Cone Beam Computed Tomography Evaluation of Buccal Alveolar Bone Changes Following Rapid Maxillary Expansion and Fixed Appliance Therapy

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

By

Adam J. Sperl

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Advisor: Thorsten Grünheid, DDS, Dr med dent, PhD

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Dedication

To my wife, Stephanie, for her continual love and support throughout my years of education.

To my parents for encouraging me to be inquisitive and to dedicate myself to the pursuit of a fulfilling profession.

Abstract

Introduction: Rapid maxillary expansion (RME) and fixed appliance therapy are commonly used to treat maxillary transverse deficiencies, but the treatment causes buccal displacement of appliance anchor teeth, which can damage the periodontium. Clinical decision making may be improved by better understanding how this treatment affects the periodontium.

Objectives: The purpose of this study was to assess factors that might affect buccal bone changes adjacent to the permanent maxillary first molar after RME and fixed appliance therapy.

Methods: Pre-treatment (T1) and post-treatment (T2) cone-beam computed tomography (CBCT) scans were obtained from 45 patients treated with RME and fixed appliance therapy. Measurements of buccal alveolar bone thickness adjacent to the mesiobuccal root of the maxillary first molar were made on CBCT images at 4 mm (B4), 6 mm (B6), and 8 mm (B8) from the CEJ. Anatomic defects of the buccal bone were recorded. T-tests were performed to compare T1 and T2 alveolar bone thickness and to determine whether teeth with post-treatment anatomic defects had thinner initial bone. Correlation analyses were conducted to examine the relationship between buccal alveolar bone thickness changes and the following variables: prescribed expansion, age at T1, time between T1 and T2, post-expansion retention time, and initial bone thickness.

Results: There was a statistically significant reduction in buccal alveolar bone thickness from T1 to T2. 47.7% of teeth and 60% of patients had anatomic defects after treatment. Teeth with T2 anatomic defects had significantly thinner buccal bone at T1. Reduction in alveolar bone was correlated with only one tested variable: initial bone thickness.

Conclusions: RME and fixed appliance therapy can result in a significant reduction in buccal alveolar bone thickness and an increase in anatomic defects adjacent to the expander anchor teeth. Anchor teeth with greater initial buccal bone thickness are likely to have a greater reduction in buccal bone thickness. Anchor teeth with thin initial buccal bone are more likely to develop post-treatment anatomic defects of the buccal bone plate.

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Introduction

Rapid maxillary expansion (RME) is an orthodontic treatment modality commonly used to address transverse deficiencies of the maxilla.[1] RME was first described in the 1860s and has been used primarily for posterior crossbite correction by widening the narrowed maxillary skeletal base.[2] RME can also be used to facilitate the correction of Class II malocclusions,[3,4,5] facilitate facemask protraction for the treatment of Class III malocclusions,[4,6-9] resolve arch length discrepancies,[4,10] and increase nasal and upper respiratory volume for the improvement of airflow.[11-23]

Conventional RME uses appliances attached to the dentition to deliver heavy forces, from 3 to 10 pounds per turn, to the right and left halves of the maxilla.[24-25] In growing patients with unfused skeletal sutures, the transmitted forces are sufficient to open the midpalatal and intermaxillary sutures, widen the maxilla, and hold the right and left halves of the maxilla at an increased transverse dimension. Subsequent callus formation and bone deposition occur at the midpalatal suture.[1,26] This orthopedic process is referred to as skeletal expansion and is typically the preferred treatment effect of RME. The force exerted on the dentition during RME also results in dentoalveolar expansion, which is comprised of alveolar bone bending and orthodontic tooth movement manifested as dental translation, dental tipping, and dental extrusion.[4,23,27-31] Dental effects are typically undesirable because they can lead to an increase in vertical dimension,[29] root resorption,[32,33] loss of alveolar bone and periodontal attachment level, and fenestration or dehiscence of the buccal cortical bone.[33-44] Fixed appliance therapy with preadjusted edgewise appliances is commonly used in conjunction with RME to address all of the treatment goals of comprehensive orthodontic treatment. Fixed appliance therapy can cause buccal tipping, rotation, and translation of teeth, all movements which may contribute to buccal alveolar bone loss and formation of anatomic defects of the bone.[45-49]

It is a fundamental goal of orthodontic treatment to maintain a healthy position of the teeth within the alveolar bone in order to maintain periodontal support and long-term dental health.[50] Therefore, it is essential to accurately assess the periodontal structures before and after orthodontic treatment. Many studies have assessed the dentoskeletal effects of RME through two-dimensional (2D) radiographic examination, which does not allow for the exact identification of changes in buccal alveolar bone.[4,30,51] More recently, studies have used cone-beam computed tomography (CBCT) to assess buccal alveolar bone changes associated with RME in relation to expansion appliance design,[33,41,43] use of deciduous and permanent teeth as anchors for the appliance,[40] rate of expansion,[36] and other variables such as age, amount of expansion, and initial bone thickness.[34] CBCT allows for accurate assessment of alveolar bone support by identifying objects based on their relative density.[52-54] However, bone associated with areas of tooth movement undergoes remodeling, is less mineralized, and as a result appears less dense on CBCT images.[57-59] The bone density in these areas does not return to normal levels for 6-24 months after tooth movement subsides.[53] All current studies are short-term, as they evaluated CBCT scans taken 0-6 months following RME. In these studies, limitations of radiographic bone assessment have to be considered when drawing conclusions from measurements that potentially represent remodeling bone.[60] Only one study evaluated variables, such as age and amount of expansion, that might help predict the alveolar response to RME.[34] No studies have yet evaluated the potential added effect of fixed appliance therapy on the periodontium. The evaluation of buccal alveolar bone before and after comprehensive orthodontic treatment with RME and fixed appliance therapy may provide a more clinically relevant assessment of cumulative treatment effects.

Literature Review

Rapid Maxillary Expansion

Emerson Angell first introduced the idea of maxillary expansion in 1860 but the treatment was controversial and was not readily accepted by clinicians over the following century. [2] In the 1960s, Haas demonstrated its efficacy and it became a popular method for treating transverse maxillary deficiencies.[1] Transverse maxillary deficiency often presents clinically as a crossbite of the posterior dentition,[61] which is a common malocclusion occurring in approximately one of ten children.[62,63] RME can facilitate the correction of posterior crossbites by widening the maxillary skeletal base.[1]

The use of RME has since expanded to include numerous other clinical applications. RME can be used to resolve arch length discrepancies by increasing maxillary arch perimeter, even in the absence of posterior crossbite.[4,10] It has been reported that every millimeter of premolar expansion corresponds to a 0.7 mm increase in the maxillary arch length.[64] The arch length gained can be used to align crowded teeth and the increase in premolar width is desirable to achieve the esthetic goal of producing a broad smile with filled buccal corridors.[65] It has also been proposed that RME can allow for the spontaneous correction of Angle Class II malocclusion as the result of the "foot-in-shoe" effect.[3,4,66] In this analogy, the mandible, or "foot," is allowed to move forward into a normal relationship only if the maxilla, or "shoe," is wide enough to accommodate it. By widening a narrowed maxilla, the mandible is allowed to grow forward and the anteroposterior discrepancy can be lessened or spontaneously resolved. Guest *et al.* reported that children treated with RME had a 1.7 mm decrease in Class II molar relationship and a 1 mm decrease in overjet when compared to an untreated control group.[3] Interestingly, RME has also been suggested to open the circummaxillary sutures to facilitate facemask protraction for the early treatment of Angle Class III malocclusions.[4,7,8] More recently, the effect of RME on airway has been investigated due to an increased focus on evaluation and potential orthodontic treatment of obstructive sleep apnea (OSA). OSA is a complex multifactorial medical condition, but nasal and oropharyngeal airway anatomy are potential contributing factors. Several studies suggest that RME is effective in increasing oral and nasal volume[11-16] and reducing the apnea/hypopnea index (AHI) in children with obstructive sleep apnea.[17,19-21]

RME is recognized as a relatively reliable and effective orthopedic procedure in growing patients.[67-69] However, many studies have evaluated the undesirable effects of expansion on the sutures, the dentition, and periodontal tissues.[29,30,32-42,44,67,70-72] The orthopedic effect of RME decreases with age and the risk of adverse side effects increases as patients reach skeletal maturity and circummaxillary sutures close.[32,34,51,74-76] A reliable guideline for the diagnosis of facial skeletal maturity does not currently exist, making it difficult to predict whether a patient will respond to RME orthopedically.[51,75,76] Surgically assisted rapid palatal expansion (SARPE), a procedure in which surgery is utilized to facilitate opening of the midpalatal suture, is the traditionally accepted approach to gain desired skeletal expansion in patients that have reached skeletal maturity.[77-79] More recently, it has been demonstrated that the maxilla can be expanded in skeletally mature patients without undergoing surgery through the use of microimplants as anchorage for the expansion forces.[80.81] This technique, termed microimplant-assisted rapid palatal expansion (MARPE), uses a miniscrew-borne expander to transmit forces to the maxilla primarily through miniscrews rather than using teeth. Unwanted dental movements and the associated sequelae are reduced because force is not applied solely to the dentition.[82] Brunetto *et al*. reported a 86.96% success rate in young adult patients (mean age of 20.9 ± 2.9 years) and stable results over a 30 month follow-up period.[80] SARPE and MARPE are effective in expanding the maxillae of skeletally mature patients and reducing adverse side-effects typically associated with RME.[83] However, their use should be limited in growing patients due to their procedural invasiveness and expense in comparison to conventional RME.

