Physical properties of root cementum: Part 11. Continuous vs intermittent controlled orthodontic forces on root resorption. A microcomputed-tomography study

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Introduction: There is still ambiguity about whether continuous or intermittent orthodontic forces produce more root resorption. This prospective randomized clinical trial was designed to compare root resorption with these 2 force application patterns. **Methods:** The sample consisted of 16 maxillary first premolars from 8 patients who required bilateral extractions as part of their orthodontic treatment. In each subject, a fixed experimental appliance was placed on the maxillary teeth on each side, allowing a buccally directed force. The force was generated by a segmental wire of β-titanium-molybdenum alloy. The first premolar on 1 side received a buccally directed continuous force, and the contralateral premolar received intermittent force. The initial force magnitude for both sides was 225 cN. After 14 days of initial continuous force, the intermittent force application was obtained with subsequently repeated periods until the end of the eighth week of a 3-day rest period followed by a 4-day force application period. Force levels were set to 225 cN at each patient visit. After the experimental period of 8 weeks, the teeth were extracted under a strict protocol to prevent root surface damage and analyzed with a microcomputed-tomography scan system, and specially designed software was used for direct volumetric measurements. **Results:** Intermittent force produced less root resorption than continuous force ($P < 0.05$). Analysis by position showed that the buccal-cervical region had significantly more root resorption than the other positions ($P < 0.001$), corresponding to a region of compression generated by tipping. **Conclusions:** The application of intermittent orthodontic forces of 225 cN for 8 weeks (14 days of force application, 3 days of rest, then 4 days of force application repeated for 6 weeks) caused less root resorption than continuous forces of 225 cN for 8 weeks. Although it might not be clinically practical, compared with continuous forces, intermittent forces might be a safer method to prevent significant root resorption. This regimen, however, could compromise the efficiency of tooth movement. (Am J Orthod Dentofacial Orthop 2009;136:8.e1-8.e8)

External surface root resorption is the active removal of mineralized and nonmineralized cementum and dentine.[1] Factors that can cause pathologic external root resorption are divided into 3

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groups: traumatic, infection related, and tooth movement related.[2,3] Although the outcomes of these root resorptive processes are similar, orthodontic root resorption is distinct from the other types; the term "orthodontically induced inflammatory root resorption" (OIIRR) has been suggested.[4]

Extensive OIIRR becomes irreversible when it extends beyond the cementum layer into dentine; it compromises an otherwise successful orthodontic outcome.[5] It is thus important to know more about the mechanism, risk factors, and preventive factors of root resorption.

Studies in the literature have investigated the relationship between interrupted or discontinuous forces compared with continuous forces and OIIRR. A pause in tooth movement is believed by many authors to allow the resorbed cementum to heal, and thus many conclude that discontinuous forces cause less root resorption.[6-13] A number of studies with varying durations and frequencies of interruption in the applied forces have led to varied

results. A scanning electron microscopy (SEM) study involved premolars in a split-mouth setup.[12] The authors found that a discontinuous force of 100 cN for 12 hours a day resulted in less OIIRR than the same force applied for 24 hours a day. A study involving young adult beagles was conducted to compare continuous (24 hours/day) with discontinuous (16 hours/day) forces.[11] Although there were great variations in forces (10-200 cN) and treatment durations (4-100 days) in that study, histologic and histomorphometric evaluations showed that the discontinuous regimen of force application caused significantly less resorption than continuous force. In another histologic study involving premolars, the spring on one side was not reactivated over 3 weeks, whereas the spring on conlateral side was reactivated every week over 3 weeks.[14] After an additional week of recovery, there was no histologic evidence of a significant difference in OIIRR.

Excessive forces from both removable and fixed appliances can provoke OIIRR. It is well accepted that the force pattern for removable appliances is intermittent and distinctly contrasts to that of fixed appliances, with their continuous forces. A radiographic study established that fixed appliances are more detrimental to the roots of maxillary incisors than activators and spring plate removable appliances.[15] Another radiographic study by the same authors involved comparing patients treated with full fixed edgewise appliances with Class II elastics and rectangular wires with patients treated with activators, plates with clasps, and vertical elastics.[16] The patients treated with fixed appliances had notable OIIRR, but the other group had none.

