Original Article

Does the rhythm and appliance type of rapid maxillary expansion have an effect on root resorption?

A comparative clinical study using micro–computed tomography

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ABSTRACT

Objectives: To evaluate the volume, amount, and localization of root resorption in the upper first premolars by micro–computed tomography (micro-CT) after three different rapid maxillary expansion appliances and two different activation rhythms.

Materials and Methods: The patients were divided into three groups; Hyrax, acrylic cap splint (ACS), and full coverage acrylic bonded (FCAB) appliances. Each group was then divided into the following two subgroups: rapid maxillary expansion (RME) and semirapid maxillary expansion (SRME). After expansion was completed, the appliances were stabilized for 12 weeks during the retention period. For each group, 10 premolars (for a total of 60 premolars) were scanned with the micro-CT (SkyScan). The reconstructed 3D images of each root sample were divided into six regions. The resorption craters on these six different root surfaces were analyzed by special CTAn (SkyScan) software for direct volumetric measurements. Kruskal-Wallis one-way analysis of variance and Mann-Whitney *U* tests were used for statistical analysis.

Results: The total volume of root resorption was less with FCAB than with ACS and Hyrax ($P < .001$). In all groups, a greater volume of resorption was found on the buccal surface than on the lingual surface ($P < .001$). No significant differences were found between the RME and SRME groups ($P > .05$).

Conclusions: All expansion appliances caused root resorption in the upper first premolar teeth, but FCAB may be safer in terms of root resorption. The resorption craters were generally concentrated on the buccal surface. There was no effect of activation rhythm on root resorption. (*Angle Orthod.* 2021;91:293–300.)

KEY WORDS: Rapid maxillary expansion; Semirapid maxillary expansion; Root resorption; Micro-CT

INTRODUCTION

Rapid maxillary expansion (RME) treatment has been widely used for 160 years and has been accepted as an effective treatment method in patients exhibiting transverse and/or sagittal maxillary deficiencies, rhinologic and/or respiratory problems, and cleft lip and palate.[1–3] RME devices may be tooth borne, tooth-tissue borne, bone borne, or a combination. The conventional activation protocol for RME appliances is two turns per day until the desired expansion has been achieved.[4,5] However, some investigators have claimed that rapid separation of the maxillary bones results in a relapse tendency in the long term and that relatively slower expansion of the maxilla would probably produce less tissue resistance on the surrounding structures. Therefore, they recommend two turns each day for the first 5 days and three turns each week afterward, namely, semirapid maxillary expansion (SRME).[1,6]

The biomechanical principles governing tooth movement can be used to separate the maxillofacial bones by RME. However, the magnitude of the forces required to separate the mid-palatal suture is approx-

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Table 1. Distribution of the Patients According to Groups: Mean and Standard Deviation of the Age and Activation Amount

	Patient, n	Sample, n	Mean Age ± SD, y	Activation ± SD, Turns
Hyrax-RME	5	10	13.08 ± 1.15	34.80 ± 5.44
Hyrax-SRME	5	10	14.58 ± 0.66	34.60 ± 3.57
ACS-RME	5	10	13.79 ± 0.88	32.20 ± 4.71
ACS-SRME	5	10	14.26 ± 1.32	35.41 ± 6.69
FCAB-RME	5	10	13.01 ± 1.37	38.60 ± 5.36
FCAB-SRME	5	10	13.55 ± 1.34	32.60 ± 6.26

imately 900–4500 g, which is very high compared with what is required to move teeth.[1,4,5] Severe forces are applied to the upper premolar and molar teeth, inducing hyalinization of their periodontium. This allows a transfer of loading to the maxillary halves, promoting opening of the midpalatal suture.[4,5] Notable complications that may occur after an RME procedure are bone dehiscence and root resorption of the anchor teeth due to the heavy forces.[4,7–11]

The examination of root resorption craters in three-dimensional (3D) configurations with high-dimensional resolutions is possible using micro–computed tomography (micro-CT).[11–13] Micro-CT has been used as an imaging and evaluation technique in different fields of dentistry.[11–16] No comparative clinical study has examined the effects of RME and SRME protocols with different appliance designs on root resorption. Therefore, the aim of this study was to investigate the volume and amount of root resorption craters in the upper first premolars using micro-CT after Hyrax, acrylic bonded cap splint, and full-coverage appliances with two different maxillary expansion rhythms.

MATERIALS AND METHODS

The human ethical committee of İnönü University (2014/23) approved this study. This randomized and blinded clinical trial was conducted in the Department of Orthodontics, İnönü University. Thirty patients (17 girls and 13 boys) within the age range of 13–15 years were selected (Table 1). All patients had severe transverse maxillary deficiencies, upper dental misalignment, and orthodontic indications for both maxillary expansion and the extraction of the first upper premolars. Patients with any systemic disease, parafunctional habits, history of trauma, craniofacial anomaly, bruxism, and fillings or root canal treatment in the upper premolar teeth were not included in this investigation.

