Orthodontics & Craniofacial Research

ORIGINAL ARTICLE

S. Akyalcin
S. P. Alexander
R. M. Silva
J. D. English

Evaluation of three-dimensional root surface changes and resorption following rapid maxillary expansion: a cone beam computed tomography investigation

Authors' affiliations:
S. Akyalcin, S. P. Alexander, J. D. English, Department of Orthodontics, School of Dentistry, The University of Texas Health Science Center at Houston, Houston, TX, USA
R. M. Silva, Department of Endodontics, School of Dentistry, The University of Texas Health Science Center at Houston, Houston, TX, USA

Correspondence to:
S. Akyalcin
Department of Orthodontics
School of Dentistry
The University of Texas Health Science Center at Houston
7500 Cambridge Street, Suite No: 5130
Houston, TX 77021, USA
E-mail: sercan.akyalcin@uth.tmc.edu

Akyalcin S., Alexander S. P., Silva R. M., English J. D. Evaluation of three-dimensional root surface changes and resorption following rapid maxillary expansion: a cone beam computed tomography investigation
Orthod Craniofac Res 2015; **18**(Suppl.1): 117–126. © 2015 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd

Structured Abstract

Objectives – To evaluate root surface changes and resorption following toothborne rapid maxillary expansion (RME) using cone beam computed tomography (CBCT).
Setting and Sample Population – The Department of Orthodontics at The University of Texas Health Science Center. Twenty-four consecutively treated patients (mean age: 12.8 years) requiring maxillary expansion.
Material and Methods – An observational cohort included 48 CBCT images collected prior to (T1) and 4.8 months after (T2) RME from the study sample. Maxillary (study group) and mandibular (control group) first molars ($n = 48$) and first premolars ($n = 48$) were segmented and digitally registered using a 'best-fit' algorithm. Linear surface and volumetric changes between the study and control groups were compared using independent sample *t*-tests. Additionally, individual root length measurements were compared between the T1 and T2 images in each group using paired *t*-tests.
Results – All study teeth had significant changes for the evaluation of maximum linear surface area and volumetric changes as compared to control teeth ($p < 0.05$). On average, premolars and molars in the study group experienced a root shortening of 0.36–0.52 mm ($p < 0.05$). Color-coded diagrams demonstrated thinning and resorption occurring primarily at the apex and buccal aspects of the roots. Severity of these changes was individual-specific, as root resorption patterns were non-uniform.
Conclusion – Significant volume loss, linear surface area changes, and thinning/shortening of maxillary first molar and premolar roots were common findings with the use of toothborne RME therapy.

Key words: maxillary expansion; root resorption; three-dimensional imaging

Date:
Accepted 11 November 2014

DOI: 10.1111/ocr.12069

© 2015 John Wiley & Sons A/S.
Published by John Wiley & Sons Ltd

Introduction

Root resorption is an undesirable complication of orthodontic treatment as orthodontic forces trigger this clinical problem (1–3). Respectively, 2 and 5% of adolescents and adults develop root resorption of 5 mm or more in at least one tooth during their active treatment (4–6). However, the incidence of resorption among orthodontically treated individuals differs between studies because of the variability and potential shortcomings of the evaluation techniques. A striking cone beam computed tomography (CBCT) investigation on 152 patients subjects with Class I malocclusion revealed that practically, all participants and up to 91% of all teeth showed some degree of root shortening upon the completion of orthodontic treatment (7).

Dental tipping is the most widely seen orthodontic movement and before the teeth can be moved in the desired fashion, some degree of dental tipping inevitably occurs (8, 9). In addition to the orthodontic force applications, orthopedic forces used to correct a transversally deficient maxilla also cause significant buccal tipping of the posterior teeth (10–14). Studies show that heavy buccally directed forces produce significantly more resorption than light forces (15–17). As toothborne rapid maxillary expansion (RME) therapy relies on the transmission of heavy forces to the maxilla by the anchor teeth, root resorption of these teeth is a well-documented finding in histologic investigations (18–21). However, it is shown that the quantitative value of root resorption in these studies might be questionable as root resorption craters may be missed due to their small size and/or irregular shape (22). Traditionally, root resorption is studied on anchor premolar teeth that are extracted upon the completion of RME therapy as part of the individual’s treatment plan. High variability of root morphology and curved anatomy of the premolars are other confounding factors that may further complicate the interpretation of conventional histologic investigations of root resorption (22, 23).

