Original Article

Buccal alveolar bone changes following rapid maxillary expansion and fixed appliance therapy

Adam Sperl[a]; Laurence Gaalaas[b]; John Beyer[c]; Thorsten Grünheid[d]

ABSTRACT

Objectives: To assess factors that may be associated with buccal bone changes adjacent to maxillary first molars after rapid maxillary expansion (RME) and fixed appliance therapy.

Materials and Methods: Pretreatment (T1) and posttreatment (T2) cone-beam computed tomography scans were obtained from 45 patients treated with RME and preadjusted edgewise appliances. Buccal alveolar bone thickness was measured adjacent to the mesiobuccal root of the maxillary first molar 4 mm, 6 mm, and 8 mm apical to the cementoenamel junction, and anatomic defects were recorded. Paired and unpaired *t*-tests were used to compare alveolar bone thickness at T1 and T2 and to determine whether teeth with posttreatment anatomic defects had thinner initial bone. Correlation analyses were used to examine relationships between buccal alveolar bone thickness changes and amount of expansion, initial bone thickness, age at T1, postexpansion retention time, and treatment time.

Results: There was a statistically significant reduction in buccal alveolar bone thickness from T1 to T2. Approximately half (47.7%) of the teeth developed anatomic defects from T1 to T2. These teeth had significantly thinner buccal bone at T1. Reduction in alveolar bone thickness was correlated with only one tested variable: initial bone thickness.

Conclusions: RME and fixed-appliance therapy can be associated with 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 have less reduction in buccal bone thickness and are less likely to develop posttreatment anatomic defects of buccal bone. (*Angle Orthod.* 2021;91:171–177.)

KEY WORDS: Alveolar bone; RME

INTRODUCTION

Rapid maxillary expansion (RME) is commonly used to address transverse deficiencies of the maxilla.[1] First described in 1860, RME has been used primarily for posterior crossbite correction.[2] More recently, RME has also been reported to facilitate the correction of Class II and Class III malocclusions,[3–5] resolve arch length discrepancies,[4] and increase upper respiratory volume to improve airflow.[6]

Conventional RME uses tooth-borne appliances to deliver heavy forces to the maxilla. In growing patients, the transmitted forces are sufficient to open the midpalatal suture, hold the halves of the maxilla apart, and allow subsequent callus formation.[1,7] This process, known as "skeletal expansion," is typically the preferred effect of RME. However, the forces exerted on the teeth also cause dentoalveolar expansion, which comprises alveolar bending and translation, tipping, and extrusion of teeth.[4,8,9] The dental effects are typically undesirable because they can cause an increase in vertical dimension, root resorption, and loss of periodontal attachment, including fenestration or dehiscence of the buccal cortical bone.[10–17] RME is often followed by fixed appliance therapy, which,

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through buccal tipping, rotation, and translation of teeth, may also contribute to alveolar bone changes.[18]

Since orthodontic treatment aims to maintain periodontal health, it is essential to assess the bony support of teeth before and after treatment. However, conventional two-dimensional radiographs do not allow exact identification of buccal alveolar bone. More recently, cone-beam computed tomography (CBCT) has been used to assess the alveolar bone changes associated with RME.[10–12,15,17] CBCT allows for more accurate assessment of alveolar bone support by identifying objects based on their relative density.[19–21] However, bone in areas of tooth movement undergoes remodeling, is less mineralized, and, as a result, appears less dense on CBCT images for 6–24 months after tooth movement subsides.[22] All current studies have evaluated changes on CBCT scans taken 0–6 months after RME. In these studies, the limitations of radiographic assessment of remodeling bone have to be considered. Additionally, no studies have yet evaluated the potential added effect of fixed appliance therapy. The evaluation of buccal alveolar bone before and after comprehensive orthodontic treatment may provide more clinically relevant information on the cumulative effects of RME and fixed appliance therapy. So far, only one study has evaluated variables, such as age and amount of expansion, that might help predict the alveolar response to RME.[11] Therefore, the aim of this study was to assess whether factors such as age, amount of expansion, treatment time, or initial bone thickness were associated with buccal bone changes after RME and fixed appliance therapy. The following null hypotheses were tested: (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; and (2) buccal alveolar bone thickness and anatomic defects of the buccal alveolar bone are not correlated with age, amount of expansion, treatment time, or initial bone thickness.