Until recently, OIIRR was mainly detected with 2-dimensional (2D) measurement techniques such as radiographs,[17,18] light microscopy,[19] and SEM.[20-22] Although 2D radiographyis the most conservative diagnostic tool for clinical detection of root resorption in patients, 3-dimensional (3D) techniques such as stereoimaging with SEM images[23-25] and x-ray microcomputed tomography (micro-CT)[26,27] might allow more accurate and reliable measurements for researchers. Medical computed tomography (CT) might be helpful for detecting root resorption, but its high cost and high radiation exposure to patients limit its clinical use at present.[28]

Our aims in this study were to investigate quantitatively, with micro-CT, the amount of OIIRR induced by controlled bucally applied intermittent and continuous forces on premolars and to identify the surfaces where root resorption is more prevalent.

This study is a sequel in the series investigating the physical properties of root cementum and root resorption at the University of Sydney in Australia.

MATERIAL AND METHODS

Sixteen maxillary first premolars were collected bilaterally from 8 patients who required extractions as part of their orthodontic treatment (ethical approval, project 5/98, Human Ethics Review Committee-CSHAS). These patients (2 boys, 6 girls; mean age, 16.5 years; range, 13.4-18.6 years) were ready to start comprehensive orthodontic treatment. Because of the differences in bone density and root anatomy between the maxilla and the mandible, and to allow comparison with previous studies, only maxillary premolars were used.

The patients were selected according to the strict criteria described previously and completed a written informed consent form.[29] After the initial study models and digital photographs of the subjects were taken, a heavy orthodontic force of approximately 225 cN on both first premolars was applied for 14 days. The forces were designed to facilitate buccal tipping tooth movement.

The experimental appliance consisted of 0.022-in SPEED brackets (Strite Industries, Cambridge, Ontario, Canada) bonded to the buccal surfaces of the maxillary first molars and first premolars on working models. They were then transferred to the patient by using an indirect bonding method with light-cured adhesive (Transbond Plus, 3M Unitek, Monrovia, Calif). Occlusal stops (Transbond Plus, 3M Unitek) were placed on the occlusal surfaces of the mandibular first molars to prevent occlusal interferences, allowing free buccal tipping of the first premolars and helping to minimize spring deformation (Fig 1).[30]

A 225-cN buccally directed force was applied to the maxillary first premolars with a β-titanium-molybdenum alloy 0.017 × 0.025-in sectional wire (3M Unitek) attached to the bracket on the first molars. The wire was activated by bending buccally in the transverse plane. The force magnitude was measured to the nearest 5 cN with a strain gauge (Dentaurum, Ispringen, Germany).

The initial buccally directed continuous force of 225 cN was activated over 14 days, allowing for the lag phase associated with tooth movement. The subjects were recalled and started the intermittent phase of force loading on a randomly selected first premolar. At this visit, the segmental wire on the intermittent side was removed and the subject released. The subject returned 3 days later to have the wire reactivated to 225 cN of force. The wire on the contralateral side was also measured for force decay and adjusted as necessary to maintain 225 cN of force. After 4 days of further activation, the wire was again removed on the intermittent side, and the above regimen was repeated 5 more times. The total duration of the study was 8 weeks (56 days), and each patient was seen 15 times, including the initial consultation to ascertain suitability (Fig 2).
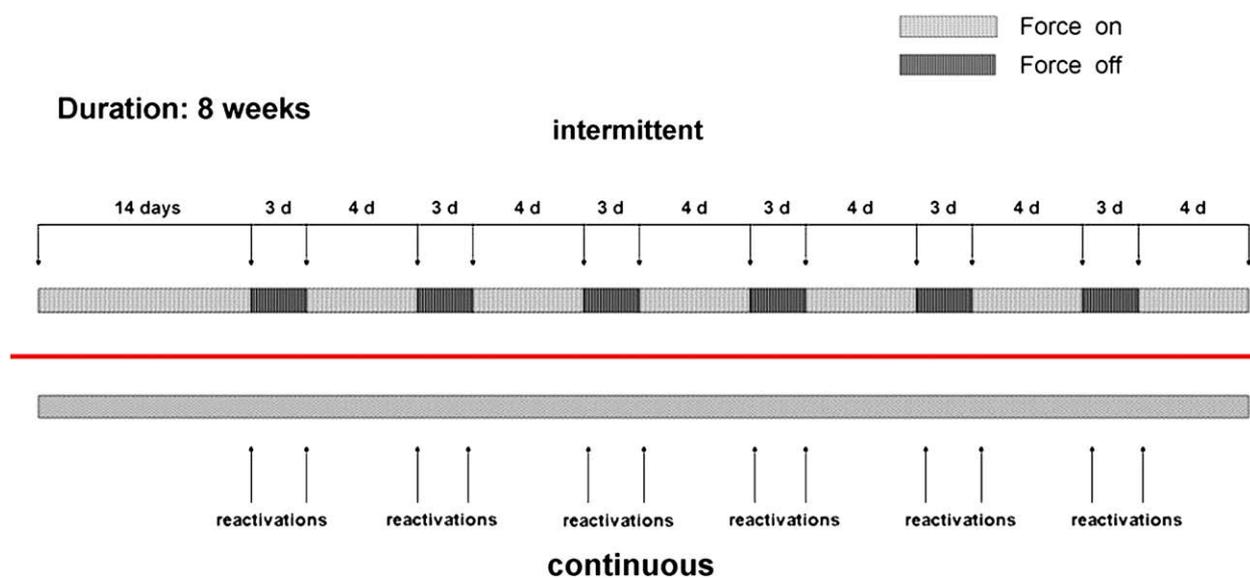
Fig 1. Experimental appliance.

