Bone response to buccal tooth movements—with and without flapless alveolar decortication

Stephen Ruso*, Phillip M. Campbell**, Jeffrey Rossmann***, Lynne A. Opperman****, Reginald W. Taylor** and Peter H. Buschang**

*Private Practice Orthodontist, Tampa, FL, USA, and Departments of **Orthodontic, ***Periodontic, and ****Biomedical Sciences, Baylor College of Dentistry, Texas A&M University, Dallas, TX, USA

Correspondence to: Peter H. Buschang, Orthodontic Department, Baylor College of Dentistry, Texas A&M Health Science Center, 3302 Gaston Ave., Dallas, TX 75246, USA. E-mail: phbuschang@bcd.tamhsc.edu

SUMMARY

OBJECTIVE: To evaluate the biological response of alveolar bone surrounding maxillary second premolars to flapless alveolar decortication and moderate, continuous forces in a buccal direction.

MATERIALS AND METHODS: Using a randomized split-mouth experimental design, unilateral alveolar decortication was performed with a piezotome flapless alveolar decortication unit around the maxillary second premolars of six female dogs. The contralateral side received a sham surgery. The maxillary second premolars were moved buccally with archwires (initial 163.9 cN expansive force) for 9 weeks, followed by 2 weeks of consolidation. Intraoral, radiographic, and model measurements were performed to evaluate tooth movements; the amount and quality of surrounding bone were quantified using micro-CT; bone formation was evaluated histologically.

RESULTS: The experimental premolars were expanded and tipped significantly (P < 0.05) more than the control premolars (1.35 times and 2.05 times as much, respectively). Peak rates of tooth movement occurred around 5 weeks. Dehiscences were observed on both the experimental and control sides, with no statistically significant side differences in buccal bone height (BBH). Micro-CT analyses showed less mature bone in the apico-buccal and cervico-lingual regions around the experimental teeth. Hematoxylin and eosin sections demonstrated fenestrations on the cervico-buccal bone on both sides. The experimental side showed substantially more new bone formation and modeling of apico-buccal, cervico-lingual, and buccal bone than the control side.

CONCLUSIONS: Archwire expansion resulted in reductions in BBH. Piezosurgical flapless alveolar decortication, in combination with archwire expansion, increased tooth movements and tipping and produced less bone, less dense bone, and less mature bone.

Introduction

The number of adults seeking comprehensive orthodontic treatment is increasing (McKiernan et al., 1992; Mathews and Kokich, 1997), and treatments must be approached differently because of their physiology, oral health considerations, and psychological profiles. Adult case starts have risen in recent years, from 15.4 per cent of case starts in 1981 to 20 per cent in 2009 (Keim et al., 2009). Improved esthetics is their chief concern (McKiernan et al., 1992; Sergl and Zentner, 1997). Unfortunately, patient age is related to increased treatment time (Vig et al., 1990); cell mobilization and the conversion of collagen fibers are slower in adults (Ong and Wang, 2002). Adults are also more likely to present with compromised periodontal status (Mathews and Kokich, 1997; Ong and Wang, 2002).

Moderate to severe incisor irregularity has been observed in up to 39 per cent of Americans aged 18 to 50; posterior crossbites occur in 9.5 per cent of this age group (Proffit et al., 1998). Tooth size–arch length discrepancies and crossbites can be eliminated by decreasing tooth mass or increasing arch perimeter through expansion. Since adults’ midpalatal and circummaxillary sutures may be resistant to expansion (Revelo and Fishman, 1994; Knaup et al., 2004), dentoalveolar expansion with archwires is often performed. However, archwire expansion raises concerns because there is insufficient understanding of the periodontal consequences. Potential negative outcomes include buccal tipping (Lundgren et al., 1996; Cattaneo et al., 2011), root resorption (Brezniak and Wasserstein, 1993; Owman-Moll et al., 1996), and buccal alveolar bone loss (Paventy, 2009; Cattaneo et al., 2011).

Selective alveolar decortications (SAD), or corticotomies, have been proposed as a potential way of making treatment more efficient, while mitigating the negative periodontal outcomes associated with dentoalveolar expansion. SAD does induce a regional acceleratory phenomenon (RAP) and accelerate tooth movements in a mesial-distal direction (Cho et al., 2007; Iino et al., 2007; Lee et al., 2008;
Sebaoun et al., 2008; Mostafa et al., 2009; Sanjideh et al., 2009; Wang et al., 2009). The RAP is an acceleration of existing biological processes, associated with decreased bone density and increased perfusions and bone turnover (Frost, 1983). SAD has also been used to treat transverse maxillary constrictions in non-growing individuals through buccal expansion, with several case reports showing clinical success (Dibart et al., 2009; Hassan et al., 2010). Traditional SAD procedures involve the elevation of a full-thickness mucoperiosteal flap, which can result in the reduction of alveolar bone height (Schlee et al., 2006). Yaffe et al. (1994) also showed that full-thickness flap reflection elicits a RAP, cautioning that dehiscence may occur after flap reflection in areas where the alveolar bone is thin.

