Midpalatal suture density ratio: Assessing the predictive power of a novel predictor of skeletal response to maxillary expansion

A Thesis submitted to the faculty of the Graduate School of the University of Minnesota

By

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Acknowledgements

Dedication

To my incredibly strong wife, Alex, who has shown nothing but selfless love and support through the whole journey to get to this point. This thesis is just as much a testament to all your hard work and support as it is to all the hours that were poured into this project, manuscript, and residency.

To my children, Anthony, Sebastian, Zoe, and Dominic, who have taught me more than I could ever hope to learn in all these years of schooling. Thank you for pointing me to the things that matter.

Abstract

INTRODUCTION: Rapid maxillary expansion (RME) is a common orthodontic treatment for treatment of maxillary transverse deficiency, however the inability to determine the precise timing of fusion of the midpalatal suture creates difficulty for clinicians to prescribe the appropriate treatment, surgical or non-surgical expansion.

OBJECTIVES: The purpose of this study was to assess the predictive power of the midpalatal suture density ratio (MPSD) for skeletal response to RME.

METHODS: Initial pre-orthodontic and final post-orthodontic cone-beam computed tomography (CBCT) scans were obtained and examined from orthodontic patients treated with RME. MPSD ratios were calculated from pre-treatment images, and a prediction was made for amount of skeletal expansion obtained after treatment. Predicted values were compared to actual values of post-treatment CBCTs, followed by the use of regression analyses to investigate correlations between MPSD and skeletal expansion (GPFd) and equivalence testing to analyze the performance of the predicted measurements.

RESULTS: Neither the skeletal (MPSD ratio) nor the dental (U6 CT) measurements were strongly correlated with actual GPFd change for any group. The predicted skeletal expansion using MPSD was not equivalent to the actual skeletal expansion achieved using an equivalence test margin of ±0.05; however, using the margin ±0.1, the two measures were shown to be equivalent for the female subgroup ($p=0.0063$) and for the 12 to 13 years of age subgroup ($p=0.0018$).

CONCLUSIONS: The results suggest that the midpalatal suture density ratio is not correlated with the amount of long-term skeletal expansion achieved at the level of the palate. Utilization of the midpalatal suture density ratio was ineffective in predicting the amount of long-term skeletal expansion achieved from pre-treatment cone-beam CTs.

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Introduction

Rapid maxillary expansion (RME) is a common orthodontic treatment that has been used since the 1860s[1] to correct transverse deficiencies of the maxilla and the maxillary dentition. RME treatment has historically been utilized for posterior crossbite correction by widening the narrowed maxillary skeletal base and for gaining arch perimeter to alleviate dental crowding, however the applications have since extended. McNamara advocated the use of RME to facilitate the correction of Angle class II or class III malocclusions.[2–5] Additionally, more recent considerations of the airway and breathing have led to an increased use of RME for improving airflow by increasing nasal/upper airway volume.[6,7]

Although there are various designs, the appliance is fabricated to attach to the dentition, and the heavy forces generated by the expander transmit through the teeth to the halves of the maxilla. In growing patients with patent skeletal sutures, the forces directed through the teeth to the skeletal bases are intended to open the midpalatal suture, and separate and hold the hemimaxillae apart to encourage callus formation and subsequent bone deposition resulting in *skeletal expansion*. Conventional RME uses a tooth-borne appliance to apply its force indirectly to the maxilla, therefore there are also dental responses to this force application, manifesting in dental tipping and bending of the alveolus described as *dentoalveolar expansion*. It has been reported that of the total expansion, 39-49% is attributed to dental tipping and 6-13% to alveolar bending.[8–10] Typically, it is desirable to maximize the skeletal effects and minimize the dental effects, as the dental tipping may lead to loss of alveolar bone and periodontal attachment level,[11,12] root resorption,[13] and fenestrations of the buccal cortex.[14] As a patient matures, the bony sutures progressively close by bony interdigitation, which increases their tensile strength and reduces the ability to force open the suture during conventional RME.[15–17] Consequently, RME is performed more often in young patients. Adults with fused palatal sutures require surgical intervention to obtain an increase in skeletal width, which increases costs and risks to the patient.[14] Surgically-assisted rapid maxillary expansion (SARME) usually involves making a midline cut in addition to all the surgical cuts of a LeFort I osteotomy with the exception of maxillary down fracture, which allows the halves of the maxilla to separate with little

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obstruction.[14,18] Alternatively, maxillary width can be obtained intraoperatively by utilizing a multiple-piece LeFort osteotomy.[14,18]

The physiological maturation process of the midpalatal suture was described in detail by Melsen, who studied human autopsy material in depth to increase the understanding of the suture we aim to manipulate with rapid maxillary expansion.[15] Thorough knowledge of the anatomy and maturation process of the midpalatal suture is important to gauge a patient's expected response to RME. Melsen described three main maturation stages: the infantile, the juvenile, and the adolescent periods.[15] The suture is Y-shaped in the infantile period, then progresses to a more tortuous suture in the juvenile period, then becomes more complex and interdigitated in the adolescent period.[15] Later in adulthood, the suture eventually becomes obliterated by calcified tissue.[17,19]

These general stages of sutural maturation exhibit wide variation among individuals regarding the continuum between initiation of interdigitation and complete fusion of the suture, and variation in these processes can exist even within the same suture.[17,20] As a consequence of the varying degrees of skeletal maturation and fusion of the midpalatal suture in patients for whom RME is prescribed, there is some amount of guesswork involved in the attempt to optimize treatment timing. To aid the clinical decision whether maxillary expansion should be corrected with conventional RME or whether surgical assistance would be necessary, several indicators of midpalatal suture maturation have been proposed, each with their own limitations.[21–27] Chronological age has historically been used as a guideline to make an inference about the stage of sutural maturation,[21,28] but has been put into question due to the wide variation in timing.[29] In addition to age, other proposed mechanisms for gauging the stage of sutural maturation use skeletal maturity indicators (SMI) on hand-wrist radiographs,[21,30] cervical vertebral maturation (CVM),[28,31] and assessment of the midpalatal suture on occlusal radiographs.[29] More recently, midpalatal suture maturation (MPSM) was proposed as a 5-stage classification of sutural interdigitation as assessed on cone beam computed tomograms (CBCTs),[16] however there have not yet been any studies to determine its predictive abilities.

The only way to be certain whether RME could be performed on a patient outside of the growth phase is by trial and error, which results in negative side effects when the treatment is unsuccessful.[32] A reliable way to more closely predict a patient's skeletal and dentoalveolar response to RME prior to initiating treatment has the potential of increasing treatment success by allowing clinicians to provide a more accurate prognosis for success in RME candidates who are approaching the end of, or are outside of, their growth period. An adolescent patient with early closure of the suture could be identified to avoid the potential negative side effects of attempting conventional RME; conversely, a young adult with late-closure of the suture may be able to avoid a SARME in favor of conventional RME, which would prevent the cost and risks of the surgical procedure.

The field of orthodontics has begun to see a slow shift away from traditional two-dimensional radiography in favor of the use of three-dimensional CBCT for orthodontic treatment planning.[33] CBCT has increased in popularity as it has some diagnostic advantages over traditional two-dimensional imaging.[34,35] Specifically relating to the midpalatal suture, it is possible to visualize the suture at many different levels by orienting axial slices through the area of interest without superimposition of other anatomical structures. This creates a potential for the development of various qualitative[16] and quantitative[36] assessments of midpalatal suture maturation that may help clinicians decide between conventional RME or surgically-assisted expansion options.

Recently, a novel predictor of skeletal response has been developed by Grünheid *et al*: the midpalatal suture density (MPSD) ratio using CBCT.[36] This measurement is a comparison of the gray density value of the midpalatal suture to the gray density of the lateral hard palate, expressed as a ratio. This allows for a *quantitative* measure of calcification of the suture to serve as proxy for bony interdigitation, reducing the error involved with traditional visual qualitative assessments. In the early stages of maturation of the midpalatal suture, the sutural gap between the halves of the maxilla largely consists of uncalcified connective tissue, since there is no bony interdigitation.[15,36] This appears radiolucent on the CBCT with a density similar to tissue of the soft palate, so the MPSD would be close to 0.[36] As the suture continues to mature, there is

increased bony interdigitation, and the MPSD increases due to the combination of uncalcified connective tissue and calcified osseous tissue within the suture. Ultimately, the suture matures to a degree where the amount of calcified tissue approaches that of cortical bone, which would result in a MPSD ratio close to 1.[36] In the study by Grünheid et al., there was a statistically significant negative correlation between the pre-treatment midpalatal suture density ratio and the skeletal width increase measured at the greater palatine foramina.[36] This promises the potential for clinical use of this measurement to aid everyday clinical decision-making. Discovery of this negative correlation elucidates the trend of skeletal response, however it warrants further investigation as to whether the measurement can accurately predict skeletal expansion within a clinically appropriate range. The objective of this study is to evaluate the reliability of the MPSD calculation as a predictive measure of the skeletal response to expansion.