Fig 2. Experimental design.

The maxillary first premolars were then extracted by a pediatric dentist at Sydney Dental Hospital with specific instructions as outlined previously to avoid surgical trauma to the root cementum.[23] Immediately after extraction, the teeth were stored in individually marked containers of Milli-Q deionized water (Millipore, Bedford, Mass), a suitable medium for storage.[31] The periodontal ligament was removed and the teeth disinfected by using a previously described method in which the teeth were subjected to an ultrasonic bath for 10 minutes, followed by disinfection in 70% alcohol for 30 minutes, and then storage in Milli-Q.[27] The teeth were bench dried before imaging.

Micro-CT is a variant of the medical CT scan system that allows imaging of the interior microstructure of materials nondestructively and with high spatial resolution.[32] The software enables reconstruction of the complete internal microstructure of the teeth and can reproduce fully 3D data sets with isotropic sample spacing down to approximately 1 μm.

In this study, the sample quantification by micro-CT was done with the same methodology as described previously by using the updated SkyScan-1172 x-ray desktop microtomographer and software (SkyScan, Aartselaar, Belgium).[27]
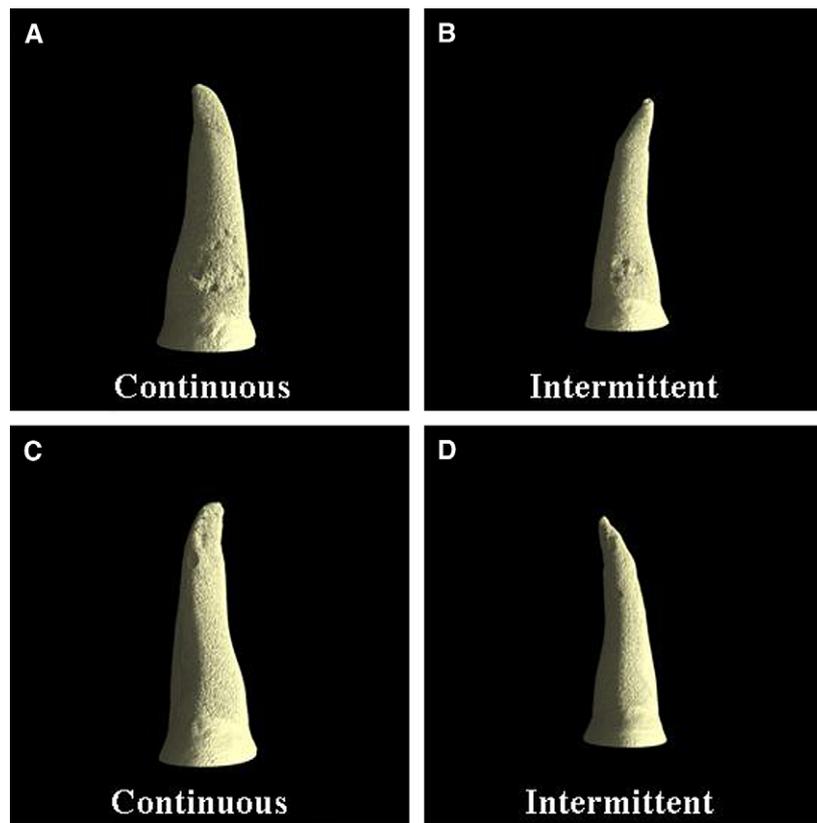
Fig 3. Three-dimensional images showing root resorption craters: **A,** continuous force, buccal view; **B,** continuous force, lingual view; **C,** intermittent force, buccal view; **D,** intermittent force, lingual view.