It is suggested that patients at risk of severe apical root resorption can be identified according to the amount of resorption during the initial phases of the treatment using conventional two-dimensional (2-D) radiography adjusted for projection errors (6). Regardless of the projection geometry, conventional radiographs are not good means of quantitative evaluation and demonstration of the actual root resorption pattern (22, 24). Scientific studies that compare the use of 2-D radiographs to three-dimensional (3-D) evaluations agree that root resorption following orthodontic treatment is underestimated when evaluated with conventional radiography (3, 25, 26).

Cone beam computed tomography offers a 3-D evaluation of the roots free of projection errors *in vivo*. In our study, we aimed to test the hypothesis that a 3-D surface registration analysis of the maxillary molars and premolars obtained from CBCT scans would reveal changes to the roots due to the use of RME appliances.

Materials and methods

The sample

The study sample was formed using the records of 24 individuals (14 females, 10 males; 12.8 ± 0.22 years) that required five to eight mm of maxillary expansion as part of their comprehensive orthodontic treatment. All subjects had their first molars and premolars completely erupted at pre-treatment and had a complete set of images taken before and at the end of the retention period of expansion therapy. Individuals who had craniofacial anomalies, compliance problems, need for surgically assisted RME, and previous orthodontic treatment history were excluded from the sample. Approval for the study was granted by the Institutional Review Board of the University of the University of Texas Health Science at Houston (HSC-DB-13-0248).

All of the subjects had a complete set of CBCT images available before (T1) and 4–6 months after (T2) toothborne RME. CBCT images were captured with exposure parameters of 85 kVp, 4.0 mA, 8.01 s, 180 μm voxel size and with volume dimensions of 8 × 8 cm (Carestream Kodak

9300; Carestream Health, Inc. Rochester, NY, USA). The image reconstruction time was approximately 2 min.

Each subject had a Hyrax appliance that was supported bilaterally by two bands on each of the maxillary first molars with extension of expansion arms from bands anteriorly palatal to the second and first premolars. Maxillary expansion was started at the beginning of orthodontic treatment for all the subjects, and the appliance was activated one turn (1/4 mm/turn) per day until the maxillary alveolar arch constriction was overcorrected. That is, the appliances were activated until the palatal cusps of maxillary first molars were in contact with the buccal cusps of mandibular first molars. The average expansion measured at the mesiolingual cusps of the molars at the gingival level was 6.45 ± 0.15 mm for the sample. The total expansion time was 3–4 weeks with a mean of 25.8 days. Upon the completion of active expansion, the RME appliances were held in place between 4 and 6 months with an average retention period of 4.8 months. The appliances were then removed, and T2 images were obtained.

Measurements

Density values of different tissues, that is, teeth vs. bone, were identified in Hounsfield units (HU) and were used to segment the maxillary (study group) and mandibular (control group) first molars (n = 48) and first premolars (n = 48) using the commercial software (Anatomage, San Jose, CA, USA). The same HU were used for the same individual's T1 and T2 CBCT scans. Upon the completion of the segmentation process, the images were converted to individual stereolithography (STL) files (Fig. 1). Eight STL files were generated for each CBCT scan corresponding to the appropriate time period: right and left maxillary and mandibular first molars, and right and left maxillary and mandibular first premolars.

Based on the mean values of the percentages of root resorption (maxillary first molar, palatal root: 10.5%, mesiobuccal root: 13.7%, distobuccal root: 10.5%) following RME reported in a previous study (23), the effect size was calculated using a statistical program (G*Power 3.1; Heinrich Heine Universitat Dusseldorf Institute fur Experimentelle Psychologie, Dusseldorf, Germany). According to *a priori* computed sample size analysis using the same software program, it was estimated that to detect significant differences ($p < 0.05$, effect size d:0.48 and with 70% power) between the study and control teeth, an inclusion of 42 teeth with STL images is required in the groups.

In our study, 48 STL images were used from each type of tooth investigated, where right and left teeth of the same type were pooled. Hence, there were two types of study teeth: right and left maxillary first molars (n = 48) and first premolars (n = 48), and two types of control teeth: right and left mandibular first molars (n = 48) and first premolars (n = 48). The rationale