LITERATURE REVIEW

Midpalatal Suture: Anatomy and Maturation

The midpalatal suture is the midline connection between bilateral halves of the maxillary and palatine bones. The anterior portion of the hard palate is comprised of the palatine processes of the bilateral maxillary bones that meet together in the midsagittal plane. Immediately posterior to the maxillary portion of the palate, the horizontal plates of the palatine bones meet at the midline to form the posterior aspect of the midpalatal suture (Figure 1).[37] Where the maxillary and palatine bones meet there is an interpalatine suture, which runs perpendicularly to the midpalatal suture.
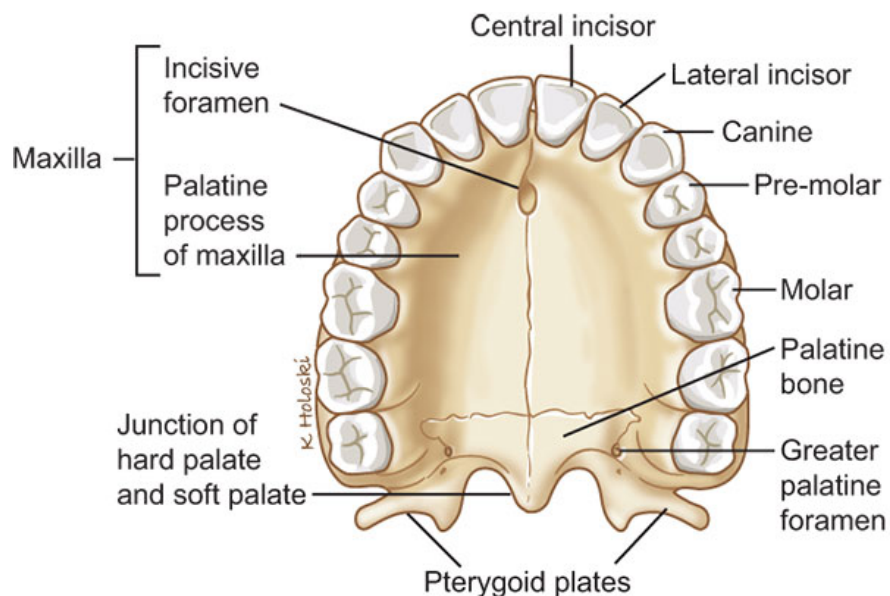
Figure 1. The bones that form the midpalatal suture meet in the midsagittal plane (Image from Head and Neck Cancer Guide[38])

Björk pioneered much of the foundational study of growth and development of the craniofacial system, including that of the hard palate.[39,40] The maturation process of the midpalatal suture has been studied using histologic and micro-computed tomography of autopsy samples, which Melsen describes using a three-stage maturation process.[15,17] In the infantile period, from a coronal-slice perspective, the suture appears as very broad and Y-shaped with the vomer bone lodged in a furrow between the two halves of the maxilla (Figure 2).[15] The juvenile period is characterized by bony projections into the suture from the right and left maxilla creating

a winding suture. In the adolescent period, bony interdigitation continues and the suture becomes progressively more tortuous.[15] Finally in adulthood, around the third decade of life, the suture eventually becomes obliterated by calcified tissue.[17,19]
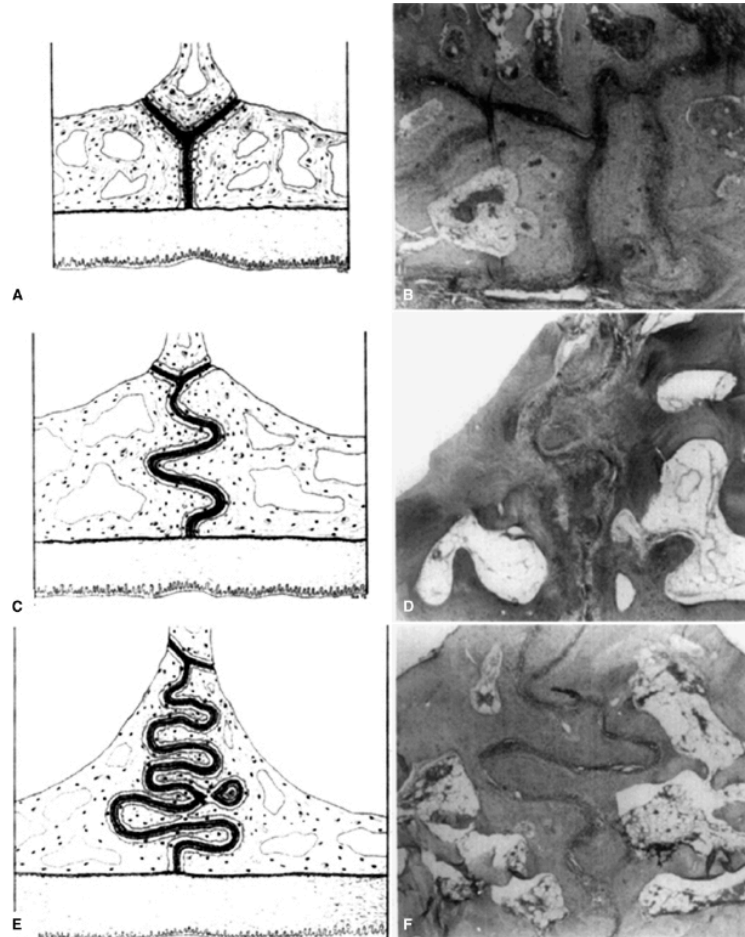
Figure 2. Stages of midpalatal suture maturation: (A) Diagrammatic representation of the suture of the infantile period. (B) Histologic frontal section of the infantile suture of a 1-year-old child. (C) Diagrammatic representation of the suture of the juvenile period. (D) Histologic frontal section of the juvenile suture of the 10-year-old boy. (E) Diagrammatic representation of the suture of the adolescent period. (F) Histologic frontal section through the suture of a 12.5-year-old girl. (Image taken from Melsen, 1975)

As this process progresses, the bony projections continue to interlock and the suture is considered "closed" around age 16 years in females and 18 years in males. In adulthood, around the third decade of life, the suture eventually becomes obliterated by calcified tissue.[17,19] The fusion process begins at the posterior aspect of the suture and progresses anteriorly,[17] but there

is considerable variation between individuals with regard to timing for the initiation of obliteration and its rate to complete fusion.

Rapid Maxillary Expansion

Angell was the first to introduce the concept of maxillary expansion in 1860 in order to correct maxillary transverse deficiency to resolve a posterior crossbite,[1] but the validity of the treatment remained under question. It was not until a century later that maxillary expansion became widely accepted, largely due to the work of Haas who demonstrated the efficacy and legitimacy of the treatment.[41] RME has since been utilized to various degrees for many treatment aims such as increasing arch length to alleviate dental crowding,[3] facilitating Class II or III correction,[2,5] increasing oronasal volume in efforts to improve obstructive sleep apnea (OSA)[42–44] and nocturnal enuresis,[45] and for esthetic goals of producing wider smiles with more filled buccal corridors.[46] RME applies forces that cause gradual opening of the midpalatal suture, compression of the periodontal ligament, alveolar process bending, and dental tipping.[41,47] It has been reported that there is an increase in arch length of 0.7mm for every 1mm of expansion in the premolars.[48] Some literature promote the use of RME regardless of presence of posterior crossbite to alleviate mild to moderate dental crowding.[3,4] McNamara described a theory of Class II correction with the application of maxillary expansion, explained with the foot-in-shoe analogy.[2] If the maxilla (the "shoe") is too narrow, then the mandible (the "foot") is unable to move forward to fit and interdigitate with the maxillary dentition ("Pantoffelvergleich", suggested by Alfred Körbitz, 1914). The theory is that by widening the maxilla and the maxillary dentition, the anteroposterior discrepancy can spontaneously correct by the mandible moving forward into a normal relationship. Conversely, RME has been suggested to assist the use of a protraction facemask for young patients in obtaining skeletal Class III correction by loosening the circummaxillary sutures for more effective protraction.[5] The effect of expansion on patient airway has been investigated with some controversy regarding its therapeutic effect on reducing OSA severity and its various symptoms such as nocturnal enuresis.[45] While OSA is a multifactorial condition in which patient anatomy accounts for only one factor, several studies have shown an increase in oral and nasal

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volume and reduction of the apnea/hypopnea index (AHI) with RME therapy in children with obstructive sleep apnea.[42,44,45,49]

Although RME has been recognized as a safe, reliable orthopedic procedure that allows elimination of the maxillary transverse deficiency in growing patients,[9,50–52] there are many studies that have investigated the unwanted effects of expansion on periodontal tissues, sutures, and the dentition.[9,51,53–55] With an increase in skeletal maturity and closure of the circummaxillary sutures, the risk of these side effects increases, necessitating surgical assistance to achieve the desired skeletal width.[17,56,57] There is a lack of a definitive, reliable guideline that enables the orthodontist to diagnose facial skeletal maturity, resulting in some patients that may receive treatments that are inappropriate.

More recently, it has been demonstrated that it is possible to expand the maxilla in more skeletally mature patients without the usual surgical interventions of SARPE, but using microimplants as anchorage instead.[58,59] This novel technique is termed microimplant-assisted rapid palatal expansion (MARPE). A miniscrew-borne expander applies forces primarily to the microimplants to transmit the forces directly to the bony maxilla instead of the teeth or periodontium, thus eliminating unwanted dental tipping.[60] There are various appliance designs and a recent clinical study using one design found an 86.96% success rate in young adult patients (mean age of 20.9 ± 2.9 years), with stable results after 30 months of follow-up.[58] Interestingly, Cantarella *et al.* found that MARPE resulted in a significant increase in width at the interzygomatic level, whereas traditional tooth-borne RME has shown negligible effects on the displacement of the zygomatic bone.[28] The zygomatic bone tended to rotate outward along with the maxilla with a common center of rotation located near the superior aspect of the frontozygomatic suture, more posteriorly and laterally than what has been reported in the literature for tooth-borne expanders. Bone bending takes place in the zygomatic process of the temporal bone during miniscrew-supported maxillary expansion.[59,60]

Effects of Maxillary Expansion

The introduction of CBCT has allowed the dental and skeletal effects of RME to be examined independent of each other since the image can be viewed from many perspectives.[61] Without superimposition of bilateral structures and magnification distortion, anatomical structures can be analyzed more precisely than ever before in several planes of space,[62] making repeatable measurements and landmark identification achievable for a wide variety of applications.[63,64] Concerning treatment effects of RME, making linear, angular, and surface change measurements on the three-dimensional CBCT image allows for separation of the dentoalveolar from the skeletal effects.