Rapid Maxillary Expansion Effects

Changes in anatomic structures associated with RME were assessed using dental casts and 2D radiographs prior to the regular use of CBCT in orthodontics,[30,84,85] making it difficult to determine specific treatment effects on the dentition and skeletal structures. The use of 2D imaging for the assessment of three-dimensional (3D) structures is problematic because the images are difficult to reproduce, magnification of structures closer to the X-ray source occurs, and bilateral anatomic structures overlap and are superimposed on one another.[86] CBCT images allow for a more accurate and reproducible assessment of the dentoalveolar and skeletal effects of RME because they allow for repeatable landmark identification without any superimposition or magnification of anatomic structures.[87-89]

Numerous studies have explored the effects of RME on both dentoalveolar and skeletal structures in 3D using CBCT.[32-44,61,67-70,90-95] Both skeletal and dentoalveolar expansion contribute to the total amount of expansion.[4] It has been reported that skeletal expansion at the hard palate (Figure 1) accounts for 12.6-52.8% of the total expansion[44,67,69,90,92,96] and greater expansion is observed at the premolar level (55%) than at the molar level (38%).[61]

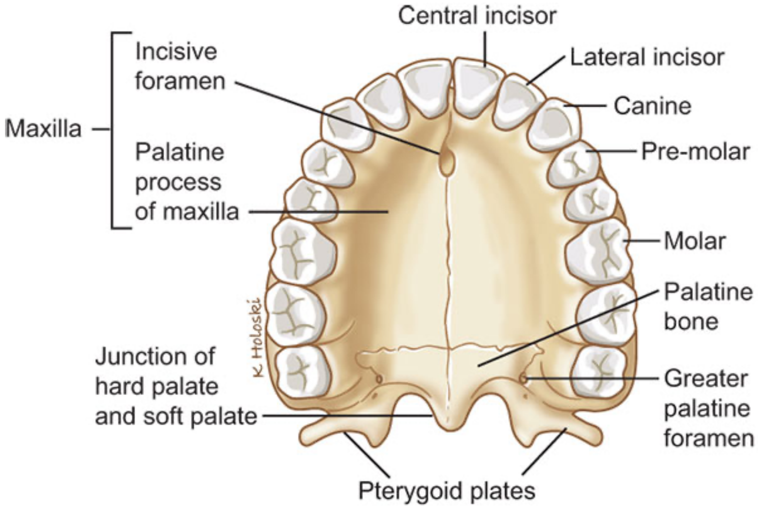

Figure 1. Anatomy of the hard palate. The midpalatal suture is the midline suture of the hard palate. It connects the right and left palatine processes of the maxilla and the horizontal plates of the palatine bones. The interpalatine suture is perpendicular to the midpalatal suture at the junction of the maxillary and palatine bone (from Head and Neck Cancer Guide[100]).

Other studies have confirmed this triangular expansion pattern when viewed from the occlusal. The maxilla opens with a center of rotation near the third molar region; maximum opening occurs at the incisor region and gradually decreases toward the posterior part of the palate.[4,27,61,92,97,98] The lack of opening in the posterior region may be due to the interlocking of the pyramidal processes of the palatine bone with the immovable medial and lateral pterygoid plates of the sphenoid bone.[51,99] Conversely, alveolar bending is reported to be greater in the anterior than the posterior, accounting for 6-13% of the total expansion.[61] Orthodontic tooth movement, manifested as dental tipping, ranges from 3.4 to 9.2 degrees and accounts for the remaining 39-49% of total expansion.[97] Similar to alveolar bending, the amount of tipping increases from anterior to posterior.[61] Overall, skeletal expansion accounts for a greater proportion of total expansion in the anterior. In contrast, alveolar bending and dental tipping account for a greater proportion of total expansion in the posterior.

In the vertical dimension, when viewed frontally, the maxillary suture shows greater separation inferiorly than superiorly, resulting in pyramidal or "inverted V shape" opening.[4,44,90,94] The pyramidal expansion pattern is more pronounced in older patients and more parallel expansion is found in younger patients.[93] An increase in nasal width and a decrease in maxillary sinus width can be expected as the result of this separation of the intermaxillary suture.[23,61] It has also been observed that RME causes flattening of the palatal vault and stretching of the mucoperiosteum of the palate.[4,11,101] In addition, it has been reported that the maxilla is displaced downward and forward during RME.[23,51,61,102] The combination of the downward and forward movement of the maxilla, buccal tipping of the alveolus and maxillary molars, and extrusion of the palatal cusps of the maxillary molars leads to the downward and backward rotation of the mandible often observed with RME.[4,23,103]

The opening of a diastema between the maxillary central incisors is a highly visible change accompanying RME. This separation is approximately half the distance the expansion screw has been activated;[11] however, separation between the incisors should not be used as an indication of the amount of sutural separation.[51] After RME, the midline diastema is either closed orthodontically or spontaneously corrects due to the elastic recoil of the transseptal periodontal fibers.

RME forces are mainly directed at the midpalatal and intermaxillary sutures, but the circummaxillary sutures are also affected and may play a role in resisting orthopedic expansion. The circummaxillary sutures (Figure 2) function to unite bones, absorb forces, act as joints that permit relative movement between bones, and play a role as sites of growth.[26,76,101]

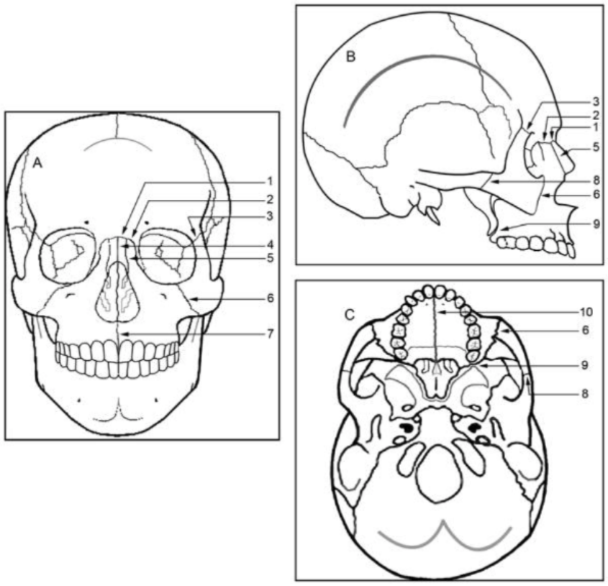

Figure 2. Diagram of the circummaxillary sutures: **A,** frontal; **B,** lateral; **C,** axial views. 1, Frontonasal; 2, frontomaxillary; 3, frontozygomatic; 4, internasal; 5, nasomaxillary; 6, zygomaticomaxillary; 7, intermaxillary; 8, temporozygomatic; 9, pterygomaxillary; 10, midpalatal suture (from Ghonemia *et al.*[105]).

Forces produced by RME are transmitted through the circummaxillary sutures to the facial bones. Due to this force application, the sutures are reported to undergo small changes in transverse dimension ranging from 0.30 to 0.45 mm.[94] The sutures directly in contact with the maxilla have been found to exhibit greater opening than those further away,[31,104,105] but the amount of opening is highly variable.[94] RME can even produce measurable stress at the cranial base, however, the amount of stress is only moderate in adolescent patients, precluding the likelihood of any serious complications resulting from the injury of nerves and vasculature in the area of the foramina.[106] The relationship of RME and the circummaxillary sutures must be understood because the sutures may provide resistance to expansion forces and their change in dimension may contribute to observed treatment changes, such as the downward and forward movement of the maxilla.[9]

RME also produces undesirable dentoalveolar effects. The heavy, intermittent forces applied by expansion appliances compress the periodontal ligament around the anchor teeth causing bending of the alveolar bone and tipping of the dentition.[4,30,31,36,38] As much as 65% of total expansion may be attributed to dental changes in adolescent patients.[107]

The most significant side effects associated with the dental component of RME are root resorption and periodontal attachment loss.[32-43] RME anchor teeth have been reported to experience loss of root volume ranging from 5.77 to 13.70% and root shortening ranging from 0.28 to 0.51 mm.[32,33] Loss of alveolar bone support (Figure 3) resulting in periodontal attachment loss is perhaps an even more clinically significant side effects of RME in both growing and non-growing patients.[33-43]

