DENTO-ALVEOLAR DISTRACTION AND RESULTING TOOTH VITALITY

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2020

Major Subject: Oral Biology

ABSTRACT

Introduction: The purpose of this study was to evaluate the tooth vitality following Dental Alveolar Distraction at a rate of 1 mm/day.

Methods: Seven mongrel hound dogs had the second mandibular premolars extracted with removal of all bone except the lingual plate in the site. The third premolar with the surrounding bone was sectioned off of the lingual plate and distracted mesially at a rate of 1 mm/day. The contralateral side had no appliances to ensure vitality. The distractor was turned each day for 6 days with measurement of actual jackscrew activation to compare against cast measurements of the teeth following distraction. Laser Doppler Flowmetry was used pre and post treatment to evaluate vitality. The transport segments were harvested with surrounding bone and analyzed under μCT.

Results: There was no loss in vitality in the distracted teeth. No root resorption was seen in the experimental teeth. The teeth moved approximately 70% of the distance the distractor was activated. A significant difference in the bone quality was noted between each side indicative of healing bone. There was a significant increase in the alveolar width following distraction.

Conclusions: DAD is a safe procedure to accelerate the movement of teeth.

ACKNOWLDGEMENTS

I would like to thank my committee chair, Dr. Peter Buschang, and committee members, Dr. Michael Ellis, Dr. Phillip Campbell, and Dr. Yan Jing, for their work and effort in the completion of this project as well as insight into their expertise with tooth movements. I want to thank Gerald Hill for his dedication to the care of the dogs, and in guidance though the many phases of execution in this project. I would additionally like to thank Dr. Parul Sangwan for her help in this project. I would not have been able to plan and coordinate this project without her guidance. My residency experience including the classes of 2018, 2019, 2020, 2021, and 2022 I would also like to thank for helping me shape into the researcher and clinician that I am. Lastly, I want to thank my wife, Dr. Sara Patenaude, for her support throughout all aspects of this project.

CONTRIBUTORS AND FUNDING SOURCES

The dissertation committee chaired by Dr. Peter Buschang, including Dr. Phillip Campbell, and Yan Jing from the department of orthodontics and Michael Ellis from the department of oral and maxillofacial surgery, supervised this project. The Robert E. Gaylord Endowed Chair in Orthodontics provided the funding necessary to complete this project.

The student completed all other work for this dissertation with the assistance of Dr. Buschang for the statistical analyses. And Ying Lui for running of the microcomputed tomography scans.

NOMENCLATURE

μCT	Microcomputed Tomography
DAD	Dento-Alveolar Distraction
EPT	Electric Pulp Test
LDF	Laser Doppler Flowmetry
MOP	Micro-Osteoperforations
NiTi	Nickel Titanium
PD	Periodontal Distraction
RAP	Regional Acceleratory Phenomenon

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INTRODUCTION

One of the main drawbacks to orthodontic treatment is its length. Treatment time increase multiple risks factors, including white spot lesions, root resorption, and decreased patient compliance. Additionally, it has triggered the rise of do-it-yourself orthodontics, treatment that is not doctor supervised. These treatment approaches have caused major complications in patients, but market themselves under the pretense of "faster and cheaper treatment than braces." Finding ways to reliably decrease treatment time safely, while treating to a high standard, is paramount.

Even with perfect compliance, the rate of tooth movement in bone is severely limited. This is no new issue in orthodontics. Historically, bone was viewed as the main obstacle to tooth movement; its removal and alteration was the main strategy for pushing the limits of orthodontics, even as late as the 1920s. With time, the trend in treatment had moved to less invasive methods. Many of these produced no significant improvement, if any at all. As orthodontics better understood the RAP, its induction became the goal, where increased bone turn over and healing leads to increased tooth movement. This ranged from simple MOPs, or tiny holes through the gingiva and underlying cortex, which have no effect on tooth movement rate, to corticotomies with corticectomies, in which bone is severely undermined in the path of tooth movement. Bone has again become the main focus as the key resistance factor to tooth movement.

Even with the advancement in the rates of movement through RAP affected bone, faster tooth movement rates are still desired. Additionally, the RAP is limited in duration of treatment effect by the body's rate of healing. In order to move teeth fast, they must be moved faster than the body can heal. Distraction osteogenesis has emerged as the way to fill this need. There are two techniques for distracting teeth, periodontal distraction and dento-alveolar distraction. The former suffers from being a difficult and delicate procedure with high risk, such as damaging the tooth root during the procedure.[1] Additionally, it appears to be limited to single rooted teeth. Dento-alveolar distraction (DAD) does not have these drawbacks, although it is more invasive. The tooth/teeth to be moved are moved within the segment of bone housing them, while any bone in the path of movement is removed prior to movement. The DAD technique is promising and has been shown to effectively move teeth rapidly at rates approaching 1 mm/day. Additionally, patients have been reported to heal well, and have little to no periodontal concerns following the procedure. However, vitality of these distracted teeth remains largely unknown.