Three different maxillary expansion appliances were used: Hyrax, acrylic cap splint (ACS), and full coverage acrylic bonded (FCAB). The Hyrax[5] is a tooth-borne appliance and consisted of a screw soldered directly to bands cemented on the first premolars and molars (Figure 1a). The ACS[3] appliance is also a tooth-borne appliance, but tooth anchorage was extended from the first premolars to the second molar on both sides. Acrylic resin extended over the occlusal and middle third of the buccal surfaces of all posterior teeth (Figure 1b). The FCAB[1,2] appliance is a tooth-tissue-borne device. A screw was embedded in acrylic between the first molars as close as possible to the palate, with the resin covering the occlusal and labial surfaces of all maxillary permanent teeth and the palate (Figure 1c). These three maxillary expansion appliance groups were divided into two subgroups of RME and SRME according to the screw activation protocol. The activation rate was prescribed to be one turn in the morning and another turn in the evening each day until the desired expansion in the RME groups was achieved. In the SRME groups, the activation protocol included two turns per day for the first 5 days followed by one turn every 2 days. Randomization was accomplished at the start of the study using prepared random number tables. One researcher evaluated the patients, and the other author conducted study enrollment. Patients were divided into the following six groups:

1. Hyrax-RME
2. Hyrax-SRME
3. ACS-RME,
4. ACS-SRME

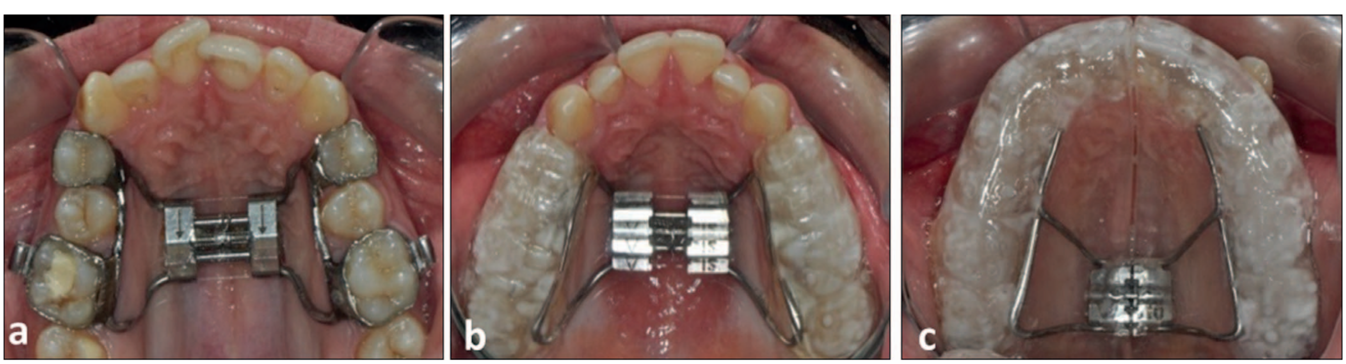

Figure 1. Appliances used in this study. (a) Hyrax appliance. (b) Acrylic cap splint appliance. (c) Full coverage acrylic bonded appliance.