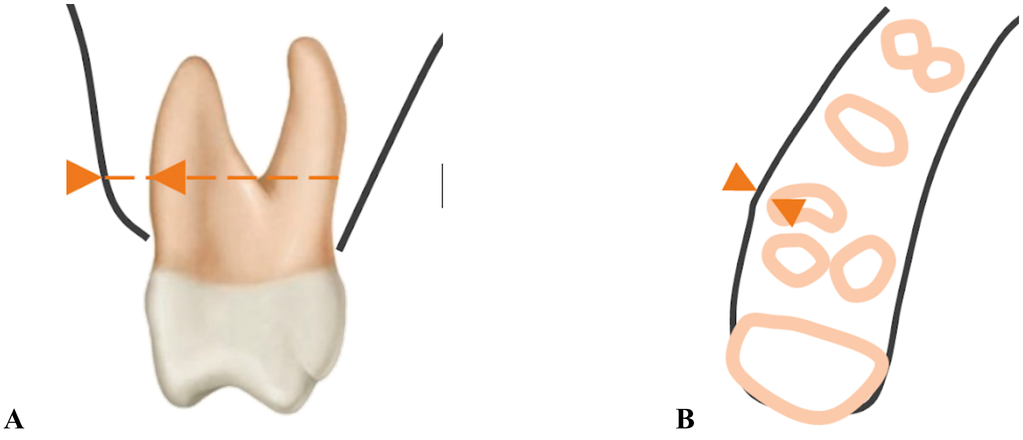

Figure 3. Schematic representation of alveolar bone surrounding the maxillary right first molar: **A**, coronal plane of space; **B**, axial plane of space. The distance between arrows represents the buccal alveolar bone thickness (from Moon *et al.*[83]).

Lemos Rinaldi *et al*. reported an average decrease in bone level of 0.23 to 5.09 mm and an average decrease in buccal alveolar bone thickness of 0.78 to 1.65 mm depending on the type of expansion appliance and protocol used.[33] He also found that anatomic defects of the buccal alveolar bone were present on 28% of total evaluated teeth, but up to 60% of teeth in patients treated with a Hyrax-style expander and the alt-RAMEC expansion protocol, in which opening and closing of the expansion appliance is alternated to facilitate loosening of the circummaxillary sutures.[33]

Dogra *et al*. found a significant reduction in buccal bone plate thickness and increase in palatal bone plate thickness, suggesting buccal translation of teeth within the alveolar bone.[41] Numerous other studies have also found a significant reduction in buccal bone thickness and marginal bone level associated with RME anchor teeth.[34,36,40-43] Rungcharassaeng *et al.* found that age, appliance expansion, and initial buccal bone thickness showed significant correlation to buccal bone changes and dental tipping, but rate of expansion and retention time had no significant association.[34]

Orthodontics and Periodontal Considerations

Orthodontic treatment aims to maintain or improve periodontal condition to promote the long-term health and stability of the dentition.[50] The periodontium is considered healthy when the crest of the interproximal bone is positioned within 2 mm apical to the cementoenamel junction (CEJ) and the alveolar cortical bone is intact.[108] The loss of alveolar marginal bone height at least 4mm apical to the interproximal bone is considered a dehiscence. A fenestration is an isolated defect of the cortical bone without involvement of the marginal bone.[109] Overall, proper orthodontic treatment in patients with good oral hygiene has not been linked to any significant long-term effects on periodontal attachment or bone levels.[50,110,111] However, certain tooth movements, such as buccal tipping and translation, have been linked to the formation of alveolar bone dehiscence, connective tissue loss, and gingival recession.[45-49,109,112] In addition, thin buccal alveolar bone and alveolar bone dehiscences are associated with gingival recession.[112-114] Thin gingival biotype and female gender also may predispose patients to an increased incidence and degree of gingival recession following orthodontic treatment.[115,116] Because of the association of bone support and soft tissues, the assessment of alveolar bone changes provides valuable indirect evidence for periodontal stability.[60] Proper clinical and radiographic assessment of the periodontal structures is essential in orthodontic diagnosis, treatment planning, and evaluating treatment outcomes.

Cone Beam Computed Tomography

CBCT images are obtained using a rotating apparatus to which an x-ray source and detector are fixed on each side of the patient's head. A cone-shaped source of ionizing radiation is directed through the middle of an area of interest from the source to the detector. Multiple planar projection images of the field of view (FOV) are acquired as the source and detector rotate around the subject. Each slice is reconstructed in 2D and then the 2D images are stacked to construct a 3D image.[117] This method allows for rapid image acquisition as well as a relatively lower amount of radiation compared to traditional medical computed tomography (CT).[118,119] The main disadvantage of CBCT in comparison to medical CT is the limitation in image quality due to noise and decreased resolution caused by increased scatter radiation.[117]

The use of CBCT in clinical practice has increased because of its diagnostic advantages over traditional 2D imaging for orthodontic treatment planning. CBCT images maintain the geometry of structures and eliminate the magnification and superimposition of bilateral anatomic structures commonly associated with 2D images,[118,119] allowing for accurate and reliable measurement of objects in all planes of space.[120-125] Despite its diagnostic advantages, the regular use of CBCT for comprehensive orthodontic diagnosis and treatment planning has been debated.[125,126] The fundamental principles of radiation protection-- justification, optimization, and dose limitation--

should always be followed when considering radiation exposure for orthodontic reasons.[127] Thus, the debate of CBCT use in orthodontics is largely regarding whether the diagnostic advantages outweigh the additional radiation exposure of CBCT compared to 2D imaging. A recent systematic review on this topic suggests that CBCT cannot be regarded as a standard method of diagnosis and its use should be limited to cases in which conventional radiography fails to provide a correct diagnosis of pathology, such as cases with impacted canines, root fractures, and suspected condylar pathology.[128] However, justification of CBCT use for the evaluation of alveolar bone was not specifically evaluated in this review.

In contrast to 2D imaging, CBCT allows for evaluation and measurement of buccal alveolar bone in both the coronal and axial planes of space.[52-56] However, spatial resolution, the minimum distance needed to distinguish between two objects in close proximity, creates potential issues in the measurement of buccal bone thickness.[53,129] Spatial resolution is influenced by partial volume averaging, noise, and artifacts.[53]

Partial volume averaging occurs when the size of a voxel is larger than the object or the densities it represents, occurring most often at the margin of an object or at the boundary of two substances of differing densities.[117,130] In these cases, the voxel displays an average of the two densities present. For example, if the voxel represents an area with ⅓ cortical bone and ⅔ gingiva, the voxel will appear more radiolucent than bone and the viewer will not account for the bone which is actually present in the voxel. The best way to limit volume averaging is by reducing voxel size, but smaller voxels require more radiation and are more prone to noise.[59]

Noise also decreases spatial resolution and is primarily the result of scatter radiation hitting the detector and clouding the resultant image.[131] Smaller voxels are more sensitive to scatter radiation, so noise increases as voxel size decreases.[132] The amount of scatter radiation increases with an increasing FOV, also resulting in greater noise.[59] The best way to decrease noise is by using the smallest FOV that encompasses the region of interest.

Artifacts, such as those created by metallic restorations or appliances, also decrease spatial resolution.[53] Metallic structures can result in streaking artifacts and noisy projection reconstructions because the density of the metal affects how the scanner interprets and reconstructs surrounding structures.[117,133] CBCT is also sensitive to motion artifact created by the subject moving during the scan.[134] The best way to limit motion artifacts is to decrease the scan time, but decreased scan time also results in fewer data acquisitions,[135] leading to under sampling of the anatomic structures and making resolving fine details difficult.[117]

Despite its limitations, CBCT imaging has been shown to be reliable for the measurement of buccal alveolar bone, as measurements of bone thickness and height on CBCT have been found to correspond with direct measurements.[55] However, negative predictive values are high and positive predictive values are low for fenestration and dehiscence detection with CBCT, indicating instances in which defects are noted on CBCT but not present clinically.[56] Controversy exists regarding the effect of voxel size and scan settings on the accuracy of buccal bone measurements. Cook *et al*. reported that buccal alveolar bone measurements on CBCT scans with an 8 cm FOV, 0.2 mm voxel size, and 26.9 s duration did not differ significantly from those on scans with a 13 cm FOV, 0.3 mm voxel size and 4.8 s duration.[52] Conversely, Wood *et al*. found that smaller voxel size scans were more accurate in assessing buccal alveolar bone.[54] Spatial resolution is multifactorial but it can be generalized that the best CBCT settings for assessment of buccal alveolar bone are small voxel size, medium to long scan time, and small FOV. However, CBCT scans acquired for orthodontic treatment are typically of medium voxel size, short scan time, and large FOV, making them acceptable, but not ideal, for the assessment of buccal alveolar bone.

Aims and Hypotheses

The purpose of this study was to assess factors that might affect buccal bone changes adjacent to the mesiobuccal root of the maxillary first molar following RME and fixed appliance therapy.

