Effects of micro-osteoperforations on tooth movement and bone in the beagle maxilla

Chris L. Cramer,[a] Phillip M. Campbell,[b] Lynne A. Opperman,[c] Larry P. Tadlock,[b] and Peter H. Buschang[b]
Spokane, Wash, and Dallas, Tex

Purpose: The purpose of this study was to determine how micro-osteoperforations (MOPs) affect tooth movements, bone turnover, bone density, and bone volume. **Methods:** A split-mouth experimental design with 7 beagle dogs was used to evaluate bone surrounding maxillary second premolars that had been retracted for 7 weeks. One month after the maxillary third premolars were extracted, 8 MOPs (1.5 mm wide and 7 mm deep) were created without flaps with the use of the Propel device (6 were placed 3 mm distal to the second premolar and 2 were placed in the premolar furcation) on one randomly chosen side. The maxillary second premolars were retracted bilaterally with the use of 200 g nickel-titanium closed coil springs. Tooth movements were measured intraorally and radiographically. Microscopic computed tomography was used to evaluate the material density and volume fraction of bone distal to the premolars. Hematoxylin and eosin–stained and fluorescent sections were used to examine the bone remodeling. **Results:** Neither the intraoral ($P = 0.866$) nor radiographic ($P = 0.528$) measures showed statistically significant side differences in tooth movements. There also were no statistically significant differences in the density ($P = 0.237$) or volume fraction ($P = 0.398$) of bone through which the premolars were being moved. Fluorescent and histologic evaluations showed no apparent differences in osteoblasts, osteoclasts, or mineralization of bone near the teeth being moved. Bone healing was evident in and near the MOP sites, which had nearly but not completely healed after 7 weeks. Regions of acellular bone were evident extending ~0.8 mm from the MOP sites. **Conclusions:** MOPs placed 3 mm away from teeth do not increase tooth movements and have limited and transitory effect on bone. (Am J Orthod Dentofacial Orthop 2019;155:681-92)

Depending on case complexity, the duration of most comprehensive orthodontic treatments ranges from 1 to 3 years, with nonextraction cases requiring 21-27 months and extraction cases requiring 25-35 months.[1] Treatment times depend on the orthodontic mechanics used, patient cooperation, and, particularly in extraction cases, the distance that teeth need to be moved.[2-4] Longer treatment times increase the risk of root resorption,[5,6] decalcification,[7] and periodontal problems.[8] To mitigate these problems, orthodontic research seeks to reduce treatment times while still providing uncompromised treatment results.

Orthodontic tooth movements are physiologically rate-limited by the speed of alveolar bone modeling and remodeling.[9] Most tooth movements occur at ~1 mm per month.[10-15] Tooth movements can be increased by inducing the regional acceleratory phenomenon (RAP) by means of corticotomy procedures.[16-18] The RAP is a response to the injury caused by these procedures; it accelerates existing biologic processes, decreases the amount and density of bone, and increases bone turnover.[19] The transient osteopenia produced by the RAP allows for faster tooth movements.

Corticotomy procedures designed to stimulate the RAP, as popularized by the Wilcko brothers, require raising a full-thickness flap and cutting through the cortical bone around teeth to be moved.[20] Dog studies have shown that teeth move approximately twice as fast when flaps and alveolar decortication are

[a]Private practice, Spokane, Wash.
[b]Department of Orthodontics, Texas A&M University College of Dentistry, Dallas, Texas.
[c]Department of Biomedical Sciences, Texas A&M University Health Science Center, Dallas, Texas.
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Address correspondence to: Peter H. Buschang, Professor and Director of Orthodontic Research, Orthodontic Department, Texas A&M University College of Dentistry, Dallas, TX; e-mail, phbuschang@tamhsc.edu.
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performed.[17,18] However, the procedures are not without risk, including inherent surgical risks of infection, nerve damage, and anesthesia complications, potential loss of alveolar bone height,[21] and possible dehiscences where thin alveolar bone exists.[22] To reduce these risks, flapless procedures have been introduced, with conflicting results.

A rat study showed that flap surgeries and 3 micro-osteoperforations (MOPs) produced twice as much molar movements than when raising a flap alone, suggesting that MOPs were sufficient to induce the RAP.[23] A similar rat study reported enhanced tooth movements initially, but no significant differences in overall tooth movements after 42 days.[24] Studying rates of tooth movements in rodents is problematic because their teeth are 40-50 times smaller than human teeth, making it difficult to appropriately scale the appliances' effects and maintain forces within acceptable ranges.[25] Recently, flapless awl perforations of dentoalveolar bone in dogs produced no significant differences in either tooth movements or the bone surrounding the tooth that was moved.[26,27] A clinical trial using the Propel device to place MOPs in upper premolar extraction sites reported twice as much experimental than control tooth movement over the first 28 days of canine retraction.[28]

The purpose of the present experiment was to evaluate the effects of MOPs—produced with the use of Propel—on tooth movements and bone. The goal was to evaluate tooth movements over a longer time period in a larger animal model, and to relate any differences in tooth movements that might exist to the amount and quality of bone surrounding the tooth being moved.

MATERIAL AND METHODS

Seven skeletally mature male beagle dogs, ~24 months of age and weighing 21-25 pounds, were used. All had fully erupted dentitions and were healthy. The sample size was based on previous split-mouth dog studies that used similar numbers of dogs and showed limited (25%-35%) but statistically significant differences in tooth movements. Dogs were selected because they are one of the best animal models for investigating tooth movements and bony adaptation.[29,30] The housing, care, and experimental protocol were approved by the Institutional Animal Care and Use Committee at Texas A&M University College of Dentistry. The dogs were maintained on a soft diet to minimize damage to the orthodontic appliances.