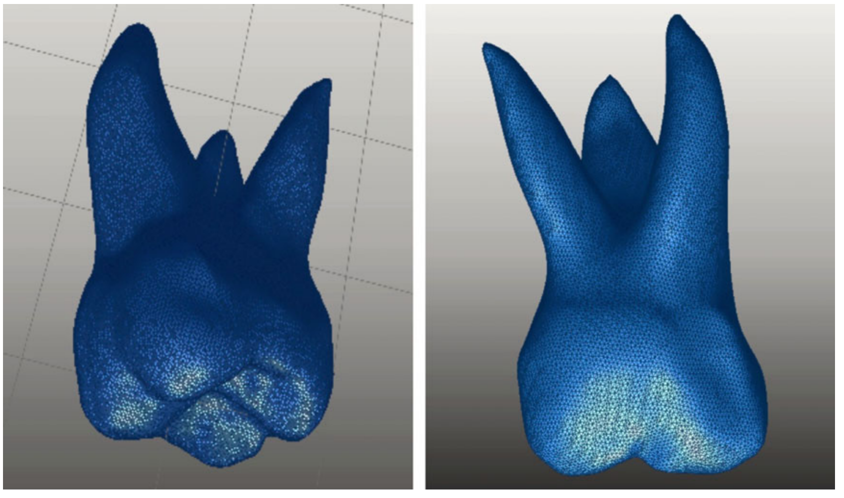

Fig. 1. 3-D STL image of a maxillary first molar: distal proximal (left) and buccal views.

behind pooling the left and right sides of the same type of teeth is that expected amounts of root resorption on the left and right sides of the jaw are similar in both the maxilla and the mandible (17, 23).

Stereolithography images were used with commercial software (Rapidform, Inus Technology, Inc, Seoul, South Korea) in pairs that corresponded to the evaluation phases of T1 and T2 for the same tooth. For orientation purposes, at least five random surface points that referred to a similar location were manually selected on the buccal, lingual, mesial proximal, distal proximal, and occlusal aspects of the T1 and T2 STL images (Fig. 2a–c). The STL image pairs were then registered with the 'best-fit' algorithm of the software utilizing all points that constitute the surface shells of the 3-D images. Following the initial registration, fine detail overlays were performed two times. The same procedure was carried out for both the study and control groups. Once superimposed, a 3-D surface registration analysis (Fig. 2d,e) was performed. This analysis calculated the average linear surface change between the two 3-D images based on data from all points of the surface shells (Fig. 3). Additionally, maximum linear distance between the surface shell areas of the 3-D images was also recorded and evaluated as the maximum linear surface change (Fig. 4).

Upon the completion of the surface registration analysis, T1 and T2 STL images were segmented immediately below the cemento-enamel junction (CEJ) to exclude the crowns. Root volumes were then computed using the same software. Additionally, each individual root length was measured using the cusp tips on the crown and the most apical point on the root of the 3-D T1 and T2 STL images (Fig. 5). The same investigator performed all analyses and measurements.