Various studies have explored the effects of RME treatment in three dimensions using CBCT.[8–10,52,55,65–69] It has been reported that skeletal maxillary expansion accounted for 12.6-52.8% of the total expansion[9,10,50,66,70] and that there is greater skeletal expansion at the premolar level than the molar level, with 55% and 38%, respectively. Alveolar bending accounts for about 6-13% of the total expansion achieved, the amount of which increases as you move posteriorly.[8] Dental tipping typically accounts for the remainder of the total expansion (39-49%), the magnitude of which has been reported to range from 3.4 degrees to 9.2 degrees.[71] Similar to the trend for alveolar bending, the amount of dental tipping also increases from anterior to posterior.[8]

Maxillary expansion concentrates forces across the midpalatal suture to obtain skeletal correction, however there are other circummaxillary sutures to consider in the facial complex, namely the zygomaticomaxillary, zygomaticofrontal, zygomaticotemporal, frontomaxillary, frontonasal, nasomaxillary, and internasal sutures. Several studies that address the facioskeletal changes observed with RME, including the response of these circummaxillary sutures, found that there are small changes in width across each of these sutures, ranging from 0.3-0.45mm.[68] There were greater effects in sutures that directly articulate with the maxilla (zygomaticomaxillary and frontomaxillary) than the more distant sutures,[72–74] however these were highly variable for different sutures and even sometimes within the same suture.[68] Considering the skeletal effects from a coronal perspective, RME is described to have a pyramidal nature to skeletal expansion in that width gain decreases moving superiorly.[10,68] This is partially attributable to the comparatively

mild effect on these circummaxillary sutures as the midpalatal suture is separated. Young patients treated with RME tend to have a more parallel expansion, but the pyramidal effect is accentuated with age and skeletal maturity and as these circummaxillary sutures continue to mature and interdigitate.[67]

In addition to skeletal effects, maxillary expansion produces dental effects that need to be considered. Heavy, intermittent forces are applied from the expansion appliance to the teeth, which lead to compression of the periodontal ligament, causing bending of the alveolar bone and tipping of posterior teeth.[13,75,76] Both maxillary molar and premolar teeth tip buccally in response to forces applied from the expander that are coronal to the center of resistance of the teeth.[48] The proportion of total expansion that is attributed to true skeletal width gain as well as dental and alveolar tipping has been previously studied; Krebs reported that 65% of the total expansion was the result of dental changes in adolescent patients.[77] Ghoneima *et al.* reported that the maxillary alveolar width increases more than maxillary base width, suggesting that alveolar bone tipping likely accounts for the majority of expansion.[78]

The dental component to maxillary expansion can lead to adverse effects, namely those of root resorption and periodontal attachment loss.[12,13] In patients treated with RME, roots of posterior teeth have been reported to show a mean volume loss between 5.77 and 13.70%.[13] Periodontal attachment loss after expansion in skeletally mature patients is another adverse effect that requires consideration, and is another reason demonstrating that proper pre-treatment diagnosis of skeletal maturity is crucial. In a study comparing adult patients treated non-surgically with traditional RME with SARME patients, the non-surgical group exhibited crown lengthening of posterior teeth caused by periodontal attachment loss.[12] Immediately post-expansion, the premolars of the non-surgical group showed 0.7mm attachment loss and 1.2mm at the follow up visit, whereas the SARME group exhibited no attachment loss immediately post-expansion and 0.5mm attachment loss at the follow up visit. Similarly in molars, the non-surgical group had 0.8mm attachment loss immediately and 1.3mm at follow-up, whereas the SARME group had 0.2mm immediately and 0.6mm at follow-up.[12]

Assessment of Skeletal Maturity

Normal skeletal maturation involves progressive interdigitation and ultimate fusion of the facial sutures, resulting in progressively increased resistance to opening the midpalatal and cirummaxillary sutures with RME treatment. Historically, several methods have been employed to infer about the patient's stage of maturation to aid in treatment decisions and to provide an accurate prognosis for success. Patient chronological age is naturally the first and simplest attempt to gauge the stage of skeletal maturation, however chronological or dental age has not been demonstrated to predictably correlate with the stage of skeletal maturation.[22,79] Skeletal maturity can be advanced or delayed in varying degrees from chronological age.[79] Chronological age in young adulthood fails to predictably indicate actual midpalatal suture maturation.[29]

The timing for facial growth and maturation has been demonstrated to correlate well with that of overall skeletal maturity,[22] therefore methods to determine the onset of peak growth velocity have been utilized for timing orthodontic treatment to take advantage of the growth spurt. Skeletal maturity assessments have been made in orthodontics using two primary methods: morphological characteristics of cervical vertebrae on lateral cephalograms and of bones of the hand on hand-wrist radiographs.[22,80] CVM assessment describes the method that has been used to determine growth status by categorizing stages of skeletal maturity based on the visual radiographic appearance of cervical vertebrae 2-6 from lateral cephalograms.[81] An estimate of individual growth potential can be inferred based on the stage of maturation of the cervical vertebrae.[81] Another common method is the utilization of hand-wrist radiographs to relate certain skeletal maturation features of the hand to pubertal growth status.[22] A specific sequence of indicators are analyzed such as the calcification of the sesamoid bone and the staging of epiphyseal capping or fusion of certain phalanges of the fingers.[22] This assessment tool has been shown to correlate well both for overall horizontal and vertical facial growth, as well as for maxillary and mandibular growth.[22] Baccetti *et al.* concluded that patients treated before peak skeletal growth velocity demonstrated more pronounced transverse craniofacial changes at the skeletal level than those treated later.[28]

Despite some opinions indicating the value of these tools for predicting skeletal growth, others have found that neither CVM nor the hand-wrist methods have a distinct advantage over chronological age in the prediction of facial growth timing.[26,27] This is useful information to demonstrate trends retrospectively, however is of little use when faced with the clinical decision of whether to use conventional RME or rely on surgical assistance to expand the maxilla of a patient who is past peak-growth yet may retain some growth potential.

Occlusal radiographs have also been suggested as a means to evaluate midpalatal suture maturation before expansion,[21,29] with inconsistent findings. One study found a positive correlation between maturation development and midpalatal suture fusion as determined by occlusal radiographs.[21] Another study used cadaveric tissue blocks of the palate and compared the radiographic appearance of the suture on occlusal radiographs to the histologic sections of the suture.[29] The authors found that whether or not a suture is visible radiographically depends more on how the main course suture runs in relation to the x-ray path rather than the percentage of obliteration or patency of the suture.[29] To compound the issue, superimposition of other anatomical structures often obscures the view of the complete suture and makes meaningful use of these images difficult.[29] In approximatively 50% of the young adult sample in which the suture was radiologically not visible (which would have been radiologically classified as 'fused'), no obliteration at all was found.[29]

Cone-Beam Computed Tomography

It is still a matter of debate whether or not CBCT is the current standard of care for comprehensive orthodontic treatment due to concerns of unnecessarily increased radiation exposure,[33,82] however there are many diagnostic advantages of three-dimensional imaging with respect to orthodontic diagnosis and treatment planning. Costs are significantly decreased compared to medical CT and the decreased resolution demands for use in orthodontics allow for a significantly reduced radiation dose and shortened acquisition times.[34,35] The accuracy and reliability of measurements from CBCT images has been well established; the absence of magnification and distortion of the 1:1 geometry allows for precise landmark identification and

accurate measurements of objects and dimensions, including unerupted teeth, bony and soft tissue dimensions in any plane of space.[33,83–86]

CBCT technology allows for visualization of the suture without obstruction from other anatomical structures. Using this advantage, a 5-stage system for midpalatal suture maturation (MPSM) was developed by Angelieri *et al.* that provides a more direct assessment of the midpalatal suture morphology and stage of development rather than more distant skeletal landmarks such as cervical vertebrae.[16,23,31,87] In this method, CBCT slices of the midpalatal suture are assessed qualitatively and placed into stages based on appearance of bony interdigitation.[16] This shows a promising alternative to traditional methods, however its clinical use in predicting skeletal response to maxillary expansion has yet to be demonstrated.

More recently, a novel predictor of skeletal response has been developed by Grünheid *et al.*: the midpalatal suture density ratio (MPSD).[36] CBCT gray values have been shown to strongly correlate with bone volume fraction, making CBCT a good modality for making bone-quality measurements.[88] The MPSD is a measurement comparing the average gray density value of the midpalatal suture to the gray density of the lateral hard palate, expressed as a ratio. The density measurement taken of the lateral hard palate serves as the upper limit for radiodensity for each subject, as it represents fully calcified cortical bone; this accounts for varying mineral densities between individuals. Similarly, the density measurement taken at the soft palate serves as the lower limit for radiodensity, as it represents non-calcified soft tissue. This would be analogous to radiodensity of the palatal mucosa of the hard palate or the connective tissue of a patent midpalatal suture. This allows for a quantitative measure of sutural mineralization to serve as proxy for bony interdigitation, reducing the error involved with visual qualitative assessments. The MPSD was found to negatively correlate with the amount of prescribed skeletal expansion after treatment with traditional RME,[36] however its usefulness as a predictive measure for skeletal response to expansion has yet to be studied.

Aims and Hypotheses

The primary aim of this study is to determine the predictive power of the MPSD for skeletal response in patients treated with rapid maxillary expansion. A secondary aim is to provide a repeatable method for predicting skeletal response to RME using the measurements from pre-treatment CBCTs and the equation established by Grünheid *et al.* based on the MPSD ratio: *GPFp = 0.60 x MPSD ratio + 0.50.*

It was hypothesized that there is a statistically significant negative correlation between the MPSD and skeletal response to maxillary expansion at the level of the greater palatine foramen. It was further hypothesized that there is a high degree of equivalence between the *predicted* skeletal response using pre-treatment MPSD ratios and *actual* skeletal response as measured on post-treatment CBCTs. Thus, the midpalatal suture density ratio has a high predictive power of skeletal response to rapid maxillary expansion.

Materials and Methods

       The study was performed under the approval of the Institutional Review Board at the University of Minnesota (Study number 00003544). The pre-treatment and post-treatment records of 78 orthodontic patients were utilized. Inclusion criteria consisted of adolescent and teen patients with maxillary transverse deficiency who were treated with RME using a Hyrax appliance as a part of comprehensive or phase I orthodontic treatment at the University of Minnesota School of Dentistry. Patients who had incomplete treatment records, previous orthodontic treatment, congenital malformations including cleft lip and palate, inappropriate diagnostic quality of CBCT images, or previous history of periodontal disease were excluded from the study. The CBCT images were from adolescents and teen subjects with an age range of 8 to 18 years to include a population with varying degrees of sutural maturation. Treatments were carried out by 47 orthodontic residents at the University of Minnesota.

       The descriptive information was recorded from each subject's treatment record including age at the time of initial records, sex, Hyrax expander design, the amount of prescribed expansion (number of turns of the expander key translated to amount of expander activation expressed in mm), expander retention time after cessation of activation (in weeks), and total treatment time (in months). The distribution of the 78 subjects by sex is shown in Table 1; 40 subjects (51.3%) were treated with a 4-banded hyrax appliance, and 38 subjects (48.7%) were treated with a 2-banded hyrax appliance. Table 2 shows the sample population separated into one of three age groups: 8 to 11 years (>8 to <12 years), 12-13 years (≥12 to ≤14 years), and 14-18 (>14 to 18 years of age).

Table 1. Descriptive statistics of categorical variables for the sample population

Variable	Category	Occurrence	Percentage
Sex	Male	36	46.2%
	Female	42	53.8%

Table 2. Descriptive statistics of categorical variables for the sample subgroups.