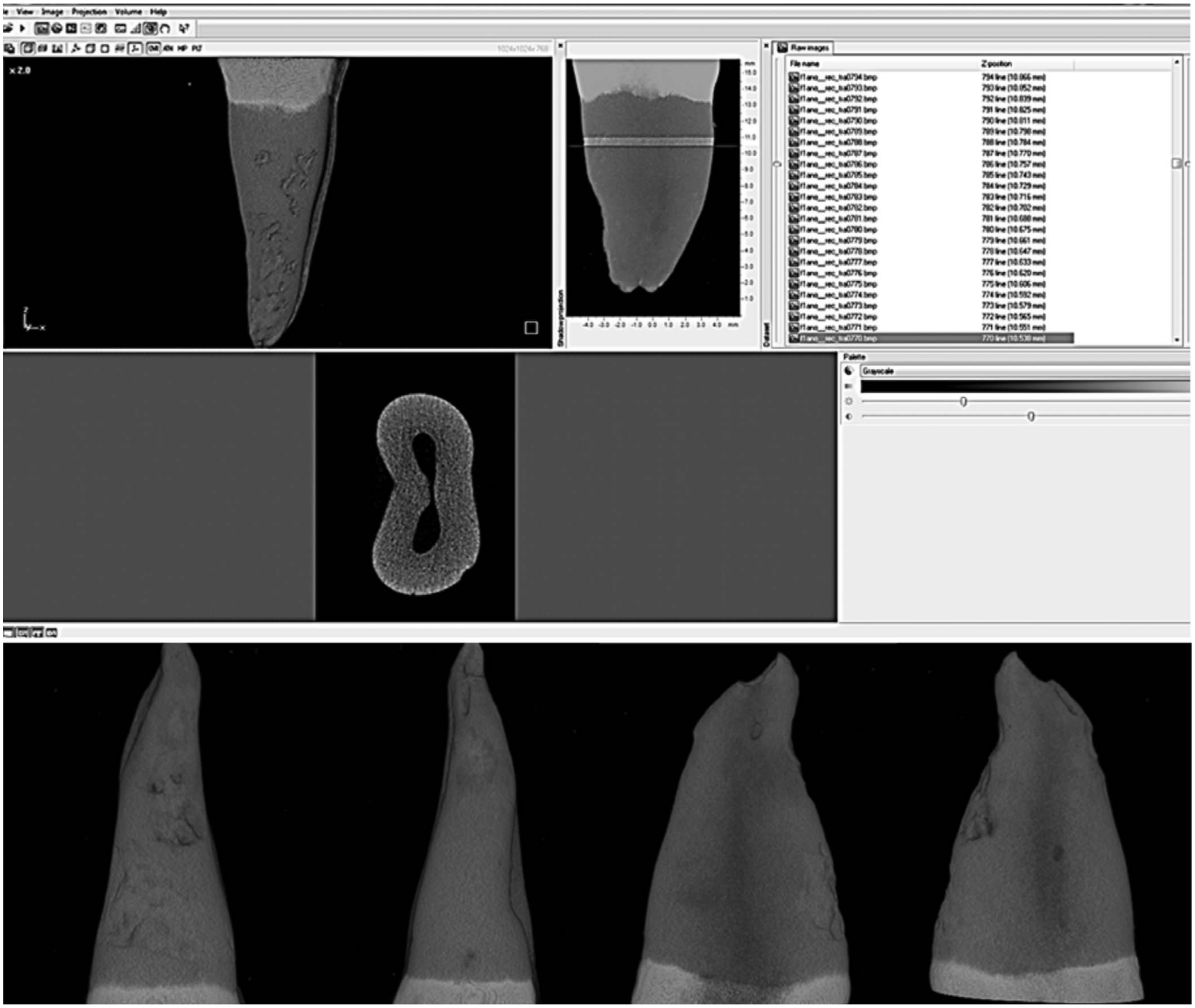

Figure 2. Micro-CT image of maxillary first premolar.

5. FCAB-RME
6. FCAB-SRME

Each group consisted of the 10 maxillary first premolars of five patients. To determine the sample size for each group, a power analysis was carried out based on an alpha significance level of .05 and a beta value of .1 to achieve 80% power to detect an average difference of 0.5 mm^3 ($\pm$0.20 mm^3) in resorption craters on root surfaces among the different groups (version 3.0.10, G*Power; Franz Faul, Universität Kiel, Germany).[13] The power analysis showed that at least eight samples for each group were required. For this reason, each group consisted of 10 maxillary first premolars. After the retention phase, the same oral surgeon extracted the left and right premolars. The teeth were washed with an isotonic solution without applying pressure and touching the root surfaces and then disinfected for 30 minutes with 70% alcohol. The teeth were stored in sterile tubes containing distilled water.

Micro-CT Analysis

All samples were scanned with an X-ray desktop microtomographer (SkyScan 1172; Bruker, Kontich, Belgium). The micro-CT system was set to 100 kV and 100 mA with the aid of a 0.5 mm Al + Cu filter. The scanned data were transformed into images with NRecon (version 1.6.9.4, SkyScan). Reconstructed 3D images were then viewed and processed using the data analysis software CTAn (version 1.13.5.1, SkyScan; Figure 2). The resorption crater volumes on the root surface were analyzed in six regions. The entire root surface was divided vertically into three sections:

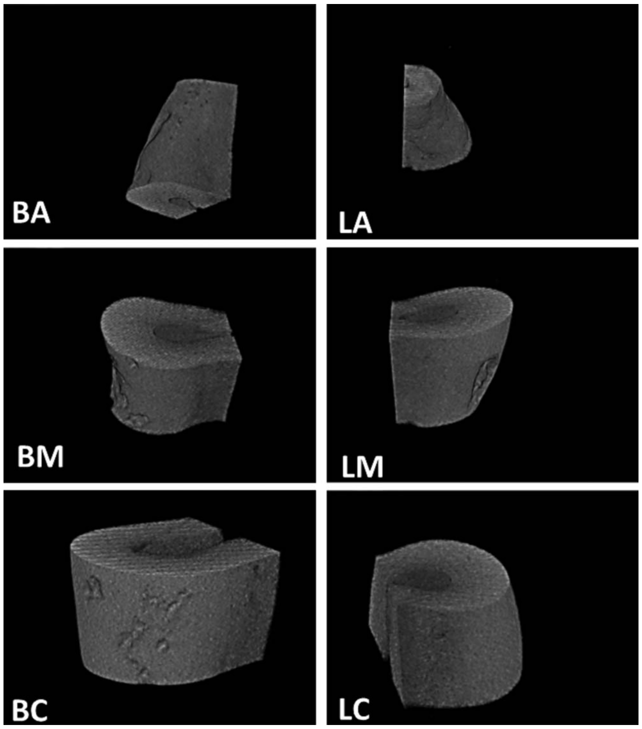

Figure 3. Separation of the root vertically in three sections (apical, middle, cervical) and horizontally in two sections (buccal, lingual). BC indicates buccal cervical; LC, lingual cervical; BM, buccal middle; LM, lingual middle; BA, buccal apical; LA, lingual apical.

cervical, middle, and apical. Each section was then divided into two subregions: buccal and lingual. These regions were called the buccal cervical (BC), lingual cervical (LC), buccal middle (BM), lingual middle (LM), buccal apical (BA), and lingual apical (LA) regions (Figure 3). In the reconstructed 3D images of each sample, the cross-sectional images showing the whole resorption craters on the buccal or lingual surface of the tooth were located. Then, the region of interest was drawn for each sampled image. In the second phase, the thresholding of the lesion density was defined. Lastly, through custom processing, the lesion depth in each selected image was measured (Figure 4).

Statistical Analysis

The results were analyzed using the Statistical Package for Social Sciences software (version 22, SPSS for Windows). Descriptive statistical data (means and standard deviations) were calculated. Nonparametric statistical tests were conducted to determine the volumes and numbers of resorption craters. Kruskal-Wallis one-way analysis of variance test and Mann-Whitney *U* test with the Bonferroni correction were performed for statistical assessments. The results were considered significant at $P < .05$.

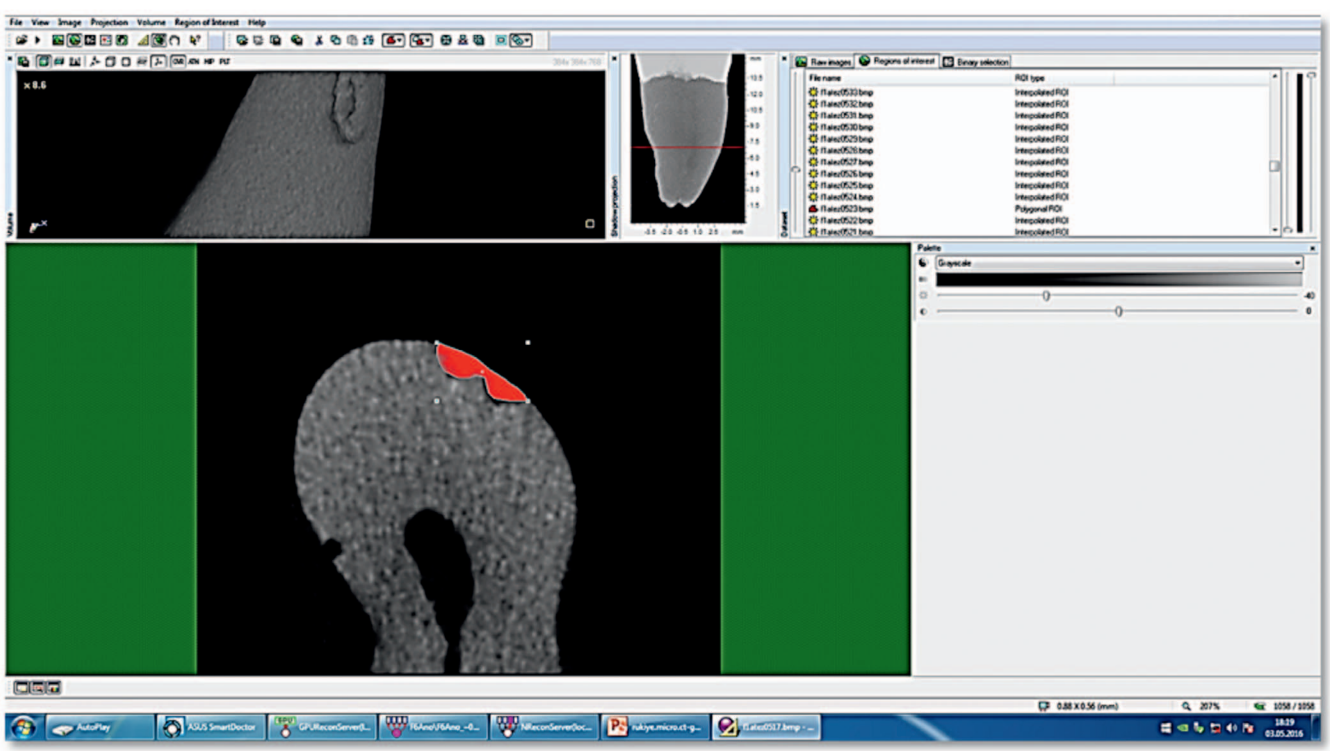

Figure 4. CTAn 1.15.4.0 (Skyscan, Kontich, Belgium) software, isolation of resorption crater from the root surface.