After a 10-day quarantine, the dogs were sedated by means of an intramuscular injection of ketamine mixed with xylazine, after which dental prophylaxis was performed. Photographs and periapical radiographs were taken. The radiographs were taken with the use of a custom designed cephalostat (Fig 1, *A*), which standardized the x-ray tube position, the dog's head, and the size 4 film position (Figs 1, *B-F*).

Triad custom tray material (Dentsply, York, Pa) was used to make maxillary impression trays. Alginate impressions of the maxilla were poured in die stone and the models were used for appliance fabrication. Local anesthetic was administered via regional infiltration, and the maxillary third premolars were sectioned, elevated, extracted, and allowed to heal.

The appliances were fabricated with the use of the stone models (Fig 2). Orthodontic band material was custom pinched and welded to fit the maxillary canines, second premolars, and fourth premolars. The interior aspect of each band was microabraded, and the bands were perforated to maximize retention.

Headgear tubes of 0.051″ diameter were soldered bilaterally to the orthodontic bands on the second and fourth premolars. Stainless steel orthodontic wire 0.051″ in diameter was soldered bilaterally to the canine bands and inserted through the headgear tubes on the bands of the fourth premolars. These wires served as "guard wires" to protect the appliance. An additional 0.051″-diameter wire was soldered bilaterally to the fourth premolar bands, serving as a "guide wire" along which the second premolar was translated. Stainless steel was used to minimize friction. Tipping and binding were minimized by the 0.051″ wires that closely fit the nominal 0.051″ headgear tubes. Spring attachment loops made of 0.020″ stainless steel wires were soldered to the distal aspect of the second premolar bands and to the mesial aspect of the fourth premolar bands.

Twenty-eight days after extraction of the maxillary third premolars, the animals were prepared for appliance placement and MOP surgery. The experimental side was chosen with the use of an electronically generated random number table. After initial sedation, 8 MOPs were made on the experimental side with the use of the Propel device (Fig 2). The Propel miniscrew tip was inserted to the device's maximum allowable depth (7 mm). Two MOPs were performed within the furcation area of the maxillary second premolar, ~4 mm apart (Fig 3). Six additional MOPs were performed ~3 mm or 7 mm distal to the second premolar, configured in a rectangular pattern. No MOPs were performed on the control side. The goal was to place enough MOPs to affect all of the bone through which the tooth was to be moved, assuming an effect extending at least 3 mm for each MOP.

With the use of a diamond tip bur, retention grooves were cut around the canines, second premolars, and fourth premolars. The teeth were microetched and

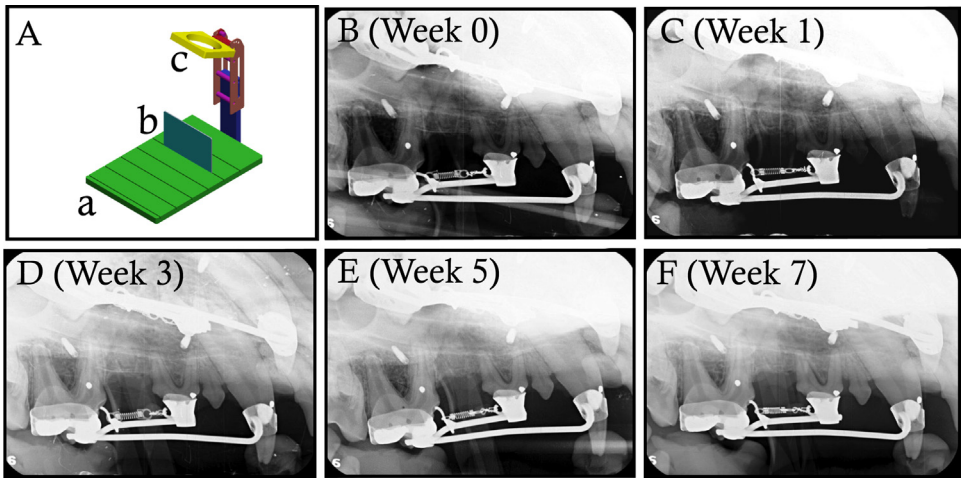

Fig 1. A, Dog cephalostat with baseplate (*a*), occlusal plate (*b*), and x-ray tube holder (*c*). **B-F,** Radiographs from week 0 to week 7 for one dog.

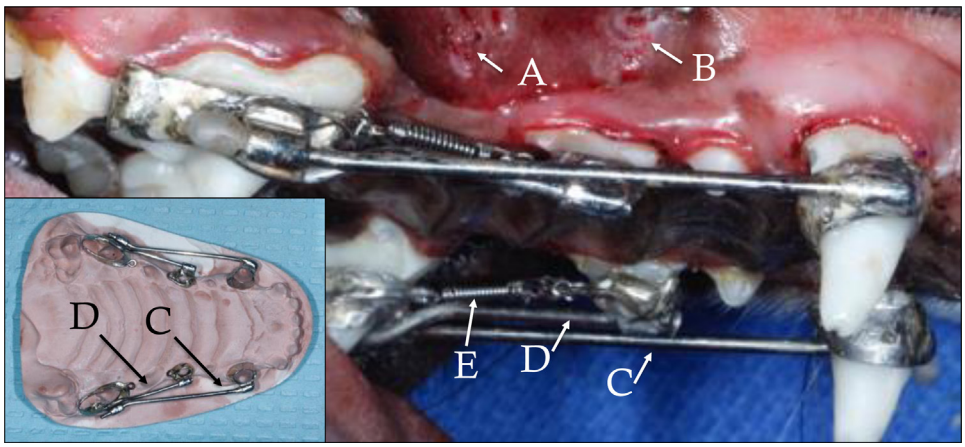

Fig 2. Appliance design and MOP placement: distal MOP field (*A*); MOPs in the furcation (*B*); stainless steel guard wire (*C*); stainless steel guide wire (*D*); and 200 g NiTi closed coil spring (*E*).

then etched with 37% phosphoric acid gel for 15 seconds. After irrigating and drying the teeth, the appliance was cemented as a single unit on each side of the arch with the use of light-cured RelyX Unicem 2 Automix (3M ESPE, Neuss, Germany) resin cement. The appliances were activated by attaching 6 mm medium NiTi closed coil springs (Ormco, San Dimas, Calif) from the soldered hook on the second premolars to the soldered hook on the fourth premolars with the use of 0.008″ stainless steel ligature wire. The springs were activated to 200 g. Forces were verified with the use of a Correx force gauge.