Age Subgroup	Occurrence	Percentage
8 – 11 years	20	25.6%
12 – 13 years	39	50.0%
14 – 18 years	19	24.4%

There were two Hyrax appliance designs that were used in this study: a 4-banded or a 2-banded appliance with jackscrew at the depth of the palate. The 4-banded expander design had both the first premolars and first molars banded, whereas the 2-banded expander design had the first molars banded with soldered extension arms extending anteriorly to the first premolars (Figure 3). The force was transmitted to the first premolars, the second premolars, and the first molars with each expander design. The protocol for the active expansion period included turn of the expansion screw once daily until the appropriate level of correction was achieved according to the judgment of the treating clinician. After the completion of active expansion, there followed a period of retention where the appliance was left in place passively. The post-expansion retention period averaged 17.5 weeks (±14 weeks), after which the appliance was removed and comprehensive or phase I treatment was resumed until the orthodontic treatment objectives were reached and the treatment was complete. The application of preadjusted edgewise appliances to begin active tooth movement was initiated during the post-expansion retention time for the patients receiving comprehensive treatment; in the cases of younger patients treated with phase I orthodontics, the 4 incisors were bonded either during or after the active expansion phase.

Figure 3. Typical Hyrax expander designs used for RME in this study. (A) 4-banded expander, (B) 2-banded expander

Descriptive statistics for the sample are shown in Table 3.

Table 3. Descriptive statistics of continuous variables for the sample population

	Mean ± SD	Median	Range
Age at T_1 (y)	13.01 ± 1.66	12.92	8.74 - 17.82
Amount of RME activation (mm)	8.09 ± 2.40	8.00	3.25 - 16.00
Expander retention time (w)	17.49 ± 13.97	14.00	1.00 - 77.00
Total treatment time (mo)	29.16 ± 7.32	28.70	11.52 - 48.84

All imaging for the study was completed on an i-CAT Next Generation CBCT scanner (Imaging Sciences International, Hatfield, PA). Both pre-treatment (T_1) and post-treatment (T_2) images were taken with full field-of-view (17 x 23 cm) at 120 kV and 18.54 mAs, with a pulsed scan time of 8.9 seconds and a voxel size of 0.3 mm. This resulted in a slice thickness of 0.3 mm for all scans.

All measurements were performed on the digital imaging and communications in medicine (DICOM) images using InVivo6 imaging software (version 6.0, Anatomage Dental, San Jose, CA). All measurements were performed by a single examiner. In order to blind the examiner to both the subject and time point, each CBCT image obtained at T_1 and T_2 was randomized using a random number generator and assigned an arbitrary numerical identifier. Both linear and average gray density measurements were taken, and all linear measurements were made to the nearest 0.1 mm. Linear measurements comprise of one linear *dental* measurement and one *skeletal* measurement. The dental measurement consisted of the intermolar width taken at the mesio-lingual cusp tips between both upper first molars. The skeletal measurement involved linear measurement of the width between the lateral margins of the right and left greater palatine foramina (GPf). Gray density measurements were taken from defined regions of the midpalatal suture (GDs), soft palate (GDsp) and palatal process of the maxilla (GDppm). The process for taking these measurements will henceforth be described.

The DICOM image was oriented to bisect the palatal plane in 3 dimensions: first oriented from an axial slice through the hard palate and centered through the midpalatal suture,

then through the center of the hard palate from a sagittal slice parallel to the palatal plane, and finally through the center of the hard palate from a coronal slice parallel to the palatal plane. (Figure 4).
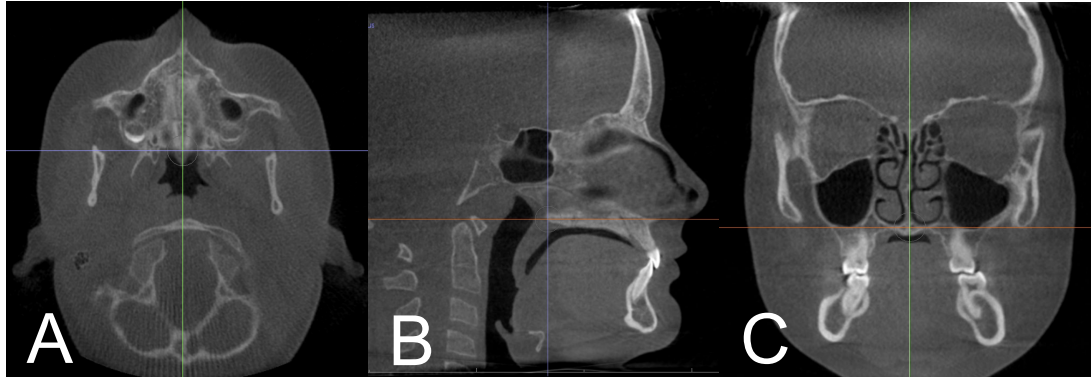
Figure 4. Orientation of the 3-D reconstructions in Invivo6 Imaging software. The image was centered along the hard palate in the axial view (A), the sagittal view (B), and the coronal view (C).

Linear Measurements

The linear distance between the greater palatine foramina was measured to quantify the skeletal effects of RME on slices from T_1 and T_2 CBCT images. The distance between the greater palatine foramina (GPFd) was measured between the lateral margins of the foramina on an axial slice through the center of the hard palate (Figure 5).

27.46 mm
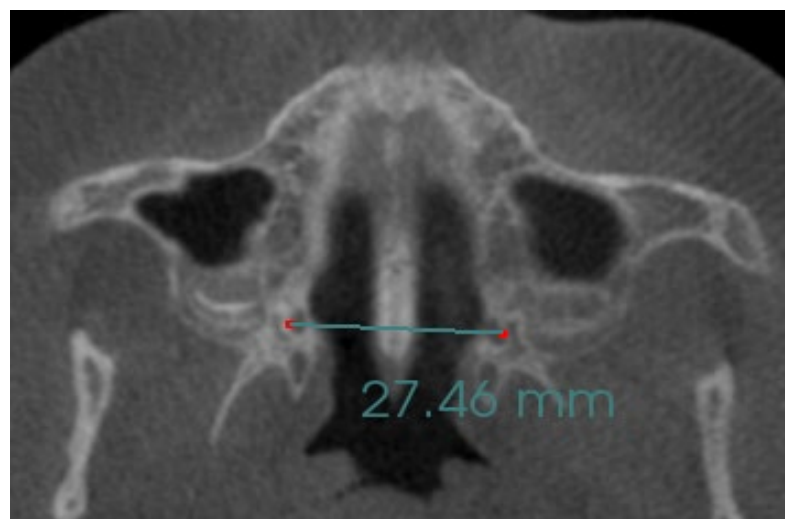
Figure 5. Linear skeletal measurement. Distance was measured between the lateral margins of the greater palatine foramina (GPFd)

To account for the variable amount of expansion performed between subjects, each distance was presented as a proportion of the prescribed expansion by dividing the difference in distances between T_1 and T_2 by the amount of prescribed activation of the expander. Prescribed expansion is determined by the number of expander key turns completed divided by the amount of screw opening per turn (0.25 mm) to obtain a total amount of prescribed expansion. The difference in distance between the final and initial time points at the level of the greater palatine foramen divided by the prescribed expansion was termed the greater palatine foramina proportion (GPFp).

$$Greater\ palatine\ foramina\ proportion\ (GPFp) = \frac{T2\ GPFd - T1\ GPFd\ (mm)}{Prescribed\ expander\ activation\ (mm)}$$

The linear dental measurements were taken at points between the maxillary first molars. Viewing a coronal slice through the first molars, a measurement of the intermolar width was taken at the mesio-lingual cusp tips (Figure 6). The total amount of expansion remaining at the end of comprehensive treatment can be measured using these measurements.
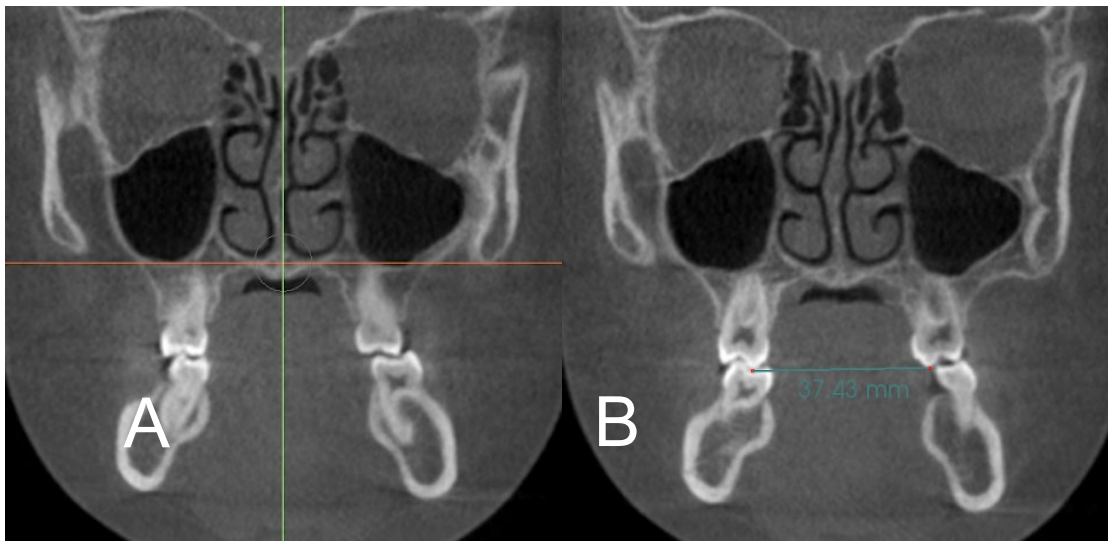
Figure 6. Linear dental measurement. (A) View from the coronal plane oriented through the center of the hard palate sagittally and axially, (B) Intermolar width were taken at the mesio-lingual cusp tips.

Density measurements

For the MPSD ratio, the measurements were made in Invivo6 (version 6.0, Anatomage Dental, San Jose, CA). The T_1 DICOM images were oriented to the palatal plane in a sagittal view and frontal view to yield a 0.3 mm thick axial slice through the center and parallel to the hard palate as described previously (Figure 4). A gray density value is assigned to each voxel of a CBCT image by the software on an arbitrary scale, specific to the machine and exposure settings. The average gray density values were measured and recorded for defined regions of the suture (GDs), palatal process of the maxilla (GDppm), and soft palate (GDsp) (Figure 7). GD_s was measured through the most central axial slice through the hard palate.