Dibart et al. (2009) introduced a flapless alveolar decortication procedure termed ‘piezocision’. Buccal vertical incisions are made through the soft tissue between every tooth, not including the papilla, and piezoelectric osseous cuts are made through the buccal cortical layer only. Piezosurgery cuts hard tissues with a modulated ultrasonic frequency, leaving nerves, blood vessels, mucosa, periodontal ligament (PDL), and other soft tissue unharmed (Stübinger et al., 2005; Schlee et al., 2006; Labanca et al., 2008). It has been claimed that rapid tooth movements can be achieved without extensive surgical trauma, with the preservation of periodontal support (Dibart et al., 2009).

Flapless piezosurgical alveolar decortication is attractive due to the potential for less morbidity, the preservation of soft tissues, and reduced cost. However, the magnitude of the surgical insult might be expected to be less than traditional SAD due to the lack of a full-thickness flap. Since the magnitude of the RAP is proportional to the magnitude of the surgical insult (Cohen et al., 2010), it is possible that piezosurgical flapless alveolar decortication may not be as effective as traditional SAD. Due to the lack of experimental evidence, the aim of the present study was to evaluate the effects of flapless piezosurgical alveolar decortication on tooth movements and bony adaptation.

Methods and materials

Sample

Approval for the project was obtained from the Institutional Animal Care and Use Committee (IACUC) at the Texas A&M University Baylor College of Dentistry. Six female, periodontally healthy, foxhound-mix dogs, weighing 25–30 kg and between 1 and 2 years of age, were used as the experimental model. Canines are excellent models for studying bone and tooth movements due to similarities in bone turnover rate, as well as bone composition, density, and quality (Gong et al., 1964; Aerssens, 1998; Ren et al., 2007; Ai et al., 2008). A 1.1 mm pilot hole was drilled in the midline of the palate at the level of the second premolars, and the body of a 1.5 mm diameter, 9 mm long miniscrew (Jazi Dental, Allentown, PA) was used as a stable reference point for measuring radiographic tooth movements.

Appliance fabrication and delivery

Custom impression trays were fabricated with Triad TruTray material (Dentsply USA, York, PA) from a dry foxhound skull. Initial alginate impressions were poured with dental stone. Initial models were used to fabricate surgical guides, radiographic guides, and custom orthodontic appliances.

Custom bands for the maxillary canines, second premolars, and fourth premolars were fabricated from band material (Dentaurum, Ispringen, Germany). Molar brackets with a 0.022” slot size, double buccal tubes, and 0.051” headgear tubes (3M Unitek, Monrovia, CA) were welded and then soldered to the molar and canine bands. The canine brackets had 0° offset and 0° torque; the molar brackets had 10° offset and −14° torque. Damon Q maxillary premolar brackets (Ormco, Orange, CA) with 0° offset and −11° torque were welded to the second premolar bands. The average interbracket distance was 25.8 mm (SD = 1.6) from the canine to the second premolar, and 28.3 mm (SD = 1.2) from the second premolar to the fourth premolar. The bands were perforated four times with a 0.25 mm round bur, and the internal surface was microetched with 60 micro alumina particles. The appliances were then polished and pumiced to prevent irritation.

Retentive grooves were placed in the maxillary canines, second premolars, and fourth premolars with a high-speed handpiece and a 330 carbide bur. The teeth were then etched with 37 per cent phosphoric acid gel for 30 seconds. All-Bond 3, primers A and B (Bisco, Richmond, BC, Canada) were mixed and applied to each tooth; after 10 seconds All-Bond 3 adhesive resin was applied and cured for an additional 10 seconds. The bands were filled with the 3M Transbond XT (3M Unitek) and seated onto the prepared teeth. The composite was light-cured for 40 seconds per tooth.

Surgery

The dogs were initially sedated with a mixture of 2.2 mg/kg body weight Ketamine (Bioniche Teoranta, Galway, Ireland) and 0.22 mg/kg Xylazine (IVX Animal Health Corp., St. Joseph, MO). Buccal and palatal anesthesia was achieved using local infiltrations of 2 per cent lidocaine with 1:100 000 epinephrine (Patterson Dental, St. Paul, MN).

