
Left	**P1**	**T1**	7	110.94 ± 10.65	127.5	94.75
		T2	7	108.61 ± 6.89	116.15	100.45
		T2-T1	7	-2.34 ± 10.67	8.5	-22.4
	M1	**T1**	8	105.16 ± 6.04	112.95	97.45
		T2	8	106.61 ± 5.55	116.00	98.50
		T2-T1	8	1.46 ± 5.55	12.20	-4.90

Table 12. Matched-paired t-test comparing T1 and T2 mean palatal alveolar angle (o) at P1 and M1 on the right and left sides.

			N	**Mean ± SD**	**Mean Diff ± SD**	**SD**	**P-value**	**Sig Diff**
Right	**P1**	T1	7	111.12 ± 8.96	8.29 ± 13.22	13.22	0.15	NS
		T2	7	119.41 ± 15.97				
	M1	T1	7	104.45 ± 8.76	3.06 ± 4.87	4.87	0.15	NS
		T2	7	107.51 ± 8.66				
Left	**P1**	T1	7	110.94 ± 10.65	-2.34 ± 10.67	10.67	0.58	NS
		T2	7	108.61 ± 6.89				
	M1	T1	8	105.16 ± 6.04	1.46 ± 5.55	5.55	0.48	NS
		T2	8	106.61 ± 5.55				

Dental Tipping

Dental tipping in degrees was defined as the difference between the dental tipping angle (DTA) measured at T1 and T2 for the anchored teeth. Mean DTA (^{o}) at P1 and M1 on the right ranged from 82.25-91.60^o and 87.00-101.65^o respectively for T1 and 82.40-95.90 ^{o} and 93.45-111.10^o respectively for T2 (Table 13). Mean DTA ^{o} at P1 and M1 on the left ranged from 79.75-97.75^o and 92.85-103.05^o respectively for T1 and 92.15-104.00^o and 95.85-111.50^o respectively for T2 (Table 13). Note that P1 and M1 DTA on the right and P1 DTA on the left was measured for 7 patients while M1 DTA on the left was measured for 8 patients. A Matched-paired t-test showed a significant difference was found between DTA values for the right M1 and left P1 and M1 positions ($p < 0.05$) (Table 14).

Table 13. Average dental tipping angle (o) measured at P1 and M1 on the right and left sides.

	Position		**N**	**Mean ± SD**	**Max**	**Min**
Right	**P1**	**T1**	7	87.55 ± 3.40	91.60	82.25
		T2	7	90.11 ± 4.37	95.90	82.40
		T2-T1	7	2.56 ± 5.39	6.20	-9.20
	M1	**T1**	7	94.82 ± 5.94	101.65	87.00
		T2	7	102.94 ± 7.40	111.10	93.45
		T2-T1	7	8.01 ± 4.82	17.70	2.65
Left	**P1**	**T1**	7	90.21 ± 5.47	97.75	79.75
		T2	7	99.38 ± 3.83	104.00	92.15
		T2-T1	7	9.17 ± 6.03	18.65	1.35
	M1	**T1**	8	98.21 ± 3.86	103.05	92.85
		T2	8	103.84 ± 6.16	111.50	95.85
		T2-T1	8	5.63 ± 2.77	9.90	2.00

Table 14. Matched-paired t-test comparing T1 and T2 mean dental tipping angle (o) at P1 and M1 on the right and left sides.

			N	**Mean ± SD**	**Mean Diff ± SD**	**P-value**	**Sig Diff**
Right	**P1**	T1	7	87.55 ± 3.40	2.56 ± 5.39	0.26	NS
		T2	7	90.11 ± 4.37			
	M1	T1	7	94.82 ± 5.94	8.01 ± 4.82	0.005	**
		T2	7	102.94 ± 7.40			
Left	**P1**	T1	7	90.21 ± 5.47	9.17 ± 6.03	0.007	**

		T2	7	99.38 + 3.83			
	M1	T1	8	98.21 + 3.86	5.63 + 2.77	0.0007	***
		T2	8	103.84 + 6.16			

** p < 0.01, *** p < 0.001

Buccal Bone Thickness

Buccal bone thickness (BBT) was measured for the first premolar (P1), mesiobuccal root of first molar (MB-M1) and distobuccal root of first molar (DB-M1 (Table 15). Right and left P1 BBT decreased on average by 0.54 + 0.53 mm ($P < 0.05$) and 0.68 + 0.70 mm ($P < 0.05$) respectively. Right and left MB-M1 BBT decreased by 0.60 + 0.46 mm and 0.39 + 0.50 mm respectively while right and left DB-M1 BBT reduced by 0.49 + 0.27 mm and 0.27 + 0.25 mm respectively. Matched-paired t-tests showed the reduction in buccal bone thickness for the first molars were all significant ($P < 0.05$) except for the mesiobuccal root of the left first molar ($P > 0.05$). Note all variables were measured for 7 patients except for MB-M1 and DB-M1 on the left, which were measured for 8 patients.

Table 15. Average buccal bone thickness (mm) measured at first premolar (P1), mesiobuccal root of first molar (MB-M1) and distobuccal root of first molar (DB-M1) on the right and left sides.

	Position		**N**	**Mean + SD**	**Max**	**Min**
Right	**P1**	**T1**	7	1.05 + 0.60	1.90	0.37
		T2	7	0.51 + 0.74	1.49	-0.56
		T2-T1	7	-0.54 + 0.53	0.27	-1.25
	MB-M1	**T1**	7	1.14 + 0.69	2.15	0.20
		T2	7	0.54 + 0.83	1.39	-0.82
		T2-T1	7	-0.60 + 0.46	-0.09	-1.43
	DB-M1	**T1**	7	1.88 + 0.83	2.82	0.58
		T2	7	1.39 + 0.96	2.79	-0.03
		T2-T1	7	-0.49 + 0.27	0.02	-0.82
Left	**P1**	**T1**	7	1.29 + 1.06	3.48	0.43
		T2	7	0.61 + 0.71	1.41	-0.42
		T2-T1	7	-0.68 + 0.70	0.08	-2.07
	MB-M1	**T1**	8	1.06 + 0.92	2.87	0.12
		T2	8	0.67 + 0.89	1.78	-0.7

		T2-T1	8	-0.39 + 0.50	0.25	-1.16
	DB-M1	**T1**	8	2.00 + 0.98	3.38	0.83
		T2	8	1.73 + 0.87	2.76	0.64
		T2-T1	8	-0.27 + 0.25	0.06	-0.63

Table 16. Matched-paired t-test comparing T1 and T2 mean buccal bone thickness (mm) for P1, MB-M1, and DB-M1 on the right and left sides**.**

			N	**Mean + SD**	**Mean Diff + SD**	**P-value**	**Sig Diff**
Right	**P1**	T1	7	1.05 + 0.60	-0.54 + 0.53	0.04	*
		T2	7	0.51 + 0.74			
	MB-M1	T1	7	1.14 + 0.69	-0.60 + 0.46	0.01	*
		T2	7	0.54 + 0.83			
	DB-M1	T1	7	1.88 + 0.83	-0.49 + 0.27	0.003	**
		T2	7	1.39 + 0.96			
Left	**P1**	T1	7	1.29 + 1.06	-0.68 + 0.70	0.04	*
		T2	7	0.61 + 0.71			
	MB-M1	T1	8	1.06 + 0.92	-0.39 + 0.50	0.07	NS
		T2	8	0.67 + 0.89			
	DB-M1	T1	8	2.00 + 0.98	-0.27 + 0.25	0.02	*
		T2	8	1.73 + 0.87			

* $p < 0.05$; ** $p < 0.01$

Craniofacial Expansion

Facial bony changes due to expansion treatment were evaluated at the zygomatic and infrazygomatic areas illustrated on superimposed three-dimensional skeletal color maps (Figure 16). Zygomatic expansion (mm) ranged from 0.44-1.05 mm on the right and 0.45-1.56 mm on the left. Infrazygomatic expansion (mm) ranged from 0.57-1.60 mm on the right and 0.45-1.56 mm on the left (Table 17). A Matched-paired t-test showed significant differences were found between the expansion at the zygomatic and infrazyomatic area respectively on the left and ride sides ($p < 0.05$) (Table 18).

Table 17. Average right and left zygomatic and infrazygomatic expansion (mm) measured at T1 and T2 from three-dimensional superimposition color maps in Figure 12.

	Position	N	Mean $\pm$ SD	Max	Min
Right	**Zygomatic**	8	0.73 $\pm$ 0.24	1.05	0.44
	Infrazygomatic	8	1.13 $\pm$ 0.38	1.60	0.57
Left	**Zygomatic**	8	0.93 $\pm$ 0.36	1.56	0.45
	Infrazygomatic	8	1.35 $\pm$ 0.32	1.78	0.95

Table 18. Matched-paired t-test comparing the changes of respective right and left zygomatic and infrazygomatic expansion (mm)

	Position	N	Mean $\pm$ SD	Mean Diff $\pm$ SD	P-value	Significant Difference
Right	**Zygomatic**	8	0.73 $\pm$ 0.24	0.04 $\pm$ 0.14	0.013	*
	Infrazygomatic	8	1.13 $\pm$ 0.38			
Left	**Zygomatic**	8	0.93 $\pm$ 0.36	0.42 $\pm$ 0.04	0.00033	***
	Infrazygomatic	8	1.35 $\pm$ 0.32			

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Original data collected for all tested variables are listed in Appendix A.