Table 2. Comparison of Root Resorption Volumes (mm³) Among the Groups and Buccal-Lingual Surfaces

	Buccal, Mean ± SD	Lingual, Mean ± SD	Total, Mean ± SD	P^a
Hyrax-RME	0.170 ± 0.093 a	0.090 ± 0.080 a	0.260 ± 0.160 a	<.001***
Hyrax-SRME	0.129 ± 0.040 b	0.072 ± 0.060 a	0.201 ± 0.060 a	<.001***
ACS-RME	0.150 ± 0.134 a	0.080 ± 0.080 a	0.230 ± 0.190 a	<.001***
ACS-SRME	0.161 ± 0.092 a	0.050 ± 0.024 b	0.211 ± 0.100 a	<.001***
FCAB-RME	0.120 ± 0.072 b	0.040 ± 0.035 b	0.156 ± 0.090 b	<.001***
FCAB-SRME	0.108 ± 0.060 b	0.044 ± 0.054 b	0.152 ± 0.100 b	<.001***
P^b	<.05*	<.01**	<.05*	

[a] *P* comparison of buccal and lingual surfaces: according to the Mann-Whitney *U* test (with Bonferroni correction).

[b] *P* comparison of appliances groups: according to the Kruskal-Wallis one-way analysis of variance and the Mann-Whitney *U* test (with Bonferroni correction), there is no statistically significant difference between groups with the same letters.

* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

RESULTS

The descriptive statistical data of the total, buccal, and lingual volumes of root resorption among the groups are presented in Table 2. Among all the groups, the FCAB-RME and FCAB-SRME groups had the lowest volume of root resorption, and this difference was statistically significant ($P < .05$). No statistically significant difference was found among the Hyrax-RME, Hyrax-SRME, ACS-RME, and ACS-SRME groups with respect to the total resorption crater volume ($P > .05$). Generally, the total volume of root resorption was less in the tooth-tissue–borne FCAB groups than in the tooth-borne ACS and Hyrax groups ($P < .001$). In addition, a greater volume of resorption was found on the buccal surface than on the lingual surface in all groups ($P < .001$).

When the volume of resorption was analyzed in the six different root regions, the FCAB-RME and FCAB-SRME groups showed significantly smaller resorption crater volume than the others in the BC region ($P < .01$). A significantly higher root resorption volume was observed in the ACS-RME group in the LC region ($P < .05$). Second, a significantly lesser root resorption volume was observed in the ACS-RME group in the LA region, whereas higher root resorption volumes were detected in the Hyrax-RME and Hyrax-SRME groups in the same region ($P < .01$). Finally, there were no significant differences in root resorption volumes observed in the BM and LM regions ($P > .05$; Table 3).

The number of root resorption craters according to localization is shown in Tables 4 and 5. Statistically significant differences were found among the groups. The lowest number of craters was detected in the FCAB-SRME group ($P < .01$) and the highest in the ACS-RME and ACS-SRME groups ($P < .05$; Table 4). In addition, a greater resorption number was observed on the buccal surface than on the lingual surface in all groups. The BC, BM, and BA regions in the FCAB-RME group showed the significantly lowest number of resorption craters. In addition, the FCAB-SRME group had the significantly lowest number of resorption craters in the LC, LM, and LA regions ($P < .05$), and the ACS-SRME group had the higher number of resorption craters in the BC and BA regions ($P < .05$; Table 5).

When the cervical, middle, and apical regions were analyzed in all groups, the differences between the cervical and middle regions were significant in terms of root resorption volume ($P < .05$); the apical region showed significantly less root resorption than the cervical and middle regions. The number of root resorption craters was significantly lower in the cervical region ($P < .01$), and no significant difference was found between the apical and middle regions ($P > .05$; Table 6).