Only one tooth was scanned at a time. During image acquisition, each tooth rotated over 180°, and, at each position, an x-ray absorption radiograph (shadow image) was acquired. All teeth were scanned with magnification equivalent to 16 times (17.08 μm pixel size) by using a rotation step of 0.45° and an exposure time of 1.904 seconds. A total of 420 shadow images were acquired for each tooth during this first step and saved as 16-bit TIFF (tagged image file format) files.

After acquisition, axial slice-by-slice reconstruction was undertaken by using a specific software implementation of the Feldkamp cone-beam algorithm (NRecon, version 1.4.2, SkyScan 1172).[33]

The 16-bit TIFF shadow images generated raw reconstructed cross-section data with the reconstruction algorithm. The individual axial slices were generated as 1024 × 1024 pixel bitmap images having an 8-bit gray-scale dynamic range. The gray-scale values in each data set were calibrated so that the 8-bit range fully mapped the variations between the pixels with maximum x-ray attenuation (ie, the most opaque) and those with minimum x-ray attenuation (ie, transparent). One thousand 2D axial images for each tooth were generated.

The 3D reconstruction of the tooth images was carried out with VG Studio Max software (version 1.2, Volume Graphics GmbH, Germany), which allowed visualization of all aspects of the scanned tooth (Fig 3). The buccal and lingual surfaces of the teeth were analyzed, and each surface was divided into thirds (cervical, middle, and apical). Each root resorption crater was identified, its position on the tooth recorded, and its coordinates noted. The craters were isolated and saved as separate files of bitmap image stacks.

Volumetric measurements were obtained by using convex hull software (Chull 2D) developed by the Electron Microscope Unit at the University of Sydney. Each crater was measured individually from its bitmap image stack, and then the sums for the root resorption volume for each tooth and each surface were calculated.

A minor limitation associated with this volume estimation software was how the craters are closed by the convex hull algorithm. In general, a convex hull creates a surface closure that is a local minimum in terms of its surface area. This effectively creates a flat closure that approximates the original tooth surface to a greater or lesser extent depending on the curvature of the tooth

Table I. Estimated (model-based) mean cube root OIIRR volume (mm) for each force

Force*	Mean	SE	95% CI
Intermittent	0.815	0.035	(0.732, 0.898)
Continuous	0.985	0.035	(0.902, 1.067)

*Forces were significantly different ($P = 0.011$), but subjects were not significant ($P = 0.07$), based on ANOVA.

surface at the crater. When a tooth surface is convex, flat closure will be more likely to underestimate crater volume. The converse is also true: the software will overestimate volume in areas of concavity. This small error is mitigated, however, because this method of crater volume measurement is based on direct imaging of the tooth as a 3D object. Hence, the error in volume estimate was considered negligible.

Statistical analysis

Analysis was performed on the root resorption data with the Statistical Package for Social Sciences (SPSS for Windows, version 14, SPSS, Chicago, Ill). Root resorption crater volumes were summed to obtain totals for each tooth, each surface (buccal, lingual), vertical thirds (coronal, medial, apical), and each position (combination of surface and vertical thirds). The volumes of the resorption cavities were transformed into cube root volume readings, a methodology used in previous 3D volume root resorption studies.[23,26,27]

We were interested in comparing amounts of root resorption on teeth subjected to various forces and at different positions. These comparisons can be carried out by using volumes but are statistically more robust if the volumes are transformed to linear measurements. Essentially, resorption is measured not by volume but by the radius of an equivalent hemispheric volume.

Analysis of variance (ANOVA) models were constructed for the various (cube root) volumes, with force and surface, vertical thirds, and position as the fixed factors and subjects as the random factor. When a factor was significant and had more than 2 levels (eg, position), mean values were compared with the Bonferroni adjustment for multiple comparisons.