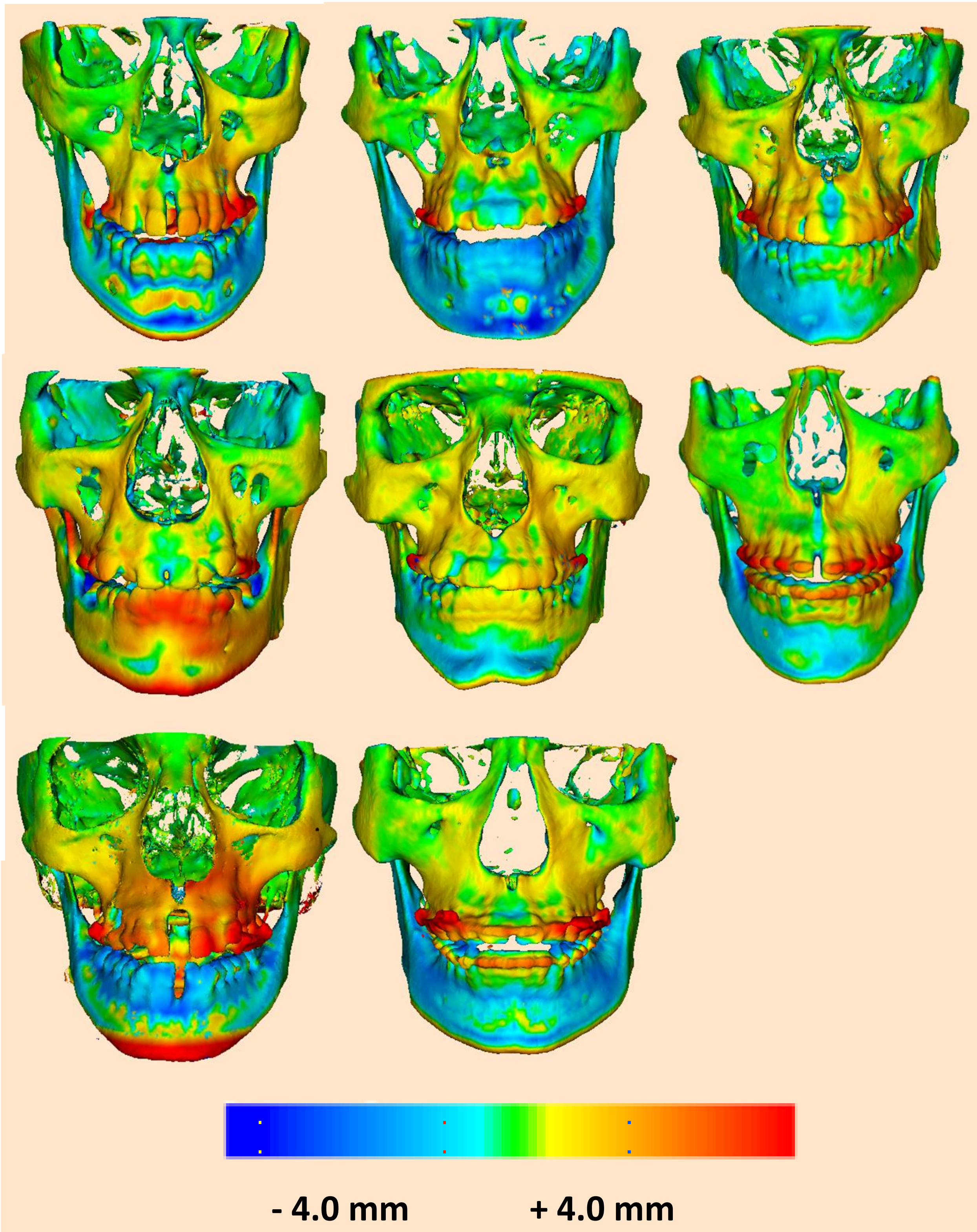

Figure 15. Three-dimensional skeletal color maps of superimpositions of T2 over T1 registered at the anterior cranial base with a scale of -4 to +4 mm. Red represents outward displacement of T2 relative to T1. Blue represents inward displacement of T2 relative to T1.

DISCUSSION

Microimplant-assisted rapid palatal expansion (MARPE) has recently been offered to adult patients as a treatment option for correcting maxillary transverse discrepancy. However, there is limited information on the effects of this newer expansion technique specifically in skeletally matured patients in the orthodontic literature. Existing studies have discussed treatment outcomes of MARPE in samples described by their chronological age without information on their skeletal or midpalatal suture maturation. It is generally known that chronological age is not a precise index in predicting skeletal maturation[58] and there is tremendous variability in the developmental stages of the midpalatal suture relative to chronological age.[7] While some authors noted fusion of the median palatal suture between ages 15 to 19 years old[19, 78, 89], others reported a lack of fusion in this suture at age 32,[89] 54,[62] and 71[63]. Histological data suggested that patients who show an advanced stage of skeletal maturation at the midpalatal suture may have difficulty undergoing conventional maxillary expansion due to synostoses and numerous bony bridge formations across the suture.[11, 78] In a recent investigation by Jang [58] et al, they found that the Cervical Vertebral Maturation (CVM) method have strong correlations and high associations with the maturation stage of the midpalatal suture on CBCT images. This means that the CVM method may be used to speculate on the maturation of the midpalatal suture according to its morphology and is a more useful index than either chronological or dental age.[58]

Maxillary transverse growth spurt and growth completion, has been shown to follow distance and velocity curves similar to those for body height by implant studies.[10, 19] The maturation of the cervical vertebrae, as assessed by the CVM method, has been considered a reliable biological indicator for skeletal maturity.[10, 11] Peak in mandibular growth has been reported to occur between cervical stage 3 and stage 4 (CS3 and CS4).[10, 11] An individual presenting with CS4 is identified to have surpassed the peak in mandibular growth 1 or 2 years before this stage.[10, 11] It has been demonstrated that rapid maxillary expansion during or after the peak would induce more pronounced dentoalveolar than skeletal effects.[10, 11] Jang [58] et al suggested that nonsurgical maxillary expansion may be recommended before stage 3 in CVM, and a surgical approach may be considered in later CVM stages.[58] In order to understand the effectiveness of MARPE relative to treatment timing, outcomes of orthopedic expansion of the maxilla need to be evaluated with respect to skeletal maturation.

Orthodontic investigators have increased the use of cone-beam computed tomography (CBCT) due to the limitations of conventional 2-dimensional (2D) assessment. Factors such as superimposition of anatomic structures and difficulty in landmarks identification and head position reproducibility render 2D radiologic methods inadequate in evaluating the skeletal, dental, and periodontal effects of treatments.[41] It has been shown that CBCT imaging, with adequate resolution, can overcome these limitations and enable accurate quantitative of a target area with no distortion, such as alveolar bone thicknesses.[41, 71] Therefore, the main objective of this retrospective, pilot study was to evaluate the skeletal, dentoalveolar, and periodontal responses of MARPE immediately at the end of the active expansion phase in skeletally matured patients, as assessed by the CVM method[11], using CBCT imaging.

Skeletal Expansion

Midpalatal Suture Separation

The total expansion achieved with an expansion appliance is a combination between skeletal (orthopedic) expansion and dentoalveolar (orthodontic) expansion.[36] Skeletal expansion refers to the direct separation of the maxillary halves at the midpalatal suture.[49] Dentoalveolar expansion refers to the buccal alveolar bone bending and dental tipping beyond sutural expansion that resulted from the expansion procedure.[36] In this study, total expansion and its components were evaluated at the first molar area.

Data of the current study shows that micro-implant assisted rapid palatal expansion (MARPE) is effective at separating the midpalatal suture and correcting maxillary transverse discrepancies in nongrowing patients. Authors of previous MARPE reports also agree with this finding; [22, 26, 69] but it should be noted that their classification of an adult patient was based on chronological age. All subjects demonstrated successful maxillary expansion, evident by the opening of the midpalatal suture. The average total expansion (ΔIMW) and sutural transverse expansion at the first molar, measured immediately at the completion of appliance activation, was 6.26 $\pm$ 1.31 mm and 2.55 $\pm$ 0.71 mm respectively. This indicated that 41% of skeletal expansion and 59% of dentoalveolar expansion contributed to the total expansion observed at the first molar. Other reports have also found that sutural expansion is approximately less than or equal to 50% of total expansion.[36, 66] However, in these studies, the authors used conventional appliances to expand the maxilla in younger patients.[36, 66] Garrett[36] et al found sutural separation accounted for 38% of total expansion at the first molar in their patients (mean age 13.8 years) using the hyrax expander.[36] Generally, it is believed that expansion therapy applied before the pubertal growth peak would contribute to more significant skeletal separation of both maxillary and circummaxillary structures.[83] Compared to the results of previous reports on the use of conventional RPE in younger patients, this study have demonstrated that MARPE is effective at providing skeletal widening of the maxilla in post-pubertal patients.

Skeletal anchorage is believed to apply higher forces directly to the maxillary bone[40] and localize lateral forces to the midpalatal suture.[22] If bone-anchored instead of traditional expanders were used in a young patient population with growth potential, a larger amount of sutural expansion may be observed. This suggestion was supported by other authors who found bone-borne expanders produced greater orthopedic changes and additionally fewer dentoalveolar tipping than tooth-borne maxillary expanders.[71, 83] Additionally, Blais et al[40] noted bonded RPE and bone-anchored RPE accounted for 41% and 65% of mean maxillary basal expansion relative to mean screw expansion respectively in patients ranging between age 11.3-17 years old. The authors explained that the large expansion percentage difference was due to the direct effects that bone-anchored RPE had on the palate rather than the surrounding maxillary molars.[40].

In this study, the percent of greatest mean palatal expansion associated with mean screw expansion was 52%, which was less than the results reported by Blais et al.[40] However, it should be noted that patients in this study were all skeletally matured according to the CVM method[11] and a mean age of 21.9 $\pm$ 9.73 years. Based on these factors, achieving maxillary skeletal expansion without surgical assistance in these type of patients was traditionally thought to be impossible or would result in serious problems.[37, 64, 98] Furthermore, the amount of skeletal expansion found in this study was similar to an investigation by Chamberlain and Proffit[24] who reported approximately 46% of skeletal expansion was achieved immediately after SARPE with tooth borne devices in patients ranging from age 15-54 years old.[24] In this study, both the pterygoid junction and the midpalatal suture between the incisor roots were separated,[24] which was an advantage over the current study with regards to achieving greater skeletal expansion. However, measurements were made from posteroanterior cephalograms[24], which makes accurate comparison with this study difficult. Compared to previously reported skeletal expansion achieved from SARPE in adolescent and adult patients, MARPE may be considered highly effective in achieving non-surgical maxillary expansion in skeletally matured patients.

The pattern of midpalatal suture separation observed with MARPE in this study was parallel on average, in both the coronal and frontal perspective. The amount of suture opening at the canine, first premolar, second premolar, and first molar area differed from each other by no more than 0.47 $\pm$ 0.17 mm and was shown to be nonsignificant. This indicated that sutural expansion at the level of the palate was rather uniform throughout its length anteroposteriorly, which agrees with findings of other previous authors.[22, 70] However, Lin et al.[71] demonstrated midpalatal suture opening occurred in a triangular pattern superoinferiorly, with the least increase at the nasal floor and the greatest increase at the hard palate (n =15; age = 18.1 $\pm$ 4.4 years). The contrasting findings may be due to the different amounts of appliance activation performed in each study. Subjects received greater than 7 mm of activation in the study by Lin et al[70] while the appliance was activated less than 7 mm (mean = 5.61 $\pm$ 1.19 mm) in the present study. Although microimplants were placed on the palatal slopes, which has been shown to minimally rotate the dentoalveolar units,[68] the larger amount of maxillary expansion attempted by Lin et al.[70] may inevitably cause the maxillary halves to tip further away from the fulcrum of rotation located close to the frontomaxillary suture.[39]

Nevertheless, some patients individually demonstrated a slight V-shaped expansion pattern in this study, with the base facing anteriorly or towards the oral cavity in the coronal and frontal view respectively. Variations in the suture opening pattern may be due to differences in the appliance being placed more anteriorly, on the inclines of the anterior palate distal to the second or third rugae, versus posteriorly, on the flat surface of the palate 1 mm anterior to the soft palate approximating at the level of the permanent first molar. It has been reported that posterior positioning of the expander device may allow for application of lateral forces against the pterygomaxillary buttress bone, which would allow for more parallel separation of the maxillary halves during expansion.[22] On the other hand, anterior positioning of the micro-implant supported expander appliance may provide a force distribution similar to the four-point hyrax appliance.[70]

Upper Facial Bony Displacement

In this study, lateral widening of the upper facial bony structures, namely at the zygomatic and infrazygomatic areas as well as the nasal floor, was also noted following immediate end of appliance activation. Superimposed three-dimensional skeletal colors maps showed there was significantly greater expansion at the infrazygomatic area than the zygomatic area, which was 2.48 $\pm$ 0.7 mm and 1.66 $\pm$ 0.6 mm respectively. The difference in pretreatment and post-expansion treatment CBCT measurements at the nasal floor also demonstrated an increase of 2.53 $\pm$ 0.53 mm in width, which was slightly larger than the expansion achieved at the infrazygomatic area by 0.05 $\pm$ 0.17 mm. This finding agrees with other studies[14, 22, 33, 41, 83] and may support the theory that maxillary expansion increases airflow and improve nasal breathing.[44]