Table 3. Comparison of Root Resorption Volumes (mm³) of Six Different Surfaces Among the Groups[a]

Group	Buccal Cervical	Lingual Cervical	Buccal Middle	Lingual Middle	Buccal Apical	Lingual Apical
Hyrax-RME	0.065 ± 0.040 a	0.023 ± 0.030 a	0.055 ± 0.060	0.041 ± 0.037 a	0.050 ± 0.040 a	0.021 ± 0.020 a
Hyrax-SRME	0.049 ± 0.020 ab	0.020 ± 0.027 a	0.035 ± 0.030	0.030 ± 0.030 ab	0.020 ± 0.012 ab	0.022 ± 0.017 a
ACS-RME	0.060 ± 0.070 a	0.040 ± 0.053 b	0.050 ± 0.044	0.032 ± 0.040 ab	0.042 ± 0.050 a	0.005 ± 0.005 b
ACS-SRME	0.075 ± 0.046 a	0.016 ± 0.006 a	0.054 ± 0.040	0.025 ± 0.025 ab	0.031 ± 0.030 ab	0.018 ± 0.021 ab
FCAB-RME	0.030 ± 0.030 b	0.011 ± 0.021 a	0.051 ± 0.050	0.012 ± 0.0141b	0.013 ± 0.008 b	0.014 ± 0.015 ab
FCAB-SRME	0.032 ± 0.028 b	0.016 ± 0.030 a	0.051 ± 0.030	0.016 ± 0.022 ab	0.025 ± 0.021 ab	0.012 ± 0.020 ab
P	< .01**	< .05*	> .05	< .05*	< .001***	< .01**

[a] According to the Kruskal-Wallis one-way analysis of variance and the Mann-Whitney *U* test (with Bonferroni correction), there is no statistically significant difference between groups with the same letters.

* $P \leq .05$; *** $P \leq .01$; **** $P \leq .001$.

Table 4. Comparison of Root Resorption Number Among the Groups and Between Buccal and Lingual Surfaces

	Buccal, Mean ± SD	Lingual, Mean ± SD	Total, Mean ± SD	P^a
Hyrax-RME	9.100 ± 4.150a	5.200 ± 2.010a	14.300 ± 5.81a	<.001***
Hyrax-SRME	8.400 ± 4.480a	5.100 ± 1.912a	13.500 ± 4..719a	<.001***
ACS-RME	9.500 ± 4.881a	5.600 ± 3.240a	15.100 ± 6.261a	<.001***
ACS-SRME	11.005 ± 4.670a	5.500 ± 1.840a	16.500 ± 1.800a	<.001***
FCAB-RME	7.900 ± 5.445ab	3.800 ± 2.660b	11.700 ± 6.240ab	<.001***
FCAB-SRME	7.200 ± 4.240b	3.400 ± 2.503b	10.600 ± 5.440b	<.001***
P^b	<.05	<.05	<.01	

[a] *P* comparison of buccal and lingual surfaces: according to the Mann-Whitney *U* test (with Bonferroni correction).
[b] *P* comparison of appliances groups: according to the Kruskal-Wallis one-way analysis of variance and the Mann-Whitney *U* test (with Bonferroni correction), there is no statistically significant difference between groups with the same letters.
* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

DISCUSSION

Isaacson and Ingram[5] measured forces produced by a single activation of the RME appliance and reported that to be between 3 and 10 lb. Heavy forces produced by RME induce external root resorption in the anchor teeth.[7–11] In the current study, the occurrence of root resorption was shown in all RME groups. However, root resorption was less in the FCAB-RME and FCAB-SRME groups. The Hyrax and ACS-RME appliances caused greater root resorption in the upper first premolars. Previous orthodontic studies comparing RME and SRME investigated dentoskeletal effects, long-term stability, periodontal effects, nasal airway, and conductive hearing loss.[1,6,17–19] However, no previous study has compared the root resorption occurring after RME and SRME with different appliance designs using micro-CT.

Root resorption resulting from orthodontic treatment has been associated with many biological and mechanical risk factors. Some of the mechanical factors include the type of orthodontic force or movement and duration of treatment time. Systemic status, dentition, preorthodontic trauma exposure, and genetics are some of the biological factors.[20] The effect of RME on root resorption was studied previously using histologic,[7,8] scanning electron microscopy (SEM),[9] two-dimensional periapical or panoramic radiography,[21] and cone-beam computed tomography[10] (CBCT) methods. Three-dimensional analysis of the craters cannot be obtained via histological analysis. Root resorption is a 3D phenomenon, and the resorption crater size and volume must be measured accurately.[12,13] Histologic studies require a precise technique, and the quantitative measurement of root resorption was unreliable, because the material disappeared during histological sectioning.[13] There are some disadvantages of SEM methods, such as the need for advanced sample preparation methods, destruction to the dental tissue during preparations, and the impossibility of 3D volume measurements.[14–16] Although CBCT images are obtained very quickly, CBCT techniques have some limitations, such as high cost, ethical considerations of high radiation doses, low resolution for monitoring of dental morphology, and sensitivity to metal artifacts.[11,22] The resolution of CBCT is not sufficient for reconstructing small objects such as tooth root resorption craters.[22] With the development of micro-CT, a resolution of less than 10 μm has been reached.[13–16,21] A micro-CT imaging system enables the high-resolution 3D imaging of mineralized tissue. The advantages of this system include the following: preparing the sample for screening is not necessary, the root surface is not damaged during the scan, it is reproducible, and 3D volumetric data can be obtained from the object being scanned.[13–16]