MATERIALS AND METHODS

This retrospective cohort study was approved by the Institutional Review Board at the University of Minnesota. The pretreatment (T1) and posttreatment (T2) CBCT scans of 45 patients (18 boys, 27 girls) were used. The study sample was a convenience sample of patients who underwent both RME and fixed appliance therapy. It was believed this sample offered clinical relevance because it represented the outcomes of comprehensive orthodontic treatment. The patients were treated in a university clinic by 12 orthodontic residents under the supervision of nine faculty orthodontists. Patients were excluded if they had previous orthodontic treatment, history of periodontal disease, incomplete treatment records, or metallic restorations in the maxillary first molars. Descriptive patient information is summarized in Table 1.

Table 1. Descriptive Statistics of Continuous Variables for the Sample Population[a]

Variable	Mean ± SD	Range
Age at T1, y	13.01 ± 1.33	10.40–16.10
Amount of expansion, mm	8.08 ± 2.60	3.25–16.00
Postexpansion retention time, wk	18.82 ± 15.63	1.00–77.00
Treatment time T1–T2, y	2.44 ± 0.52	1.34–3.76

[a] SD indicates standard deviation.

The patients were treated with Hyrax expanders with soldered wires along the palatal surfaces designed to evenly disperse force over all maxillary premolars and first molars. The expanders were activated once daily (0.25 mm) until the appropriate amount of expansion was obtained. Expanders were removed after a variable postexpansion retention period, which was at the discretion of the supervising faculty orthodontists (Table 1), and preadjusted edgewise appliances were placed.

All CBCT images were full field of view (17 × 23 cm) scans obtained with an i-Cat Next Generation (Imaging Sciences International, Hatfield, Pa) at 120 kV, 18.54 mA, a pulsed scan time of 8.9 seconds, and a voxel dimension of 0.3 mm. CBCT analysis was performed by a single examiner using Dolphin Imaging software (v11.9, Dolphin Imaging and Management Solutions, Chatsworth, Calif). The images were analyzed in a random order to limit measurement bias. All measurements were repeated after a 4-week washout period for 15 randomly chosen CBCT scans to assess repeatability of the measurements.

A multiple planar view mode was used to orient the images. In the axial view, the buccal furcation of the maxillary right first molar was identified. The axial image was then oriented so that the buccal plate adjacent to the mesiobuccal root was parallel to the vertical axis of the image window. In the sagittal view, a reference line was positioned on the long axis of the mesiobuccal root of the maxillary first molar. Orientation in the axial and sagittal views resulted in a coronal image, which was refined so that the buccal plate was parallel to the vertical axis of the image window.

Linear measurements of alveolar bone thickness were made at 4 mm, 6 mm, and 8 mm apical to the buccal cementoenamel junction (CEJ) of the right and left maxillary first molar as follows. In the coronal view, a reference line was placed at the buccal CEJ. The line was then moved 4 mm apically using the ruler in the image window as a guide. The distance from the outer surface of the mesiobuccal root to the outer surface of the buccal cortical bone was then measured using the