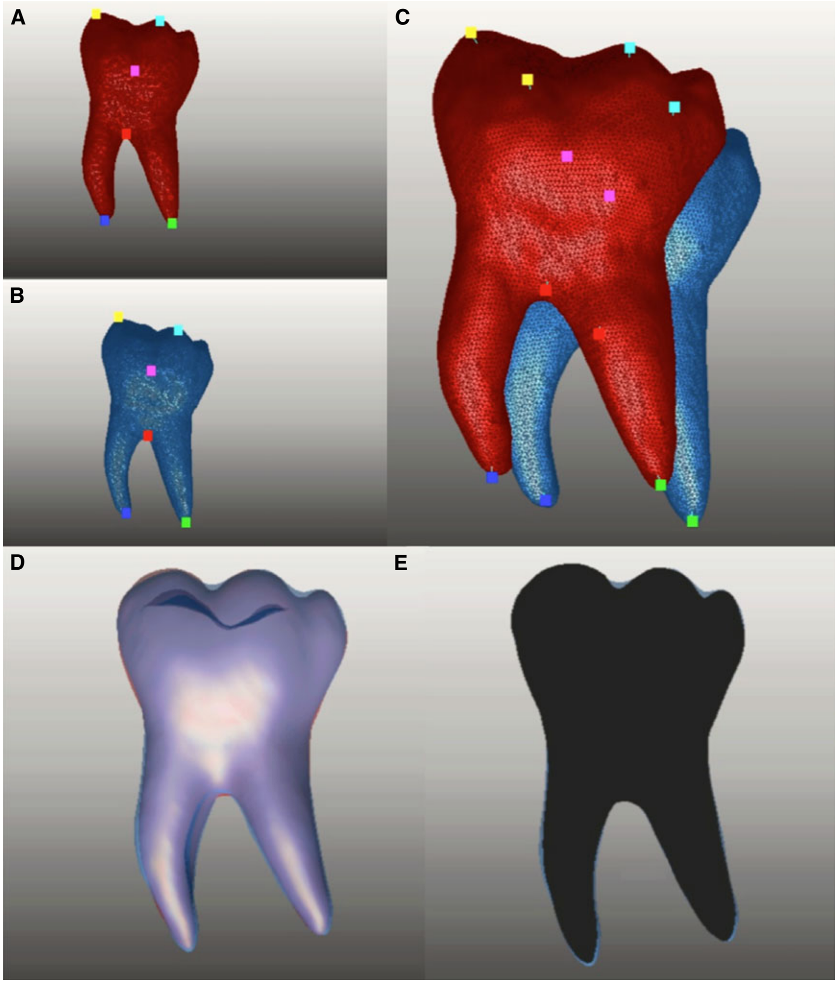

Fig. 2. 3-D surface registration process of a mandibular first molar: Orientation of the 3-D STL images was carried out by selecting at least five random points on the buccal, palatal/lingual, mesial approximal, distal approximal, and occlusal aspects of the T1 (A) and T2 (B) images of the same tooth. These points referred to a similar location on the paired T1 and T2 images (C). The STL image pairs were then registered, and surface registration analysis was applied to evaluate the average and maximum linear differences between the two 3-D images (D). Maximum correlation between the two images resulted in no evident surface changes between the T1 and T2 images (E).

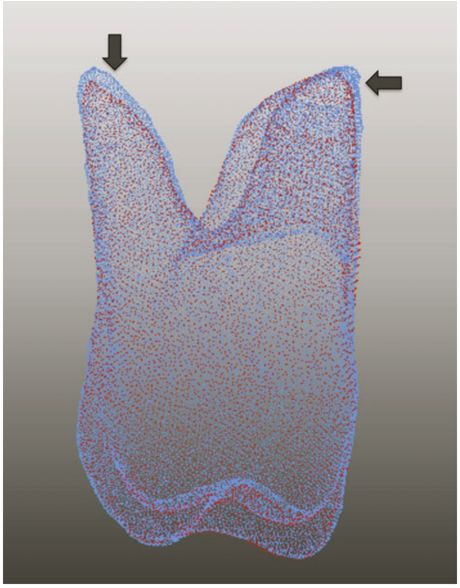

Fig. 3. Registered T1 (blue) and T2 (red) images of a maxillary right first molar – distal proximal point map view. Linear differences between the two 3-D images were calculated based on the data from all points of the surface shells. The majority of the root surface area is virtually intact despite thinning and resorption (see the arrows) on the buccal aspects of the roots.

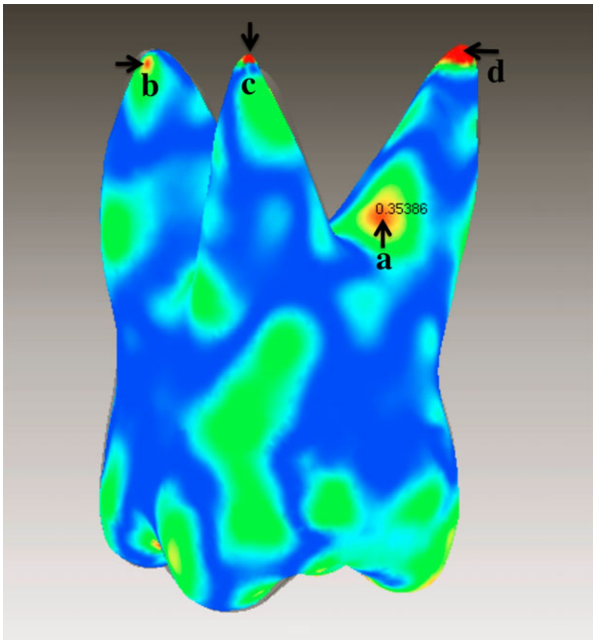

Fig. 4. Registered T1 and T2 images of a maxillary right first molar – mesial proximal color map view. Varying colors depict the surface match between the two images: blue–green (excellent–good match), yellow–red (reduced–poor match). Maximum linear change on the buccal aspect of the palatal root of the maxillary first molar is recorded as 0.35 mm over a small resorption area (a). Other arrows (b–d) point out to similar resorption areas observed on the buccal aspects of the apices.