To standardize the intraoral measurements, notches were cut into the cusp tips of the teeth. With the use of digital calipers, the distance between the second premolar and fourth premolar was measured. Three replicate caliper measurements were made at each measurement occasion and averaged. The intraclass correlation of the averaged replicate measurements was 0.985, with a 95% confidence interval of 0.97-0.99.

Intraoral caliper measurements, photographs, and periapical radiographs were again taken at weeks 1, 3, 5, and 7. At each occasion, the NiTi spring was retied and calibrated with the use of the Correx gauge to ensure that 200 g of force was being delivered. A single blinded investigator (C.L.C.) recorded all intraoral measurements. After week 1, the soft tissues covering the MOP sites were fully healed so that the experimental and

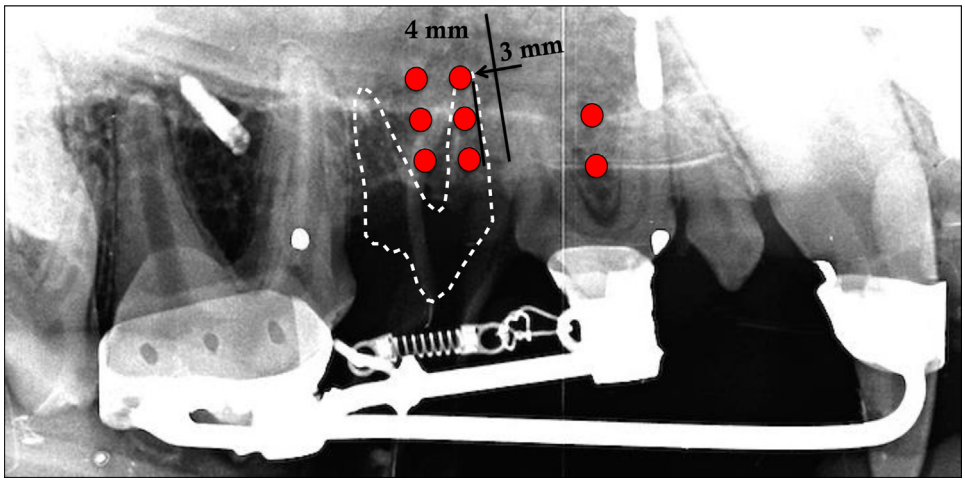

Fig 3. Radiograph showing the approximate locations of the 6 MOPs placed 3-7 mm from tooth root and 2 MOPs placed in the furcation. Red dots represent 1.5-mm-diameter × 7-mm-deep MOPs. Extracted tooth outlined.

control sides could not be distinguished. Calcein green (10 mg/kg intravenously) was administered at week 3. Alizarin red (20 mg/kg intravenously) was administered at week 5, and calcein green was again administered at 6.5 weeks.

After 7 weeks of second premolar retraction (day 49), the animals were again sedated and final periapical radiographs, caliper measurements, photographs, and impressions were obtained. The common carotid arteries were then both cannulated, the external jugular veins were severed, and an intracardial injection of 2 cc beuthanasia-D was given. After cessation of heart function, 1.5 L saline solution followed by 1 L 4% paraformaldehyde was flushed through the cannulas, and the maxilla was harvested and stored in paraformaldehyde.

Periapical radiographs were imported into Viewbox 4.0 (DHAL Software, Kifissia, Greece) to quantify second premolar translation and tipping. A single blinded investigator digitized the radiographs.

The mesial crest of the fourth premolar, the distal crest of the canine, the mesial and distal root apices of the second premolar, and the furcation of the second premolar were digitized (Fig 4). A line connecting the alveolar crests of the canine and the fourth premolar was used as the alveolar crest reference line. The angle (α) formed between the long-axis line of the second premolar (drawn from the second premolar's root apex midpoint to the furcation) and the alveolar crest reference line was used to assess tipping. The midpoint of the furcal bone along the long axis of the second premolar, which served as an approximate center of resistance, was projected perpendicularly onto the alveolar crest reference line. The distance of that point to the mesial crest of the fourth premolar along the reference line was used to measure second premolar translation.

For microscopic computed tomographic (μCT) assessment of bone density, each side of the maxilla was sectioned to include the second premolar, its furcation, and the distal bone into which the second premolar was being moved (Fig 5). The specimens were stabilized in a 27-mm-wide μCT tube with their buccal surfaces perpendicular to the tube's long axis. The tube was filled with 70% ethanol, sealed with parafilm, and scanned with the use of the Scanco μCT 35 scanner at 30 μm resolution, using 55 kVp, 145 μA and 800 ms integration time. Bone volume fraction and bone density were calculated with the use of Analyze v12.0 software.

The same volumes of interest were defined for analysis on the experimental and the control sides of the maxilla by a blinded operator. Each included the alveolar bone immediately distal to the second premolar (Fig 5). The volume was constructed as a 0.3 mm × 0.3 mm square cross-section (occlusal view) extending down the middle 80% of the distal root at the midbuccolingual position. The bone volume–to–total volume ratio and bone density were measured for each volume of interest.