More specifically, the aims of this study were:

1. To determine whether RME and fixed appliance therapy treatment causes a decrease in buccal alveolar bone thickness adjacent to the mesiobuccal root of the permanent maxillary first molar.
2. To determine whether RME and fixed appliance therapy treatment leads to the formation of anatomic defects (dehiscence, fenestration, complete disruption) of the buccal alveolar bone adjacent to the mesiobuccal root of the permanent maxillary first molar.
3. To determine whether chronologic age, amount of prescribed expansion, treatment time, retention time, or initial bone thickness are correlated with the change in buccal alveolar bone thickness following RME and fixed appliance therapy.
4. To determine whether initial bone thickness is correlated with the formation of anatomic defects (dehiscence, fenestration, complete disruption) of the buccal alveolar bone following RME and fixed appliance therapy.

The following null hypotheses were made:

1. There are no differences in buccal alveolar bone thickness and anatomic defects of the buccal alveolar bone before and after treatment with RME and fixed appliance therapy.
2. Buccal alveolar bone thickness and anatomic defects of the buccal alveolar bone are not correlated with any of the variables tested.

Materials and Methods:

This retrospective records review study was conducted with approval of the Institutional Review Board at the University of Minnesota (Study Number 00008662). Written informed consent had been obtained from all study subjects for use of their diagnostic records for research purposes. The pre-treatment (T1) and post-treatment (T2) CBCT scans of 45 orthodontic patients treated at the University of Minnesota School of Dentistry, Division of Orthodontics were used. All patients were between the ages of 10 and 16 years and had maxillary transverse deficiency treated with RME using a Hyrax expansion appliance as part of comprehensive orthodontic treatment. Patients were excluded if they had previous orthodontic treatment, history of periodontal disease, congenital malformations including cleft lip and palate, incomplete treatment records, metallic restorations in the permanent maxillary first molars, or non-diagnostic CBCT images due to motion artifact.

Descriptive information was collected from each patient's record including age at T1 (in years), sex, Hyrax expander design (2-banded or 4-banded), the amount of prescribed expansion (in mm, derived from the number of prescribed expander turns), expander retention time after discontinuation of activation (in weeks), and total time between T1 and T2 (in years) as an analog for total treatment time. Table 1 and 2 show the descriptive statistics for the categorical and continuous variables.

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

	Category	Occurrence	Percentage
Sex	Male	18	40%
	Female	27	60%
Expander Design	2-banded Hyrax	22	48.9%
	4-banded Hyrax	23	51.1%

Table 2. Descriptive statistics of continuous variables for the sample population

	Mean (SD)	Median	Range
Age at T1 (years)	13.01 (1.33)	12.96	10.4 - 16.1
Total time between CBCT scans (years)	2.44 (0.52)	2.38	1.34 - 3.76
Expander retention time (weeks)	18.82 (15.63)	14	1 - 77
Amount of prescribed RME expansion (mm)	8.08 (2.60)	7.75	3.25 - 16

Treatment Protocol

Patients were treated with either a 2-banded Hyrax expander or a 4-banded Hyrax expander (Figure 4). The 2-banded expander had bands on only the permanent maxillary first molars with soldered extension arms extending along the palatal surfaces of the premolars to the mesial portion of the palatal surface of the first premolar. The 4-banded expander had bands on both the first molars and the first premolars with a soldered connection between the palatal surfaces of the bands. Both expander types were designed to evenly disperse force over the first premolars and permanent first molars. Each expander type was activated once daily, with one quarter millimeter per activation, until the appropriate amount of expansion was obtained at the discretion of the treating clinician (Table 2). The expander was left cemented in place passively for an average post-expansion retention period of 18.82 weeks. Preadjusted edgewise appliances (full fixed appliances) were applied either during expansion or during the post-expansion retention period. After expander removal, comprehensive orthodontic treatment with preadjusted edgewise appliances was continued until the orthodontic treatment objectives were achieved.

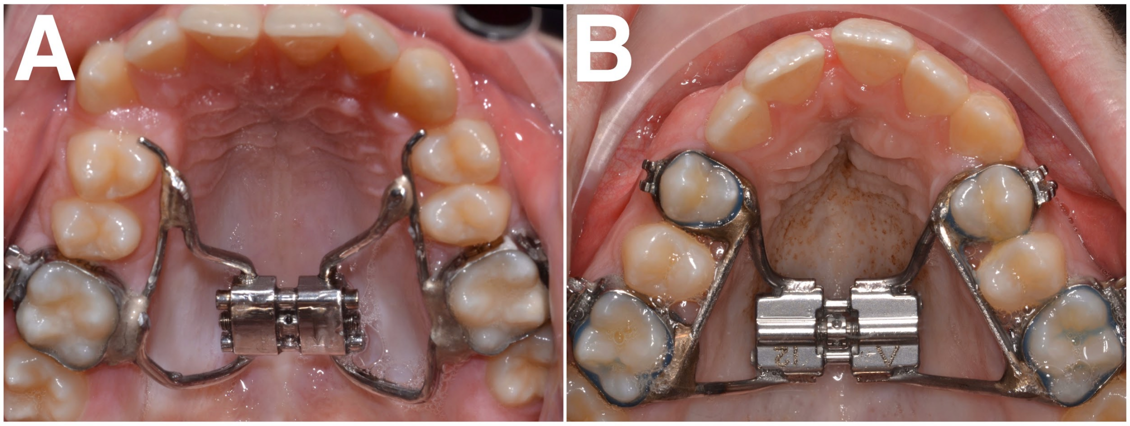

Figure 4. Typical Hyrax expander designs used in this study: **A**, 2-banded expander; **B**, 4-banded expander.

Data collection

All CBCT images had been obtained using an i-Cat Next Generation CBCT scanner (Imaging Sciences International, Hatfield, PA) with the following settings: full field of view (17 x 23 cm), 120 kV, 18.54 mA, pulsed scan time of 8.9 seconds, and a voxel dimension of 0.3 mm.

CBCT analysis was performed by a single examiner on digital communications in medicine (DICOM) images using Dolphin Imaging software (version 11.9, Dolphin Imaging and Management Solutions, Chatsworth, CA). Images obtained at T1 and T2 for each patient were assigned random numbers 1-90 and were measured in the corresponding random sequence to limit measurement bias. All measurements were repeated by the same examiner after a 4-week washout period for 15 randomly chosen CBCT scans to assess repeatability of the measurements.

Dolphin Imaging's multiple planar views mode was first used to orient the images to evaluate the region of the permanent maxillary first molar. This mode displays three separate cross-sectional planes (axial, coronal, and sagittal) of the three-dimensional image (Figure 5). Three colored reference lines are also present, and each corresponds to scrolling of the tomographic sections in a specific plane of space: red refers to the sagittal plane, blue refers to the axial plane, and green refers to the coronal plane.

In the axial view, the furcation region of the maxillary right first molar was identified by scrolling through the axial slices until the area where the buccal roots were slightly separated was visualized. The axial image was then oriented so the buccal plate adjacent to the mesiobuccal root of the maxillary right first molar was parallel to the vertical axis of the image window (Figure 5, A). In this view, the sagittal (red) and coronal (green) reference lines were positioned over the center of the mesiobuccal root. In the sagittal view, the coronal (green) reference line was positioned on the long axis of the mesiobuccal root of the maxillary first molar (Figure 5, B). Orientation in the axial and sagittal views resulted in a coronal image, which was refined so the buccal plate was parallel to the vertical axis of the image window, resulting in adequate visualization of the alveolar buccal cortical bone and molar root axis to be measured (Figure 5, C and D).