The results of the present study demonstrated that appliance design or type was more important than activation rhythm on root resorption. There was less root resorption in the first premolars with the FCAB

Table 5. Comparison of Root Resorption Number of Six Different Surfaces Among the Groups[a]

Group	Buccal Cervical	Lingual Cervical	Buccal Middle	Buccal Apical	Lingual Middle	Lingual Apical
Hyrax-RME	2.100 ± 1.290a	1.200 ± 0.918	2.800 ± 1.751a	2.000 ± 0.816a	4.200 ± 2.573a	2.000 ± 1.250a
Hyrax-SRME	2.400 ± 2.319a	1.000 ± 0.820	3.000 ± 1.822a	1.900 ± 1.100a	3.000 ± 1.414a	2.200 ± 1.316a
ACS-RME	2.600 ± 1.900a	1.400 ± 1.350	3.500 ± 2.550a	2.100 ± 1.450a	3.400 ± 2.170a	2.100 ± 1.663a
ACS-SRME	3.700 ± 1.640b	1.000 ± 0.942	4.300 ± 1.702b	1.700 ± 1.418ab	3.000 ± 2.108a	2.800 ± 1.620a
FCAB-RME	1.600 ± 0.970a	0.900 ± 1.730	2.700 ± 2.162a	1.600 ± 1.173ab	3.600 ± 3.204a	1.300 ± 1.340b
FCAB-SRME	2.400 ± 1.780a	1.100 ± 1.450	2.900 ± 1.730a	1.300 ± 1.160b	1.900 ± 1.792b	1.000 ± 1.816b
P	<.05*	>.05	<.05*	<.05*	<.05*	<.05*

[a] According to the Kruskal-Wallis one-way analysis of variance and the Mann-Whitney *U* test (with Bonferroni correction), there is no statistically significant difference between groups with the same letters.
* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

Table 6. Comparison of Resorption Crater Total Volume (mm³) and Numbers Measured in Three Different Regions of the Root Surface[a]

	Volume, Mean ± SD	Number, Mean ± SD
Cervical	0.071 ± 0.068*a	3.600 ± 2.441*a
Middle	0.074 ± 0.070*a	5.000 ± 2.890*b
Apical	0.045 ± 0.039*b	4.740 ± 3.218*b
P	<.01**	<.05*

[a] According to the Kruskal-Wallis one-way analysis of variance and the Mann-Whitney *U* test (with Bonferroni correction), there is no statistically significant difference between groups with the same letters.

* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

appliance. The Hyrax and ACS appliances caused greater root resorption in the upper first premolars, which was independent of the activation rhythm. The reason for this was that the heavy forces resulting from expansion were transmitted directly to the teeth, which were anchored with these two appliances. The FCAB appliance has been reported to have certain advantages over Hyrax and ACS appliances. Relevant studies have also suggested that the type of movement observed with full-coverage appliances might be due to additional tissue support and surface coverage, which limits unwanted force loading and tipping or rotation of the teeth by increased rigidity.[1,2] In addition, the reduced occlusal locking and interferences due to the acrylic occlusal surfaces may have influenced the development of less resorption.

Postexpansion root resorption emerged directly on the supporting teeth or the accumulated residual stresses caused resorption. This finding was supported by previous studies.[8,10] In their study using SEM, Barber and Sims[9] observed no root resorption in the premolar teeth that were not attached to the appliance. This may have been due to the low sensitivity of the SEM technique used in the imaging of resorption. Resorption may have occurred, but it might not have been detected.

Histological studies of root resorption with the Haas and Hyrax appliances showed that tissue-borne (Haas-type) appliances led to less buccal root resorption and smaller, more shallow resorption lacunae in comparison with the tooth-borne Hyrax appliances. Odenrick et al.[8] concluded that removing the force application point from the teeth would lead to less root resorption, in agreement with the current results. Erverdi et al.[7] found that the tooth-borne and tissue-borne appliances were not different in terms of the amount of root resorption. However, in analyzing the distribution of resorption lacunae, more coronal lacunae were found in the cap splint group, because the tooth-supported cap splint appliance caused more tipping with lateral forces. In the current study, both the resorption volume and the number of resorption craters were found to be greater on the buccal root surface than on the lingual root surface. Depending on the forces applied in the transverse direction during maxillary expansion, the movement of the teeth to the buccal surface creates more pressure and compression areas on the buccal surface. Therefore, the resorption craters are concentrated on the buccal surface. This finding was supported by previous studies in which more root resorption was detected on the buccal surface after RME.[8,10,11,17]

Yildirim and Akin[11] compared the bone-borne and tooth-borne RME appliance effects on root resorption using micro-CT. Their study was a well-designed investigation, and the results of the tooth-borne appliance group were very similar to the current study. However, the methodologies were very different between the studies. First, Yildirim and Akin[11] used a different RME appliance design: one side of this appliance covered the teeth with acrylic, and the other side of the appliance was anchored to the palatal bone with a screw. That appliance was designed for their experiment and not suitable for routine clinical use. However, the current research studied three different, commonly used RME appliances.