Five randomly selected specimens were used for hematoxylin and eosin (H&E) staining. Each was sectioned through the distal root of the second premolar, so that each included the distal half of the second premolar root plus the bone containing the distal MOP field. The specimens were decalcified in ethylenediaminetetraacetic acid, dehydrated in graded alcohol, cleared with xylene, infiltrated, embedded in paraffin, and sectioned along the sagittal plane to a thickness of 5-6 μm. Starting with the section closest to the buccal cortical surface,

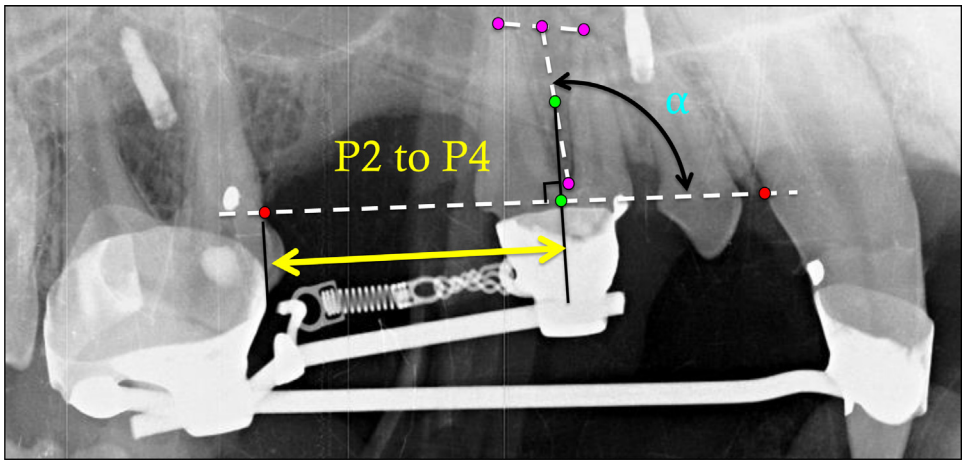

Fig 4. Radiographic reference landmarks and planes used to measure distance from P2 to P4 and tipping angle (α).

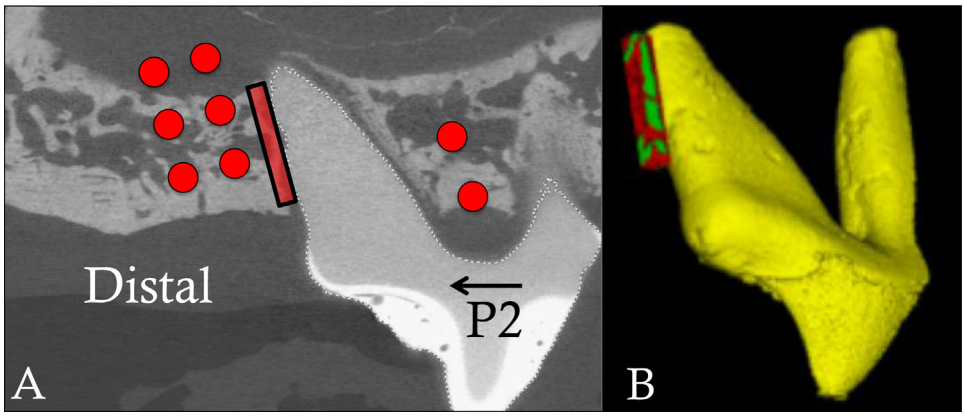

Fig 5. MOP locations and μCT volume of interest. **A,** μCT volume of interest (*red rectangle*) and MOP locations (*red dots*). **B,** 3D volume of interest. Red dots represent 1.5-mm-diameter × 7-mm-deep MOPs.

every 15th to 20th section was selected, with ~10 sections per tooth being thus mounted to glass slides and stained with H&E to evaluate the bone in and surrounding the MOPs. The section images were captured at ×20 magnification and digitized with the use of an Olympus VS120 Virtual Slide Scanner. Two undecalcified specimens were sectioned to include the second premolar roots and furcation, along with the bone containing the distal MOP field. Alizarin red and calcein green staining images were captured at ×5 magnification and digitized with the use of an Eclipse 80i microscope.

Statistical analysis

IBM SPSS version 23 was used to perform the statistical analyses. Because the skewness and kurtosis statistics showed normal distributions, the data were summarized with means and standard deviations. Side differences were evaluated with the use of paired *t* tests.

RESULTS

Healing proceeded normally without any signs of swelling or infection. One dog had an experimental spring disengaged at week 3, a bent control-side guard wire at week 5, and a bent control-side guard wire at week 6.5. Another dog had a control-side guard wire solder joint that failed at week 5. The appliances were repaired the same day that the problems were detected.

Intraoral caliper measurements showed statistically significant ($P < 0.05$) space closure between the second

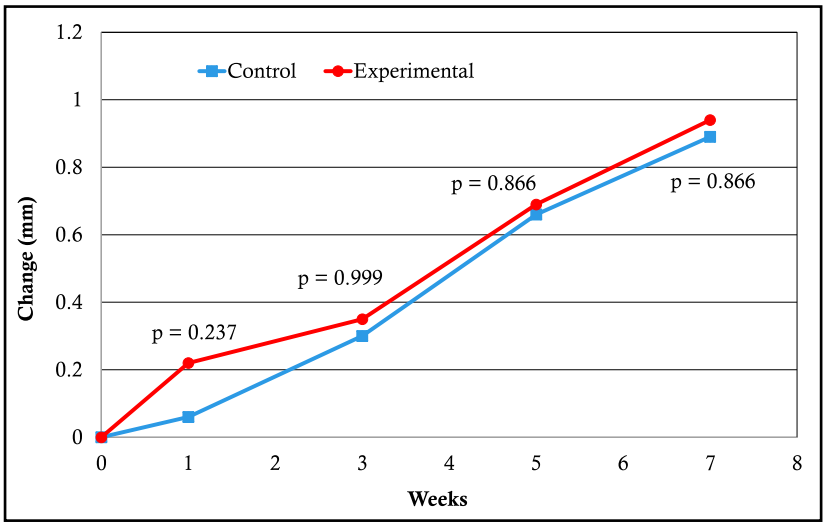

Fig 6. Intraoral caliper measurements of P2-P4 space closure over 7 weeks of tooth movement.

and fourth premolars. The crowns moved 0.86 ± 0.47 mm and 0.94 ± 0.41 mm on the control and experimental sides, respectively (Fig 6). There was no statistically significant group difference at any of the 5 measurement occasions.