RESULTS

The factors used in the first ANOVA were subject (random factor) and force (fixed factor), which included continuous and intermittent forces. Forces were significantly different ($P = 0.011$) but subjects were not ($P = 0.07$). The mean cube root total volumes were 0.815 mm for intermittent force and 0.985 mm for con-
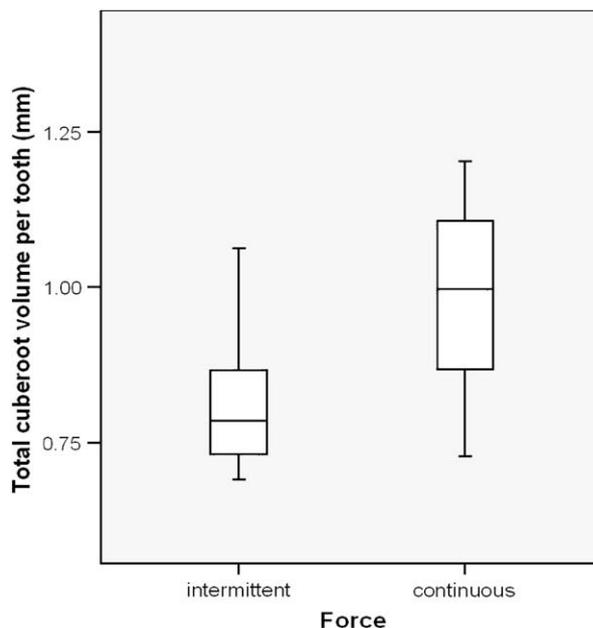

Fig 4. Total cube root volume of the resorption cavities from intermittent and continuous forces.

tinuous force (Table I). This is shown in the boxplots in Figure 4.

The factors used in the second ANOVA were subject (random factor), and force and position (fixed factors). The root surface was divided into regions according to the location of the resorption. There were 3 vertical thirds (apical, middle, and cervical) and 2 surfaces (buccal and lingual), giving a total of 6 positions. It was found that positions were significantly different ($P < 0.001$), but subjects were not ($P = 0.09$), nor in this context were forces ($P = 0.37$), although the intermittent force still had a lower mean than the continuous force (0.276 vs 0.323 mm).

The mean cube root volumes of each position are shown in Table II and Figure 5, with more than twice (and up to 8 times) the amount of root resorption in the buccal-cervical position than any other position. Analysis by position also showed that the buccal-cervical position had significantly greater root resorption than the other positions ($P < 0.001$), with no other significant differences.

DISCUSSION

It has been proposed that, if the force that induces orthodontic movement is greater than the partial pressure of the periodontal capillaries (26 g/cm^2), periodontal ischemia will occur and lead to root resorption.[19,34-36] It has also been stated that, when pressure decreases below this threshold, root resorption ceases.[37] Many

Table II. Estimated (model-based) mean cube root OIIRR volume (mm) for each position

Position*	Mean	SE	95% CI
Buccal-cervical[†]	0.714	0.063	(0.589, 0.839)
Buccal-middle	0.199	0.063	(0.074, 0.324)
Buccal-apical	0.227	0.063	(0.102, 0.351)
Lingual-cervical	0.090	0.063	(-0.035, 0.215)
Lingual-middle	0.254	0.063	(0.129, 0.379)
Lingual-apical	0.315	0.063	(0.190, 0.440)

*Positions were significantly different ($P <0.001$), and subjects ($P = 0.09$) and forces ($P = 0.37$) were not significant, based on ANOVA.
[†]Buccal-cervical was significantly different from all other positions ($P <0.001$) with the Bonferroni adjustment for multiple comparisons.

Fig 5. Cube root volume of the resorption cavities for each position of the root surfaces from intermittent and continuous forces. *BC,* Buccal-cervical; *BM,* buccal-middle; *BA,* buccal-apical; *LC,* lingual-cervical; *LM,* lingual-middle; *LA,* lingual-apical.

animal[38-40] and human[27,36,41-44] studies have agreed that force magnitude is directly correlated with the severity of OIIRR. However, other studies disagree with this.[45-47] These studies were histologic, involving 2D measurements of a 3D phenomenon, and therefore might not be as accurate and reliable as 3D tools such as micro-CT.[24]

Previous resorption studies at the University of Sydney used 25 cN as the light force and 225 cN as the relatively heavy force.[23,27,48] It was decided to use heavy forces of 225 cN in this study to ensure adequate OIIRR to allow comparison. The results can also be directly compared with our previous resorption studies.