A split-mouth design was used, with the experimental side randomly assigned. On the experimental side, a custom surgical guide was used to plan the surgery (Figure 1A). Periapical radiographs of the maxillary second premolar were taken with the guide in place (Figure 1B). Mesial, distal, and interradicular incisions of the soft tissues were made with a surgical scalpel; no flaps were reflected. Buccal
bone decortication was performed to a depth of approximately 5 mm with a piezosurgery unit (Piezosurgery Inc., Columbus, OH) equipped with the 0.75 mm wide OT6 osteotomy insert tip (Piezosurgery Inc.) under copious irrigation. Fifteen millimeter long cuts were made mesial and distal to the roots; a ‘V’ shaped cut was made apical to the furcation, with each leg of the cut measuring 10 mm. Periapical radiographs were taken intraoperatively to verify the alignment of the osteotomies and to ensure that the root structures had been avoided. The control side received a sham surgery consisting of soft-tissue incisions, scoring of the periosteum, and sutures. All animals healed without complications by day 7. For the histomorphometric analyses, oxytetracycline was administered at 3 and 9 weeks; calcein was administered at week 6.

Appliance activation

The archwires were then ligated, and 0.045 inch stainless steel wires spanning the headgear tubes were placed for stability (Figure 2). Composite resin was added to the ends to prevent sliding and soft tissue irritation. Initially (T0), 0.017” by 0.025” copper nickel titanium archwires (Ormco) were placed. The mean initial activation force was 163.9 cN (SD = 9.8). After 2 weeks (T2), 0.019” by 0.025” superelastic nickel titanium archwires (Orthodirect, Farmington, NY) were placed. The larger rectangular archwire was chosen due to the ability to place steps in the wire, as well as its constant activation, regardless of temperature.

Measurements

Initial records included alginate impressions, maxillary occlusal radiographs, periapical radiographs, and intraoral measurements of tooth position. Radiographs, intraoral caliper measurements, and probing depths were taken immediately post-surgery and every week for 11 weeks (Supplementary Figure 1). Notches, drilled into the cusp tips of the teeth, served as stable references for weekly caliper width measurements. A minimum of two occlusal radiographs were taken each week using digital radiographic sensors (Air Techniques Inc., Melville, NY) and a number 4 size film. The orientations of the images were standardized with custom radiographic guides that were fabricated for each dog from the stone models using rigid 1.5 mm acrylic sheets; an XCP external paralleling device was attached to the acrylic sheet (Dentsply-Rinn, Elgin, IL).

The radiographs were imported into Dolphin Imaging (Dolphin Imaging and Management Solutions, Chatsworth, CA) and traced. A stable midsagittal reference plane was constructed superimposing on the midpoint of the implant and orienting on the midpalatal suture (Supplementary Figure 2). The perpendicular distances from the lingual aspects of second premolar bands to the midsagittal reference plane were measured.

Final alginate impressions were again taken and poured in die stone. Custom acrylic stents were fabricated to assess tipping; photographs were taken; the images were imported into Dolphin Imaging; and angular measurements were recorded. The difference in the angular measures between the initial and final record was used to quantify the amount of tipping that occurred.

Specimen retrieval

Following 9 weeks of active tooth movement and 2 weeks of consolidation, the dogs were sedated with 2.2 mg/kg Ketamine and 0.22 mg/kg Xylazine and sacrificed (day 77). Block of bone (37 mm wide and 30 mm high) containing half of the maxillary first premolar, the entire maxillary

Figure 1 (A) Maxillary second premolar with radiographic guide in place; (B) radiograph of second premolar with guide; (C) alveolar decortication performed with piezosurgery unit with copious irrigation; (D) diagram of alveolar decortication performed with piezosurgery unit.

Figure 2 (A) buccal view of cemented appliance with archwire ligated and stabilizing bar in place; note the interbracket distance and deflection in archwire; (B) occlusal view.
second premolar, and half of the maxillary third premolar were sectioned from the disarticulated maxillae.

Data analysis

The bone blocks were loaded in 37 mm diameter Scanco tubes (one per tube) using a standardized orientation and scanned with a micro-CT scanner (ScanCo Medical, Bassersdorf, Switzerland) at 37 μm. A scout-view radiograph was used to define the region of interest.

Six distinct regions of interest of bone were selected for each specimen based on the direction of tooth movement (Figure 3), including two buccal regions adjacent to the apical aspects of the mesial and distal roots, two lingual regions adjacent to the apical aspects of the mesial and distal roots, and two lingual regions adjacent to the coronal aspect of the mesial and distal roots. The most coronal region on the buccal aspect was not analyzed due to bone loss that had occurred in all 12 blocks.

The volumes of interest were defined by a single operator using Scanco MicroCT v.6.0 software (Figure 4A). Vertically 40 slices were traced, not including the first five slices from the root apices and the first five slices from the alveolar crest. The mesial and distal boundaries of the volumes were defined manually by drawing a line perpendicular to the long axis of the sample and tangent to either the mesial or distal border of the root (Figure 4B). For the areas of interest located on the buccal aspect, the medial boundary was defined by the lamina dura, and the lateral border was defined by the buccal surface. For areas of interest on the lingual aspect, the lateral boundaries were defined by the lamina dura and the lingual surface or approximately 1.5 mm, whichever was less.