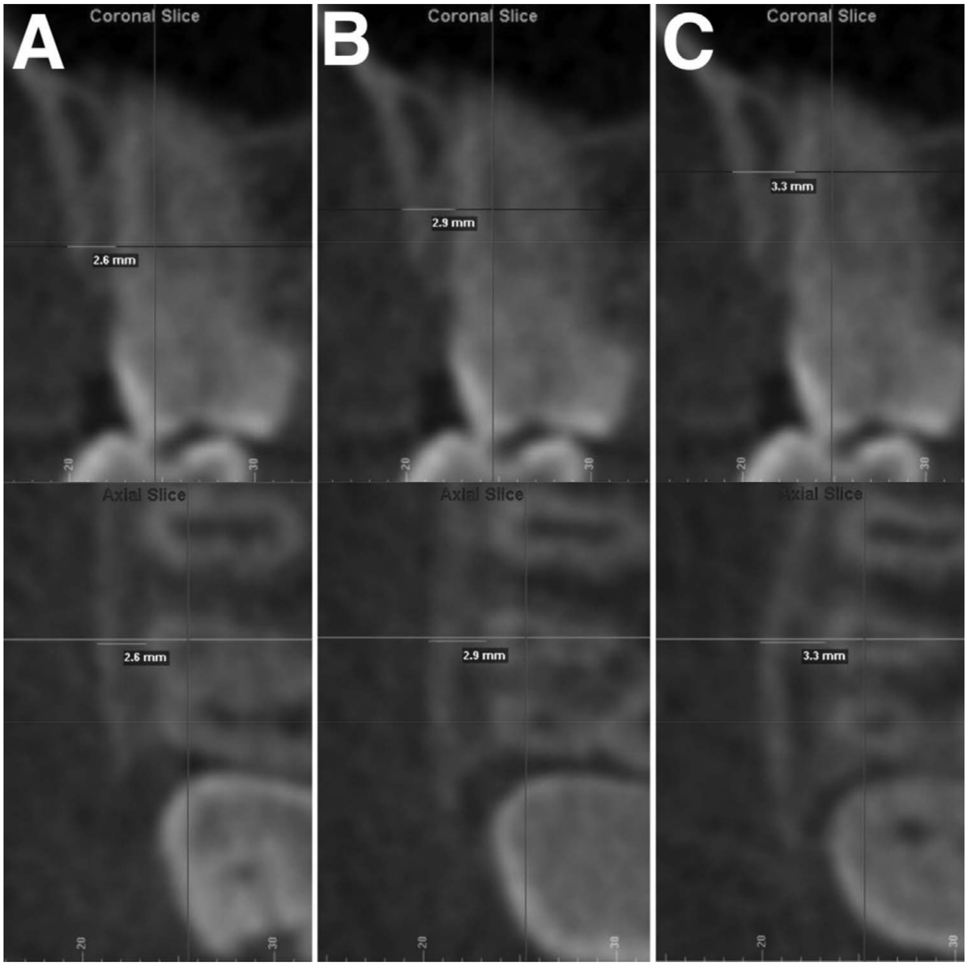

Figure 1. Measurement of buccal alveolar bone thickness on coronal (top) and axial (bottom) CBCT sections: (A) 4 mm, (B) 6 mm, and (C) 8 mm apical to the cementoenamel junction. The left side of each figure segment is the buccal side.

software's linear measuring tool. The same measurement was also made in the corresponding axial image for verification. The measurements were repeated at 6 mm and 8 mm apical to the CEJ using the same method (Figure 1). If the alveolar bone was not visible on the images, the site was quantitatively assessed as 0 mm and qualitatively assessed as dehiscence, fenestration, or complete disruption of the alveolar bone.

Statistical Analysis

Intraclass correlation coefficients were calculated to assess repeatability of the measurements. Paired *t*-tests were performed to determine whether right- and left-side buccal bone changes 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 then performed to evaluate whether the change in buccal alveolar bone thickness at each level was significant. Unpaired *t*-tests were performed to determine whether there was a significant difference in bone thickness at T1 between patients with and without anatomic defects at T2. Spearman correlation coefficients were calculated to examine the relationship between buccal bone thickness changes and continuous variables (amount of expansion, age at T1, time between T1 and T2, postexpansion retention time, and alveolar bone thickness at T1). Analyses were performed in SAS 9.4 (SAS Institute Inc, Cary, NC) with P values less than .05 considered statistically significant.

RESULTS

Intraclass correlation coefficients for all measurements were $\geq$0.95 (Table 2). The buccal alveolar bone thickness at each level assessed is shown in Table 3. There was a statistically significant reduction in bone thickness from T1 to T2 at all levels. The average reductions were 0.51 mm, 0.73 mm, and 0.98 mm at 4 mm, 6 mm, and, 8 mm apical to the CEJ, respectively.