Radiographic measurements also showed statistically significant space closure on both sides, with 0.79 ± 0.50 mm of movement on the control side and 1.06 ± 0.43 mm of movement on the experimental side (Fig 7). Group differences were not statistically significant ($P > 0.05$) at any of the measurement occasions. There appeared to be slightly (0.2 mm) greater tooth movements on the experimental side between weeks 1 and 3, but the difference was not statistically significant. The second premolars tipped 0.73 ± 3.14° and 0.45 ± 2.98° on the control and experimental sides, respectively, which also was not statistically significant (Fig 8).

The μCT analyses showed that the density of the alveolar bone adjacent to the second premolar was slightly higher on the control (4639 ± 339 mg HA/cm^3) than on the experimental (4467 ± 273 mg HA/cm^3) side, but the difference was not statistically significant (Fig 9, *A*). Bone volume fraction of bone adjacent to the second premolar was lower on the experimental (0.33 ± 0.13) than on the control (0.37 ± 0.18) side. This difference also was not statistically significant (Fig 9, *B*).

The H&E sections showed vacated Howship lacunae and osteoclasts resorbing mature alveolar bone on the compression side of both control and experimental teeth (Figs 10 and 11). The thickness of the bone front was nearly uniform from the coronal to the apical aspect of the root surface. The experimental alveolar bone was similar in appearance to the control bone (Figs 10 and 11), with new woven bone being formed at the extraction site margins on both sides. On the tension side, osteoblasts and newly formed woven bone were observed, with a bone front cement line apparent at the intersection of new and old bone (Fig 12).

MOPs in the furcation and distal fields were visible on the H&E sections. A mixture of woven and lamellar bone was seen within the MOP borders (Fig 11). There was osteoblastic and osteoclastic activity extending ~300 μm from the MOP. The MOP were surrounded by acellular regions, generally extending 200-500 μm. One MOP showed an acellular region extending ~800 μm from the MOP border. Another acellular region extended to the resorbing tooth socket. There were small clusters of lacunae with osteocytes in close proximity to haversian canals. Beyond the acellular region, the experimental bone appeared to be similar to the control bone. In the control samples, the bone adjacent to the resorbing bone front was mostly cellular (lacunae contained osteocytes), although a few empty lacunae were evident (Fig 10).

Except in and near the MOP sites, the fluorescent images showed similar amounts of bone mineralization on the experimental and control sides (Fig 13). Bone mineralization was most evident in and around the original MOP border (Fig 14).

DISCUSSION

The overall increases in tooth movements produced with the use of MOPs were small, indicating that the effects were limited. After 7 weeks, the teeth on the

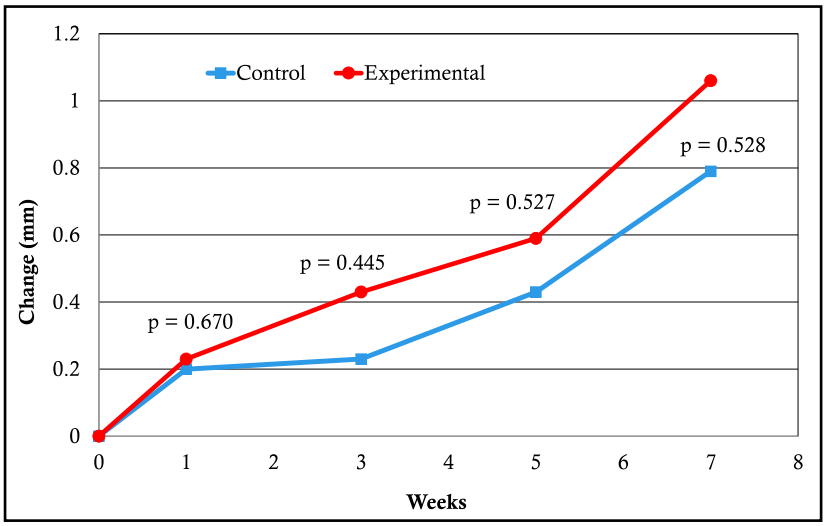

Fig 7. Radiographic measurements of P2-P4 space closure over 7 weeks of tooth movement.

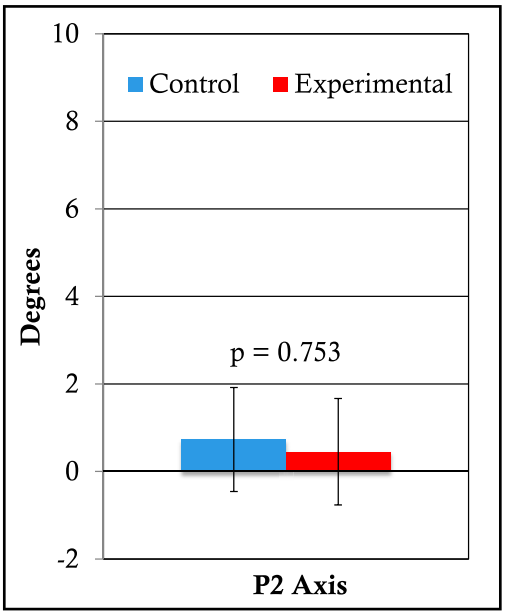

Fig 8. Radiographic measurements of P2 tipping.

experimental side had moved only 0.05-0.27 mm more than the teeth on the control side. These differences were not statistically significant. Experimental rat studies have reported both increases and no differences in tooth movements.[23,24] The limited effect and small sample size in the present study make it impossible to rule out the possibility of a treatment effect. However, even if the differences had been statistically significant, they are too small to be clinically useful.