Statistical analysis

Maximum and average linear surface changes together with root volume measurements were compared between the study and control groups using independent sample *t*-tests. Additionally, the individual root length measurements were compared between the T1 and T2 images in each group using paired *t*-tests. Commercial software (IBM SPSS Statistics, version 21; IBM, Armonk, NY, USA) was used for statistical analyses. Level of significance was set at $p < 0.05$. Records of 10 randomly selected subjects were re-evaluated and re-measured 4 weeks after the initial data analysis. Error study was performed using the Dahlberg's formula. The within-observer repeatability was evaluated using intraclass correlation coefficients (ICCs).

Results

The mean test–retest ICC between the first and second evaluations was 0.91 (95% CI 0.86–0.94), which indicated a high level of repeatability for the measurements used in the study. Descriptive and statistical evaluations for the variables used in this study are presented in Tables 1–3. Operator error for linear surface changes and volumetric measurements varied between 0.001 mm to 0.027 mm and 0.22 mm^3 to 0.98 mm^3, respectively. Operator error for the individual root length measurements did not exceed 0.1 mm.

Linear surface changes

The mean average linear surface changes for the maxillary first molars and first premolars (study group) were -0.13 ± 0.025 and -0.12 ± 0.032 mm, respectively, and were not significantly different from the mandibular teeth (control group), which were 0.04–0.05 mm ($p > 0.05$). The mean maximum linear surface change for maxillary first molars and first premolars (study group) were -0.54 ± 0.04 mm and -0.44 ± 0.02 mm, respectively, and significantly greater than mandibular first molars and first premolars (control group), which were

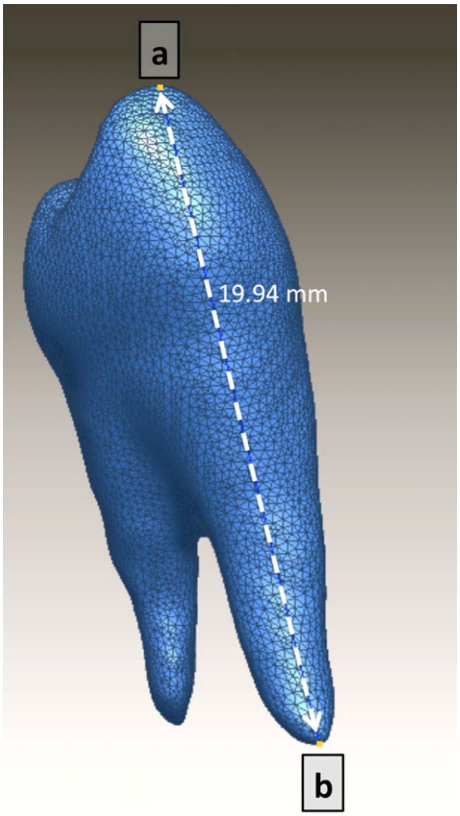

Fig. 5. Root length measurements were carried out by selecting two points for each root: cusp tip (a) and most apical point on the root (b). Buccal root length measurement (see line between points a and b) of a maxillary first premolar is recorded as 19.94 mm in this example.

0.10 ± 0.009 mm and 0.10 ± 0.009 mm, respectively (Table 1; $p < 0.05$).

Volume changes

The mean volume changes in the study group from T1 to T2 showed average decreases of 37.4 mm^3 for the first molar and 12.4 mm^3 for the premolar roots (Table 2). In contrast, the control group showed minor increases in root volume for both the molar (5.2 mm^3) and the premolar (2.7 mm^3). Comparisons between the two groups showed these differences were significant for both the molar and premolars ($p < 0.05$).

Root length changes

Individual root length values from T1 to T2 for the study group showed significant decreases (Table 3; $p < 0.05$). On the average, molars and premolars in the study group experienced a root shortening of 0.36–0.52 mm. The greatest changes were recorded for the palatal (0.52 mm) and mesiobuccal (0.49 mm) roots of the first molars. On the contrary, mandibular (control group) molar and premolars had root length increases of 0.07–0.11 mm, but these differences were not significant ($p > 0.05$).