There was also an increase in the prevalence of anatomic defects of the buccal alveolar bone adjacent

Table 2. Intraclass Correlation Coefficients for All Repeated Measurements[a]

Level	Right	Left
4 mm apical CEJ	0.95	0.96
6 mm apical CEJ	0.99	0.95
8 mm apical CEJ	0.99	0.96

[a] CEJ indicates cementoenamel junction.

to the maxillary permanent first molars from T1 to T2 (Table 4). While no defects were present at T1, there were defects associated with 47.7% of the studied teeth and 60.0% of the studied patients at T2. The majority of the defects were fenestrations, accounting for 84.4% of the defects, while dehiscence and complete disruption of the buccal alveolar bone accounted for 6.7% and 8.9% of the defects, respectively. Examples of these defects are shown in Figure 2.

Teeth with defects at T2 had significantly thinner buccal alveolar bone adjacent to their mesiobuccal root at T1 than those with no defects at T2 (Table 5). The amount of bone loss was negatively correlated ($P <$ .0001) with the bone thickness at T1. The Spearman correlation coefficients were –0.55, –0.65, and –0.79 at 4 mm, 6 mm, and 8 mm apical to the CEJ, respectively, indicating that teeth with greater initial buccal bone thickness had less reduction in buccal bone thickness. In contrast, a reduction in buccal alveolar bone thickness was not significantly correlated with the amount of expansion, age at T1, time between T1 and T2, or postexpansion retention time ($P >$ .05; Table 6).

DISCUSSION

Orthodontic treatment with RME and fixed appliances causes buccal displacement of teeth, which can result in buccal alveolar bone loss. This study assessed factors that might affect buccal bone change. The principal finding was that a reduction in buccal alveolar bone thickness was related only to the pretreatment bone thickness but not to the amount of expansion, age, postexpansion retention time, or overall treatment time.

Table 3. Buccal Alveolar Bone Thickness (mm) Pretreatment (T1) and Posttreatment (T2) at Each Vertical Level Assessed[a,b]

Level	T1	T2	Change T2–T1
4 mm apical CEJ	1.35 ± 0.57	0.85 ± 0.49	–0.51 ± 0.43***
6 mm apical CEJ	1.25 ± 0.70	0.52 ± 0.53	–0.73 ± 0.49***
8 mm apical CEJ	1.48 ± 0.90	0.49 ± 0.57	–0.98 ± 0.64***

[a] CEJ indicates cementoenamel junction.
[b] Results are mean ± standard deviation.
*** $P <$ .0001.

Table 4. Occurrence of Anatomic Defects of the Buccal Alveolar Bone Adjacent to the Maxillary Permanent First Molars Pretreatment (T1) and Posttreatment (T2)[a]

	Maxillary First Molars (n = 90)		Patients (n = 45)	
Type of Defect	T1	T2	T1	T2
Fenestration	0	38	0	24
Dehiscence	0	3	0	2
Complete disruption	0	4	0	3

[a] Two teeth were associated with both a dehiscence and a fenestration of the buccal alveolar bone.

The mesiobuccal root of the maxillary first molar was chosen for evaluation because it is directly related to the buccal bone plate and is the anchor-tooth root that is most susceptible to changes associated with RME. CBCT was used to measure bone changes as it allowed for evaluation of buccal alveolar bone in both the coronal and axial planes.[19–22] However, the scan parameters were not ideal for assessing thin anatomic structures, such as buccal alveolar bone,[20,21,23] as the CBCT scans had been taken for general orthodontic diagnosis and treatment planning. Despite this, the measurement precision was excellent as evidenced by the high intraclass correlation coefficients.[24]

There was a significant reduction in buccal alveolar bone thickness over the course of treatment, which agreed with findings of other studies that addressed the effects of RME.[10–17] Hence, the first null hypothesis was rejected. It is well established that RME causes alveolar bending and dental tipping, which influence bone thickness.[4,8–11] 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 buccally than the apex. It is conceivable that tipping was limited by the expander design and occurred paired with alveolar bending. It is also conceivable that the fixed appliance therapy that followed, using a bracket prescription with built-in buccal root torque at the maxillary first molar, may have led to a greater reduction in bone thickness at the apical portion of the root.