When MOPs in the present study were placed ≥3 mm from the tooth being moved, they did not increase tooth movements, because they had no major effect on either the amount or density of bone adjacent to the teeth being moved. Swapp et al, who created flapless cortical injuries, also found no differences in bone density or bone volume in medullary bone and no differences in tooth movements.[27] Because the RAP effect appears to be proportional to the amount of injury,[9,31] and because MOPs might be expected to produce less of an insult than flaps, a lesser effect on bone adjacent to the teeth and lesser increases in tooth movements might be expected.

It has been suggested that MOPs should be placed within a 10-mm radius of the tooth to be moved.[32] However, the primary visible effects of the MOP in the present study were limited to ~1-1.5 mm from the edge of the MOP. Moreover, there was an acellular region of bone (ie, empty lacunae) found extending up to 0.8 mm from the MOP border. Acellular bone results when osteocytes undergo apoptosis in response to excessive bone strain and microfracture,[33] such as with the insertion of miniscrews.[34] Although the control bone exhibited no more than 5% acellular bone, as previously reported for other control samples,[33] ~20%-85% of the bone surrounding the MOP sites was acellular. Because osteocytes can resorb bone more efficiently from within their extensive canalicular network than osteoclasts can resorb the external surface of bone,[35] the localized acellular bone may take longer to demineralize and resorb, which could serve as an impediment to tooth movement. Bone associated with the hyalinization that occurs during tooth movement is also acellular, and tooth

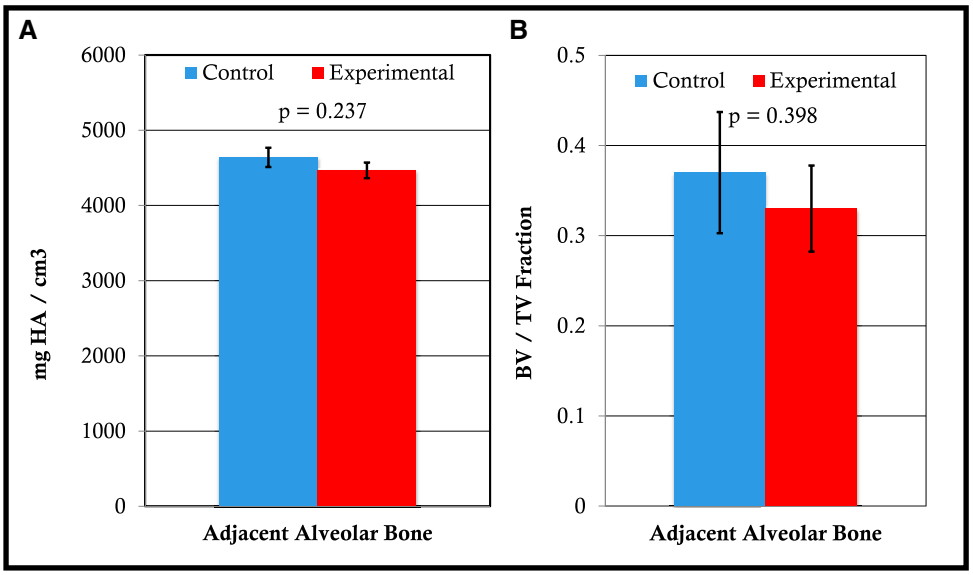

Fig 9. A, Density of bone immediate distal to the second premolars, extending down 80% of the distal root at the midbuccolingual position. **B,** Volume fraction (bone volume/total volume [BV/TV]) of bone immediate distal to the second premolars, extending down 80% of the distal root at the midbuccolingual position.

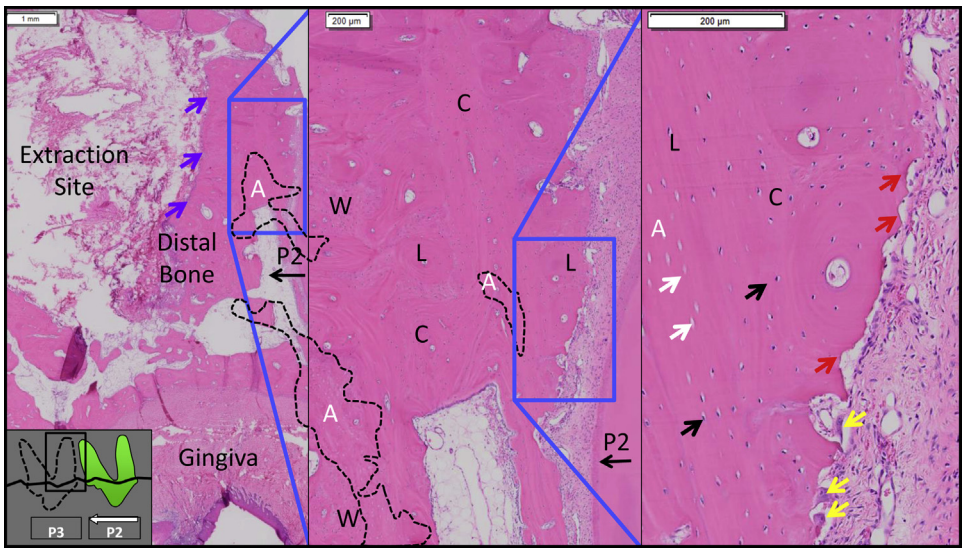

Fig 10. Control-side H&E sections with successive magnifications. Purple arrows: woven bone adjacent to extraction site; white arrows: empty lacunae; black arrows: lacunae with osteocytes; yellow arrows: osteoclasts; red arrows: vacated Howship lacunae. *C:* cellular bone; *A:* acellular bone; *W:* woven bone; *L:* lamellar bone; *P2:* second premolar.