Each of the six volumes of interest was analyzed separately using the Standard Scanco Bone Trabecular Morphometry software. Bone density (mg HA/cm³), bone volume to total volume ratio (BV/TV), trabecular thickness (mm), trabecular number (1/mm), and the space between trabeculae, referred to as trabecular separation (mm), were quantified.

Using the 3D reconstructions and individual 2D slices, additional assessments were performed using the scale ruler. Buccal bone height (BBH), a de facto measure of dehiscence, was measured from the most lingual aspect of buccal bone at the level of the root apex to the beginning of the dehiscence.

Histology

Half of the specimens were randomly selected for histomorphometric analysis. They were dehydrated in increasing concentrations of alcohol up to 100 per cent, infiltrated and embedded in methyl methacrylate for polymerization, and sequentially sectioned (50 μm) with a Leitz 1600 saw microtome (Leica Microsystems, Buffalo Grove, IL) in a buccolingual direction, perpendicular to the buccal plate. The sections were then polished and mounted to a glass slide.

The other half of the specimens were selected for histological analysis with hematoxylin and eosin (H&E) staining. Following micro-CT evaluation, they were decalcified in EDTA and placed in 70 per cent ethanol, followed by two changes each of 95 per cent and 100 per cent ethanol, followed by xylene baths. The specimens were
then infiltrated and embedded in paraffin, sectioned (6 μm) with a microtome in a buccolingual direction, and stained with H&E.

Statistics
Multilevel statistical models were used to statistically determine the amounts of tooth movement and resorption that occurred. The models were developed using the MLwiN software (Center for Multilevel Modeling, Institute of Education, London, UK) and iterative generalized least squares estimating procedures.

The fixed portion of each model determined the polynomial that best fit the repeated measurements of tooth movement as a function of time. The terms were tested statistically based on the standard errors; higher-order terms were rejected sequentially until a lower-order term attained significance ($P < 0.05$). The constant term described the tooth movement or resorption at day 15; the linear term described the rate of change (velocity); the quadratic term described the change in rate (acceleration); and the cubic term described changes of acceleration.

Additional statistical analyses were performed using SPSS software (SPSS Inc., Chicago, IL) to evaluate the micro-CT specimens. Non-parametric Wilcoxon signed rank tests were used to compare the experimental and control groups. A probability level of less than 0.05 was used for statistical significance.

Results
Linear and angular measurements
Probing depths showed no statistically significant side differences. The mesiogingival, lingual, and distolingual sites showed no changes in probing depth over time. The three buccal sites showed slight increases in pocket depth during the first 5 weeks, and decreases thereafter. Only the increases (0.9–1.25 mm) observed over the first 5 weeks at the right and left buccal sites were statistically significant.

During the expansion phase (weeks 0 through 9), the inter-second premolar distance increased 7.6 ± 0.9 mm, while the inter-canine width and inter-fourth premolar distances decreased 3.3 ± 0.3 mm and 0.3 ± 0.1 mm, respectively (Table 1, Figure 5A). After a 2 week consolidation, at sacrifice (week 11), the inter-second premolar expansion finished at 7.9 ± 0.8 mm. At the end of consolidation, inter-canine and inter-fourth premolar widths had decreased 3.6 ± 0.5 mm and 0.2 ± 0.2 mm, respectively.

The radiographic measurements showed that the experimental second premolar expanded 3.2 mm during active expansion, with the peak rate of 1.3 mm/week of tooth movement occurring at 5.1 weeks (Figure 5B). Some relapse occurred during the consolidation period, resulting in a net expansion of 3.1 mm. The control second premolar expanded 2.4 mm during the active expansion phase, attained a peak velocity of 1.0 mm/week at 5.3 weeks, and relapsed to 2.2 mm during consolidation. At the end of active tooth movement, the side difference in the amount of second premolar movement was statistically significant ($P = 0.049$); the experimental side showed 135 per cent as much expansion as the control.

Comparisons of the pre- and post-treatment models showed that the control and experimental second premolars underwent 10.7° ± 6.0° and 21.9° ± 8.1° of tipping, respectively, with significantly ($P = 0.028$) more tipping on the experimental side.

Micro-CT Analysis
The 3D reconstructions showed buccal dehiscence on both the control and the experimental sides, including all 12 specimens (Figure 6). BBHs of the mesial and distal experimental roots were approximately 0.5 mm less than the control BBHs (Table 2). Wilcoxon signed rank tests showed that the side differences were not statistically significant.