It must be assumed that physiologic growth and remodeling of the nasomaxillary complex occurred in the study population. Transverse maxillary growth includes sutural separation of the hemimaxillae, is greater posteriorly than anteriorly, and has been reported to occur at average rates of 0.12–0.48 mm per year.[25–28] Since the present study did not include an untreated control group, it was not possible to determine whether the findings of buccal alveolar bone thickness changes, and anatomic defects of the buccal alveolar bone may be associated with physiologic growth and remodeling.

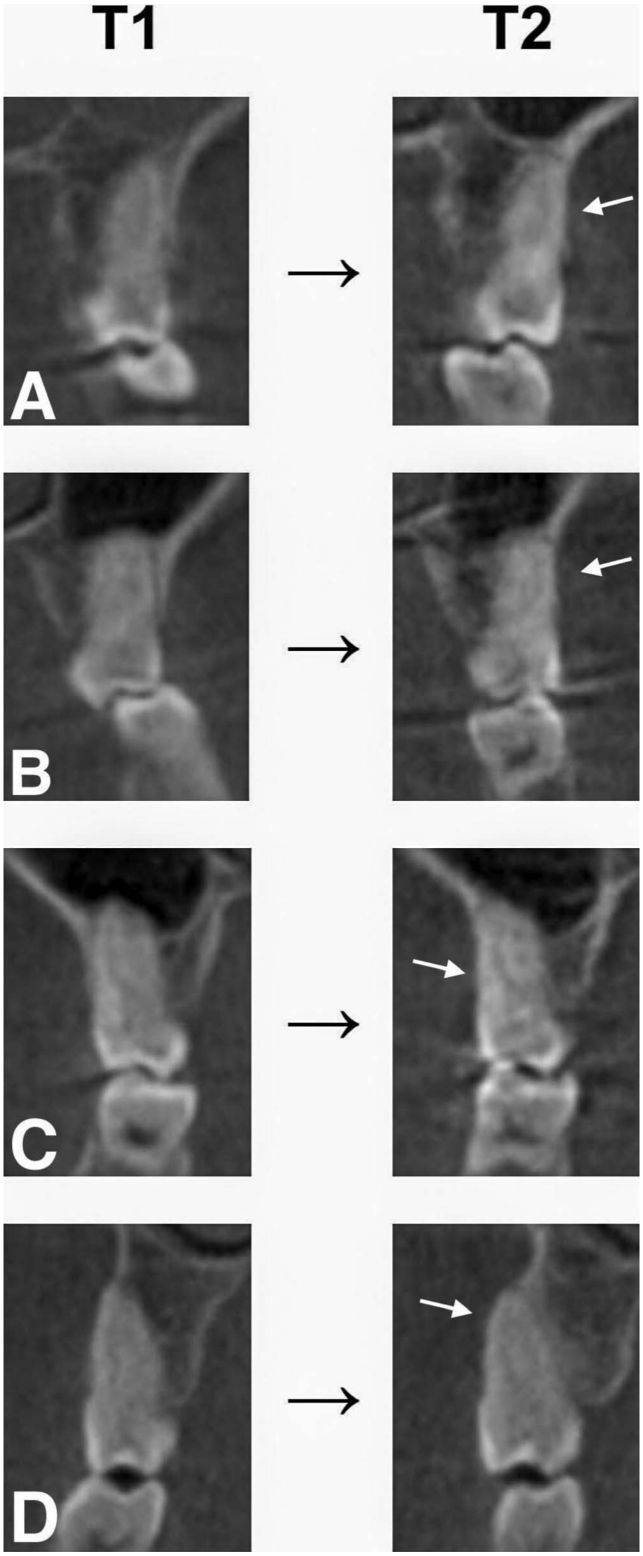

Figure 2. Examples of anatomic defects of the buccal alveolar bone adjacent to the maxillary permanent first molars at T2: (A and B) fenestration, (C) dehiscence, (D) complete disruption of the buccal bone. White arrows point to bony defects on the buccal side of the tooth.