Discussion

Our method allowed us to study the root surface changes and resorption to the anchor teeth following RME in a non-invasive fashion. The ability of evaluating these changes three-dimensionally with both quantitative and qualitative measures provides us with a better appreciation of these changes. Baysal et al. (23) evaluated root resorption following maxillary expansion through the use of CBCT and determined that there was a statistically significant

***Table 1.* Comparison of linear surface changes from T1 to T2 between the maxillary (study) and mandibular (control) groups**

Tooth type	Group	N	T1–T2 Mean (mm)	SD	p
First molar – maximum linear surface change	Maxillary	48	0.54	0.043	<0.001
	Mandibular	48	−0.10	0.009	
First premolar – maximum linear surface change	Maxillary	48	0.44	0.027	<0.001
	Mandibular	48	−0.10	0.009	
First molar – average linear surface change	Maxillary	48	0.13	0.025	0.155
	Mandibular	48	−0.04	0.007	
First premolar – average linear surface change	Maxillary	48	0.12	0.032	0.732
	Mandibular	48	−0.05	0.009	

Table 2. **Comparison of volumetric (mm^3) changes between the maxillary (study) and mandibular (control) groups**

	Group	N	T1–T2 Mean (mm^3)	SD	p
Molar roots	Maxillary	48	37.4	18.4	<0.001
	Mandibular	48	−5.2	16.3	
Premolar roots	Maxillary	48	12.4	11.3	<0.001
	Mandibular	48	−2.7	8.82	

Table 3. **Individual root length measurements before and after expansion therapy in maxillary (study) and mandibular (control) groups**

	N	Mean (mm)	SD	p
Maxillary molar mesiobuccal				
T1	48	19.6	0.9	<0.001
T2	48	19.2	0.9	
Maxillary molar distobuccal				
T1	48	19.4	0.8	<0.001
T2	48	19.0	0.8	
Maxillary molar palatal				
T1	48	20.7	0.8	<0.001
T2	48	20.2	0.9	
Maxillary premolar buccal				
T1	48	21.1	0.7	<0.001
T2	48	20.7	0.6	
Maxillary premolar palatal				
T1	48	19.9	1.0	<0.001
T2	48	19.5	0.9	
Mandibular molar mesial				
T1	48	20.5	0.7	0.112
T2	48	20.7	0.6	
Mandibular molar distal				
T1	48	20.2	0.4	0.058
T2	48	20.3	0.3	
Mandibular premolar				
T1	48	21.8	0.4	0.143
T2	48	21.9	0.4	

difference in root volumes between the pre-expansion and post-expansion periods. However, their study only analyzed the maxillary teeth, which are directly exposed to forces generated by the expansion appliances. In the present study, we were able to use the mandibular teeth from the same sample group that were subjected to maxillary expansion as localized controls to enhance our findings and to add to the existing information in the literature.

According to our findings, significant volume decreases were detected for the maxillary teeth. This was in agreement with the findings of recent investigations (23, 27). Although, the mandibular teeth had slight increases in their volumes, these changes were very small and not significant. This may theoretically be explained by the continuous cementum formation due to changes in the occlusion. However, there is no certain comparison as the opposing maxillary teeth are also affected by heavy forces generated through the RME appliances. The changes in the control group may also be overestimated by the operator error. Similarly, mandibular teeth had slight increases for the root length measurements. Upon analyzing each individual root length, all the maxillary molars and premolars experienced significant decreases, while the mandibular teeth experienced non-significant changes.

In a study by Castro et al. (28) that examined frequency of apical root resorption due to orthodontic therapy, the most significant amount of resorption in the posterior teeth occurred on the distal roots of the maxillary first molars. Our results showed slightly more resorption occurring on the palatal root, and this could be a result of differential forces generated by RME. RME appliances deliver a much greater buccal force to the teeth than traditional orthodontic appliances. In cases where the sutural opening is limited and/or complicated by other cranial structures, alveolar bending and buccal tipping of the teeth occur at a variable rate (29, 30). Therefore, increased tendency for resorption of the palatal root of maxillary first molars in the current study may be linked to the buccal tipping of the teeth and consequent compression of PDL against the palatal bone adjacent to this root tip.

One of the unique aspects of the current study was the evaluation of the root surface area changes through a three-dimensional registration analysis. According to our findings, maximum linear surface change difference between the study and the control groups was 0.5–0.6 mm ($p < 0.05$). However, when looking at the mean linear changes at all points of the surface area, no significant differences were recorded between the two groups of teeth. This was due to the non-uniform character and small size of the resorption areas, which did not significantly affect the average surface changes. Additionally, the majority of the root surface area remained virtually intact.

It is observed that following expansion therapy, the roots of the maxillary first molars and premolars will experience some structure loss on the roots that are characterized by resorption and development of craters in common areas such as the apices and the buccal aspects of the roots. This is also true when a part of the root experiences thinning/shortening as a result of force application. In a study to investigate the side effects of RME treatment, Langford (18) reported that the resorption primarily occurs on the buccal surface of the teeth. Our findings are in agreement with his conclusions. Qualitative inspection of the resultant images in the present study showed most of the changes from T1 to T2 occurred at the apex of the maxillary teeth and on the buccal aspects of the roots. However, root surface area changes may not indicate any clinical concerns as the overall root structure remained virtually unchanged as observed by both quantitative and qualitative methods.