The bone in the apico-buccal region of the mesial root showed significantly less percentage bone volume, more trabeculae, thinner trabeculae, and less bone density on the experimental than control side (Table 3). The differences in trabecular separation were small and not statistically

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Polynomial model describing buccal movement of maxillary second premolar movements (mm) in foxhound-mix dogs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements</td>
<td>Constant Estimates</td>
</tr>
<tr>
<td>Intraoral Inter-canine width</td>
<td>36.504</td>
</tr>
<tr>
<td>Inter-second premolar width</td>
<td>44.839</td>
</tr>
<tr>
<td>Inter-fourth premolar width</td>
<td>59.482</td>
</tr>
<tr>
<td>Radiographic Control</td>
<td>18.985</td>
</tr>
<tr>
<td>Experimental</td>
<td>20.046</td>
</tr>
</tbody>
</table>
significant. The bone in the apico-buccal region of the distal root showed the same pattern, but none of the differences were statistically significant ($P > 0.05$).

The bone in the apico-lingual region of the distal root showed significantly less percentage bone volume ($P = 0.043$) and thinner trabeculae ($P = 0.043$) on the control than experimental sides (Table 4). None of the other comparisons of apico-lingual bone showed statistically significant differences.

The bone in the cervico-lingual region of the mesial root showed significantly smaller bone volume fractions on the experimental than control sides of both roots. The same region on the distal root also showed significantly more trabeculae ($P = 0.028$) and thinner trabeculae.

**Histomorphometry**

The experimental side showed more florescence, indicating a higher rate of bone turnover, than the control side (Figure 7). In contrast with the well-defined green bands of oxycodone, the calcein fluorescence was diffuse and in soft tissues, indicating that it had been poorly absorbed.

Additionally, there appears to be only one distinct green band. Buccal bone apposition was evident on the periosteal surface of the experimental second premolar immediately below the dehiscence. Midway down that buccal alveolar plate, a reversal zone was evident, with bone apposition on the surface of the bone adjacent to the PDL. On the lingual side of the tooth, bone apposition occurred at the most cervical portion of the alveolaris adjacent to the PDL; the most apical portion showed minimal turnover. The control second premolar showed a similar pattern, with less new bone.

**Histology (H&E) staining**

Compared to the controls, the experimental bone appeared less mature in both the apico-buccal and cervico-lingual regions. The experimental and control apico-lingual bone were similar. The cervico-buccal alveolar bone showed fenestrations on both the control and experimental sides (Figure 8D, Figure 9C). On the experimental side, osteoblasts were evident on both the periosteal and PDL surfaces of the alveolar crest. Osteoblasts were also seen on the periosteal surface of the control side.

The apico-buccal and cervico-lingual regions on the experimental side showed extensive bone remodeling.

**Table 2** Comparison of mesial and distal root buccal bone heights (BBH).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>Experimental</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Mesial BBH (mm)</td>
<td>5.4</td>
<td>2.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Distal BBH (mm)</td>
<td>4.3</td>
<td>2.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Bone response to buccal tooth movements was evident in the study. Several blood vessels were present, and a demarcation between older, more mature lamellar bone and the new woven bone was evident. Numerous osteoclasts were also present. A disorganized, dense network of Sharpey’s fibers was evident between the woven bone and the thick cementum layer, indicative of tensional forces on the PDL. The apico-buccal region on the control side also showed evidence of remodeling, though not as extensive as on the experimental side. New woven bone was present, as were some osteoclasts. The PDL was thinner than on the experimental side, consistent with less tipping on the control side.

The apico-lingual region on the experimental side showed evidence of bone remodeling. Numerous blood vessels, new woven bone, osteoblasts, along with mature lamellar bone and cement lines were evident. A large resorption cavity was visible in the thick layer of cementum. Prominent Sharpey’s fibers indicating tensional forces were evident. The control side appeared markedly similar to the experimental side in terms of remodeling.