movements are disrupted because the necrotic areas have been resorbed.[36]

It appears that MOPs may produce slight, early, and temporary increases in tooth movements. In the present study, the experimental side exhibited somewhat greater—albeit not statistically significant—increases in tooth movements during the first 2 weeks, but not thereafter. The effects were probably temporary; faster tooth movements after corticotomies are limited to the first 4-6 weeks.[16,18,24,37] If faster tooth movements

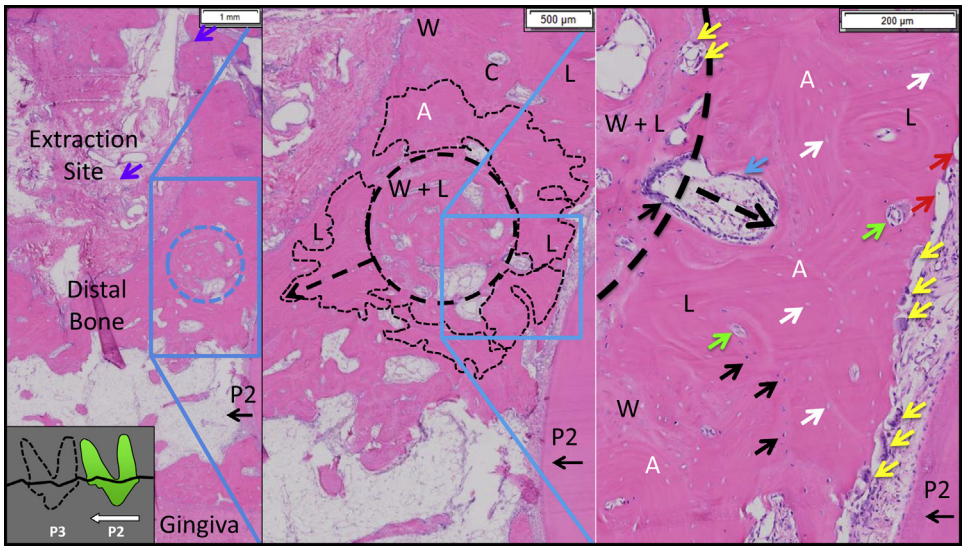

Fig 11. Experimental-side H&E sections with successive magnifications. Purple arrows: woven bone adjacent to extraction site; white arrows: empty lacunae; black arrows: lacunae with osteocytes; green arrows: active Haversian canals; blue arrows: osteoblasts; yellow arrows: osteoclasts; red arrows: vacated Howship lacunae. *C:* cellular bone; *A:* acellular bone; *W:* woven bone; *L:* lamellar bone; *P2:* second premolar.

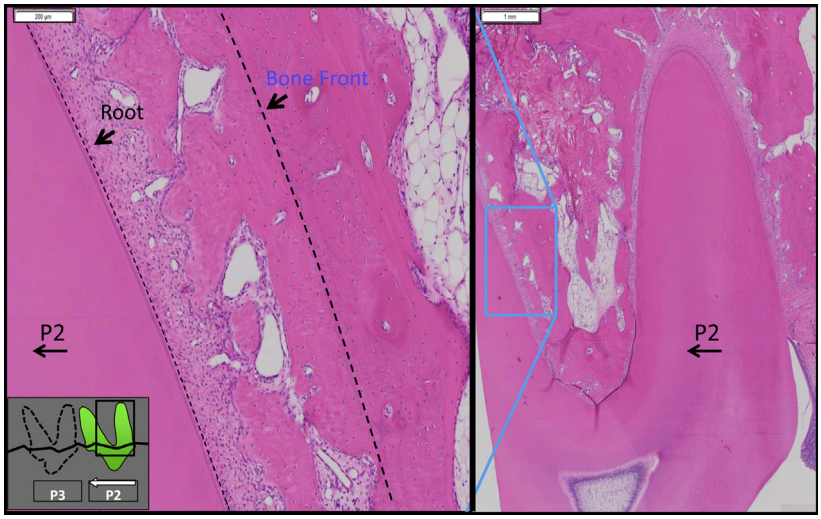

Fig 12. Control-side second premolar with magnification of bone front.

occurred in the present study, they were likely due to distant demineralization (ie, demineralization that occurred at some distance from the MOP). Importantly, the distant demineralization that occurred was limited in both duration and amount.

The MOPs in the present study were placed ~3 mm from the tooth being moved, which is well beyond the area of injured bone. In addition to attracting osteoclasts to the injured area, osteocytes serve as an interconnected network of mechanosensors that respond to local bone strain.[38] Upon sensing injury, osteocytes can directly demineralize bone within their extensive canalicular network.[35] Osteocytes communicate with numerous other osteocytes via intercellular gap junctions, and with osteoclasts at the bone surface.[38] Distant demineralization by osteocytes may be needed to provide calcium for local injury repair. The demineralization by osteocytes and their possible signaling to osteoclasts

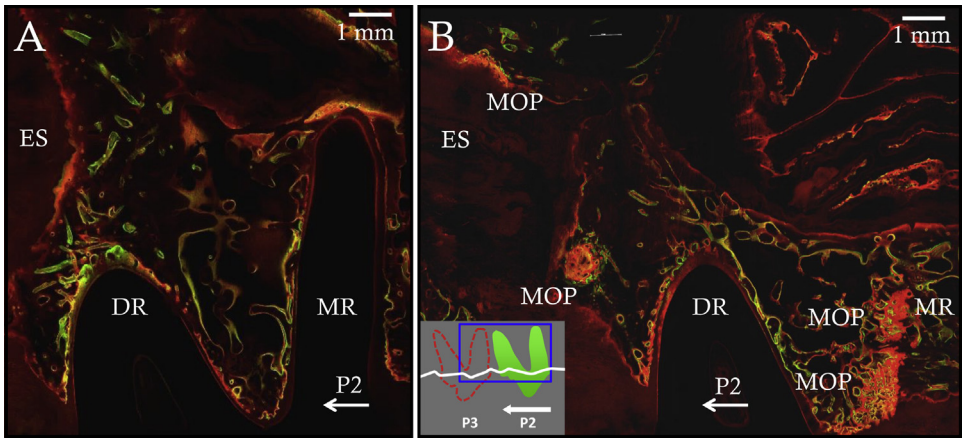

Fig 13. A, Control and **B,** experimental fluorescent sections, showing micro-osteopereforations (*MOP*), along with extraction spaces (ES), distal root (*DR*), and mesial root (*MR*) of second premolar (*P2*).