In the frontal plane of the upper maxillofacial structures, the decreasing upward expansion effect indicated a slight triangular expansion pattern with the base at the level of the nasal floor. This observation agrees with results of previous 2D[26] and 3D[22, 41] data on bone-borne expansion. It has been stated that the midpalatal suture begins to close in the mid 30s at the posterior end; however, some facial sutures including the frontozygomatic may remain open even in older age groups.[94] This makes it possible for lateral displacement of the upper craniofacial structures following expansion. The pattern of transverse craniofacial expansion may be attributed to the stress distribution that occurred along the circummaxillary sutures, resulting in lateral rotation of the maxillary halves around the estimated center of rotation located at the frontonasal suture.[83]

Furthermore, this study showed that expansion of the zygomatic, infrazygomatic, and nasal cavity areas amounted to 30%, 44%, and 45% of the screw expansion. In a recent systematic review conducted on patients ages 6 to 14.5 years old, it was concluded that expansion of the midpalatal suture and nasal cavity ranged from 20% to 50% and 17% to 33% of the total screw expansion respectively.[86] Compared to the results reported in these younger patients, the data obtained in the current study indicate that effective expansion was achieved with MARPE in nongrowing patients. This observation agrees with Carlson et al[22] who found notable expansion at the zygoma and the maxilla accounted for 38% to 61% of the screw expansion respectively. Expansion of the upper craniofacial structures have been considered signs of successful orthopedic correction since the reason for failures of nonsurgically assisted RPE have been related to facial skeletal rigidity.[15, 22]

Dentoalveolar Expansion

Alveolar Bone Bending and Dental Tipping

Buccal bending or tipping of the alveolar process is a common finding of maxillary expansion with an expander device. [36, 41, 70, 83] It has been described as any additional palatal alveolar plate expansion beyond that of sutural separation.[36] In this study, the expansion of the palatal cortical plates (ΔPMW) beyond that of the suture opening at the first molars was 0.73 $\pm$ 0.04 mm, which accounted for 12% of total expansion. This indicated the remaining fraction of total expansion derived from dental tipping was 47% at the first molar (2.98 $\pm$ 0.56 mm). Similarly, Garrett et al[36] found alveolar bending and dental tipping contributed 13% (0.84 mm) and 49% (3.27mm) to total expansion at the first molar respectively with the hyrax appliance in patients with a mean age of 13.8 years.[36] Contrary to the belief that nonsurgical expansion in adult patients would result largely in alveolar bone bending and dental tipping,[64, 86, 102] the results of this study have demonstrated that MARPE is effective at producing significant skeletal expansion without achieving severe dentoalveolar effects compared to conventional RPE. This interpretation is supported by other authors who observed bone-borne expansion also produced less tipping of the supporting teeth than conventional RPE in their study.[20, 71, 83]

Direct measurement of angular palatal alveolar bone bending and dental tipping for anchoring teeth (first premolar and molar) was attempted by measuring along the palatal alveolar shelf and long axis of the tooth respectively. Positive differences in the palatal alveolar angle (PAA) before and immediately after MARPE for the anchoring teeth were found; however, the values did not reach statistical significance. On the other hand, significant buccal dental tipping was noted for the left first premolar and both first molars. The buccal inclination observed in the alveolar bone and teeth may be related to outward rotation of the maxillary halves during expansion as they split at the midpalatal suture, with the fulcrum at the frontomaxillary suture.[22, 41, 60] In order to gain a better understanding of the dental tipping that would occur independent of alveolar bone bending, absolute dental tipping may be calculated by subtracting the change in dental inclination from the change in alveolar inclination as described by Kartalian et al.[60]

In this study, absolute dental tipping was positive for the left first premolar (11.51$^{o)}$ and both first molars (4.96^{o} and 4.17^{o} for the right and left side respectively). Since the anchoring teeth were banded and rigidly fixated to the expander, the positive buccal tipping observed may be due to parallel movement of the teeth with the appliance during active expansion.[41] Even though microimplants were used to deliver greater forces directly to the maxillary bone, the anchoring teeth may still be impacted due to possible tipping of the microimplants. Tipping of the microimplants may occur due to the small gap between the microimplant and the interior surfaces of the insertion slots.[22] In this study, the appliance was activated 5.61$\pm$ 0.19 mm on average over a mean span of 7.64 weeks $\pm$ 9.73 (2 weeks minimum, 12.86 weeks maximum). The measured sutural opening immediately at the end of active expansion phase in the coronal view ranged from 3.27 mm to 3.74 mm, illustrating the ratio of appliance activation to skeletal expansion is not 1:1.

As been stated by Chen et al[25], screws require mechanical locking for stability and force loading should occur at least 3 weeks after the placement procedure to avoid disturbing the primary healing of surrounding bone, which is a key factor for better stability. In this study, appliance activation occurred on the same day of placement. This may result in a weakened bone-implant interphase, which may cause unwanted forces to be transmitted to the teeth and subsequent dental tipping. The mechanical interdigitation of the miniscrew threads to the bone may also be compromised if the peri-microimplant tissues are inflamed due to inadequate care.[25] This factor was not systematically assessed for the study sample, although the need for meticulous hygiene care of the microimplants was emphasized. Other possible causes for dental tipping of the anchoring teeth may include the lack of bicortical engagement of the micro-implants, poor bone density,[25] and over-winding of the microimplant during installation.[25] Reliable methods should be used to assess these factors in future studies to provide a better understanding of possible causes for dental tipping with MARPE. Furthermore, although an increase in buccal inclination of the anchoring teeth were observed, the effect may be reduced through dental decompensation with orthodontic treatment, rendering buccal tipping of the teeth minimal if not negligible.[22]

The right first premolar demonstrated greater buccal inclination of the alveolar bone than the anchoring teeth as shown by an absolute dental tipping angle of -5.73°, indicating slight dental uprighting. Possible counter forces exerted by the buccal musculature at the first premolar may explain this finding.[41] Another probable cause may be resorption of the palatal bone due to compressive forces on the palatal plate by the expander arms during appliance activation.[38, 49, 80] This may lead to a greater positive change in the palatal alveolar angle that does not parallel the rotation of the maxillary halves with expansion, resulting in a negative absolute dental tipping value. The question whether palatal bone resorption did or did not occur and its permanency requires further investigation. Findings relating to the angular measurements of the palatal alveolar bone and anchoring teeth in this study should be cautiously interpreted because there was individual variability. Additionally, some CBCT scans were obscured by the image noise produced by the expander device, which made it difficult to clearly identify the palatal shelf of the anchoring teeth and may render the measurements inaccurate.

Periodontal Effects

High expansion forces may produce areas of compression on the periodontal ligament of anchoring teeth and cause alveolar bone resorption that leads to decreased buccal bone thickness.[34, 70, 102] Following conventional RPE, authors of previous reports found significant reductions in buccal bone thickness[34, 41] while others found no or minimal changes.[2, 13] In this study, buccal bone thickness decreased by 0.27 mm to 0.60 mm for the first molars after expansion. This finding was less than the reduction of buccal bone thickness found by Toklu et al.[41] for the first molars (approximately 0.7 mm to 1.2 mm) in a group of patients also treated with bone-borne expansion (mean age of 13.8 years). The difference in the results may be due the length and amount of microimplants that were used to fixate the expander device to the palate. Toklu et al use two palatal miniscrews (1.8 X 9 mm)[41] to support the appliance while four microimplants (1.5 to 1.8 X 11 mm) were used in this study sample to promote bicortical engagement of the microimplants into the palate. The bone-borne appliance design used to treat the patients of this study may be advantageous because the use of four microimplants may direct greater expansion force toward the mipalatal suture and other resistant areas (i.e. pterygomaxillary buttress bone) and away from the anchoring teeth.[22, 68] However, analysis of buccal bone thickness were performed using CBCT scans taken 3 months after the end of expansion retention in the study by Toklu et al.[41]. The additional three months post-expansion may allow for greater buccal bone remodeling and therefore, greater reductions in buccal bone reduction may be observed compared to the current study. Carlson et al.[22]also used four similar microimplants to support their bone-borne expansion device and had found thinning of the buccal plates at the maxillary first molar. However, the authors reported there was still bone coverage over the roots after expansion.[22]

The buccal alveolar bone thickness of the right and left first premolars decreased by 0.54 and 0.68 mm on average respectively in this study. The finding was slightly greater than some earlier bone-anchored expansion studies[41], which may be due to the use of the first premolars as additional support for the bone-borne device in some patients in the current study. Toklu et al.[41] explained the buccal periodontal support of the first premolars remained unchanged for their study because the bone-borne expander was attached to the palatal miniscrews instead of the first premolars. Other authors also showed the alveolar crest level was maintained[34] or the reduction was not clinically important[70] for teeth that were not used for appliance anchorage. However, these subjects were younger than those treated in the current study and may have potentially be in earlier CVM stages where maxillary expansion is less difficult to achieve.

Although thinning of the buccal alveolar bone in regions of the anchoring teeth was found to be statistically significant, the periodontal effect may be reduced overtime. A partial recovery of bone levels has been observed with uprighting of the teeth supporting the expansion device using fixed appliance therapy.[2] Some authors found the reduction in buccal bone thickness recovers after 3 months[96], 6 months[13] and even 2 years[2] following expansion. Evidence has demonstrated that lingual tooth movement leads to coronal bone apposition on the buccal alveolar crest[99]; therefore, overcorrection of maxillary constriction during expansion may facilitate buccal bone regeneration by allowing for uprighting of anchoring teeth with fixed appliaces.[34] Due to the possibility for supporting teeth to move buccally with expansion and undergo adverse periodontal changes, clinicians should consider reduction of buccal bone thickness to be a potentially important negative consequence of expansion.[34] Patients with thin bone plates and keratinized mucosa are at higher risk for bone dehiscence and gingival recession following expansion; however, recessions are triggered only by mechanical tooth brushing trauma or plaque-induced inflammation.[34] Perhaps in patients with unfavorable periodontium who requires severe maxillary transverse correction are better suited for bone-borne surgically assisted rapid palatal expansion. Currently, there are no specific guidelines in the literature that clearly define the type of patients that are better candidates for MARPE vs bone-borne SARPE.

Midpalatal Suture Maturation Assessment

To have a better understanding of the effectiveness of MARPE relative to skeletal maturity, individual midpalatal suture maturation was also evaluated using the novel classification method proposed by Angelieri et al.[6] Most of the subjects in this study had partially or completely fused midpalatal sutures (stage D or E) as listed in Table 3. It was suggested that conventional approaches of rapid maxillary expansion in these types of patients may result in large unfavorable dental and periodontal effects particularly in the molar region, even though an anterior diastema could be observed, due to difficulty of opening the suture.[6] Based on the dentoalveolar and periodontal results of the current study, MARPE have shown to be a clinically acceptable nonsurgical treatment modality for maxillary constriction in skeletally matured patients. However, it should be kept in mind that the rigidity of the midpalatal suture is only one factor that resists maxillary expansion; other areas of resistance to expansion include the zygomatic buttress and the pterygopalatine junction.[70]

CHAPTER 6: SUMMARY AND CONCLUSIONS

1. Midpalatal suture separated in 100% of subjects with no dislodged microimplant
2. Contribution to total expansion include 41% skeletal, 12% alveolar bone bending, and 48% dental tipping
3. Pattern of midpalatal suture opening was parallel in both coronal and axial view
4. Absolute dental tipping ranged from 4.17^{o} to 4.96^{o} on average, which may be clinically in significant and improved with orthodontic uprighting
5. Reduction in buccal bone thickness (0.27 mm to 0.68 mm) shown to be statistically significant but may recover overtime with orthodontic uprighting

These findings suggest that MARPE can be a clinically acceptable, nonsurgical treatment option for correcting mild to moderate maxillary transverse discrepancies, less than 7 mm, in skeletally matured adult patients. However, the current study has some limitations: the small sample size and the short-term follow up. Additionally, this study was compared with other studies that differed in various aspects including but not limited to differences in expansion appliance design, activation protocol, methods of evaluating expansion effects, and sample size and biological variability.