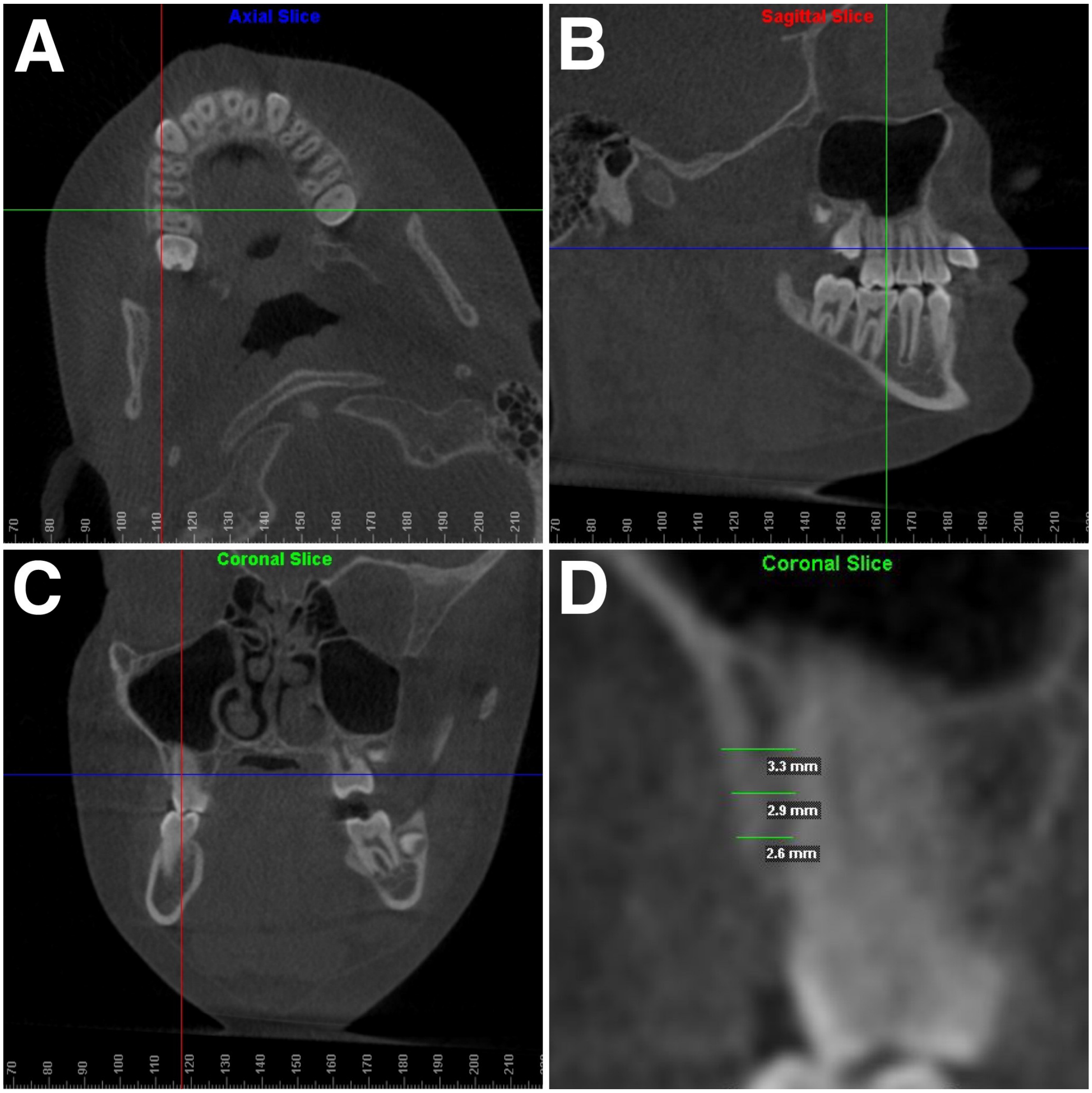

Figure 5. Orientation and measurement of CBCT slices using Dolphin Imaging software: **A**, axial orientation; **B**, sagittal orientation; **C**, coronal orientation; **D**, magnified coronal section and buccal alveolar bone measurements at B4, B6, and B8.

Linear measurements of alveolar bone thickness were made in the coronal view and again in the axial view for verification (Figure 6). In the coronal view, the axial (blue) reference line was placed at the buccal CEJ of the maxillary first molar. The axial (blue) reference line was then moved 4 mm apically, using the ruler on the left side of the image window as a guide. The linear measuring tool was used at this level to make a measurement from the outer surface of the mesiobuccal root of the maxillary first molar to the outer surface of the buccal cortical bone (Figure 6, A top). A linear measurement was also made in the corresponding axial image for verification (Figure 6, A bottom). Measurements were completed at 6 mm apical to the CEJ (Figure 6, B) and 8 mm apical to the CEJ (Figure 6, C) using the same method. Alveolar bone thickness at 4 mm (B4), 6 mm (B6), and 8 mm (B8) from the buccal CEJ of the permanent maxillary first molar were recorded. If the alveolar bone was not visible on the images, the site was quantitatively assessed as 0 mm and qualitatively assessed as a dehiscence, fenestration, or complete disruption of the alveolar bone. Orientation, linear measurements, and qualitative assessments of buccal alveolar bone thickness were also performed for the left side maxillary first molar using the previously described method.

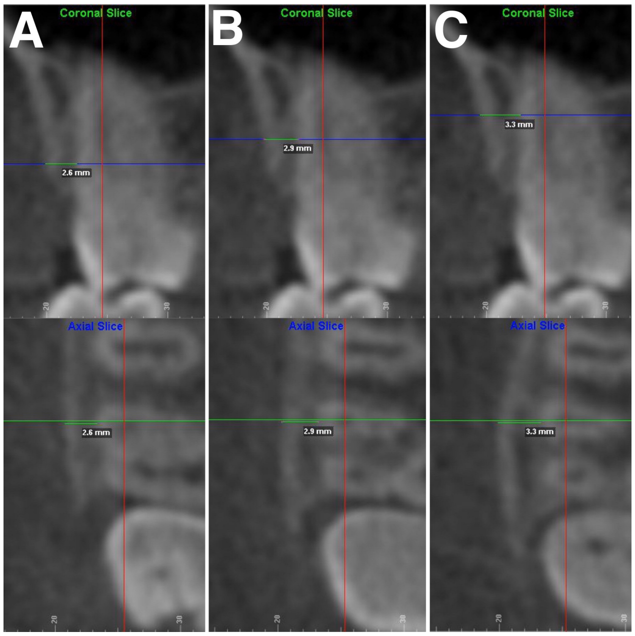

Figure 6. Measurement of buccal bone thickness on coronal (top) and axial (bottom) CBCT sections: **A**, B4; **B**, B6; **C**, B8.

Statistical Analysis

Intraclass correlation coefficients (ICCs) for each measurement were completed to assess repeatability. Descriptive statistics were calculated for age, gender, type of appliance, amount of expansion, post-expansion retention time, and treatment time. Paired t-tests were performed to determine whether right and left side buccal bone loss were significantly different. Because there were no significant differences, the right and left measurements for each patient were averaged, separately for each level. Paired t-tests were performed to evaluate whether the change in buccal alveolar bone thickness was significant at each level. Spearman correlation coefficients were calculated to examine the relationship between buccal bone thickness changes and continuous variables (prescribed expansion, age at T1, time between T1 and T2, post-expansion retention time, and initial alveolar bone thickness). Unpaired t-tests were performed to determine whether patients with and without post-treatment anatomic defects had a significant difference in initial bone thickness. Analyses were performed in SAS 9.4 (SAS Institute Inc., Cary, NC). P-values of less than 0.05 were considered statistically significant.

Results

Intraclass correlation coefficients (ICCs) for all measurements were greater than or equal to 0.95, indicating excellent intrarater reliability.[136] Right side B4, B6, and B8 measurements had ICCs of 0.95, 0.99, and 0.99, respectively. Left side B4, B6, and B8 measurements had ICCs of 0.96, 0.95, and 0.96, respectively. Reliability of repeated measurements was further assessed by using Bland-Altman plots (Figure 7).