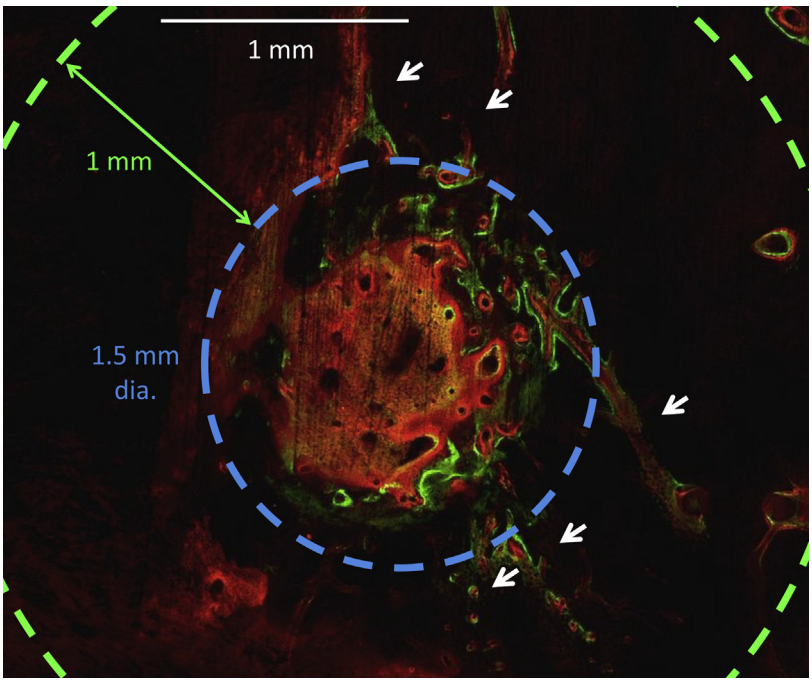

Fig 14. Magnified MOP fluorescent section. White arrows: possible microfractures undergoing repair.

appear to have only slight and temporary effects on tooth movements. Moreover, slight distant demineralization may explain the greater tooth movement produced with the use of MOPs during the first 28 days in humans.[28] Assuming that the increase in human tooth movement reported in that study was partially due to tipping, which was greater in the experimental group, the actual differences in tooth movements could have been less than reported.

Considering the entire 7-week duration of the present experiment, the control premolars moved less than might have been expected.[10] Less movement in this study may have resulted from better tipping control, which produces half as much movement as uncontrolled tipping and translation.[39] Healing time after extractions could also affect tooth movements. In the present study, extraction sites were allowed to heal for 1 month before MOP surgery and appliance activation. Canine retraction

in humans started immediately after extractions is faster than retraction started after a healing period.[40] Dog studies that allowed extraction sites to heal have also shown slower tooth movements[26,37] than dog studies that moved teeth immediately after extractions[41] (ie, the extractions cause the RAP). However, it does not appear to matter whether tooth movements start after 1 or 4 months of healing. During the first 4 weeks of tooth movement, control premolars of dogs moved slightly more after 4 months[17] than after 1 month[16] of healing, which is further supported by the control tooth movements in the present study.

Although the month-long healing period in the present study was insufficient for complete healing of the extraction site, there are several reasons why its limited duration might be expected to have had little or no experimental effect. First, the majority of bone healing in dogs occurs during the first 4 weeks, when the extraction sockets fill with newly formed bone containing large numbers of primary osteons as well as some secondary osteons; the bone matures over the next few months.[42] Moreover, the limited tooth movements that occurred in the present study were primarily, if not exclusively, through interseptal bone. This is important because split-mouth dog studies have established that the RAP effect lasts 6 weeks or less, regardless of whether teeth were moved immediately or after a healing period.[16-18,36] Importantly, it was not possible to isolate the effects of MOPs, because orthodontic tooth movements also produce the RAP.[43] That is why split-mouth studies, which equalize the effects, are essential. Previous split-mouth dog studies have shown substantial experimental effects when teeth were moved on the day of or 1 month after extraction, demonstrating that the RAP effect of corticotomies[9,16,36] and flap surgery[44] are not masked by extractions. To be clinically useful, the effects of MOPs need to be over and above any other appliances or procedures used by orthodontics, which they do not appear to be.

The results hold 2 important clinical implications. First and most important, MOPs probably do not have a clinically significant effect on tooth movements. MOPs centered in an extraction site probably will not affect movements of the adjacent teeth, because they are too far away and the injury produced is insufficient. Second, if their principal effects on bone extend only 1-1.5 mm, then the MOPs would need to be placed close to targeted teeth and in higher numbers, so that the affected areas could overlap along the surface of the tooth. This increases the risk of root damage, patient discomfort, and infection, and decreases the likelihood of patient and doctor acceptance.

CONCLUSIONS

Within the limits of this study, MOPs placed in the dentoalveolar region of dogs produced no differences in tooth movements after 7 weeks of space closure and had no significant effect on the density or bone volume fraction of medullary bone adjacent to the tooth being moved. MOPs may produce a slight and temporary increase in tooth movements during the first 2 weeks, but the effects are small, of limited duration, and clinically insignificant.

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