CHAPTER 7: RECOMMENDATIONS FOR FUTURE RESEARCH

The clinically relevant findings of this study warrant future research in this area. This study should be repeated with a larger sample size and standardized for the following, including but not limited to:

1. Appliance placement anteroposteiorly along the palate
2. Number of teeth selected for appliance anchorage
3. The number of micro-implants used for appliance fixation
4. The amount of required maxillary expansion
5. CVM stage or midpalatal suture maturation stage or both

Additionally, reliable assessment methods should be established for assessment of microimplant stability in terms of mobility detection in order to evaluate if skeletal anchorage has been compromised during active expansion. Long-term evaluations of the sample should also be conducted to gain an understanding of the permanency of the dentoalveolar and periodontal effects of MARPE and the relapse potential of this novel technique in nongrowing patients.

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APPENDICES

APPENDIX A: IRB EXPEDITED

WestVirginiaUniversity.
Office of Research Integrity and Compliance
886 CHESNUT RIDGE ROAD MORGANTOWN, WV 26506

Approval Letter Expedited

Action Date	06/10/2016
To	Peter Ngan
From	WVU Office of Research Integrity and Compliance
Approval Date	07/06/2015
Expiration Date	06/08/2017
Subject	Protocol Approval Letter
Protocol Number	1501557557R001
Title	Retrospective Evaluation of Skeletal and Dental Changes in Adults Treated with Micro-implant Assisted Rapid Palatal Expansion (MARPE)

The above-referenced research study was reviewed by the West Virginia University Institutional Review Board IRB and was approved in accordance with 46 CFR 46.101b.

It has been determined that this study is of minimal risk and meets the criteria as defined by the expedited categories listed below:

- Category 5. Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis).

Documents reviewed and/or approved as part of this submission:

HIPAA De-Identification Form.docx: 2016-06-06-04:00

Variables Recorded for Research Purposes.docx: 2015-06-26-04:00

Bibliography.docx: 2016-05-11-04:00

IRB Scientific Rationale for Research Short Version.docx: 2016-05-11-04:00

HIPAA Waiver Form 1- Uyen.docx: 2016-05-11-04:00

Documents for use in this study are available in the WVUkc system in the Notes and Attachments section of your protocol.

The Office of Research Integrity and Compliance is here to provide assistance to you from the initial submission of an IRB protocol and all subsequent activity. Please feel free to contact us by phone at 304.293.7073 with any question you may have. Thank you.

WVU Office of Research Integrity and Compliance

Date:06/10/2016

Signed:

Lilo Ast
Senior Program Coordinator

Appendix B: Statistics

Raw Data

For all purposes in this appendix, the following should be understood:

- Data sets refer to the entire data collection taken at different time periods. Data Set 1 and 2 were taken at least 2 weeks apart
- T1 represents pre-treatment values and T2 represents immediate post-treatment values.

Midpalatal Suture Expansion

Axial View

Table 23. Midpalatal suture separation (mm) measured in axial view at the level of the midpalate for the canine (C), first premolar (P1), second premolar (P2) and first molar (M1) positions.

	Data Set 1					**Data Set 2**				
	T1	**T2**				**T1**	**T2**			
	C-M1	**C**	**P1**	**P2**	**M1**	**C-M1**	**C**	**P1**	**P2**	**M1**
1	0	3.01	3.53	3	3.13	0	3.21	3.98	3.59	3.08
2	0	3.04	4.05	3.21	3.21	0	2.56	3.2	2.72	3.36
3	0	2.44	3.90	2.6	2.44	0	2.98	3.64	3.64	3.14

4	0	4.61	4.07	4.07	3.23	0	4.79	4.11	4.47	3.58
5	0	4.39	3.93	4.54	3.93	0	3.42	3.91	3.91	2.93
6	0	3.78	2.32	3.19	2.91	0	2.55	2.72	2.39	2.21
7	0	4.97	4.6	4.78	4.05	0	4.42	4.94	4.31	4.05
8	0	3.26	3.3	3.11	3.3	0	3.06	3.56	3.91	3.73
Mean	0	3.69	3.71	3.56	3.28	0	3.37	3.76	3.62	3.26
SD	0	0.90	0.68	0.79	0.52	0	0.82	0.66	0.73	0.56
Max	0	4.97	4.6	4.78	4.05	0	4.79	4.94	4.47	4.05
Min	0	2.44	2.32	2.6	2.44	0	2.55	2.72	2.39	2.21

Coronal View

Table 24. Midpalatal suture separation (mm) measured in coronal cross-sectional slice through the center of M1 at the nasal floor, middle of the palate, and palatal floor.

	Data Set 1				**Data Set 2**			
	T1		**T2**		**T1**		**T2**	
		Nasal	**Middle**	**Palatal**		**Nasal**	**Middle**	**Palatal**
1	0	2.35	2.4	2.81	0	2.56	2.57	2.68
2	0	2.39	2.31	2.48	0	3.00	3.21	2.64
3	0	2.41	2.10	2.95	0	2.21	2.20	2.79
4	0	3.26	2.24	2.58	0	3.26	2.29	3.26
5	0	2.4	2.71	3.03	0	2.55	2.23	2.87
6	0	1.65	1.93	1.93	0	1.97	2.13	2.13
7	0	3.12	4.20	3.79	0	3.10	3.92	4.19
8	0	1.94	1.97	2.97	0	2.15	2.31	3.21
Mean	0	2.45	2.49	2.82	0	2.61	2.61	3.01
SD	0	0.58	0.80	0.58	0	0.52	0.68	0.64
Max	0	3.26	4.2	3.79	0	3.26	3.92	4.19
Min	0	1.65	1.93	1.93	0	1.97	2.13	2.13

Palatal Alveolar Bone Bending

Table 25. Palatal alveolar angle (degree) measured at T1 and T2 for first premolar (P1) and first molar (M1) positions.

		Right				Left			
		T1		T2		T1		T2	
		P1	M1	P1	M1	P1	M1	P1	M1
Data Set 1	1	102.8		98.4		102.7	101.6	105.8	118.1
	2	116.5	100.7	130.2	96.6	115.8	100.9	118.3	109
	3	128.4	115.7	119.7	117.6	123.6	105.5	115.6	105.2
	4	107.8	111.3	116	114.5	109.3	111.5	119	105.8
	5		112		114.7		113.8		107.4
	6	99.1	91.9	99.8	107.1	105.1	98.1	93.8	98
	7	125.4	96.7	129.8	97.2	99.4	97.6	107	98.5
	8	112.9	106.8	142.8	114.2	130.7	111.7	115.5	119.9
	Mean	113.27	105.01	119.53	108.84	112.37	105.09	110.71	107.7375
	SD	11.01	8.81	16.38	8.76	11.53	6.50	9.10	7.99
	Max	128.40	115.70	142.80	117.60	130.70	113.80	119	119.9
	Min	99.10	91.90	98.40	96.60	99.40	97.60	93.8	98
Data Set 2	1	105.5		104.2		106.6	106	102.2	113.9
	2	117.2	95.1	110.3	97.7	111.1	102.1	112.8	103.3
	3	123.1	118.1	120.3	115.2	121.6	105.8	116.7	106.5
	4	102.1	107.1	116.9	110.6	106.3	109.7	112.5	105.6
	5		110		112.4		108.9		106.2
	6	100.2	93.8	101.7	102.1	111.8	97.8	107.1	99
	7	97.3	96.9	132.3	92.6	90.1	97.3	99.5	104.5
	8	117.4	106.2	149.3	112.6	124.3	114.2	94.7	104.9
	Mean	108.97	103.89	119.29	106.17	110.26	105.23	106.5	105.49
	SD	10.09	8.97	16.81	8.70	11.29	5.89	8.03	4.15
	Max	123.10	118.10	149.30	115.20	124.3	114.2	116.7	113.9
	Min	97.30	93.80	101.70	92.60	90.1	97.3	94.7	99

Palatal Maxillary Width

Table 26. Palatal maxillary width (mm) measured at T1 and T2 for the first molar (M1).

	T1	T2

1		
2	33.03	36.5
3	32.46	35.68
4	31.69	35.17
5	32.21	35.29
6	29.55	31.77
7	27.74	32.4
8	34.94	37.77
Mean	31.66	34.94
SD	2.363728	2.15
Max	34.935	37.77
Min	27.74	31.77

Dental Tipping

Table 27. Dental tipping angle (degree) measured at T1 and T2 for first premolar (P1) and first molar (M1) positions.

		Right				**Left**			
		T1		**T2**		**T1**		**T2**	
		P1	**M1**	**P1**	**M1**	**P1**	**M1**	**P1**	**M1**
Data Set 1	**1**	82.9	x	89.3	x	88.7	101.2	97.7	101.3
	2	84.3	90.1	85.5	94	90.5	95.7	97.2	98.4
	3	83.7	101.8	87.2	103.5	89.4	101.6	96.5	107
	4	90.1	91.6	99.6	104.8	79.4	93.3	93.6	96
	5	x	101	x	111.2	x	103.1	x	104.1
	6	91.2	91	98.4	94.4	90.1	95.3	110.2	97
	7	91.9	101.9	91.8	113.5	91.8	103.1	100.7	115.4
	8	90.6	94.1	82.1	95.9	91.8	100.1	101.6	99.8
	Mean	87.51	95.64	90.54	102.77	88.96	98.81	99.17	102.15
	SD	4.39	5.10	6.53	8.09	4.35	3.71	5.81	6.25
	Max	91.9	101.90	99.60	113.50	91.8	103.1	110.2	115.4
	Min	81.6	90.10	82.10	94.00	79.4	93.3	93.2	96

Data Set 2	**1**	84.8	x	90.8	x	88.8	98.1	100.2	112.5
	2	90	83.9	93.3	92.9	95.6	96	99.8	97.3
	3	85.5	93.9	88.5	103.6	91.4	100.1	90.7	106.1
	4	89.3	88.4	85.8	110.6	80.1	92.5	103.2	95.7
	5	x	102.3	x	108.9	x	99.4	x	107.1
	6	88.6	90.6	93.4	97.4	89.2	90.4	94.3	96.8
	7	84.9	101.1	93.9	108.7	103.7	103	102.1	107.6
	8	92.6	93.3	82.7	96.8	91.6	100.9	106.4	121
	Mean	87.59	94	89.67	102.9	91.46	97.61	99.59	105.54
	SD	3.46	6.88	4.35	7.08	7.17	4.36	5.26	8.75
	Max	92.6	102.3	93.9	110.6	103.7	103	106.4	121
	Min	82.9	83.9	82.7	92.9	80.1	90.4	91.1	95.7

Intermolar Width

Table 28. Intermolar width (mm) measured at T1 and T2 at the first molar (M1).

	T1	**T2**
1		
2	41.78	47.83
3	45.71	52.2
4	41.03	49.78
5	45.04	51.07
6	38.91	44.15
7	40.17	46.84
8	45.71	50.3
Mean	42.62	48.88
SD	2.83	2.78
Max	45.71	52.2
Min	38.91	44.15

Buccal Bone Thickness

Table 29. Buccal bone thickness (mm) measured at T1 and T2 for first premolar (P1), mesiobuccal root

of first molar (MB-M1) and distobuccal root of first molar (DB-M1) positions.