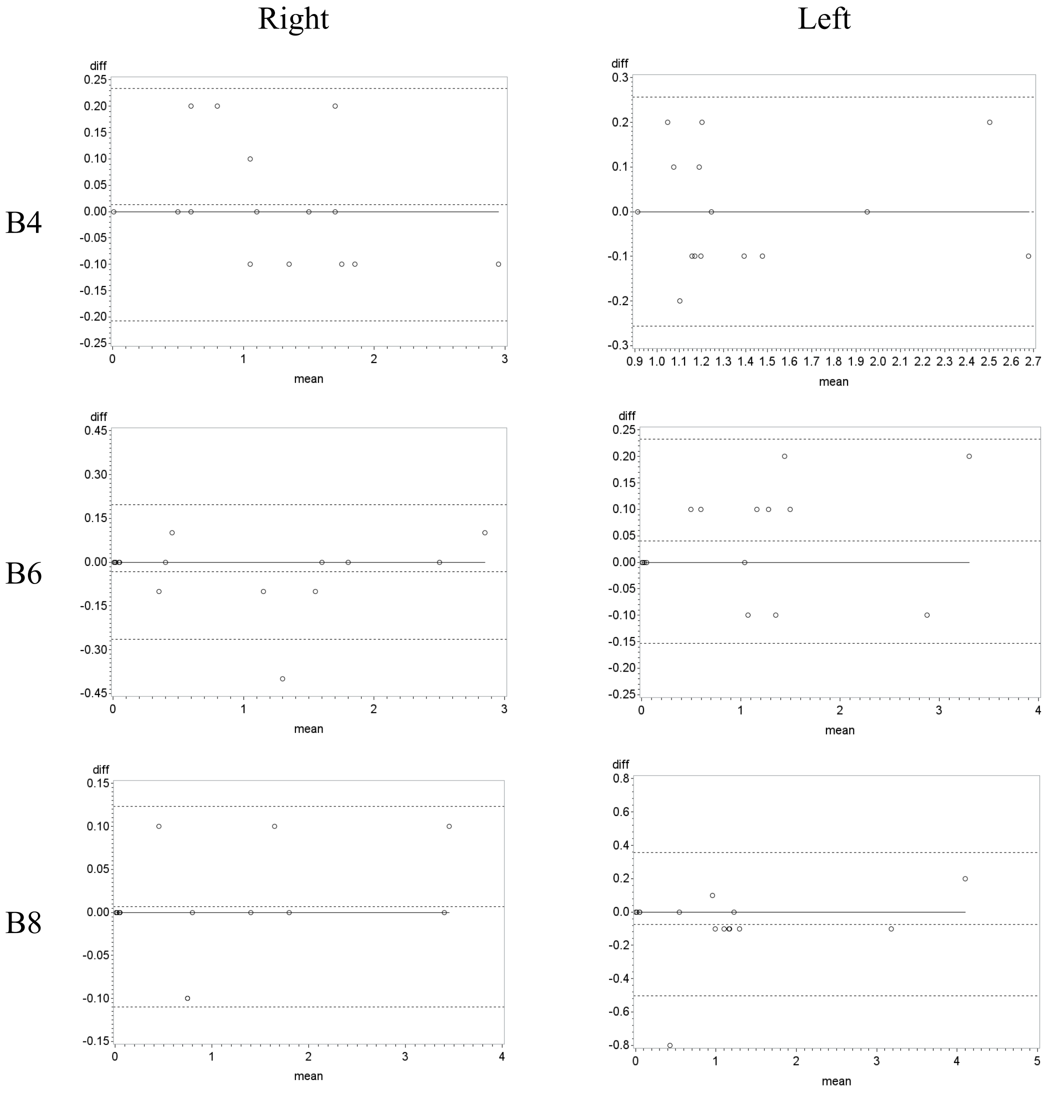

Figure 7. Bland Altman plots of agreement of right and left side linear measurements at B4, B6, and B8. The difference between the original and repeat measurements (mm) are plotted against the mean of the original and repeat measurements (mm) for each subject. Each circle represents one subject. 95% of measurement differences will lie between the limits indicated by the top and bottom dotted lines.

There was a statistically significant reduction in buccal alveolar bone thickness from T1 to T2 (Table 3). The average reductions in buccal alveolar bone thickness were 0.98 mm, 0.73 mm, and 0.51 mm at B8, B6, and B4, respectively. The mean change in bone thickness at each vertical level was statistically significantly different from zero (Table 3).

Table 3. Descriptive statistics of buccal alveolar bone thickness and mean changes between T1 and T2 at each vertical level.

	T1 Mean (SD)	**T2 Mean (SD)**	**Mean change T2-T1 (SD)**	**P value**
B4	1.35 (0.57)	0.85 (0.49)	-0.51 (0.43)	<0.0001
B6	1.25 (0.70)	0.52 (0.53)	-0.73 (0.49)	<0.0001
B8	1.48 (0.90)	0.49 (0.57)	-0.98 (0.64)	<0.0001

An increase in the prevalence of anatomic defects (dehiscence, fenestration, complete disruption) related to each maxillary permanent first molar and their adjacent buccal alveolar bone was observed (Figure 8). Anatomic defects of the buccal alveolar bone were associated with 47.7% of measured teeth and 60% of treated patients. The vast majority of defects were fenestrations, accounting for 84.4% and 82.8% of the total defects associated with measured teeth and patients, respectively (Table 4). Two of the measured teeth had both a fenestration and a dehiscence.

Table 4. Anatomic defects related to the maxillary permanent first molars and their adjacent buccal alveolar bone.

		Fenestration	**Dehiscence**	**Complete disruption**	**Total**
Maxillary first molars (N=90)	**T1**	0	0	0	0
	T2	38	3	4	45
Patients (N=45)	**T1**	0	0	0	0
	T2	24	2	3	29

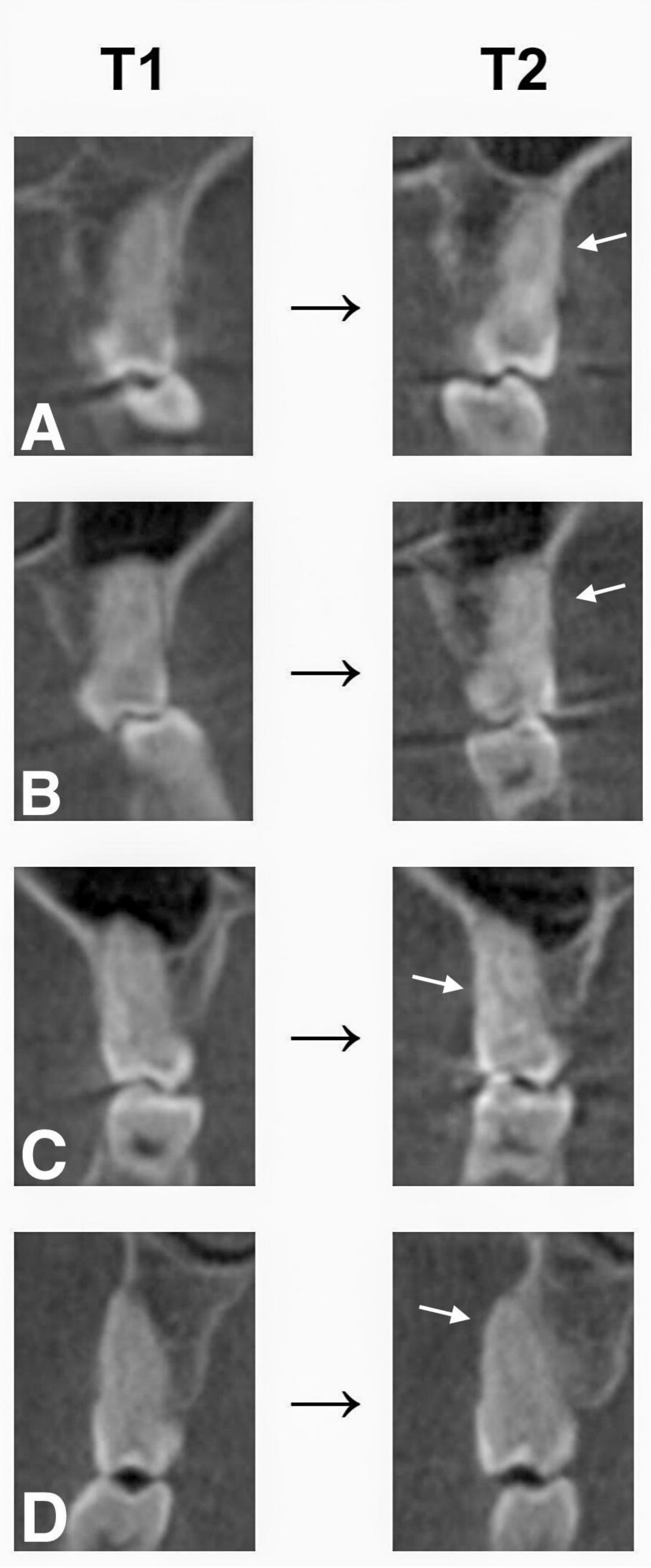

Figure 8. Examples of anatomic defects related to the maxillary permanent first molars and adjacent alveolar bone tissue observed at T2, but not at T1: **A and B**, fenestration; **C**, dehiscence; **D**, complete disruption of the buccal bone plate.

Teeth with anatomic defects at T2 had significantly lesser initial buccal bone thickness than those with no defects (Table 5). The average T1 alveolar bone thickness of patients without T2 anatomic defects was statistically significantly greater ($P<0.05$) than that of patients with T2 defects (Table 5).

Table 5. Mean T1 buccal alveolar bone thickness (mm) at each vertical level and mean differences between teeth with and without post-treatment anatomic defects.

		No defects present	**Post-treatment defect present**		
		T1 Mean (SD)	**T1 Mean (SD)**	**Mean Difference**	**P value**
All teeth (N=90)	**B4**	1.62 (0.67)	1.18 (0.50)	0.44	0.0013
	B6	1.67 (0.75)	0.97 (0.58)	0.70	<.0001
	B8	2.09 (1.02)	1.07 (0.67)	1.02	<.0001
Left (N=45)	**B4**	1.56 (0.79)	1.11 (0.47)	0.45	0.0399
	B6	1.58 (0.88)	0.93 (0.59)	0.65	0.0094
	B8	1.97 (1.06)	1.03 (0.73)	0.94	0.0028
Right (N=45)	**B4**	1.67 (0.53)	1.24 (0.54)	0.43	0.0119
	B6	1.76 (0.62)	1.01 (0.59)	0.75	0.0003
	B8	2.20 (1.00)	1.11 (0.60)	1.09	0.0003

Initial bone thickness was negatively correlated ($P<0.0001$) with the amount of bone loss. The Spearman correlation coefficients were -0.55 (B4), -0.65 (B6), and -0.79 (B8). Negative correlation, in this instance, indicates that teeth with greater initial buccal bone thickness experienced a greater reduction in buccal bone thickness (Figure 9).