Segmentation and registration techniques used in this study could be affected by confounding factors such as voxel size, scatter radiation, artifact, and other parameters related to the imaging device (31). Accordingly, it could be difficult to determine the borders between the root surface, cementum, and alveolar bone due to these factors. Therefore, our findings are limited by the currently available technology. While segmentation and three-dimensional registration techniques continue to improve, further studies are required to confirm and to expand on the current results. Additionally, a new study could be performed to examine other types of expansion protocols, as we were only able to examine the effects of a toothborne expander with a single turn/day protocol. It would also be of great interest to study the surface changes resulting from a rapid vs. slow maxillary expansion technique, intermittent vs. continuous force application, and differing age groups.

Conclusions

1. Significant volume loss, linear surface area changes, and thinning/shortening of maxillary first molar and premolar roots were common findings with the use of toothborne RME therapy.
2. Severity of changes in root size and shape was highly individual-specific, and root resorption patterns were not uniform.

Clinical relevance

Resorption of the root structure is a common undesirable side effect of orthodontic applications – particularly through the use of heavy forces such as those generated by RME devices. To our knowledge, this is the first study to examine resorption and changes of the root surface following RME application with the use of a three-dimensional surface registration analysis. Our results demonstrated the pattern and nature of this clinical complication with both quantitative and visual methods. Our findings suggested avoiding the use of toothborne RME, whenever possible, in individuals that are deemed to have a preexisting root resorption condition.