Table 5. Pretreatment (T1) Buccal Alveolar Bone Thickness (mm) Adjacent to Teeth With and Without Posttreatment (T2) Anatomic Defects[a,b]

Level	No Defect at T2	Defect at T2	Mean Difference
4 mm apical CEJ	1.62 ± 0.67	1.18 ± 0.50	0.44*
6 mm apical CEJ	1.67 ± 0.75	0.97 ± 0.58	0.70***
8 mm apical CEJ	2.09 ± 1.02	1.07 ± 0.67	1.02***

[a] CEJ indicates cementoenamel junction.
[b] Results are mean ± standard deviation.
* $P < .05$, *** $P < .0001$.

The treatment of some patients included maxillary premolar extractions and subsequent molar mesial movement during space closure. As the molar moved anteriorly in the alveolus, it may have entered a thinner or thicker area of alveolar bone, which could have influenced the buccal bone thickness measurements at T2. Vertical or rotational tooth position changes could have influenced the buccal bone thickness, too. For example, a mesially rotated molar would have thicker bone along the buccal surface of its mesiobuccal root than the same de-rotated molar in which the mesiobuccal root would have been moved into closer proximity to the buccal cortical bone. Greater rotational changes may, therefore, have resulted in greater alveolar bone thickness changes.

There was an increase in the prevalence of anatomic defects of the buccal alveolar bone associated with RME anchor teeth, which was consistent with previous research findings.[10] The relatively high proportion of patients with posttreatment defects suggested that the occurrence of a defect after RME and fixed appliance therapy is relatively universal and not limited to a small number of predisposed patients. This finding does not, however, eliminate the potential that certain characteristics, such as thin periodontal biotype, may predispose patients to the development of anatomic defects.

Fenestrations accounted for the vast majority of the observed defects, while dehiscence and complete disruption of the buccal alveolar bone were much rarer. It is important to note that a systematic overestimation of dehiscences and fenestrations from CBCT images has been reported previously. For

Table 6. Spearman Correlation Coefficients Describing the Associations Between Change in Buccal Alveolar Bone Thickness at the Levels Evaluated and Amount of Expansion, Age at T1, Time Between T1 and T2, and Postexpansion Retention Time[a]

Variable	4 mm Apical CEJ	6 mm Apical CEJ	8 mm Apical CEJ
Amount of expansion	–0.00963	–0.02236	0.08548
Age at T1	0.03112	0.10558	0.28155
Time between T1 and T2	–0.01931	–0.02220	0.03538
Postexpansion retention time	–0.13295	–0.00103	–0.05228

[a] CEJ indicates cementoenamel junction.

instance, in a study by Sun et al.,[29] alveolar defects were confirmed in only 75% and 16% of patients when dehiscence and fenestrations, respectively, were found on CBCT. These findings suggest that CBCT evaluation of alveolar bone may result in systematic overreporting of anatomic defects, particularly fenestration. The spatial resolution of the CBCT scans used in this study was likely not adequate to visualize thin buccal alveolar bone and, therefore, may have contributed to overreporting of defects. Even so, it is likely that RME and fixed appliance therapy contributed to the formation of some anatomic defects, which can lead to gingival recession and periodontal instability.

Teeth with posttreatment defects of the buccal bone plate were found to have significantly thinner bone pretreatment. Since orthodontic tooth movement involves bone resorption at the compression side, it appears logical that teeth in closer proximity to the buccal bone plate would allow less buccal movement before resorption of the cortical bone occurs. An evaluation of pretreatment bone thickness adjacent to RME anchor teeth may help determine patient-specific susceptibility to the development of defects of the buccal alveolar bone.