### Table 3: Comparison of buccal bone located on apical aspect of both mesial and distal roots.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mesial root</th>
<th>Distal root</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent bone volume (%)</td>
<td>Control</td>
<td>0.79</td>
<td>0.06</td>
<td>0.64</td>
<td>0.08</td>
<td>0.73</td>
<td>0.12</td>
<td>0.028*</td>
<td>0.53</td>
<td>0.06</td>
<td>0.109</td>
</tr>
<tr>
<td>Trabecular number (1/mm)</td>
<td>Control</td>
<td>3.40</td>
<td>0.62</td>
<td>4.82</td>
<td>1.41</td>
<td>3.98</td>
<td>0.68</td>
<td>0.028*</td>
<td>4.91</td>
<td>0.82</td>
<td>0.285</td>
</tr>
<tr>
<td>Trabecular thickness (mm)</td>
<td>Control</td>
<td>0.43</td>
<td>0.10</td>
<td>0.27</td>
<td>0.11</td>
<td>0.38</td>
<td>0.10</td>
<td>0.028*</td>
<td>0.22</td>
<td>0.02</td>
<td>0.109</td>
</tr>
<tr>
<td>Trabecular separation (mm)</td>
<td>Control</td>
<td>0.19</td>
<td>0.05</td>
<td>0.19</td>
<td>0.10</td>
<td>0.13</td>
<td>0.02</td>
<td>0.046*</td>
<td>0.17</td>
<td>0.07</td>
<td>0.285</td>
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<tr>
<td>Bone density (mg HA/cm³)</td>
<td></td>
<td>782.79</td>
<td>12.22</td>
<td>731.13</td>
<td>45.18</td>
<td>748.71</td>
<td>42.34</td>
<td>0.069*</td>
<td>740.57</td>
<td>32.64</td>
<td>0.593</td>
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* = prob < 0.05.

### Table 4: Comparison of lingual bone located on apical aspect of both mesial and distal roots.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mesial root</th>
<th>Distal root</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent bone volume (%)</td>
<td>Control</td>
<td>0.52</td>
<td>0.08</td>
<td>0.67</td>
<td>0.11</td>
<td>0.69</td>
<td>0.07</td>
<td>0.068</td>
<td>0.78</td>
<td>0.11</td>
<td>0.043*</td>
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<tr>
<td>Trabecular number (1/mm)</td>
<td>Control</td>
<td>4.79</td>
<td>0.54</td>
<td>4.14</td>
<td>0.77</td>
<td>5.06</td>
<td>0.95</td>
<td>0.273</td>
<td>4.63</td>
<td>1.08</td>
<td>0.500</td>
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<tr>
<td>Trabecular thickness (mm)</td>
<td>Control</td>
<td>0.24</td>
<td>0.05</td>
<td>0.35</td>
<td>0.14</td>
<td>0.29</td>
<td>0.10</td>
<td>0.273</td>
<td>0.36</td>
<td>0.17</td>
<td>0.043*</td>
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<tr>
<td>Trabecular separation (mm)</td>
<td>Control</td>
<td>0.23</td>
<td>0.06</td>
<td>0.21</td>
<td>0.05</td>
<td>0.17</td>
<td>0.04</td>
<td>1.000</td>
<td>0.13</td>
<td>0.04</td>
<td>0.080</td>
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<td>Bone density (mg HA/cm³)</td>
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<td>722.67</td>
<td>41.36</td>
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<td>21.36</td>
<td>751.79</td>
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<td>0.114</td>
<td>753.82</td>
<td>36.01</td>
<td>0.893</td>
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* = prob < 0.05.

### Table 5: Comparison of lingual bone located on cervical aspect of both mesial and distal roots.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mesial root</th>
<th>Distal root</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent bone volume (%)</td>
<td>Control</td>
<td>0.86</td>
<td>0.06</td>
<td>0.80</td>
<td>0.04</td>
<td>0.87</td>
<td>0.08</td>
<td>0.028*</td>
<td>0.78</td>
<td>0.08</td>
<td>0.028*</td>
</tr>
<tr>
<td>Trabecular number (1/mm)</td>
<td>Control</td>
<td>3.88</td>
<td>0.44</td>
<td>4.52</td>
<td>0.81</td>
<td>4.17</td>
<td>0.93</td>
<td>0.173</td>
<td>5.31</td>
<td>0.79</td>
<td>0.028*</td>
</tr>
<tr>
<td>Trabecular thickness (mm)</td>
<td>Control</td>
<td>0.41</td>
<td>0.07</td>
<td>0.36</td>
<td>0.08</td>
<td>0.41</td>
<td>0.10</td>
<td>0.345</td>
<td>0.27</td>
<td>0.06</td>
<td>0.028*</td>
</tr>
<tr>
<td>Trabecular separation (mm)</td>
<td>Control</td>
<td>0.13</td>
<td>0.06</td>
<td>0.12</td>
<td>0.02</td>
<td>0.10</td>
<td>0.02</td>
<td>0.600</td>
<td>0.12</td>
<td>0.02</td>
<td>0.166</td>
</tr>
<tr>
<td>Bone density (mg HA/cm³)</td>
<td></td>
<td>744.07</td>
<td>36.04</td>
<td>721.84</td>
<td>37.90</td>
<td>735.81</td>
<td>57.47</td>
<td>0.173</td>
<td>719.47</td>
<td>51.81</td>
<td>0.600</td>
</tr>
</tbody>
</table>

* = prob < 0.05.