		Right						Left					
		T1			T2			T1			T2		
		P1	MB-M1	DB-M1	P1	MB-M1	DB-M1	P1	MB-M1	DB-M1	P1	MB-M1	DB-M1
Data Set 1	1	0.97	x	x	0.7	x	x	0.84	0.61	0.79	0.64	0.76	0.87
	2	0.14	0.39	1.2	-0.65	0	0.7	0.27	0	2.43	-0.39	-0.64	1.81
	3	0.66	0.58	0.59	-0.5	-0.97	0	0.62	0.77	0.93	0	0.98	0.28
	4	1.98	2.05	2.66	0.56	1.14	2.45	3.67	3.15	3.66	1.79	1.96	2.62
	5	x	0.63	2.11	x	0	1.1	x	0.74	2.05	x	0	1.97
	6	0.86	1.61	2.68	0.46	1.29	2.78	1.37	1.66	3.18	0.74	1.3	2.6
	7	1.9	1.02	1.57	1.61	1.17	1.07	0.67	0	1.33	0.71	0	0.89
	8	0.73	1.57	2.49	1.33	0.75	1.33	1.63	1.52	2.57	1.18	1.78	2.56
	Mean	1.03	1.12	1.9	0.50	0.48	1.35	1.30	1.06	2.12	0.67	0.77	1.7
	SD	0.67	0.63	0.81	0.85	0.84	0.97	1.14	1.04	1.04	0.72	0.92	0.91
	Max	1.98	2.05	2.68	1.61	1.29	2.78	3.67	3.15	3.66	1.79	1.96	2.62
	Min	0.14	0.39	0.59	-0.65	-0.97	0	0.27	0	0.79	-0.39	-0.64	0.28
Data Set 2	1	1	x	x	0.64	x	x	0.75	0.42	0.87	0.64	0.76	0.77
	2	0.59	0	1.05	0	0	0.6	0.59	0.58	1.67	-0.45	-0.76	1.67
	3	0.48	0.63	0.57	-0.62	-0.67	-0.06	0.62	0.57	0.73	-0.47	0	1
	4	1.82	2.25	2.97	0.74	1.63	2.3	3.29	2.58	3.1	1.03	1.46	2.89
	5	x	0.72	1.72	x	0	1.26	x	0.78	2.03	x	0.61	1.91
	6	0.68	1.64	2.87	0.51	1.38	2.8	0.95	1.65	3.01	0.63	1.14	2.43
	7	1.79	1.24	1.76	1.37	0.92	1.49	0.8	0.23	1.07	0.92	-0.47	0.77
	8	1.09	1.67	2.11	1.02	0.98	1.63	1.93	1.62	2.53	1.55	1.81	2.66
	Mean	1.06	1.16	1.86	0.52	0.61	1.43	1.28	1.05	1.88	0.55	0.57	1.76
	SD	0.55	0.76	0.88	0.66	0.84	0.97	1.00	0.81	0.95	0.76	0.92	0.85
	Max	1.82	2.25	2.97	1.37	1.63	2.8	3.29	2.58	3.1	1.55	1.81	2.89
	Min	0.48	0	0.57	-0.62	-0.67	-0.06	0.59	0.23	0.73	-0.47	-0.76	0.77

Craniofacial Expansion Assessment

Table 30: Zygomatic and infrazygomatic expansion (mm) measured from three-dimensional superimposition color maps in Figure 12.

	Right Side		Left Side	
	Infrazygomatic	**Zygomatic**	**Infrazygomatic**	**Zygomatic**
1	0.57	0.44	1.78	0.96
2	1.15	0.55	1.03	0.53
3	1.26	0.91	1.25	0.91
4	1.47	1.05	1.24	0.85
5	1.07	1.02	1.50	1.20
6	0.61	0.59	1.07	0.68
7	1.60	0.75	1.75	1.56
8	0.77	0.51	0.95	0.45
Mean	1.06	0.73	1.32	0.89
SD	0.38	0.24	0.32	0.36
Max	1.60	1.05	1.78	1.56
Min	0.57	0.44	0.95	0.45

Statistical Analysis

Effect Tests

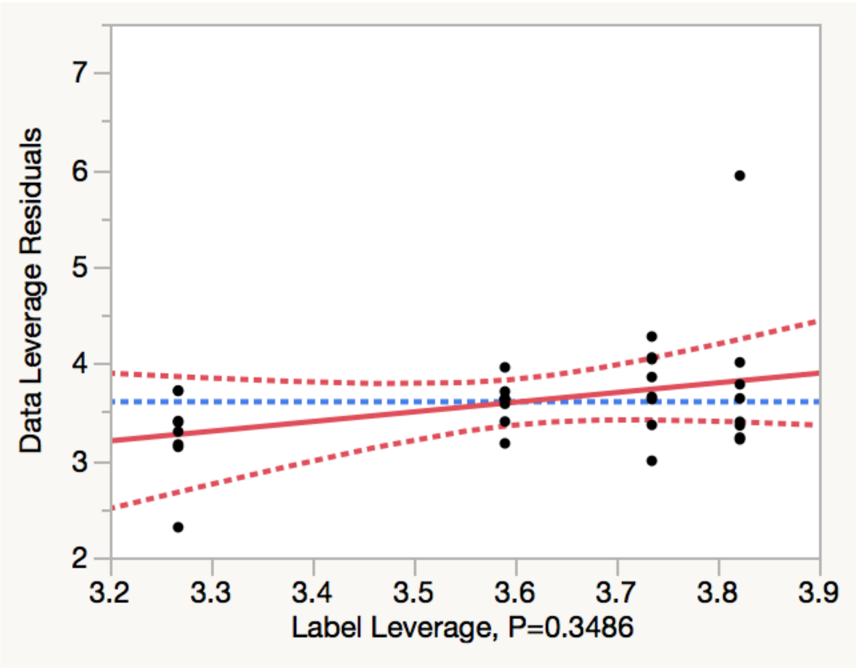
Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob > F**
subj	7	7	13.529943	4.7201	0.0026*
Label	3	3	1.424465	1.1595	0.3486

Label

Leverage Plot

Least Squares Means Table

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Column 1	Column 2	Column 3	Column 4



Level	Least Sq Mean	Std Error	Mean
Column 1	3.8218750	0.22624528	3.82188
Column 2	3.7350000	0.22624528	3.73500
Column 3	3.5900000	0.22624528	3.59000
Column 4	3.2675000	0.22624528	3.26750

LSMeans Differences Tukey HSD

α= 0.050 Q= 2.78733

LSMean[i] By LSMean[j]

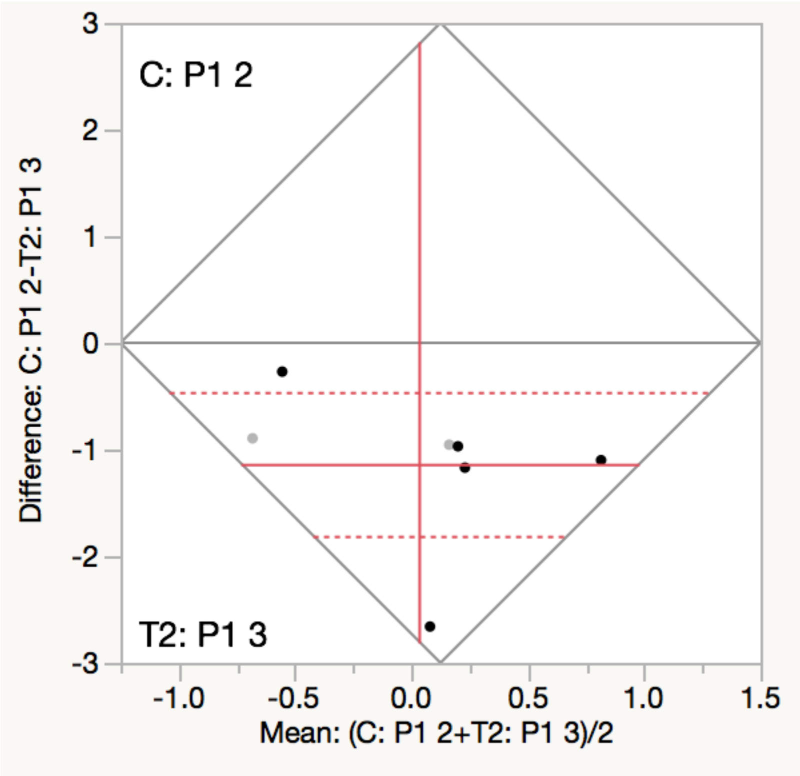
Table 31. Results from Tukey's HSD (honest significance difference) test for midplatal sutural separation in axial view at C, P1, P2, and M1 (α=0.050, Q=2.78733).

Column 1	0	0.08688	0.23188	0.55438
	0	0.31996	0.31996	0.31996
	0	-0.805	-0.66	-0.3375
	0	0.97871	1.12371	1.44621
Column 2	-0.0869	0	0.145	0.4675
	0.31996	0	0.31996	0.31996
	-0.9787	0	-0.7468	-0.4243
	0.80496	0	1.03683	1.35933
Column 3	-0.2319	-0.145	0	0.3225
	0.31996	0.31996	0	0.31996
	-1.1237	-1.0368	0	-0.5693
	0.65996	0.74683	0	1.21433
Column 4	-0.5544	-0.4675	-0.3225	0
	0.31996	0.31996	0.31996	0
	-1.4462	-1.3593	-1.2143	0
	0.33746	0.42433	0.56933	0

Level		**Least Sq Mean**
Column 1	A	3.8218750
Column 2	A	3.7350000
Column 3	A	3.5900000
Column 4	A	3.2675000

Levels not connected by same letter are significantly different. **Matched Pairs**

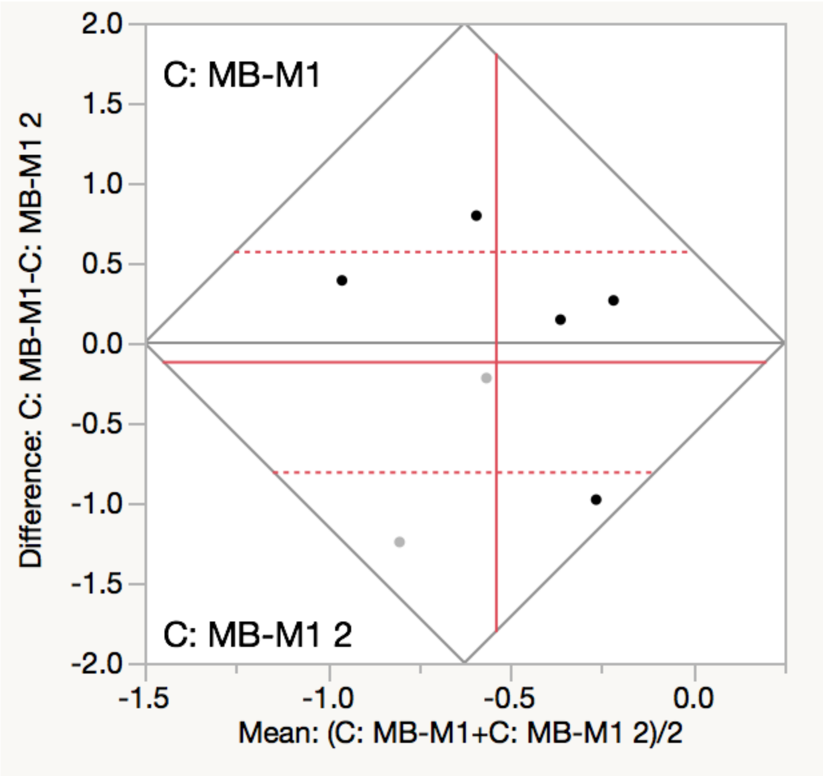
Difference: C: P1 2-T2: P1 3



C: P1 2	-0.5371	t-Ratio	-4.15547
T2: P1 3	0.60857	DF	6
Mean Difference	-1.1457	Prob > |t|	0.0060*
Std Error	0.27571	Prob > t	0.9970
Upper 95%	-0.4711	Prob < t	0.0030*
Lower 95%	-1.8204		
N	7		
Correlation	0.33592		