The average gray density value measurement for the midpalatal suture region (GDs) was taken using a 6 mm wide rectangle from the distal aspect of the incisive foramen to the distal of the first molar crown centered on the midpalatal suture (Figure 7A). The gray density measurement of the palatal process of the maxilla region (GDppm) was taken within a 4x4 mm square section of the cortical portion of the distolateral aspect of the hard palate (Figure 7B). Similarly, the gray density measurement of the soft palate region (GDsp) was taken within a 4x4 mm square of the midline portion of the soft palate (Figure 7C).
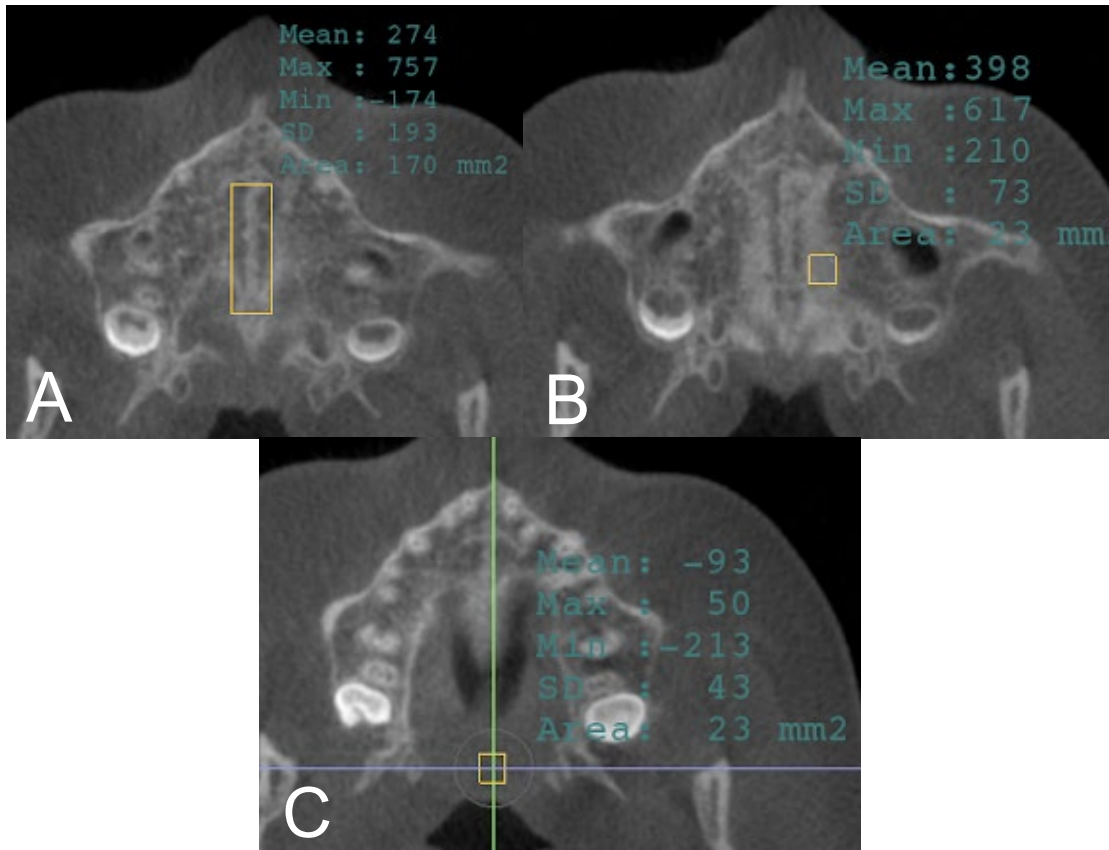
Figure 7. Average gray density value measurements for: (A) the midpalatal suture region (GDs), (B) the palatal process of the maxilla region (GDppm), and (C) the soft palate region (GDsp).

The soft palate density measurement (GDsp) was measured 5 mm from the posterior nasal spine (PNS), centered along the soft palate. From a midline sagittal view, 5 mm was measured from the PNS centered along the descending soft palate (Figure 8A) and the crosshairs were placed at the 5 mm point (Figure 8B). From an axial view a 4x4 mm square centered on the crosshairs to obtain the average gray density value (Figure 8C).
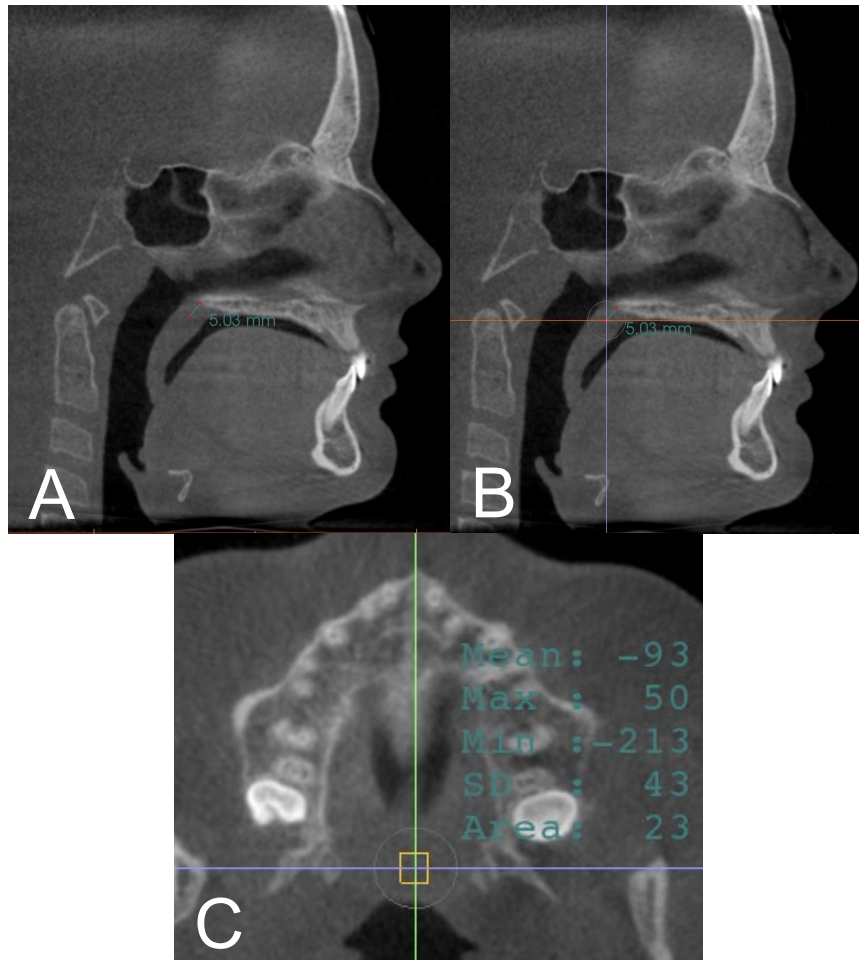
Figure 8. Orientation and obtaining the GDsp measurement. (A) From a midline sagittal view, 5mm was measured from the PNS centered along the descending soft palate, (B) the crosshairs were placed at the 5 mm point, and (C) a 4x4 mm square was centered on the crosshairs from the axial view to obtain the average gray density value.

The MPSD ratio is calculated using the average gray density value measurements described above, and follows the equation:

$$MPSD\ ratio = \frac{GDs - GDsp}{GDppm - GDsp}$$

The calculated MPSD ratio ranges from 0 to 1, with values closer to 0 representing sutures with a lesser degree of calcification and a density more similar to the soft palate. Values closer to 1 indicate more mature sutures with a higher degree of calcification and a density approaching that of palatal cortical bone.

All measurements were repeated by the same examiner after a 6-week washout period for 10 randomly chosen subjects to assess intra-examiner reliability. Acceptable reliability was established as having an interclass correlation of 0.9 or higher between both measurement time points. Once acceptable reliability was established for these subjects, data was then collected for the entire sample population.

The sutural average gray density value measurements were recorded and the MPSD ratio was calculated using the equation above. A prediction of skeletal expansion was then made using the equation established by Grünheid *et al.* (*GPFp = 0:60 x MPSD ratio + 0:50)* from the linear correlation discovered in their study.[36] All predictions for change in distance between greater palatine foramina were expressed as a *ratio of the pre-treatment prescribed expansion* so as to account for individualized amounts of expansion. T$_2$ (post-treatment) images were also randomized to avoid any comparison bias to pre-treatment images. Again, both *dental* (intermolar widths at the cusp tips) and *skeletal* (GPf) linear measurements as described above were recorded.

Statistical Methods

Descriptive statistics were calculated for age, gender, type of appliance, amount of expansion, total retention and treatment time. A linear regression analysis was performed to investigate the relationship between the MPSD and skeletal change at the greater palatine foramen (GPFd). Linear regression analyses were also carried out to test the relationships between the dental intermolar measurements (U6 CT) and skeletal change at the greater palatine foramen (GPFd). In order to investigate differences within the population, subgroup analyses were carried out to account for gender differences as well as age differences. The subjects were categorized into three age ranges for the subgroup analysis: 8-11 years, 12 to 13 years, and 14 to 18 years. Pearson's correlation coefficients were calculated for each subgroup. The *p*-value of the slope was used to determine whether a correlation existed between the variables.

Two equivalence tests were performed to determine the predictive performance of the equation developed in the Grünheid *et al.* study by assessing how close how close the *predicted* T_1 skeletal measurements coincided with *actual* skeletal T_2 measurements.[36] A prediction of final skeletal width gain within 1 mm of the actual width gain was deemed as clinically relevant. Since the skeletal response to expansion in this study is expressed as a proportion of GPFd to prescribed expansion (GPFp), rather than a discrete millimeter unit, the margins chosen for the equivalence tests were +/-0.05 and +/-0.1 from the predicted value. Based on the data of the previous study by Grünheid *et al.*, a one-millimeter change at the level of the greater palatine foramen corresponded to roughly a 0.1 value for the proportion of GPFd to prescribed expansion on average. The ±0.05 margin corresponds to a 1 mm margin, with 0.5 mm on either side of the predicted value, whereas the ±0.1 margin corresponds to a 2 mm margin, with 1 mm on either side of the predicted value. The reason for choosing two margins was to provide some perspective for the strength of the predictive ability of the MPSD ratio if we obtained favorable results; statistically significant equivalence for only the wider margin would allow the clinician to decide for themselves whether or not that margin of error is within the range of reasonable risk for a particular patient. The same equivalence testing was performed for each of the same subgroups (sex, age groups 8-11, 12-13, and 14-18 years). P-values from the equivalence test were obtained. The null hypothesis for the equivalence test is that the two measures differ by more than the margins; the alternative hypothesis is that the two measures differ by less than the margins, hence we call them equivalent.