(Figures 8B and 8C). Several blood vessels were present, and a demarcation between older, more mature lamellar bone and the new woven bone was evident. Numerous osteoclasts were also present. A disorganized, dense network of Sharpey’s fibers was evident between the woven bone and the thick cementum layer, indicative of tensional forces on the PDL. The apico-buccal region on the control side also showed evidence of remodeling, though not as extensive as on the experimental side (Figure 9A). New woven bone was present, as were some osteoclasts. The PDL was thinner than on the experimental side, consistent with less tipping on the control side.

The apico-lingual region on the experimental side showed evidence of bone remodeling (Figure 8A). Numerous blood vessels, new woven bone, osteoblasts, along with mature lamellar bone and cement lines were evident. A large resorption cavity was visible in the thick layer of cementum. Prominent Sharpey’s fibers indicating tensional forces were evident. The control side appeared markedly similar to the experimental side in terms of remodeling.
bone modeling. New woven bone was present, along with mature lamellar bone. In contrast with the experimental side, however, the prominent Sharpey’s fibers were not present on the control side.

Discussion

Alveolar decortication with piezosurgery produced greater buccal tooth movements than conventional treatment, but the differences were less than expected. The experimental teeth moved 135 per cent as much as the control teeth. Most studies of corticotomies in dogs have reported 200 per cent increases in tooth mesiodistal movements, with one as high as 440 per cent (Cho et al., 2007; Iino et al., 2007; Mostafa et al., 2009; Sanjideh et al., 2009). Since the magnitude of a RAP is proportional to the magnitude of the insult (Cohen et al., 2010), the lack of a periodontal flap could have mitigated the size and scope of the RAP. The invasiveness of a

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**Figure 7** Fluorescence microscopic images showing labeling of oxytetracycline (appearing green, delivered at weeks 3 and 9) and calcein (appearing red, delivered at week 6). Reversal zones (RZ) likely represent areas of flexure of the alveolar crest.

**Figure 8** Experimental side: (A) apico-lingual bone zone; (B) apico-buccal zone; (C) cervico-lingual zone; and (D) cervico-buccal zone. Red arrow indicates direction of tooth movement. Blue letters represent: R, root; W, woven bone; L, lamellar bone; F, fenestrations; OB, osteoblasts; OC, osteoclasts; *, Sharpey’s fibers.

**Figure 9** Control side: (A) apico-buccal zone; (B) apico-lingual bone zone; (C) cervico-buccal zone; and (D) cervico-lingual zone. Red arrow indicates direction of tooth movement. Blue letters represent: R, root; W, woven bone; L, lamellar bone; F, fenestrations; OB, osteoblasts; OC, osteoclasts.
Bone Response to Buccal Tooth Movements

Full-thickness flap is sufficient to elicit a RAP as early as 10 days (Yaffe et al., 1994), and the subsequent osteopenia of the lateral cortical bone could explain purported increases in the efficiency of buccal tooth movements with corticotomies. Additionally, piezosurgery causes less trauma than a similarly sized surgical wound caused by a diamond or carbide bur (Vercellotti et al., 2005).

The timing of peak tooth movements occurred later than expected. Peak rates occurred around week 5 in the present study, which is substantially later than the peaks reported at approximately 2–3 weeks for traditional corticotomies (Lino et al., 2007; Mostafa et al., 2009; Sanjideh et al., 2009). Buccal movements, as opposed to mesiodistal movements, may be subject to greater resistance from the cortical bone, which is more dense and less vascular than trabecular bone (Shapiro, 1988; Chen et al., 1994). The teeth had to move through the denser cortical bone surrounding the tooth as well as the buccal cortical bone, which might be expected to take longer in order to attain peak rates of movement. It is possible that the surgical insult was not ideally located to facilitate tooth movements in the buccal direction. The mesial and distal decortications performed were based on descriptions of the surgical technique (Dibart et al., 2009; Dibart et al., 2010; Keser and Dibart, 2011), and the inter-radicular cuts were added because of the divergence of the second premolar roots in dogs. The bone immediately buccal to the root (i.e. the direction of expansion) was not disturbed, perhaps resulting in a delayed osteopenia, and ultimately resulting in the difference between what was expected and what was observed.

While efforts were made to control tipping (i.e. gingival bracket placement, brackets with −11° torque, and 0.019” × 0.025” archwires), it occurred nevertheless. Buccal tipping appears to be a component of transverse archwire expansion (Paventy, 2009; Cattaneo et al., 2011). For example, Cattaneo et al. (2011) found that expansion with both the Damon and the GAC Accuform arch forms resulted in approximately 12–13° of tipping of the first and second premolars. Lundgren et al. (1996) showed 12.6° of tipping after 7 weeks of expansion. Tipping should be expected in most cases of archwire expansion because the forces are applied above the center of resistance. Group differences in lateral tooth movements were partially due to the fact that the experimental teeth were tipped approximately twice as much as the control teeth (21.9° versus 10.7°). Differences in bone turnover have been shown to change the center of rotation during mesial-distal molar movements (Verna et al., 2000). If the SAD-induced osteopenia in the present study moved the center of rotation more apically, it could explain the greater tipping observed on the experimental side.