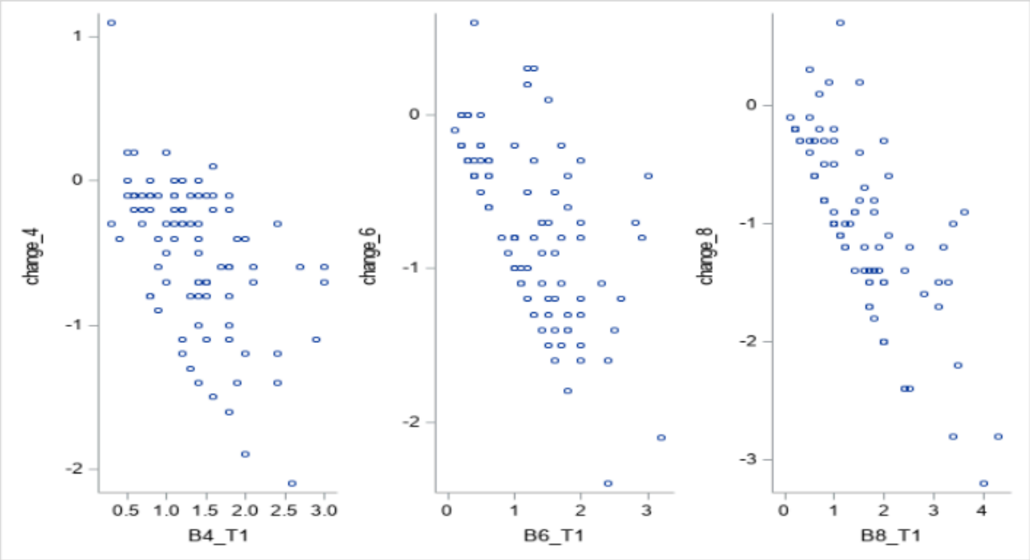

Figure 9. Correlations between buccal bone change and initial bone thickness at B4, B6, and B8.

Reduction in alveolar bone was not significantly correlated with the amount of prescribed expansion, age at T1, time between T1 and T2, or post-expansion retention time (P>0.05). A scatter plot matrix of buccal bone changes versus the continuous variables shows no obvious trends, providing a visual depiction of the lack of association between buccal bone loss and the listed variables (Figure 10).

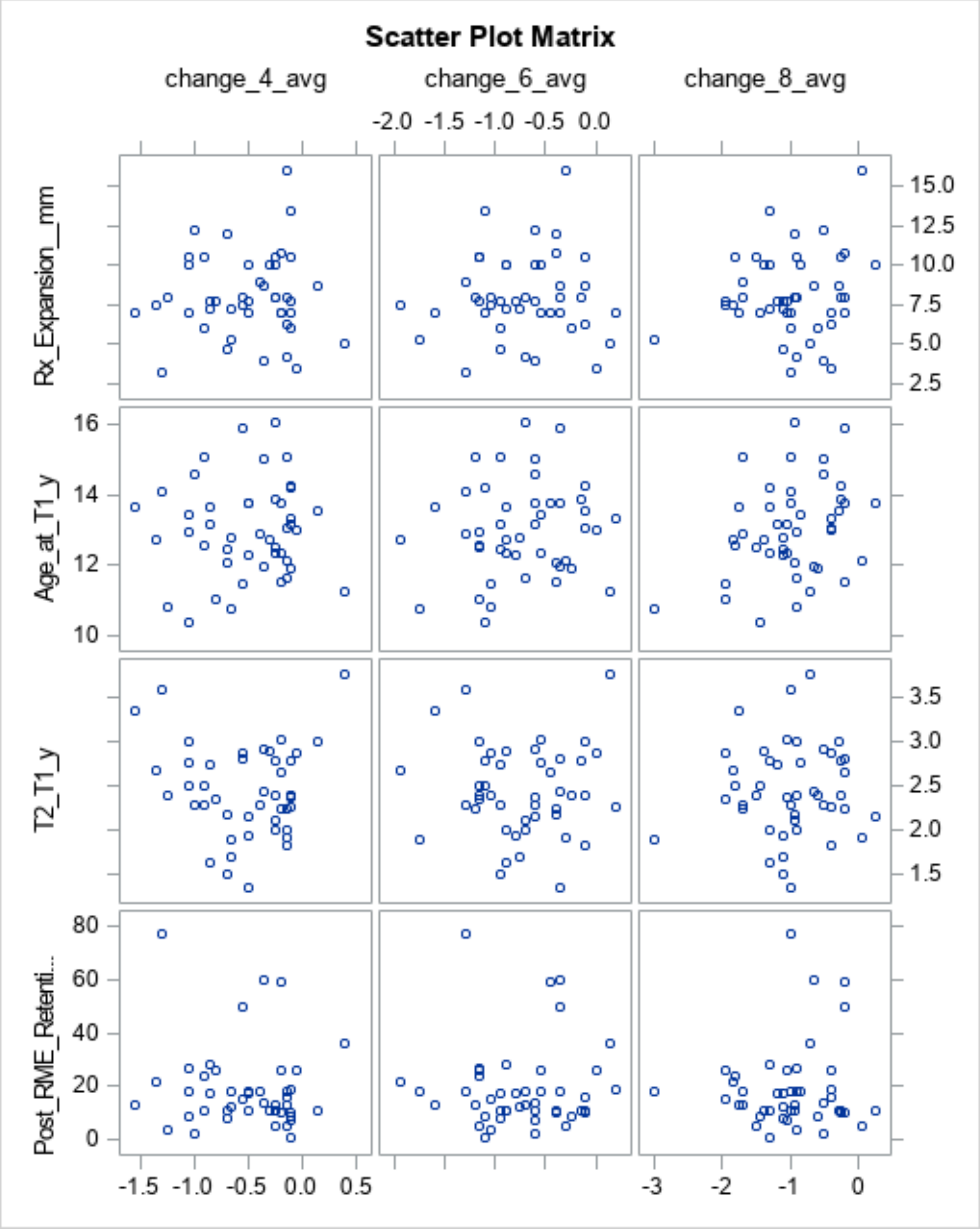

Figure 10. Correlations between buccal bone changes (B4, B6, and B8) and continuous variables (prescribed expansion, age at T1, time between T1 and T2, and post-expansion retention time).

Discussion

Orthodontic treatment with RME and fixed appliances can cause buccal displacement of anchor teeth, resulting in damage to the periodontium. This study aimed to assess factors that might affect buccal bone changes adjacent to the mesiobuccal root of the maxillary first molar following this type of treatment. The mesiobuccal root was analyzed because it is directly related to the buccal bone plate and is the anchor-tooth root that is most susceptible to dentoskeletal changes associated with RME.

A retrospective study design was chosen to ensure that patients were not exposed to ionizing radiation solely for study purposes. An untreated control group was not available and was not included due to ethical concerns related to unnecessary radiation exposure of untreated patients. The treatment variability associated with the study design was a limitation of this study. The amount of prescribed expansion was not standardized because it was customized to address individual treatment needs. To account for variable expansion amounts before proceeding with statistical analysis of other patient variables, it was confirmed that there was no correlation between the amount of prescribed expansion and the degree of buccal alveolar bone loss. The study sample was a convenience sample of patients who underwent both RME and fixed appliance therapy and had CBCT scans before and after comprehensive treatment. It was felt that this sample offered clinical relevance because it represented the long-term treatment outcomes of comprehensive orthodontic treatment with RME and fixed appliance therapy.

Treatment mechanics during fixed appliance therapy were not standardized and there is no way, based on available records, to assess whether archwires were expanded to influence transverse dimension and buccal tooth movement. In addition, a transpalatal arch (TPA) was used in some cases to retain or potentially modify the transverse position of the molars after active expansion. However, it is reasonable to assume that the transverse dimension was relatively established at least six months before T2 CBCT scans were taken, allowing sufficient time for bone density normalization on the buccal surfaces of the maxillary first molar roots.

Treatment of some patients also included premolar extractions and subsequent mesialization of the permanent molar during space closure. As a tooth moves anteriorly in the alveolus, it may enter a thinner or thicker area of alveolar bone, which could have a confounding effect on the comparison of buccal bone thickness measurements at T1 and T2. Other tooth position changes, such as vertical or rotational movements, could also influence the measurement of buccal bone thickness. For example, a mesially rotated molar will have thicker bone along the buccal surface of its mesiobuccal root than the same de-rotated molar, in which the mesiobuccal root will have been moved into closer proximity to the buccal cortical bone. Greater rotational changes may therefore result in the measurement of greater alveolar bone loss. Confounding dental movements were not controlled because the study aimed to assess the overall outcomes of treatment, including these aspects of treatment, on the buccal bone thickness and presence of anatomic defects.