The initial bone thickness was significantly negatively correlated with the amount of bone change indicating that teeth with initially thicker buccal alveolar bone experienced less reduction in buccal bone thickness during treatment. This finding is logical from a morphologic standpoint. Patients with greater initial bone thickness are often more brachyfacial, with broader apical bases, less buccally inclined teeth, and possibly thicker cortical plates. These patients are typically at less risk of hard and soft tissue loss than those who are more dolichofacial, have a narrower apical base, and have more buccally inclined teeth. It is also conceivable that a greater initial buccal bone thickness could provide more resistance to lateral dental movements. This would include potentially thicker cortical bone, which remodels less readily than trabecular bone.

It was somewhat surprising, and partially in disagreement with findings of earlier studies,[11] that the amount of expansion, age, postexpansion retention time, and overall treatment time were not correlated with buccal bone loss. Although this supports the second null hypothesis for these variables, it would appear logical that, with an increased amount of expansion and increased sutural resistance at an older age, the proportion of dentoalveolar expansion would increase too, leading to buccal alveolar bone loss. It is conceivable that this effect was washed out by the added effect of fixed appliance therapy in the present sample. However, the finding that postexpansion retention time had no significant association with buccal alveolar bone loss was consistent with results of previous studies.[11] While, theoretically, a shorter postexpansion retention period could allow for more relapse of dental tipping and subsequent buccal bone deposition, factors such as archform during fixed appliance therapy likely played a greater role in the relapse of dental tipping. Because retention time did not have a significant impact on buccal bone changes, the RME appliance should be retained in place for an adequate time to allow for bony fill of the separated midpalatal suture.

CONCLUSIONS

- Treatment with RME and fixed appliances can be associated with significant reduction in buccal alveolar bone thickness and an increase in anatomic defects adjacent to the mesiobuccal root of the maxillary first molar.
- RME anchor teeth with greater initial buccal bone thickness are less likely to lose buccal bone and develop posttreatment anatomic defects.
- The amount of expansion, age, postexpansion retention time, and overall treatment time are not predictive factors of the reduction in buccal alveolar bone thickness.

REFERENCES

1. Haas AJ. The treatment of maxillary deficiency by opening the mid-palatal suture. *Angle Orthod*. 1965;35:200–217.
2. Angell EC. Treatment of irregularities of the permanent or adult teeth. *Dent Cosmos*. 1860;1:540–544, 599–600.
3. Guest SS, McNamara JA, Baccetti T, Franchi L. Improving Class II malocclusion as a side-effect of rapid maxillary expansion: a prospective clinical study. *Am J Orthod Dentofac Orthop*. 2010;138:582–591.
4. Bishara SE, Staley RN. Maxillary expansion: clinical implications. *Am J Orthod Dentofac Orthop*. 1987;91:3–14.
5. Da Silva Filho O, Magro A, Capelozza Filho L. Early treatment of the Class III malocclusion with rapid maxillary expansion and maxillary protraction. *Am J Orthod Dentofac Orthop*. 1998;113:196–203.
6. Buck LM, Dalci O, Darendeliler AM, Papageorgiou SN, Papadopoulou AK. Volumetric upper airway changes after rapid maxillary expansion: a systematic review and meta-analysis. *Eur J Orthod*. 2017;39:463–473.
7. Wagemans PA, van de Velde JP, Kuijpers-Jagtman AM. Sutures and forces: a review. *Am J Orthod Dentofacial Orthop*. 1988;94:129–141.
8. Garib DG, Henriques JF, Janson G, Freitas MR, Coelho RA. Rapid maxillary expansion- tooth tissue-borne versus tooth-borne expanders: a computed tomography evaluation of dentoskeletal effects. *Angle Orthod*. 2005;75:548–557.
9. Starnbach H, Bayne D, Cleall J, Subtelny JD. Facioskeletal and dental changes resulting from rapid maxillary expansion. *Angle Orthod*. 1966;36:152–164.
10. Lemos Rinaldi M, Azeredo F, Martinelil de Lima E, Deon Rizzatto SM, Sameshima G, Macedo de Menezes L. Cone-