The dehiscences provide a better explanation for the increased tipping observed on the experimental side. Buccal tipping is strongly associated with dehiscence formation (Steiner et al., 1981; Garib et al., 2006; Paventy, 2009). Finite element modeling has shown that tipping movements concentrate stress at the crest of the alveolus (Rudolph et al., 2001). In the context of the present experiment, if the laterally directing tipping forces of the archwire were concentrated on the crestal bone, they could have been producing mechanical strains beyond threshold levels (Frost, 1987, 2003) and microfractures that accumulated and resulting in failures. The fact that bone was resorbing on the endosteal surface made the crest thinner and increased the likelihood of breakdown and loss.

Unexpectedly, there were no differences in vertical bone loss between experimental and control sides, despite the differences in both amount of tooth movement and tipping. This could be due to the reduction in mineral content on the experimental side, which allowed it to bend to a greater extent on the experimental than control side (Verna et al., 2000). More importantly, the vertical bone loss that occurred was probably confounded by rotation and extrusion, both of which were observed.

Fluorescent labeling showed bony apposition on the buccal periosteal surface in both control and experimental groups. Since tipping movements concentrate stresses at the crest of the alveolus, (Rudolph et al., 2001), the buccal bone below the crest would have been subjected to lesser strains, perhaps within the range that produced new bone (Lino et al., 2007; Wang et al., 2009). This was supported by the histological sections showing osteoblasts on the periosteal surface at the crest of the buccal alveolar bone. Cone beam CT data of patients treated with archwire expansion (Damon and GAC Accuform archforms) showed increases in buccal bone volume in 36 per cent of the patients (Cattaneo et al., 2011). This suggests that low archwire forces transmitted through the alveolus may cause buccal bone apposition to occur concomitantly with loss of alveolar bone height.

Despite the presence of new bone on the buccal surface, the amounts produced were not clinically sufficient for augmenting buccal bone. The force system used in this experiment, the amount of new buccal bone did not keep pace with the amounts of bone lost on the crest and periodontal surface. The loss of periodontal support would be an unacceptable outcome for most clinicians. Therefore, while there was new bone, these results should not be misinterpreted as a justification of archwire expansion, with or without alveolar decortication.

The flapless procedure used in this project was intended to preserve periosteal blood supply and other soft tissues, while creating an insult capable of eliciting a RAP of sufficient magnitude to increase the clinical efficacy of buccal tooth movement. The procedure was also predicted to either improve or have no effect on the periodontium. The results of this experiment suggest that flapless alveolar decortication minimally increases the clinical efficacy of dentoalveolar expansion. Moreover, the negative consequences (i.e. dehiscences and bone loss) appear to outweigh the positive consequence (i.e. tooth movements and bone formation). More
research must be performed on piezosurgical flapless alveolar decortication before it becomes a routine orthodontic treatment modality. Future studies have to control or eliminate the tipping that occurred. In addition, comparisons of piezosurgical SAD with and without a mucoperiosteal flap should be performed, and the efficacy of particulate bone grafting with SAD should also be examined.

Conclusions

1. Piezosurgical alveolar decortication increased tooth movements (35 per cent) and tipping (105 per cent).
2. Peak rates of tooth movement occur around 5 weeks.
3. Archwire expansion resulted in a reduction in buccal bone height, both with and without flapless alveolar decortication.
4. Flapless alveolar decortication was associated with less bone, less dense bone, and less mature bone in apico-buccal and cervico-lingual regions surrounding the tooth.

Supplementary material

Supplementary material is available at European Journal of Orthodontics online.

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References


Frost H M 1983 The regional acceleratory phenomenon: a review. Henry Ford Hospital Medical Journal 31: 3–9

Frost H M 1987 Bone “mass” and the “mechanostat”: a proposal. The Anatomical Record 219: 1–9


Gong J K, Arnold J S, Cohn S H 1964 Composition of trabecular and cortical bone. The Anatomical Record 149: 325–331


Keser E I, Dibart S 2011 Piezocision-assisted Invisalign treatment. Compendium of Continuing Education in Dentistry 32: 46–8, 50


Lee W et al. 2008 Corticotomy-/osteotomy-assisted tooth movement microCTs differ. Journal of Dental Research 87: 861–867


Bone Response to Buccal Tooth Movements


Sanjideh P A, Rossouw P E, Campbell P M, Opperman L A, Buschang P H 2009 Tooth movements in foxhounds after one or two alveolar corticotomies. European Journal of Orthodontics 32: 106–113