Matched Pairs

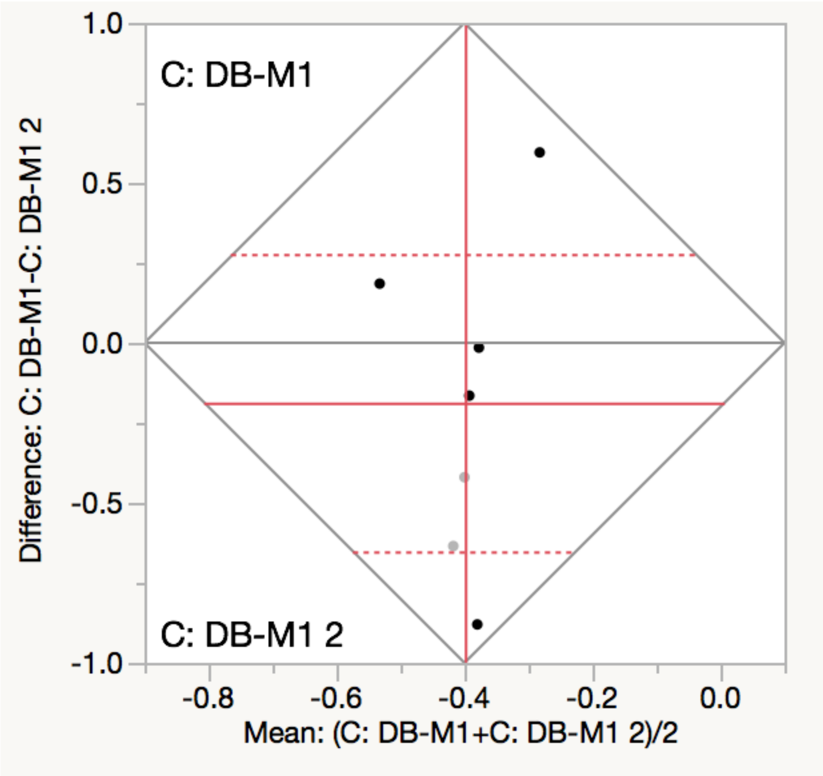
Difference: C: MB-M1-C: MB-M1 2



C: MB-M1	-0.5986	t-Ratio	-0.43118
C: MB-M1 2	-0.4771	DF	6
Mean Difference	-0.1214	Prob > |t|	0.6814
Std Error	0.28162	Prob > t	0.6593
Upper 95%	0.56767	Prob < t	0.3407
Lower 95%	-0.8105		
N	7		
Correlation	-0.2886		

Matched Pairs

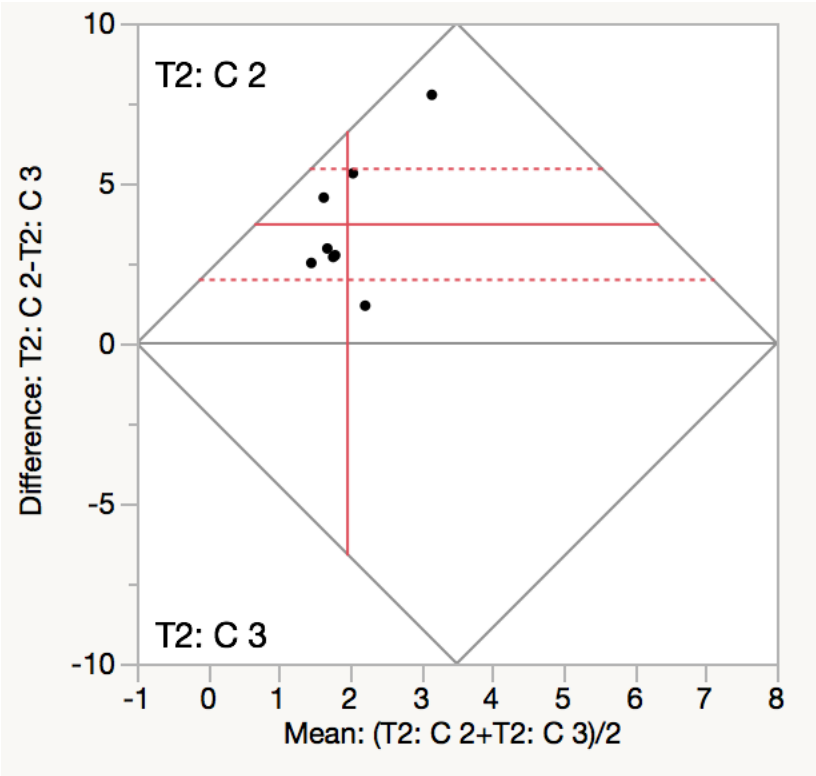
Difference: C: DB-M1-C: DB-M1 2



C: DB-M1	-0.4929	t-Ratio	-1.00412
C: DB-M1 2	-0.3021	DF	6
Mean Difference	-0.1907	Prob > |t|	0.3541
Std Error	0.18993	Prob > t	0.8230
Upper 95%	0.27403	Prob < t	0.1770
Lower 95%	-0.6555		
N	7		
Correlation	-0.8457		

Matched Pairs

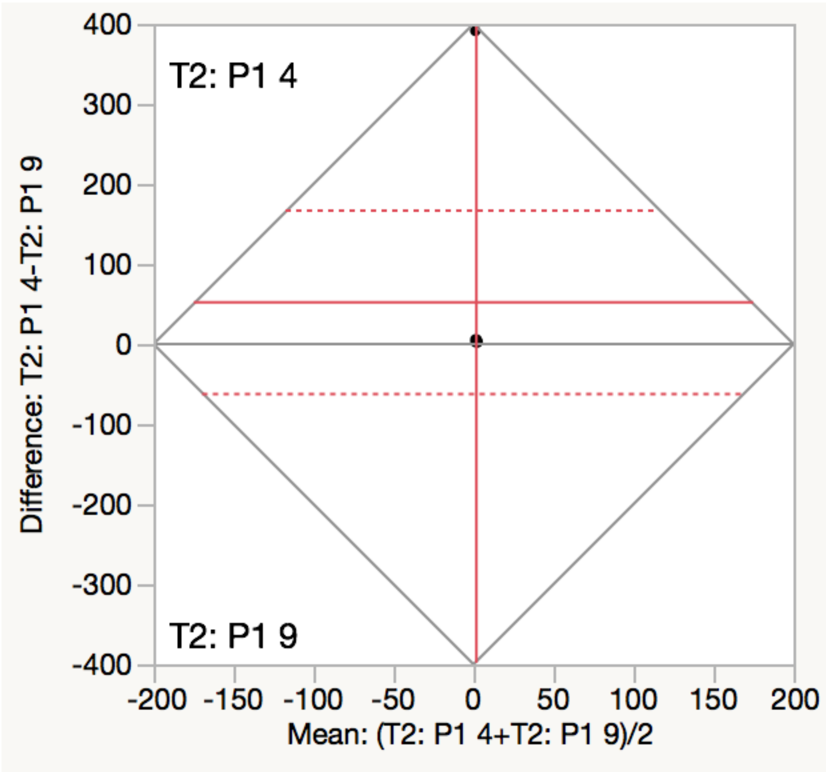
Difference: T2: C 2-T2: C 3



T2: C 2	3.82188	t-Ratio	5.069849
T2: C 3	0.10813	DF	7
Mean Difference	3.71375	Prob > |t|	0.0014*
Std Error	0.73252	Prob > t	0.0007*
Upper 95%	5.44588	Prob < t	0.9993
Lower 95%	1.98162		
N	8		
Correlation	-0.6935		

Matched Pairs

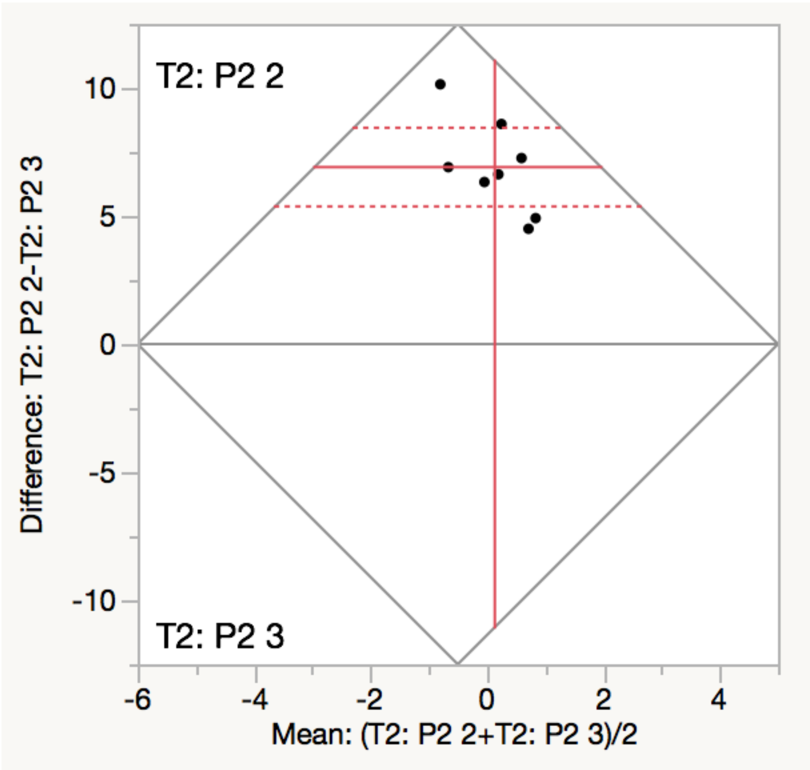
Difference: T2: P1 4-T2: P1 9



T2: P1 4	27.8663	t-Ratio	1.075245
T2: P1 9	-24.237	DF	7
Mean Difference	52.1031	Prob > |t|	0.3179
Std Error	48.457	Prob > t	0.1590
Upper 95%	166.686	Prob < t	0.8410
Lower 95%	-62.479		
N	8		
Correlation	-0.9999		