In this study, only the upper first premolar teeth indicated for extraction were evaluated, because micro-CT can be performed only in vitro. Root resorption in the molar teeth, which were part of the anchorage unit, was not analyzed. The posterior, unanchored teeth should be evaluated in future studies for hybrid (tooth-bone–borne) and pure, bone-borne RME appliances to study root resorption.

CONCLUSIONS

- RME or SRME with Hyrax, ACS, and FCAB appliances caused root resorption in the upper first premolars, but the full bonded coverage design may be safer in terms of root resorption.
- Generally, more resorption was observed on the buccal surface than on the lingual surface in all RME and SRME groups.
- Appliance design or type is more important than activation rhythm on root resorption during expansion.

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REFERENCES

1. İşeri H, Özsoy S. Semirapid maxillary expansion: a study of long-term transverse effects in older adolescents and adults. *Angle Orthod*. 2004;74:71–78.

2. Orhan M, Üsümez S, Malkoç S. Modified bonded rapid maxillary expansion appliance. *World J Orthod*. 2003;4:119–125.
3. McNamara JA. Maxillary transverse deficiency. *Am J Orthod Dentofacial Orthop*. 2000;117:567–570.
4. Almuazin M, Short L, Isherwood G, Almuazin L, McDonald J. Rapid maxillary expansion: a review of appliance designs, biomechanics and clinical aspects. *Orthod Update*. 2016;9:90–95.
5. Isaacson RJ, Ingram AH. Forces produced by rapid maxillary expansion. Part II. Forces present during treatment. *Angle Orthod*. 1964;34:261–269.
6. Mew JR. Semi-rapid maxillary expansion. *Br Dent J*. 1977;143:301–306.
7. 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 Dentofac Orthop*. 1994;106:47–51.
8. Odenrick L, Karlander EL, Pierce A, Fradcs OD, Kretschmar U. Surface resorption following two forms of rapid maxillary expansion. *Eur J Orthod*. 1991;13:264–270.
9. Barber AF, Sims M. Rapid maxillary expansion and external root resorption in man: a scanning electron microscope study. *Am J Orthod and Dentofac Orthop*. 1981;79:630–652.
10. Akyalcin S, Alexander SP, Silva RM, English JD. Evaluation of three-dimensional root surface changes and resorption following rapid maxillary expansion: a cone beam computed tomography investigation. *Orthod Craniofac Res*. 2015;18:117–126.
11. Yildirim M, Akin M. Comparison of root resorption after bone-borne and tooth-borne rapid maxillary expansion evaluated with the use of microtomography. *Am J Orthod Dentofacial Orthop*. 2019;155:182–190.
12. Chan E, Darendeliler M. Exploring the third dimension in root resorption. *Orthod Craniofac Res*. 2004;7:64–70.
13. Güler ÖÇ, Malkoç S. Effects of orthodontic force on root surface damage caused by temporary anchorage devices contact and the repair process. *Korean J Orthod*. 2019;49:106–115.
14. Malkoç MA, Sevimay M, Tatar İ, Çelik HH. Micro-CT detection and characterization of porosity in luting cements. *J Prosthodont*. 2015;24:553–561.
15. Demir N, Öztürk AN, Malkoc MA. Evaluation of the marginal fit of full ceramic crowns by the microcomputed tomography (micro-CT) technique. *Eur J Dent*. 2014;8:437–444.
16. Kucuk EB, Malkoc S, Demir A. Microcomputed tomography evaluation of white spot lesion remineralization with various procedures. *Am J Orthod Dentofac Orthop*. 2016;150:483–490.
17. Gönüldaş SR, Özsoy ÖP, Pamukçu H, Kural F. Comparison of dentofacial and periodontal effects of rapid and semi-rapid maxillary expansion. *Meandros Med Dent J*. 2017;18:33–46.
18. Ramoglu SI, Sari Z. Maxillary expansion in the mixed dentition: rapid or semi-rapid? *Eur J Orthod*. 2010;32:11–18.
19. Kilic N, Oktay H, Selimoğlu E, Erdem A. Effects of semirapid maxillary expansion on conductive hearing loss. *Am J Orthod Dentofacial Orthop*. 2008;133:846–851.
20. Nieto-Nieto N, Solano JE, Yañez-Vico R. External apical root resorption concurrent with orthodontic forces: the genetic influence. *Acta Odontol Scand*. 2017;75:280–287.
21. 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;116:467–472.
22. 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;70:276–283.