References

1. Topkara A, Karaman AI, Kau CH. Apical root resorption caused by orthodontic forces: a brief review and a long-term observation. *Eur J Dent* 2012;6:445–53.
2. Weltman B, Vig KW, Fields HW, Shanker S, Kaizar EE. Root resorption associated with orthodontic tooth movement: a systematic review. *Am J Orthod Dentofacial Orthop* 2010;137:462–76.
3. Dudic A, Giannopoulou C, Leuzinger M, Kiliaridis S. Detection of apical root resorption after orthodontic treatment by using panoramic radiography and cone-beam computed tomography of super-high resolution. *Am J Orthod Dentofacial Orthop* 2009;135:434–7.
4. Linge BO, Linge L. Apical root resorption in upper anterior teeth. *Eur J Orthod* 1983;5:173–83.
5. Mirabella AD, Artun J. Prevalence and severity of apical root resorption of maxillary anterior teeth in adult orthodontic patients. *Eur J Orthod* 1995;17:93–9.
6. Artun J, Van 't Hullenaar R, Doppel D, Kuijpers-Jagtman AM. Identification of orthodontic patients at risk of severe apical root resorption. *Am J Orthod Dentofacial Orthop* 2009;135:448–55.
7. Lund H, Gröndahl K, Hansen K, Gröndahl HG. Apical root resorption during orthodontic treatment. A prospective study using cone beam CT. *Angle Orthod* 2012;82:480–7.
8. Rudolph DJ, Willes PMG, Sameshima GT. A finite element model of apical force distribution from orthodontic tooth movement. *Angle Orthod* 2001;71:127–31.
9. Field C, Ichim I, Swain MV, Chan E, Darendeliler MA, Li W et al. Mechanical responses to orthodontic loading: a 3-dimensional finite element multi-tooth model. *Am J Orthod Dentofacial Orthop* 2009;135:174–81.
10. Christie KF, Boucher N, Chung CH. Effects of bonded rapid palatal expansion on the transverse dimensions of the maxilla: a cone-beam computed tomography study. *Am J Orthod Dentofacial Orthop* 2010;137:S79–85.
11. Ghoneima A, Abdel-Fattah E, Eraso F, Fardo D, Kula K, Hartsfield J. Skeletal and dental changes after rapid maxillary expansion: a computed tomography study. *Aust Orthod J* 2010;26:141–8.
12. Weissheimer A, de Menezes LM, Mezomo M, Dias DM, de Lima EM, Rizzatto SM. Immediate effects of rapid maxillary expansion with Haas-type and hyrax-type expanders: a randomized clinical trial. *Am J Orthod Dentofacial Orthop* 2011;140:366–76.
13. Domann CE, Kau CH, English JD, Xia JJ, Souccar NM, Lee RP. Cone beam computed tomography analysis of dentoalveolar changes immediately after maxillary expansion. *Orthodontics (Chic.)* 2011;12:202–9.
14. Lione R, Franchi L, Cozza P. Does rapid maxillary expansion induce adverse effects in growing subjects? *Angle Orthod* 2013;83:172–82.
15. Paetyangkul A, Türk T, Elekdağ-Türk S, Jones AS, Petocz P, Cheng LL et al. Physical properties of root cementum: Part 16. Comparisons of root resorption and resorption craters after the application of light and heavy continuous and controlled orthodontic forces for 4, 8, and 12 weeks. *Am J Orthod Dentofacial Orthop* 2011;139:e279–84.
16. Wu AT, Turk T, Colak C, Elekdağ-Turk S, Jones AS, Petocz P et al. Physical properties of root cementum: Part 18. The extent of root resorption after the application of light and heavy controlled rotational orthodontic forces for 4 weeks: a microcomputed tomography study. *Am J Orthod Dentofacial Orthop* 2011;139:e495–503.
17. Oh C, Türk T, Elekdağ-Türk S, Jones AS, Petocz P, Cheng LL et al. Physical properties of root cementum: Part 19. Comparison of the amounts of root resorption between the right and left first premolars after application of buccally directed heavy orthodontic tipping forces. *Am J Orthod Dentofacial Orthop* 2011;140:e49–52.
18. Langford SR. Root resorption extremes resulting from clinical RME. *Am J Orthod.* 1982;81:371–7.
19. Langford SR, Sims MR. Root surface resorption, repair, and periodontal attachment following rapid maxillary expansion in man. *Am J Orthod* 1982;81:108–15.
20. Odenrick L, Karlander EL, Pierce A, Kretschmar U. Surface resorption following two forms of rapid maxillary expansion. *Eur J Orthod* 1991;13:264–70.
21. Erverdi N, Okar I, Kücükkeles N, Arbak S. A comparison of two different rapid palatal expansion techniques from the point of root resorption. *Am J Orthod Dentofacial Orthop.* 1994;106:47–51.
22. Chan EK, Darendeliler MA. Exploring the third dimension in root resorption. *Orthod Craniofac Res* 2004;7:64–70.
23. Baysal A, Karadede I, Hekimoglu S, Ucar F, Ozer T, Veli I et al. Evaluation of root resorption following rapid maxillary expansion using cone-beam computed tomography. *Angle Orthod* 2012;82:488–94.
24. Ericson S, Kurol J. Incisor root resorptions due to ectopic maxillary canines imaged by computerized tomography: a comparative study in extracted teeth. *Angle Orthod* 2000;70:276–83.
25. Dudic A, Giannopoulou C, Martinez M, Montet X, Kiliaridis S. Diagnostic accuracy of digitized periapical radiographs validated against micro-computed tomography scanning in evaluating orthodontically induced apical root resorption. *Eur J Oral Sci* 2008;116:467–72.
26. Alqerban A, Jacobs R, Fieuws S, Willems G. Comparison of two cone beam computed tomographic systems versus panoramic imaging for localization of impacted maxillary canines and detection of root resorption. *Eur J Orthod* 2011; 33:93–102.
27. Forst D, Nijjar S, Khaled Y, Lagravere M, Flores-Mir C. Radiographic assessment of external root resoprtion associated with jackscrew-based maxillary expansion therapies: a systematic review. *Eur J Orthod* 2014;36:576–85.
28. Castro IO, Alencar AH, Valladares-Neto J, Estrela C. Apical root resorption due to orthodontic treatment detected by cone beam computed

tomography. *Angle Orthod* 2013;83:196–203.
29. Pangrazio-Kulbersh V, Wine P, Haughey M, Pajtas B, Kaczynski R. Cone beam computed tomography evaluation of changes in the naso-maxillary complex associated with two types of maxillary expanders. *Angle Orthod* 2012;82:448–57.
30. Akyalcin S, Schaefer JS, English JD, Stephens CR, Winkelmann S. A cone-beam computed tomography evaluation of buccal bone thickness following maxillary expansion. *Imaging Sci Dent* 2013;43:85–90.
31. Molen AD. Considerations in the use of cone-beam computed tomography for buccal bone measurements. *Am J Orthod Dentofacial Orthop* 2010;137:130–5.

Copyright of Orthodontics & Craniofacial Research is the property of Wiley-Blackwell and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.