Intra-examiner reliability was assessed using intraclass correlation coefficients for the linear and gray density measurements. *P*-values of less than 0.05 were considered statistically significant. Statistical analyses were performed using SAS system (Version 9.4, SAS Institute Inc, Cary, NC).

Results

All measurements demonstrated intraclass correlation coefficients (ICC) of 0.91 or greater as shown in Table 4, indicating excellent intraexaminer reliability. The linear dental measurement (U6 CT) had an ICC of 0.99. The linear skeletal measurement (GPFd), had an ICC of 0.98. The average gray density measurements (GDs, GDsp, GDppm) had ICC values of 0.96, 0.96, and 0.91, respectively.

Table 4. Intraclass correlation coefficients for linear (gray) and density (white) measurements

	Intraclass correlation coefficient (ICC)
U6 CT	0.99
GPFd	0.98
GDs	0.96
GDsp	0.96
GDppm	0.91

U6 CT – linear intermolar distance measured from the mesio-lingual cusp tips of the maxillary first molars
GPFd – linear distance between the lateral margins of the greater palatine foramina
GDs – average gray density of the midpalatal suture
GDsp – average gray density of the soft palate
GDppm – average gray density of the palatal process of the maxilla

The amount of dental and skeletal expansion remaining after comprehensive orthodontic treatment (T_2 timepoint) is displayed in Table 5. This value was obtained by subtracting the initial T_1 linear measurements from the final T_2 linear measurements. The average amount of skeletal expansion remaining as a proportion of total remaining expansion at the completion of comprehensive treatment is 54%.

Table 5. Amount of long-term skeletal and dental expansion remaining post-treatment for the overall sample population (A) and for each subgroup (B)

	ΔU6 CT (mm)	ΔGPFd (mm)	
Mean (± SD)	3.69 (± 2.95)	2.05 (± 1.13)	**A**
Min	-3.10	0.07	
Max	9.71	4.92	

	ΔU6 CT (mm)					
	Male	**Female**	**8 – 11y**	**12 – 13y**	**14 – 18y**	
Mean (± SD)	4.08 (± 3.07)	3.36 (± 2.82)	4.14 (± 3.29)	3.80 (± 2.72)	2.99 (± 3.05)	
Min	-3.10	-2.39	-3.10	-0.70	-2.39	**B**
Max	9.50	9.71	9.71	9.50	8.69	
	ΔGPFd (mm)					
	Male	**Female**	**8 – 11y**	**12 – 13y**	**14 – 18y**	
Mean (± SD)	2.66 (± 1.00)	1.52 (± 0.97)	2.33 (± 1.22)	1.94 (± 1.04)	1.97 (± 1.22)	
Min	0.58	0.07	0.07	0.12	0.35	
Max	4.92	3.87	4.06	4.92	4.47	

U6 CT – linear intermolar distance measured from the mesio-lingual cusp tips of the maxillary first molars
GPFd – linear distance between the lateral margins of the greater palatine foramina

The Pearson correlation coefficients and corresponding *p*-values for the overall sample population are shown in Table 6A. Neither the skeletal (MPSD ratio) nor the dental (U6 CT) measurements were statistically significantly correlated with actual GPFd change. There was a very weak negative correlation between MPSD and the proportion of skeletal expansion (r = -0.16), whereas the dental intermolar measurement exhibited a very weak positive relationship (r = 0.03). The scatter plot in Figure 9 displays the correlation between the MPSD ratio and the skeletal width change at the greater palatine foramen as a proportion of prescribed expansion for the overall sample population.

Table 6B displays the Pearson correlation coefficients and corresponding *p*-values for both the age and gender subgroups. Neither the MPSD ratio nor U6 CT were statistically significantly correlated with GPFd in any group. All correlations were very weak with inconsistent correlations, as some were positive and some were negative. The scatter plot in Figure 10 displays the correlations between the MPSD ratio and the skeletal width change at the greater palatine foramen as a proportion of prescribed expansion for each subgroup of the sample population.

Table 6. Pearson correlation coefficients from linear regression analyses for the overall sample population (n=78) (A), and for the age and gender subgroups (B).

	Pearson's *r*	*p* value	
Actual GPFp vs MPSD	-0.16	0.17	**A**
Actual GPFp vs U6 CT change	0.03	0.83	

	Pearson's *r*	*p* value	
Female (N=42)			
Actual GPFp vs MPSD	0.01	0.94	
Actual GPFp vs U6 CT change	0.24	0.13	
Male (N=36)			
Actual GPFp vs MPSD	-0.16	0.35	
Actual GPFp vs U6 CT change	-0.29	0.08	
Ages at T_1: 8 – 11y (N=20)			**B**
Actual GPFp vs MPSD	-0.21	0.38	
Actual GPFp vs U6 CT change	0.20	0.40	
Ages at T_1: 12 – 13y (N=39)			
Actual GPFp vs MPSD	-0.22	0.19	
Actual GPFp vs U6 CT change	-0.03	0.84	
Ages at T_1: 14 – 18y (N=19)			
Actual GPFp vs MPSD	-0.20	0.42	
Actual GPFp vs U6 CT change	-0.15	0.55	

MPSD – midpalatal suture density ratio calculation
GPFp – change in linear distance between the lateral margins of the greater palatine foramina from initial to final time points, expressed as a proportion of prescribed expansion
U6 CT – linear intermolar distance measured from the mesio-lingual cusp tips of the maxillary first molars

Figure 9. Correlation between the MPSD ratio and the skeletal width change at the greater palatine foramen as a proportion of prescribed expansion for the overall sample population.

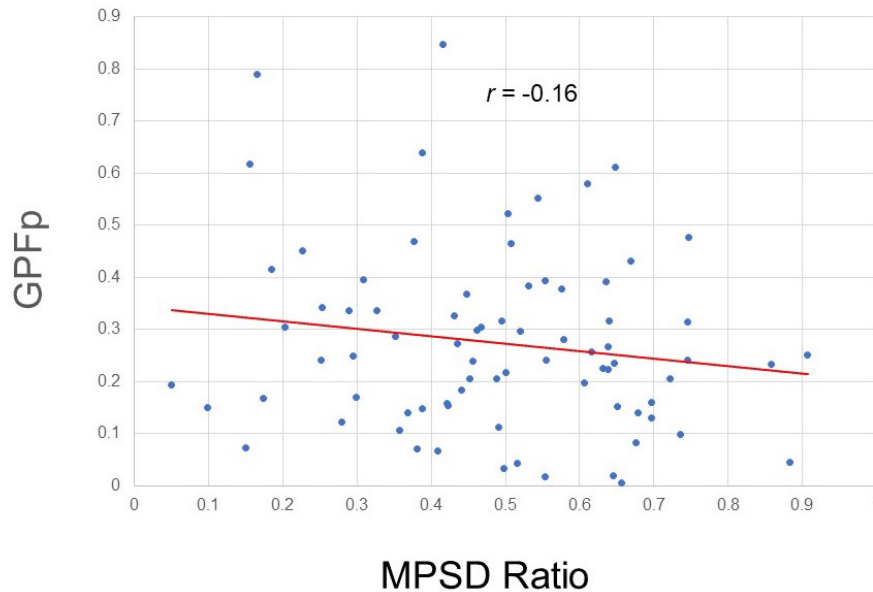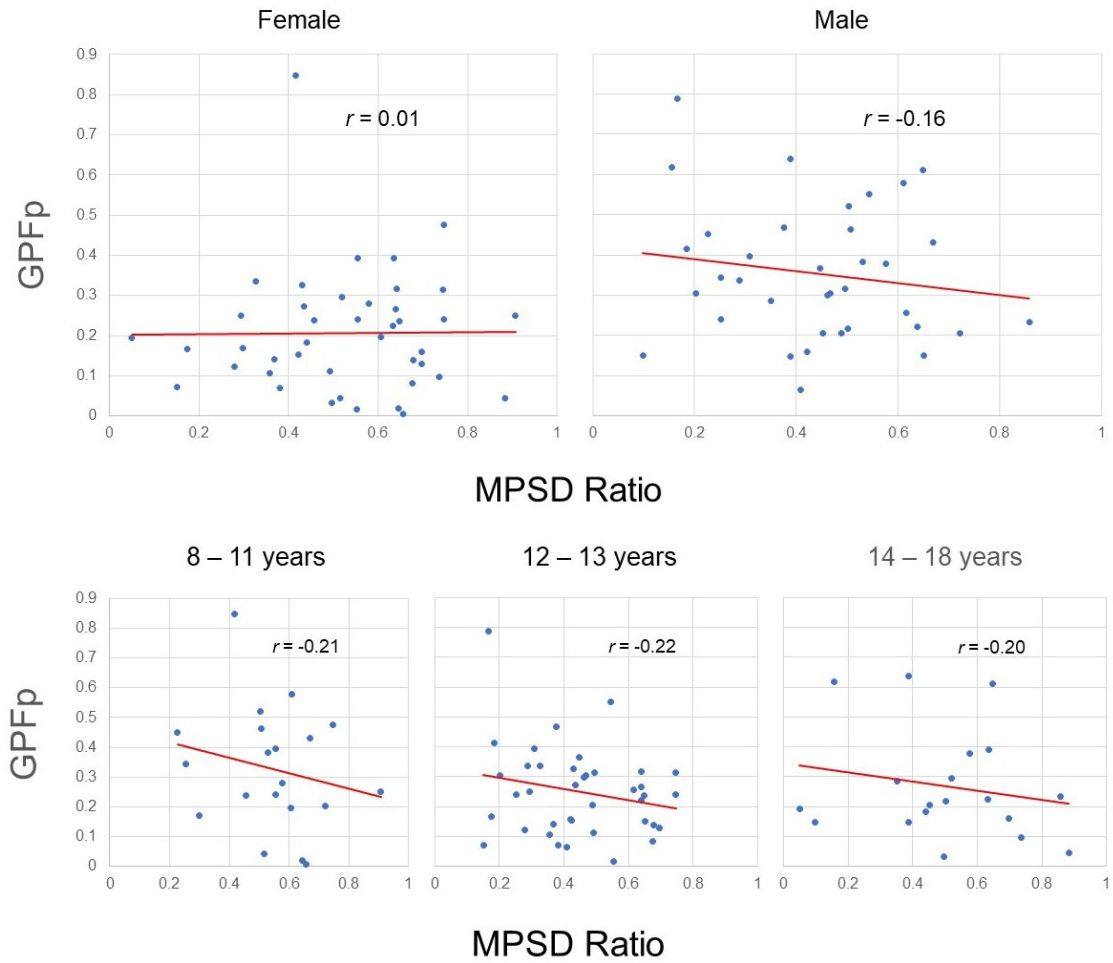**Figure 10**. Correlations between the MPSD ratio and the skeletal width change at the greater palatine foramen as a proportion of prescribed expansion for each population subgroup.