DAD studies that have evaluated vitality have, with the exception of one study, have used pulp sensibility tests, which have inherent flaws when evaluating traumatized teeth.[1–3] A small study that used a pulp vitality test showed promising results, but it only evaluated maxillary teeth.[4] Other studies have evaluated vitality based upon the appearance of the tooth,[5,6] which is insufficient. Additionally, there have been no animal studies to evaluate vitality.

LITERATURE REVIEW

The duration of orthodontic treatment is multifactorial.[7,8] Risks involved include white spot lesion formation, root resorption, and decreased patient compliance, all of which become more likely with increased treatment time.[9–13] It is important for both the patient and the orthodontist, therefore, to minimize treatment time. In orthodontic cases that require large tooth movements, one common method of decreasing treatment time is increasing the rate of tooth movement.

The orthodontic community is always looking for ways to decrease overall treatment time. Currently, the most reliable ways to increase the rate of tooth movement and decrease treatment time involve surgical procedures.[14] Since these procedures introduce additional risks and treatment costs for the patient, it is beneficial for the patient and the professional to continue searching for safe and predictable methods by which to increase the rate of tooth movement.

Orthodontic Treatment Duration and Risks

Comprehensive orthodontic treatment takes an average of 24 months for non-extraction cases and 28 months for extraction cases.[15] Beckwith and coworkers studied 140 consecutive cases out of 5 different private practice offices.[16] Patient characteristics, diagnostic factors, modality of treatment, and patient cooperation were their focus in addressing this question. A five variable multiple regression explained 46.9% of the variation in treatment time based on the number of missed appointments, number of broken brackets/ bands, poor oral hygiene, prescription of headgear wear, and the number of treatment phases. Compliance was related to the first three, headgear prescription is typically based upon treatment difficulty in growth and anchorage. The reasons for multiphase treatment are multifactorial, but according to Tulloch et al,[17] treatment in multiple phases will not decrease total treatment time or alter the modalities used in phase 2. Total treatment time for any given patient depends on a number of factors, including the distance needed to move and patient cooperation.[7,8]

The major effect limiting the length of orthodontic treatment time is the rate of tooth movement that can be achieved. Studies show that on average, teeth can be moved at a rate of 0.84-1.27 mm per month.[15,18–21] Dr. Martins et al[22] analyzed the changes and rates of canine retraction. This study is particularly valuable as they analyzed movement rates at different time points, which highlights both an initial lag phase in movement, as well as the rate of movement following that phase. They studied the rate of canine movement over the first 2 months of continuous retraction. The sample included 10 patients that were 17.4 +/- 2.6 of age who had class 1 molar relationships, required 4 premolar extractions, were maxillary and mandibular protrusive dentally, had good hygiene, and had healthy dentition. Four tantalum bone markers were placed in the maxilla (2 apical to the first molars and 2 on either side of the midpalatal suture apical to the central incisors), and 3 were placed in the mandible (two apical to the molars and 1 in symphyseal suture). Passive transpalatal arches and lingual arches were placed in the patients after leveling and aligning the segments from first molar to canine in all quadrants. A Beta-Ti 17x25 T-loop was then activated to retract the canines. The patients were evaluated at the start of retraction, 4 weeks into retraction, and 8 weeks into retraction. They found an increased rate of movement during the second 4 weeks of retraction, which supports past literature suggesting a lag phase in retraction.[23–25] They noted rates of 1.6 mm/month and 1.9 mm/month of the maxillary canine cusp tip retraction and of mandibular canine cusp tip retraction over the two months. Approximately 1 mm/month of movement during the first month, and 2-3 mm/month of movement during the second month, were achieved with uncontrolled tipping.

Given the rates of tooth movement noted, space closure is a clear limiting factor in orthodontic treatment. In order to both start space closure more quickly, without a lag, and to shorten the phase of treatment, many techniques have been tried. Attempts to increase this rate involve: (1) pharmacological methods, such as application of inflammatory mediators vitamin D[26] or prostaglandins,[27] (2) mechanical methods, for example low-level laser therapy,[28] and (3) surgical methods, such as dento-alveolar distraction[5] or corticotomies.[29] A systematic review of literature pertaining to increasing tooth movement was performed by Long et al[14]. The group reviewed RCTs to study the effectiveness of orthodontic adjunct procedures in accelerating the rate of tooth movement. Based on nine papers, Long et al. evaluated low-level laser therapy, corticotomies, electrical current therapy, pulsed electromagnetic fields, and dento-alveolar or periodontal distraction. Six outcomes were used to study the effectiveness and safety of the procedures, including total distance moved or movement rate, time required to move tooth, anchorage loss, periodontal health, pulp vitality, and root resorption. They concluded that low-level laser therapy had no effect, and that there is no current evidence suggesting electrical current or pulsed electrical fields in altering tooth movement. Corticotomies were found to be safe and effective for accelerating tooth movement. Periodontal distraction and dento-alveolar distraction were shown to be promising, but there was insufficient evidence to suggest its use.