This study lasted 56 days; this time was chosen to cover patients who might require more than 10 to 35 days for the resorption craters to appear and to allow comparison with other root resorption studies at the University of Sydney with durations of 28 and 56 days of force applications.[19,36,45,49]

As part of subject inclusion screening, the maxillary first premolars of all participants were examined with panoramic radiography first. All teeth had completed apexification, with no pretreatment root shortening visible before the study. This selection process prohibited those who were predisposed to root resorption, although previous studies showed that teeth with no forces applied can also have minor resorption.[23,25,27]

Although the force-loading design of this study was consistent with our previous studies, force decay was significant, with the force decaying on the continuous side to approximately two thirds of its initial activation level after just 7 days.[48,50] As a result, we modified the established protocol so that no reactivation was implemented during the experimental period, instead reactivating the force to 225 cN at every subsequent visit. Thus, we maintained continuous force but not at a constant level.

Resorbed lacunae in root cementum after orthodontic tooth movement appear mainly in regions of compression[3,7,19,49,51] and rarely in regions of tension.[52]
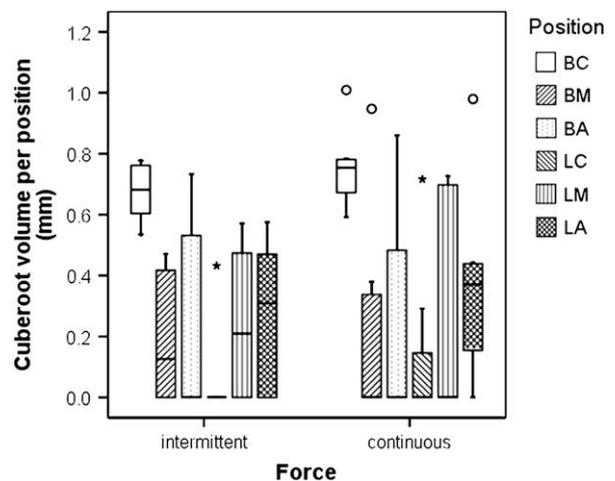
Our analysis of the 6 positions of the root surfaces showed an increased resorption distribution pattern in the buccal-cervical region; this corresponds with increased pressure in this region generated by tipping tooth movements. These findings are consistent with another 3D root resorption study in which more resorption craters were identified in the buccal-cervical area than any other location when the tooth was pulled buccally.[53] However, the patients in that study had teeth that were in malocclusion (rotated or overtipped). Therefore, despite the best attempts, a buccal force direction might not have been applied perpendicular to the long axis of the tooth. Also, crowding of adjacent teeth might have influenced the amount and the exact direction of the movement that actually occurred.

A potential area of concern was achieving an intermittent force that required no patient compliance. Thus, we decided to have an operator (D.J.B.) control the force applications. To maintain a high level of cooperation from the subjects, it was extremely important to make these appointments as convenient as possible for the patients. We chose the regimen of 3 days of rest followed by 4 days of activation for compliance rather than for biologic purposes. Even with these compromises, it was difficult to obtain willing participants; this resulted in the relatively small sample size.

Although this study found less OIIRR with intermittent force compared with continuous force, which agreed with other studies, many questions remain unanswered that could be the beginning point for more studies.[11,12] Ideally, we want to increase our sample

size to see whether any other trends are noticeable. It remains to be seen, by increasing either the duration of the resting period or the activation, what effects these 2 force patterns have on the amount and distribution of OIIRR. We used heavy forces, but what effect would a lighter force have under the same regimen? We did not measure tooth movement in this study, so we cannot be sure which force produced the most movement. It may be assumed that, although the teeth showed less root resorption with intermittent forces, they do not produce clinically efficient rates of tooth movement.

CONCLUSIONS

To quantify OIIRR with micro-CT has been established in the literature as an accurate method for identifying root resorption. To extend our series of studies about factors influencing root resorption, we used this technique to examine the differences in OIIRR produced by heavy continuous and intermittent forces. Our results showed the following.

1. Buccally directed intermittent forces for 8 weeks (after 14 days of initial continuous force application, the intermittent force application was obtained with a 3-day resting period followed by a 4-day force application period) produce significantly less total root resorption (P <0.05) than a similarly directed continuous force of the same magnitude and duration.
2. In a buccally tipped premolar, the greatest amount of root resorption was in the buccal-cervical area of the root, with at least twice the amount of any other region (P <0.001).

This report is a starting point in understanding the differences between continuous and intermittent forces with regard to root resorption, but many aspects require further investigation. These might include variations of not only the force magnitude, but also the lengths of the resting and the active periods.

Compared with continuous force, intermittent orthodontic activation might be a safe method for preventing significant root resorption. This regimen of force, however, could compromise the efficiency of tooth movement. Clinical efficiency of intermittent vs continuous force application should also be evaluated.

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