Matched Pairs

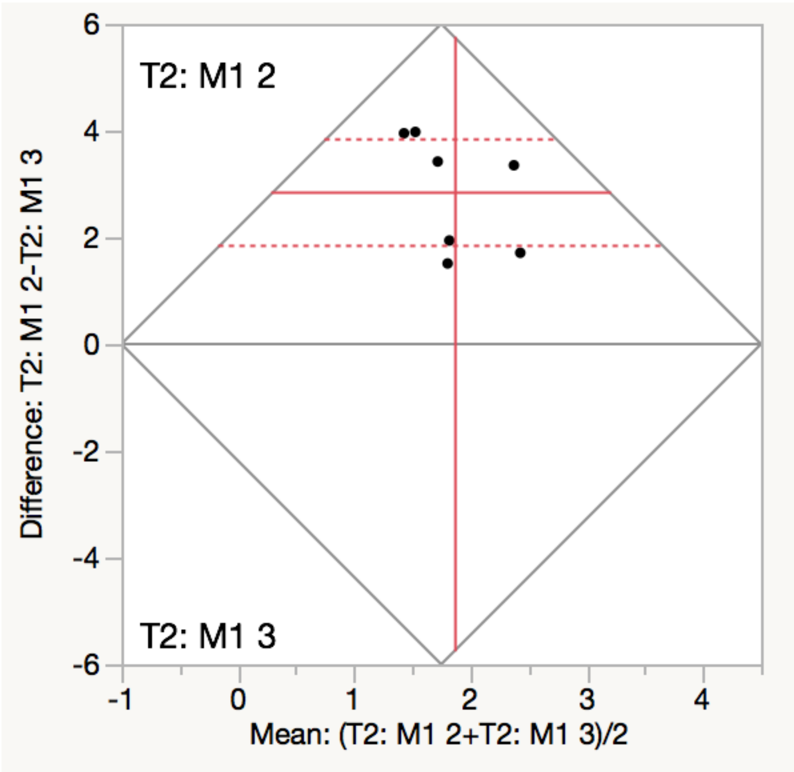
Difference: T2: P2 2-T2: P2 3



T2: P2 2	3.59	t-Ratio	10.64282
T2: P2 3	-3.3175	DF	7
Mean Difference	6.9075	Prob > |t|	<.0001*
Std Error	0.64903	Prob > t	<.0001*
Upper 95%	8.44221	Prob < t	1.0000
Lower 95%	5.37279		
N	8		
Correlation	-0.5009		

Matched Pairs

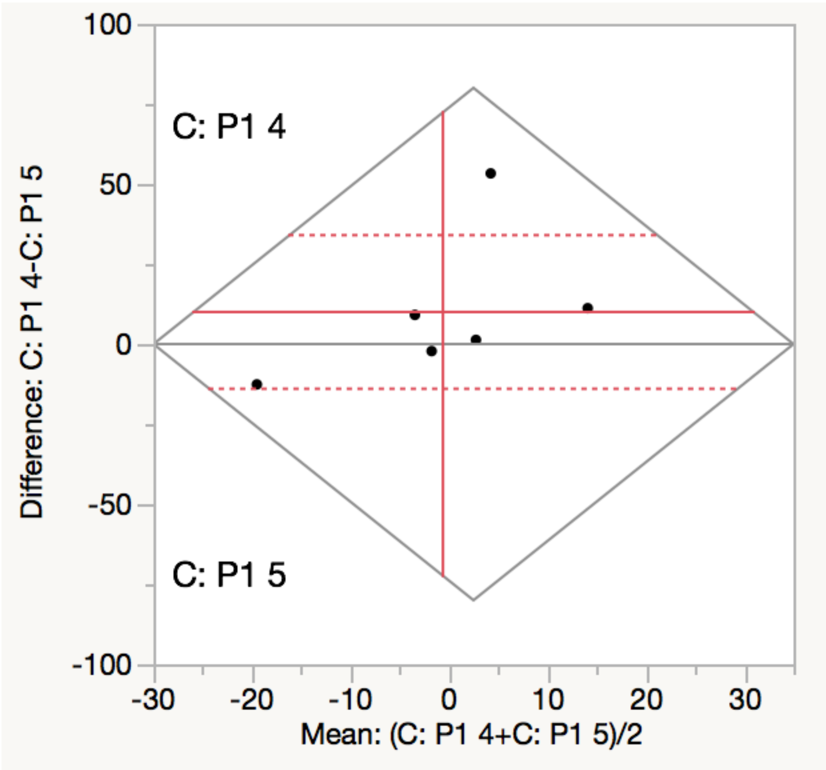
Difference: T2: M1 2-T2: M1 3



T2: M1 2	3.29071	t-Ratio	6.961473
T2: M1 3	0.45429	DF	6
Mean Difference	2.83643	Prob > |t|	0.0004*
Std Error	0.40745	Prob > t	0.0002*
Upper 95%	3.83341	Prob < t	0.9998
Lower 95%	1.83944		
N	7		
Correlation	-0.3535		

Matched Pairs

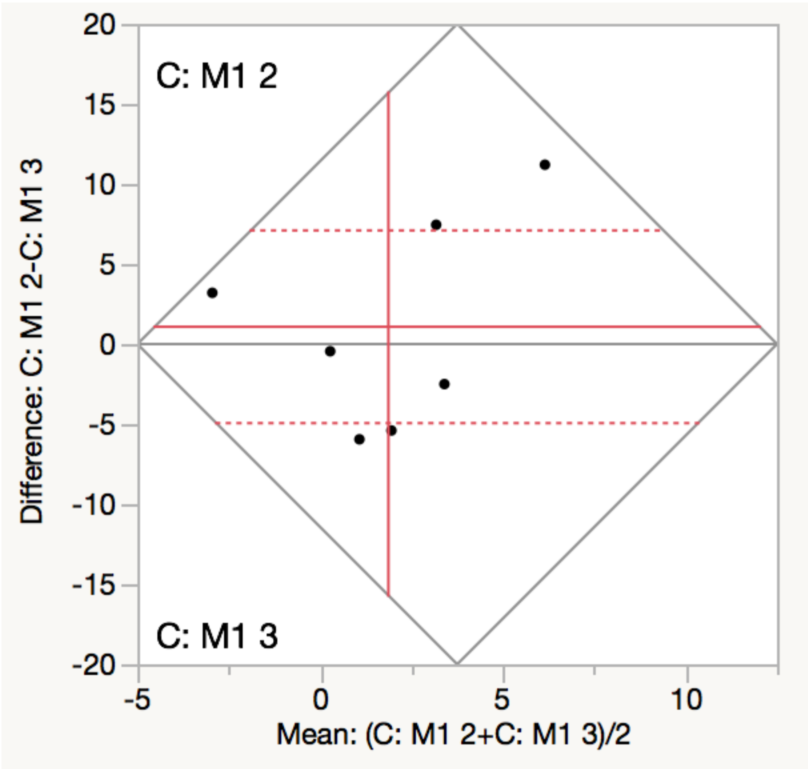
Difference: C: P1 4-C: P1 5



C: P1 4	4.40833	t-Ratio	1.0734
C: P1 5	-5.6083	DF	5
Mean Difference	10.0167	Prob > |t|	0.3321
Std Error	9.33172	Prob > t	0.1661
Upper 95%	34.0046	Prob < t	0.8339
Lower 95%	-13.971		
N	6		
Correlation	-0.0325		

Matched Pairs

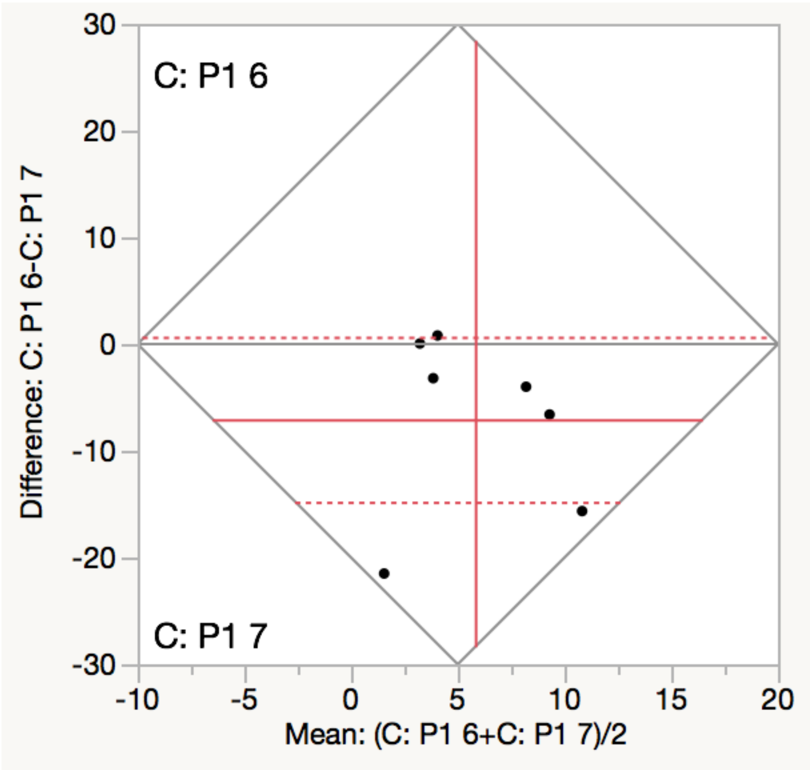
Difference: C: M1 2-C: M1 3



C: M1 2	2.40714	t-Ratio	0.438541
C: M1 3	1.32857	DF	6
Mean Difference	1.07857	Prob > |t|	0.6763
Std Error	2.45945	Prob > t	0.3382
Upper 95%	7.09664	Prob < t	0.6618
Lower 95%	-4.9395		
N	7		
Correlation	-0.1423		

Matched Pairs

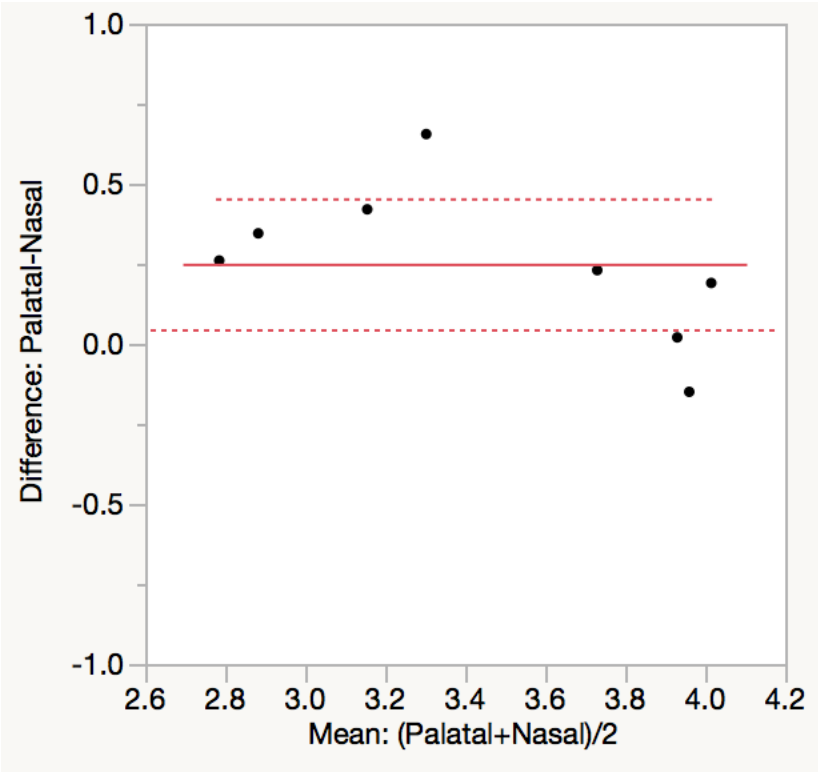
Difference: C: P1 6-C: P1 7



C: P1 6	2.27857	t-Ratio	-2.26587
C: P1 7	9.43571	DF	6
Mean Difference	-7.1571	Prob > |t|	0.0640
Std Error	3.15867	Prob > t	0.9680
Upper 95%	0.57184	Prob < t	0.0320*
Lower 95%	-14.886		
N	7		
Correlation	-0.1673		