beam computed tomography evaluation of bone plate and root length after maxillary expansion using tooth-borne and tooth-tissue-borne banded expanders. *Am J Orthod Dentofac Orthop*. 2018;154:504–516.
11. Rungcharassaeng K, Caruso JM, Kan JY, Kim J, Taylor G. Factors affecting buccal bone changes of maxillary posterior teeth after rapid maxillary expansion. *Am J Orthod Dentofac Orthop*. 2007;132:428.e1–e8.
12. Brunetto M, Andriani JS, Ribeiro GL, Locks A, Correa M, Correa LR. Three-dimensional assessment of buccal alveolar bone after rapid and slow maxillary expansion: a clinical trial study. *Am J Orthod Dentofac Orthop*. 2013;143:633–644.
13. Pangrazio-Kulbersh V, Jezdimir B, de Deus Haughey M, Kulbersh R, Wine P, Kaczynski R. CBCT assessment of alveolar buccal bone level after RME. *Angle Orthod*. 2013;83:110–116.
14. Baysal A, Uysal T, Veli I, Ozer T, Karadede I, Hekimoglu S. Evaluation of alveolar bone loss following rapid maxillary expansion using cone-beam computed tomography. *Korean J Orthod*. 2013;43:83–95.
15. Digregorio M, Fastuca R, Zecca P, Caprioglio A, Lagravère M. Buccal bone plate thickness after rapid maxillary expansion in mixed and permanent dentitions. *Am J Orthod Dentofacial Orthop*. 2019;155:198–206.
16. Lo Giudice A, Barbato E, Cosentino L, Ferraro C, Leonardi R. Alveolar bone changes after rapid maxillary expansion with tooth-born appliances: a systematic review. *Eur J Orthod*. 2018;40:296–303.
17. Garib DG, Henriques JF, Janson G, de Freitas MR, Fernandes AY. Periodontal effects of rapid maxillary expansion with tooth-tissue-borne and tooth-borne expanders: a computed tomography evaluation. *Am J Orthod Dentofac Orthop*. 2006;129:749–758.
18. Thilander B, Nyman S, Karring T, Magnusson I. Bone regeneration in alveolar bone dehiscences related to orthodontic tooth movements. *Eur J Orthod*. 1983;5:105–114.
19. Cook V, Timock A, Crowe J, Wang M, Covell D. Accuracy of alveolar bone measurements from cone beam computed tomography acquired using varying settings. *Orthod Craniofac Res*. 2015;18:127–136.
20. Molen A. Considerations in the use of cone-beam computed tomography for buccal bone measurements. *Am J Orthod Dentofac Orthop*. 2010;137:S130–S135.
21. Wood R, Sun Z, Chaudhry J, et al. Factors affecting the accuracy of buccal alveolar bone height measurements from cone-beam computed tomography images. *Am J Orthod Dentofac Orthop*. 2013;143:353–363.
22. Patcas R, Müller L, Ullrich O, Peltomäki T. Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth. *Am J Orthod Dentofac Orthop*. 2012;141:41–50.
23. Kwong JC, Palomo JM, Landers MA. Image quality produced by different cone-beam computed tomography settings. *Am J Orthod Dentofac Orthop*. 2008;133:317–327.
24. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15:155–163.
25. Björk A, Skieller V. Growth of the maxilla in three dimensions as revealed radiographically by the implant method. *Br J Orthod*. 1977;4:53–64.
26. Björk A, Skieller V. Growth in width of the maxilla studied by the implant method. *Scand J Plast Reconstr Surg*. 1974;8:26–33.
27. Hesby RM, Marshall SD, Dawson DV, et al. Transverse skeletal and dentoalveolar changes during growth. *Am J Orthod Dentofacial Orthop*. 2006;130:721–731.
28. Korn EL, Baumrind S. Transverse development of the human jaws between the ages of 8.5 and 15.5 years, studied longitudinally with use of implants. *J Dent Res*. 1990;69:1298–1306.
29. Sun L, Zhang L, Shen G, Wang B, Fang B. Accuracy of cone-beam computed tomography in detecting alveolar bone dehiscences and fenestrations. *Am J Orthod Dentofac Orthop*. 2015;147:313–323.