The equivalence test using the margin of ±0.05 demonstrated that the predicted skeletal expansion using MPSD was not equivalent to the actual skeletal expansion achieved, thus the null hypothesis is accepted. Using the margin ±0.1, the two measures were shown to be equivalent for the female subgroup (p=0.0063) and for the 12 to 13 years of age subgroup (p=0.0018). The results from the equivalence testing are shown for the overall sample population in Table 7A, and Table 7B shows the results from each of the subgroups.

Table 7. Equivalence testing for the overall sample population (n=78) (A), and for each age and gender subgroup.

	Mean	SD	*p* value H$_0$: difference <-0.05 or >0.05	*p* value H$_0$: difference <-0.1 or >0.1	
Actual GPFp	0.27	0.17			**A**
Predicted GPFp	0.21	0.11			
Difference (predicted-actual)	-0.07	0.19	0.77	0.0642	

	Mean	SD	*p* value H$_0$: difference <-0.05 or >0.05	*p* value H$_0$: difference <-0.1 or >0.1	
Female (N=42)					
Actual GPFp	0.21	0.15			
Predicted GPFp	0.18	0.11			
Difference (predicted-actual)	-0.02	0.19	0.18	0.0063*	
Male (N=36)					
Actual GPFp	0.35	0.17			
Predicted GPFp	0.24	0.11			
Difference (predicted-actual)	-0.12	0.18	0.98	0.71	**B**
Ages at T$_1$: 8 – 11y (N=20)					
Actual GPFp	0.33	0.21			
Predicted GPFp	0.17	0.10			
Difference (predicted-actual)	-0.16	0.21	0.98	0.88	
Ages at T$_1$: 12 – 13y (N=39)					
Actual GPFp	0.25	0.15			
Predicted GPFp	0.23	0.10			
Difference (predicted-actual)	-0.02	0.16	0.12	0.0018*	
Ages at T$_1$: 14 – 18y (N=19)					
Actual GPFp	0.27	0.18			
Predicted GPFp	0.20	0.14			
Difference (predicted-actual)	-0.07	0.21	0.66	0.26	

*P <0.01

Discussion

Orthodontic treatment plans are individualized to the specific needs of the patient, and current imaging technology allows for utilization of more data than has ever been available to clinicians in years past. The ability to analyze a patient's unique condition in three dimensions from ample perspectives has allowed orthodontists to better diagnose and to execute better timing and treatment modalities with regard to rapid maxillary expansion. The MPSD ratio has previously demonstrated strong correlation with skeletal response to expansion.[36] This study tested the MPSD to determine its utility as a predictive measure of skeletal response to maxillary expansion. For the patient sample in the present study, the MPSD ratio was not found to be an accurate predictor of skeletal expansion.

All correlations found in this study were weak, no correlations with an *r* value above 0.37, and none demonstrating statistical significance. The equivalence testing for the overall sample population showed that the predicted and actual GPFd measurements were not considered equivalent (*p*=0.0642), thus the null hypothesis was accepted. The equivalence testing for the various subgroups revealed a strong equivalence between predicted and actual GPFd change for females (*p*=0.0063), but poor predictive value in males (*p*=0.71). When dividing the sample into three separate age groups, there was a strong, statistically significant equivalence between predicted and actual GPFd measurements for the middle age group of 12 to 13 years of age (*p*=0.0018), but measurements for both other age groups were not equivalent. This inconsistency leads to believe that the statistically significant results obtained were likely due to chance; it is difficult to infer what distinguishing characteristics the female subjects and those in the 12-13-year adolescent age group would have to yield such polarizing results. Even if the MPSD ratio is not an accurate predictor of skeletal expansion of the general population, it would be helpful to develop a guideline outlining at what MPSD ratio threshold do the risks of conventional RME outweigh the benefits. However, due to the heterogeneity of our results, such a conclusion could not be reached.

The amount of dental and skeletal expansion remaining after comprehensive orthodontic treatment averaged of 3.69 mm and 2.05 mm, respectively. When compared to the

average amount of expansion that was prescribed for the sample before initiation of treatment (8.09 mm), the average amount that remained at the end of comprehensive treatment was 45.7%. The average amount of skeletal expansion remaining at the level of the greater palatine foramen as a proportion of this total remaining expansion at the completion of comprehensive treatment was 54%.

There are potential factors related to study design and methodology that may account for the difference in results found between this study and the previous study of Grünheid et al.[36] The increased sample size in this study could have washed out any effect that was previously seen; this study used a population sample of 78 subjects, whereas the previous study used 30 subjects. While the intra-examiner reliability was excellent in both studies (>0.9 ICC),[36] it is possible that the examiners collecting the data had slightly different methods of measuring the gray densities in the software, as there is room for some subjectivity in making these measurements. The intra-examiner reliability was excellent in both cases, however there has been no measure of inter-examiner repeatability of the MPSD measurements between studies.

There are limitations of this study due to its retrospective nature and inability to strictly standardize certain parameters. No two malocclusions are identical; therefore, some patients require more expansion than others to correct their malocclusion. The inability to standardize the amount of expander activation introduces some variability, as there could be inherent differences in the proportion of skeletal to dental effects by patients undergoing different magnitudes of expansion. To help account for these differences in amount of expander activation, the skeletal change was expressed as a proportion of prescribed expansion rather than a linear measurement. The prescribed expansion in this study was based on the patient reported number of actual completed turns of the expansion screw of the Hyrax appliance, as directed by the orthodontist. Relying on patient compliance to perform the turns of the expander screw as directed and to accurately record and report this information introduces a potential confounder to the findings of this study.

This study also examined only the long-term outcomes for patients who received maxillary expansion during comprehensive orthodontic treatment. Immediate, short-term effects

of RME therapy were not measured, as only the pretreatment and posttreatment CBCTs were used. Assessment of the long-term effects of RME treatment may arguably be more insightful clinically, as orthodontists are more concerned with the patient's final condition and tooth position and not necessarily those immediately post-expansion. However, as the length of time increases between timepoints, factors such as growth and treatment mechanics have greater influence on the final result, particularly at the level of the dentition. Additionally, there was a wide range of post-expansion retention time in this study from 1 week to 77 weeks, with a mean retention time of 17.5 weeks. Subjects with short post-expansion retention times could have experienced higher relapse from RME and could potentially weaken some of the long-term effects observed.

It is undeniable that a sizable portion of our patient population had some amount of growth between pretreatment and posttreatment scans. Isolating growth seems nearly impossible without a matched, untreated control group with similar occlusal characteristics, i.e. posterior crossbite, or a CBCT taken immediately post-expansion, neither of which seems ethically justifiable. However, the potential influence of growth on our results is not completely unknown as it has been reported that transverse maxillary growth including sutural separation of the hemimaxillae occurs at the average rates of 0.12-0.48 mm per year.[89–92] It must be assumed that this sutural growth affected maxillary width at the level of the hard palate where GPFp was measured.

Also, this study focused on the greater palatine foramen as the skeletal landmark of interest in our comparison, but it is entirely possible that this landmark might not be stable during growth. The greater palatine foramen was selected because it allows measurement of skeletal expansion at the posterior hard palate and it is an easily and reproducibly identifiable landmark, which is apical to the dentition and therefore remains unaffected by treatment with preadjusted edgewise appliances. Further research to discover stable skeletal landmarks in the transverse dimension on CBCT images would be helpful to determine the reliability of measurements taken at the greater palatine foramen.

Since the morphology of the palate is not flat, it is difficult to produce a single properly oriented axial slice that gives a good representation of the entire midpalatal suture juxtaposed to the dense cortical bone of the palatal process of the maxilla. Due to the arched morphology of the palate, the axial slice level where the midpalatal suture is most visible will sometimes omit the distolateral hard palate and instead include air space from the nasal or oral cavity (Figure 11).
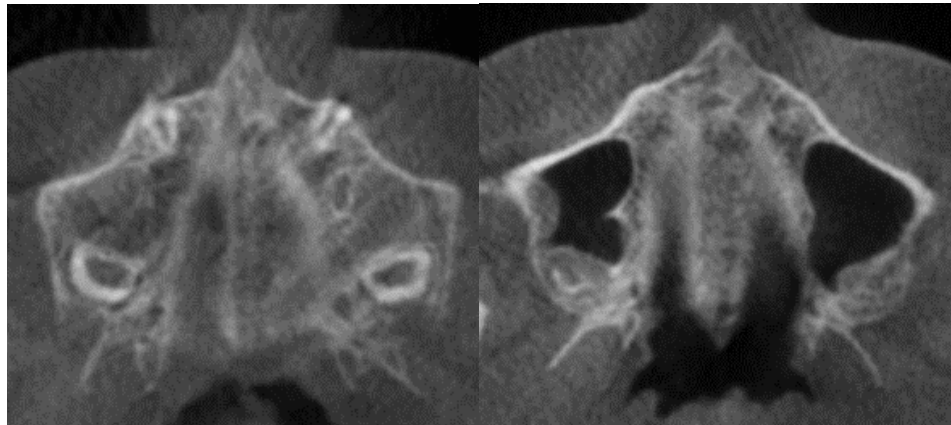

Figure 11. Comparing radiographic appearance of the midpalatal suture on axial slices. The images demonstrate nasal air spaces adjacent to the midpalatal suture rather than representative cortical bone of the hard palate.