This study used CBCT to measure bone changes, as this method of imaging allows for evaluation and measurement of buccal alveolar bone in both the coronal and axial planes of space.[52,54,55] However, the available CBCT scans were intended to be used for general orthodontic diagnosis and treatment planning and not specifically for assessing buccal bone. The accuracy of measurements of alveolar bone thickness are related to spatial resolution, which is influenced by voxel size, partial volume averaging, noise, artifacts, and image processing.[53,59,117,130-135] The exact spatial resolution of the CBCT scans taken in the University of Minnesota Orthodontic clinic is not known, but the general parameters of the scan (full FOV, 8.9 second scan time, and 0.3 mm voxel dimension) are not ideal for assessing thin anatomic structures, such as buccal alveolar bone. Spatial resolution is multifactorial, but it can be generalized that small voxel size, medium to long scan time, and a FOV limited to the area of interest are better parameters for the assessment of thin buccal alveolar bone. The relation of spatial resolution to detection of anatomic defects is further discussed below in relation to the anatomic defect findings of this study. For the purposes of this study, spatial resolution issues were unavoidable and may have influenced measurement accuracy. However, the precision of measurements was excellent, as is evident based on the high intraclass correlation coefficients (greater than or equal to 0.95) found during repeatability testing.

The statistically significant reduction in buccal alveolar bone following RME and fixed appliance therapy ($P<0.0001$) at each vertical level corroborated findings from previous studies.[33-43] It is well established that RME results in orthodontic tooth movement manifested as dental tipping and translation, which influence bone thickness.[4, 23, 27-31,33-39, 41] Interestingly, the reduction in bone thickness was progressively greater at more apical levels. Pure dental tipping would have caused a greater reduction at the coronal portion of the root, as this portion moves more buccal than the apex. It is conceivable that tipping was limited by the expander design and occurred paired with alveolar bending. A geometrical arrangement in which the alveolar process bent buccally while the root was held upright would explain a greater bone thickness reduction at more apical levels. The use of a TPA after expander removal may have maintained an upright molar position and contributed to this finding. It could also be explained by the effect of fixed appliances following RME. The bracket prescription (with approximately -14 degrees of torque at the maxillary first molar) may have resulted in buccal root torque of the maxillary posterior teeth, which moved the roots buccally and corresponds with a greater reduction in bone thickness at the apical portion of the root. In addition, due to the morphology of the dental alveolus (overall wider apically with a significant initial taper moving coronally), any changes in vertical position of the tooth would result in a more pronounced change in buccal bone measurement at the most apical measurement level.

There was an increase in the prevalence of anatomic defects (dehiscence, fenestration, complete disruption) of the buccal alveolar bone associated with RME anchor teeth, which is consistent with previous research findings.[33] Anatomic defects of the buccal alveolar bone were associated with 46.7% of measured teeth and 60% of treated patients. The relatively high proportion of patients with post-treatment anatomic defects suggests that the occurrence of a defect after RME and fixed appliance therapy is relatively universal and is not limited to a small number of predisposed patients. This finding does not, however, eliminate the potential that certain general patient characteristics, such as thin gingival biotype, may predispose patients to the development of anatomic defects. Fenestrations accounted for the vast majority of the observed defects (84.4%) associated with teeth. Dehiscence and complete disruption of the buccal alveolar bone were rare, accounting for only 6.7% and 8.9% of the observed teeth, respectively. It must be considered that Sun *et al.* found that negative predictive values are high (dehiscence, 0.82; fenestration, 0.98) and positive predictive values are low (dehiscence, 0.75; fenestration, 0.16) for CBCT detection of anatomic defects of the buccal alveolar bone.[56] That is, when dehiscence and fenestrations were found on CBCT, the alveolar defects were confirmed in only 75% and 16% of cases, respectively. These findings suggest that CBCT analysis of alveolar bone results in a systematic over-reporting of anatomic defects, particularly fenestration. It is likely that the spatial resolution of the CBCT scans used in this study was not adequate to visualize thin buccal alveolar bone and, therefore, contributed to over-reporting of anatomic defects. Even so, it is likely that RME and fixed appliance therapy contribute to the formation of some anatomic defects, which can lead to gingival recession and periodontal instability.

Teeth with post-treatment defects of the buccal bone plate were more likely to have significantly thinner bone pre-treatment. This correlation was significant at all bone levels studied (B4, B6, and B8; P=0.0013, <0.0001, <0.0001). Orthodontic movement of an anchor tooth into the buccal cortical bone can cause resorption of the bone. Teeth with thinner initial bone have a decreased threshold for the degree of allowable orthodontic tooth movement before resorption of the cortical bone occurs. It is logical that anchor teeth which experience anatomic defects of the buccal bone are in closer proximity to the buccal cortical bone at the beginning of treatment. An evaluation of pre-treatment bone thickness adjacent to RME anchor teeth may help determine patient-specific susceptibility to the development of anatomic defects of the buccal alveolar bone.

Initial bone thickness was negatively correlated (P <.0001) with the amount of bone change at B4, B6, and B8. That is, teeth with thicker initial buccal alveolar bone experienced a greater reduction in buccal bone thickness. Rungcharassaeng *et al.* also found that initial buccal bone thickness was similarly correlated with buccal alveolar bone loss.[34] In this study, the finding could be in part due to the significant number of post-treatment anatomic defects and the associated issues with measuring bone changes in those areas. A significant number of teeth (46.7%) had T2 measurements of "0 mm" due to the presence of an anatomic defect. Assigning "0 mm" to these defect areas likely underestimated the amount of buccal alveolar bone loss because it did not account for any lateral movement of the tooth after it perforated the buccal cortical plate. Teeth with these defects were also found to have thinner initial bone. Therefore, there was likely an underestimation of buccal bone thickness change in teeth with thin initial bone. Overall, it is expected that teeth with more available bone are likely to record a greater change in bone thickness from T1-T2 because there is more bone for the teeth to move through and the change is measurable.

Reduction in alveolar bone was not correlated with the amount of prescribed expansion and age at T1. Conversely, Rungcharassaeng *et al.* found that age and amount of expansion correlated with buccal bone loss.[34] As prescribed expansion increases, it is logical to assume that all effects of expansion would be increased, including dental movements and associated buccal alveolar bone loss. It would also be expected that sutural resistance, dental tipping and translation, and associated buccal alveolar bone loss would increase with age due to the increasing interdigitation of the midpalatal suture. A possible reason for this study's lack of association could be that there was an insufficient range of skeletal maturity amongst patients to detect any meaningful correlation. A similar study comparing changes in two distinct age groups (such as Phase I and Phase II orthodontic patients) could potentially provide a more reliable and clinically relevant assessment of the influence of age on buccal bone changes.

Post-expansion retention time had no significant association with buccal alveolar bone loss, which is consistent with previous studies.[34] Theoretically, a shorter retention period would allow for relapse of dental tipping and subsequent buccal bone deposition. However, due to the longevity of the study and influence of fixed appliance therapy, it is unlikely that retention time would have any significant overall impact. Factors such as archwire expansion and use of a TPA during fixed appliance therapy likely would play a greater role in whether relapse of RME-induced dental tipping was to occur. Because retention time does not have a significant impact on buccal bone changes, the RME appliance should be retained in place for an adequate time to allow for boney fill of the separated midpalatal suture.

Treatment time also had no association with buccal alveolar bone loss. Buccal bone remodels and its density, i.e. degree of mineralization, increases after orthodontic forces are relieved.[59] Therefore, it could be assumed that a longer treatment time would ensure establishment of higher bone density after RME in the areas that experienced particularly heavy lateral forces. However, the treatment times ranged from 1.34 to 3.76 years, so even the shortest treatment may have allowed for full remineralization of the bone. The thought that bone deposition occurs on the buccal surface of roots throughout the course of comprehensive orthodontic treatment may be unwarranted.

Clinical and radiographic examination of periodontal conditions, including alveolar bone support, should be routine procedures before and after orthodontic treatment. An individual risk assessment for each patient is recommended before comprehensive orthodontic treatment with RME and fixed appliance therapy. In patients undergoing RME and fixed appliance therapy, particular emphasis should be placed on the assessment of pre-treatment buccal alveolar bone thickness of anchor teeth because areas of thin bone are more susceptible to the formation of anatomic defects of the buccal alveolar bone. CBCT imaging should be completed to address a specific clinical question and specific scan parameters should be used when aiming to assess minimal bone thickness. Further prospective, long-term studies correlating radiological data of bone loss to the clinical periodontal hard and soft tissue reactions after RME and fixed appliance therapy are needed.

Conclusions

1. Comprehensive orthodontic treatment with RME and fixed appliance therapy can result in a significant reduction in buccal alveolar bone thickness and an increase in anatomic defects adjacent to the mesiobuccal root of the permanent maxillary first molar.

2. RME anchor teeth with greater initial buccal bone thickness are likely to have a greater reduction in buccal bone thickness.

3. Prescribed expansion, chronologic age, treatment time, and retention time are not predictive factors of the reduction in buccal alveolar bone thickness.

4. RME anchor teeth with thin initial buccal bone are more likely to develop post-treatment anatomic defects of the buccal bone plate.

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