Matched Pairs

Difference: Palatal-Nasal



Palatal	3.59313	t-Ratio	2.847393
Nasal	3.34688	DF	7
Mean Difference	0.24625	Prob > |t|	0.0248*
Std Error	0.08648	Prob > t	0.0124*
Upper 95%	0.45075	Prob < t	0.9876
Lower 95%	0.04175		
N	8		
Correlation	0.92489		

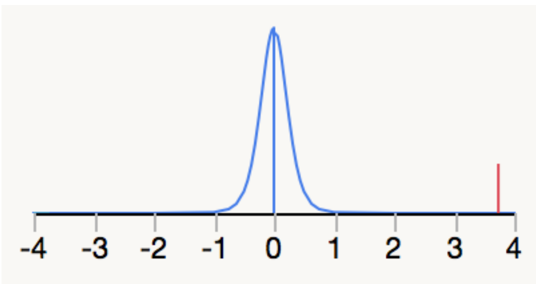
Response Data

Whole Model

Effect Summary

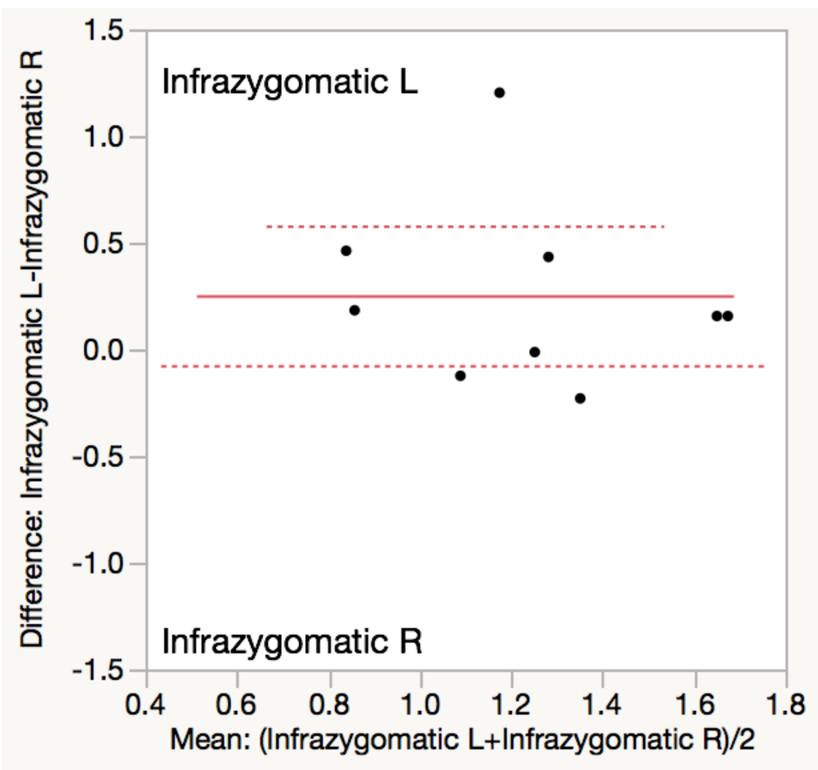
Source	LogWorth	PValue

Source	LogWorth		PValue
subj	2.587		0.00259
Label	0.458		0.34862



Matched Pairs

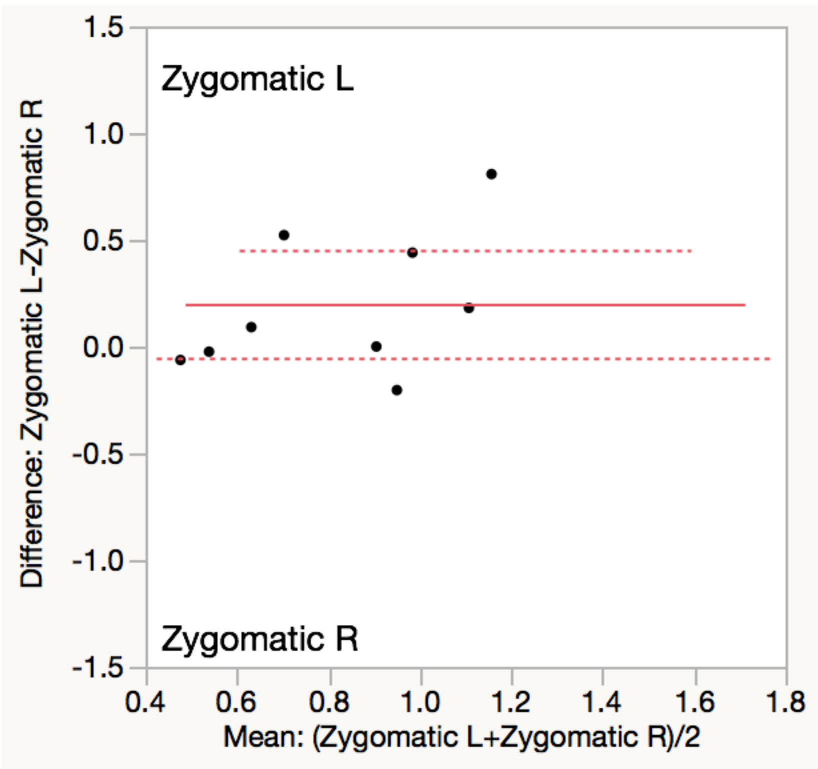
Difference: Infrazygomatic L-Infrazygomatic R



Infrazygomatic L	1.36456	t-Ratio	1.743962
Infrazygomatic R	1.11722	DF	8

Mean Difference	0.24733	Prob > |t|	0.1193
Std Error	0.14182	Prob > t	0.0597
Upper 95%	0.57438	Prob < t	0.9403
Lower 95%	-0.0797		
N	9		
Correlation	0.3267		

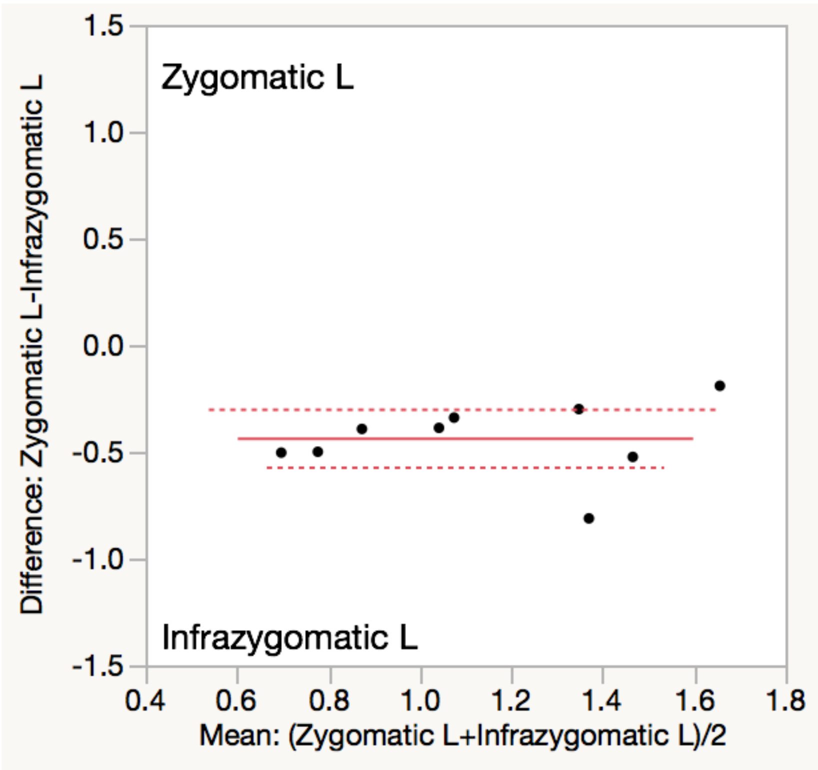
Difference: Zygomatic L-Zygomatic R



Zygomatic L	0.92544	t-Ratio	1.774518
Zygomatic R	0.73089	DF	8
Mean Difference	0.19456	Prob > |t|	0.1139
Std Error	0.10964	Prob > t	0.0569
Upper 95%	0.44738	Prob < t	0.9431
Lower 95%	-0.0583		

N	9
Correlation	0.43205

Difference: Zygomatic L-Infrazygomatic L



Zygomatic L	0.92544	t-Ratio	-7.45729
Infrazygomatic L	1.36456	DF	8
Mean Difference	-0.4391	Prob > |t|	<.0001*
Std Error	0.05888	Prob > t	1.0000
Upper 95%	-0.3033	Prob < t	<.0001*
Lower 95%	-0.5749		
N	9		
Correlation	0.87026		

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	2.52	2.894375
Variance	0.243771	0.303467
Observations	8	8
Pearson Correlation	0.598756	
Hypothesized Mean Difference	0	
df	7	
t Stat	-2.24975	
P(T<=t) one-tail	0.02961	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.05922	
t Critical two-tail	2.364624	

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	34.83429	35.04429
Variance	4.529762	4.741395
Observations	7	7
Pearson Correlation	0.989123	
Hypothesized Mean Difference	0	
df	6	
t Stat	-1.72925	
P(T<=t) one-tail	0.067247	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.134494	
t Critical two-tail	2.446912	

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.060375	1.319125
Variance	0.146793	0.103558
Observations	8	8
Pearson Correlation	0.181713	
Hypothesized Mean Difference	0	
df	7	
t Stat	-1.61426	
P(T<=t) one-tail	0.075252	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.150505	

t Critical two-tail	2.364624

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.72675	0.890625
Variance	0.057447	0.132533
Observations	8	8
Pearson Correlation	0.435621	
Hypothesized Mean Difference	0	
df	7	
t Stat	-1.37304	
P(T<=t) one-tail	0.106052	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.212105	
t Critical two-tail	2.364624	

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	31.67286	31.64286
Variance	5.635657	5.594924
Observations	7	7
Pearson Correlation	0.981017	
Hypothesized Mean Difference	0	
df	6	
t Stat	0.171873	

P(T<=t) one-tail	0.434594
t Critical one-tail	1.94318
P(T<=t) two-tail	0.869188
t Critical two-tail	2.446912

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	48.83429	48.92429
Variance	8.371195	7.164395
Observations	7	7
Pearson Correlation	0.989438	
Hypothesized Mean Difference	0	
df	6	
t Stat	-0.51896	
P(T<=t) one-tail	0.311184	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.622369	
t Critical two-tail	2.446912	

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	42.59143	42.64857
Variance	8.180848	7.879281
Observations	7	7
Pearson Correlation	0.9898	

Hypothesized Mean Difference	0
df	6
t Stat	-0.37038
P(T<=t) one-tail	0.361913
t Critical one-tail	1.94318
P(T<=t) two-tail	0.723826
t Critical two-tail	2.446912

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	2.8175	2.97125
Variance	0.28425	0.367298
Observations	8	8
Pearson Correlation	0.870152	
Hypothesized Mean Difference	0	
df	7	
t Stat	-1.45584	
P(T<=t) one-tail	0.094387	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.188775	
t Critical two-tail	2.364624	

t-Test: Paired Two Sample for Means

	Variable	*Variable*

	1	*2*
Mean	2.4825	2.6075
Variance	0.54445	0.40185
Observations	8	8
Pearson Correlation	0.829707	
Hypothesized Mean Difference	0	
df	7	
t Stat	-0.8572	
P(T<=t) one-tail	0.209854	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.419708	
t Critical two-tail	2.364624	