It follows proper reasoning, since the midpalatal suture is histologically composed of connective tissue between two bony halves of the maxilla, that a similar pattern would exist radiographically. Ideally one would expect to see a thin radiolucent band between two radiopaque palatal halves, which would allow the MPSD ratio able to compare the patency of the midpalatal suture relative to the cortical bone of the maxilla. However, the radiographic appearance of the suture often appears more like a straight and thin approximation of cortices in the midline adjacent to the trabecular bone of the maxilla (Figure 12).
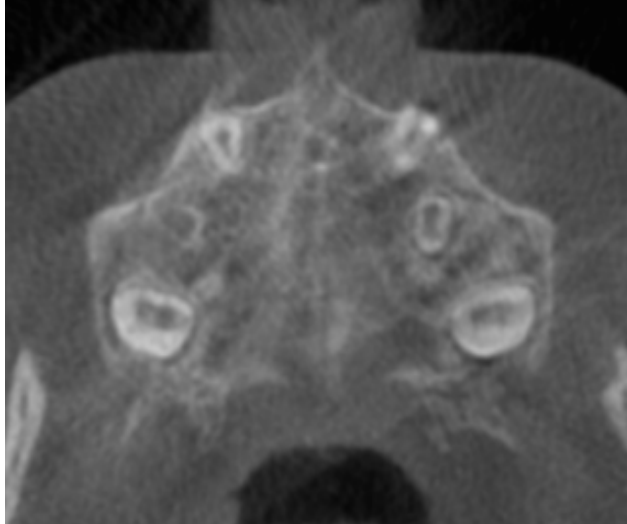
Figure 12. The midpalatal suture is often represented on an axial slice as a thin radiopaque line along the midpalate adjacent to more radiolucent trabecular bone.

This creates the radiographic appearance of a radiodense midpalatal line flanked by radiolucent palatal areas, which presents the exact opposite radiodensity pattern that would help make the MPSD useful. Angelieri *et al.* described in the MPSM method for classification that the early stages of midpalatal maturation were characterized by a relatively straight high-density line at the midline.[16,31] Further maturation of the suture was described visually to become a more scalloped, radiopaque line, followed by two radiopaque lines approximating each other separated in areas by small low-density spaces, and finally by the inability to distinguish the midpalatal suture from the parasutural bone.[16] While this MPSM classification relies on visual judgment regarding the corresponding stage, it is often difficult to distinguish visually between subjects with varying MPSD ratios. Figure 13 displays three different subjects, two with either high (close to 1) or low (close to 0) MPSD ratios toward opposite ends of the continuum, and one with an intermediate density ratio.
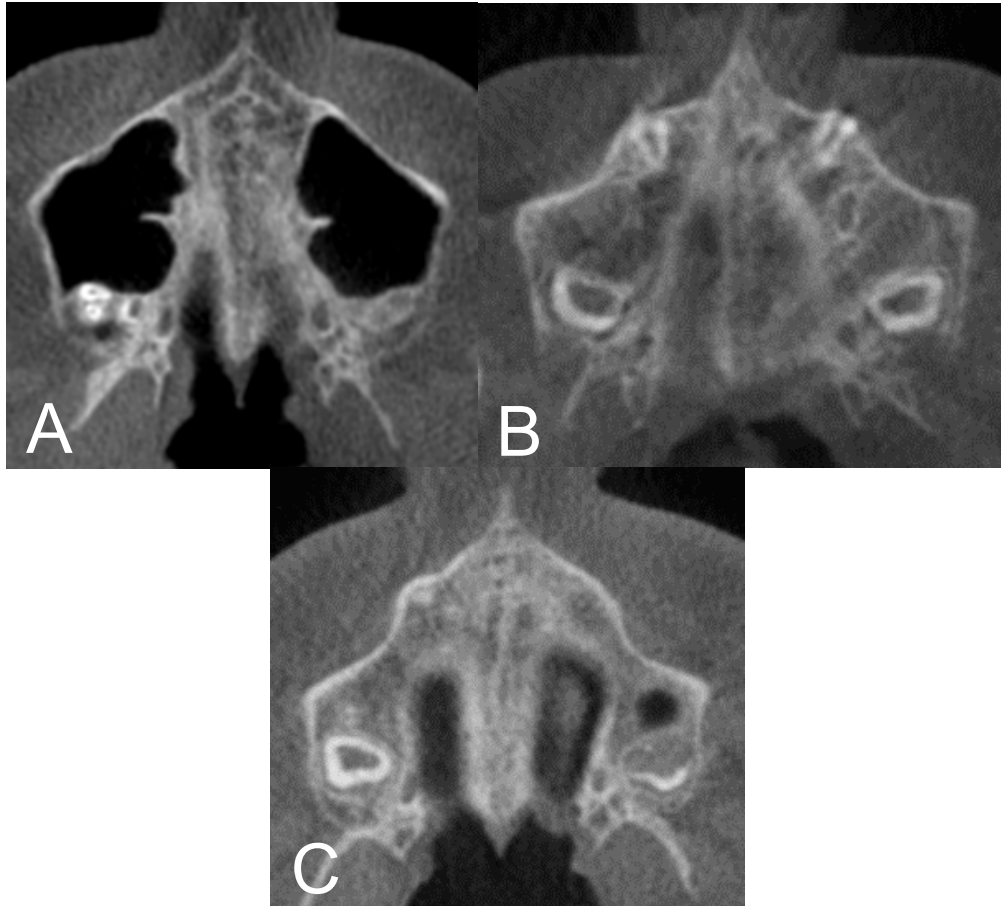
Figure 13. Comparison of radiographic presentation of varying MPSD values. (A) Subject with a low MPSD ratio of 0.156, (B) subject with intermediate MPSD ratio of 0.508, and (C) subject with high MPSD ratio of 0.858.

The inability to create a more customized selection when measuring average gray densities of a radiographical area introduces potential sources of error. Taking density measurements within a discrete rectangular area of the palate includes both adjacent cortical and trabecular bone in addition to the suture itself, which could overestimate the density of the actual sutural area. A more specific, custom selection that encompasses only the midpalatal suture could potentially increase accuracy compared to the standardized rectangular selections. Additionally, if rectangular selections of the midpalatal suture were customized to the anatomy of the patient, for example a percentage of the total width of the palate, more precise selections could be employed rather than being restricted to rectangles 6 mm in width.

35

It is known that the various circummaxillary sutures also demonstrate bony displacement in response to the forces of expansion,[68] the effects of which were not addressed in this study. Previous studies have reported that the amount of widening at these sutures is highly variable, and the sutures directly articulating with the maxilla were more affected by RME.[68,74] It has yet to be demonstrated that a lack of significant opening of other craniofacial sutures supports a decreased effectiveness of maxillary expansion in adolescents,[74] however this study included a wide age range of subjects from 8 to 18 years of age. It is possible that the maturation of these sutures contributes to the resistance to expansion to a degree that would affect our results. It is also conceivable that, in some subjects, the maturation stage varies enough among maxillary and circummaxillary sutures to render extrapolation of maturational status from the midpalatal suture to other sutures inaccurate.

It has been previously shown that increased interdigitation at the midpalatal suture can be overcome to some extent by the use of MARPE, which can help achieve true separation at the midpalatal suture in mature adults.[59,60] This leads one to consider the possibility that by focusing on the midpalatal suture we may be analyzing the wrong area altogether with respect to resistance to expansion. Focusing our attention on the classically significant buttressing effect of the infrazygomatic crest, for example, might be a more appropriate area of emphasis. In addition to the skeletal factors contributing to the resistance to expansion, dentoalveolar factors such as root length and periodontal attachment of the anchor teeth incorporated in the appliance design could have an effect on the amount of skeletal expansion achieved. A patient who has anchor teeth with large, long, upright roots surrounded by thick, periodontally healthy alveolar bone would likely obtain a different response to RME treatment than a patient with less optimal conditions.   The CBCT images most frequently utilized in orthodontics are low resolution, high noise images, since the demand for detail for orthodontic purposes is typically quite low. This allows the dosage level to also stay as low as possible for the safety of our patients. The relatively high noise level in the CBCT scans of the present study could have negatively affected the accuracy of our density measurements and poses a limitation since all images were taken with a low-dose protocol. Increasing the thickness of the slice that was used

to take the MPSD density measurements has the potential to increase the signal to noise ratio, which could improve measurement precision. It is neither practical nor safe to take a higher resolution, higher dose CBCT on every patient for the purpose of increasing signal to noise ratio, but it is conceivable that situations exist where benefits of a higher resolution image outweigh the costs of increased radiation dose. For example, a potential patient who presents with posterior crossbite and is at or near their growth completion may benefit from being prescribed a higher resolution CBCT to aid in proper diagnosis and treatment planning. Here, the benefit of selecting the appropriate surgical or non-surgical expansion treatment outweighs the risk of increased radiation dose.

The value of the MPSD ratio in aiding pre-treatment clinical decision making is inconclusive. Another repeat study with a similar sample size and range of ages would be beneficial to elucidate whether or not there truly is a correlation between the MPSD ratio and skeletal expansion. It would also be interesting to conduct a study that slightly altered the method for taking the MPSD measurements to utilize an axial slice through the palate at the cortical level rather than bisecting the thickness of the palate. Theoretically, this could provide a radiographic presentation of the palate that would include the radiolucent suture adjacent to the dense cortices of the palatal process of the maxilla, therefore facilitating a more representative comparison of the gray densities.

Future studies that examine the short-term effects of expansion in relation to the MPSD measurements would be beneficial to further investigate the utility of the MPSD measurement as a short-term predictor. A study to explore the inter-examiner repeatability of the MPSD would help determine the usefulness of this measurement as a routine tool to be used in everyday clinical practice. The aim for clinical use of the MPSD ratio is to help determine whether or not a patient approaching maturity should be prescribed conventional or surgical expansion. Therefore, a focus on more mature subjects in late adolescence and early adulthood where the response to expansion is more unpredictable would give insight to the population where the measurement would be most applicable. Additionally, it would be interesting to examine the sutural densities of the various circummaxillary sutures both to compare them to the density of

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the midpalatal suture and to investigate the relationship between circummaxillary sutural

density and response to maxillary expansion.

Conclusions:

1. The results suggest that the midpalatal suture density ratio is not statistically significantly correlated with the amount of long-term skeletal expansion achieved at the level of the palate.

2. Utilization of the midpalatal suture density ratio was ineffective in predicting the amount of long-term skeletal expansion achieved from pre-treatment CBCTs.

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