Historical Background

Originally, orthodontists believed that bone was the main obstacle to overcome in accelerating tooth movements. In 1921 Cohnstock removed the palatal plates for immediately repositioning teeth. Bichlmayr in 1931 removed the cortical plates at extraction sites for retraction of anterior teeth. In 1931, Skogsborg, and later in 1947, Ascher, used vertical interdental osteotomies, also known as septotomies, to reduce treatment times by 20-25%. Bichlmayr, Skogsborg, and Ascher used these techniques when treating protrusive cases and noted difficulties with stability.[30–32] The limited scope of these aforementioned procedures, as well as their trouble with stability, led Kole to reexamine these techniques. In 1959 Kole published a different method for accelerating tooth movements, using vertical and apical corticotomies, in conjunction with heavy forces. This left just the trabecular bone holding the teeth in place, which would theoretically provide less resistance to tooth movement. The belief that the bone was the main factor in slowing movement is summed up well by Kole. "Practical experience has shown that we may achieve a quicker movement of the teeth when a corticotomy has been performed, since the main resistance to movement is encountered in the cortical layer."[32] In 1972, Suya used vertical corticotomies with facial and lingual horizontal cuts to create blocks of bone to accelerate tooth movement.[30] This was based upon the work of Kole, who thought it necessary to leave trabecular bone holding the teeth for periodontal support. Unlike Kole who was moving blocks of teeth, Suya felt this concept could be applied to individual teeth.

Internally, the structure and density of bone has been shown to be of key importance in determining the rate of orthodontic tooth movement. Hashimoto et al[33] took 21 ten-week-old Wistar rats and separated them into 3 groups of 7. The three groups included an ovariectomy group (OVX), an ovariectomy and zolendronate (OVX + ZOL) group, and a control group. Ovariectomy removes the effect of estrogen and produces osteoporotic mice. Zolendronate had been previously shown to prevent the effects of osteoporosis after ovariectomy. The controls also underwent a sham operation. Using NiTi coils, the first molar was protracted in the mice. In order to assess the bone quality, micro CT analysis was performed on the tibias at multiple time points. The tooth movement was 0.2 mm (OVX), 0.15 mm (control), and 0.10 mm (OVX + ZOL). The bone density in the OVX group was noticeably reduced. In the OVX + ZOL group, bone mineral content was higher than in the control group. This supports the idea that bone is the main obstacle because increased movements were found in the osteoporotic group and reductions in movement were found in the group with Zolendronate.

Corticotomies involve raising a mucoperiosteal flap followed by surgical cuts or perforations of cortical layers of bone surrounding teeth to be moved. The procedure was reintroduced and popularized by the Wilcko brothers, who emphasized that corticotomies increase the rate of tooth movement by inducing the regional acceleratory phenomenon (RAP).[34] Frost first described the RAP as an inflammation process following bone injury. Cellular signaling promotes osteoclastogenesis, which results in decreased density and increased turnover of bone near the injury.[35] To increase tooth movement rate, a bone injury can be performed near a tooth of interest. The decrease in bone density in the nearby area allows for faster bone resorption and faster tooth movement. It has been documented that the extent of injury to bone is positively related to the decreases in both the amount and density of bone, as well as increases in tooth movements.[36,37]

Besides corticotomies, it has also been shown that the surgical process of raising a mucoperiosteal flap alone induces the RAP. Yaffe et al demonstrated resorption of cortical and trabecular bone following flap procedures on the lingual and/or buccal surfaces of rats' mandibular alveolar ridges.[38] These findings were encouraging, because a flap procedure is much less invasive than decortication, and yet, produces the bony changes needed for increased tooth movement, albeit less tooth movement than corticotomies.[34,39–41] In 2017, Owen et al. showed a 25.3% increase in tooth movement and a 9.1% decrease in medullary bone density in beagle dogs following mucoperiosteal flap only surgery. Since orthodontists typically do not lay flaps, this procedure would pose an extra expense for patients in having to see another professional. Combined with the extent of the acceleratory effects the authors questioned whether flap alone is justified as an adjunct procedure in orthodontics.

In order to achieve acceleration of tooth movement with minimal morbidity risk, flapless bone damage was explored as a method to produce the RAP. Aside from the drawbacks mentioned by Owen et al, there are inherent risks in corticotomy and flap procedures. These include the risk of alveolar bone loss, and even dehiscence in areas of thin alveolar bone.[42] Multiple flapless procedures have been explored.[43,44]

Micro-osteoperforations (MOPs) created with the PROPEL device, have been particularly popular. Cramer et al[43] studied the effects of MOPs and the PROPEL device. They used a split-mouth design of 7 beagle dogs analyzed the bone surrounding retracted teeth after seven weeks. Prior to tooth movement, the maxillary third premolars were extracted, and healing was allowed for one month. Following the healing period, 8 MOPs (1.5mm wide and 7mm deep) were placed without flaps using the PROPEL device (6 were placed 3mm distal to the second premolar and 2 were placed in the furcation) on one randomly chosen side. Both maxillary second premolars were retracted with 200g NiTi closed coils. There was no significant difference between the control and experimental groups in tooth movements or in the density of bone surrounding the teeth. Histologic analysis showed no side difference in osteoblasts, osteoclasts, or mineralization of the bone near the teeth being moved. The MOP sites were almost completely healed after seven weeks. Regions of acellular bone were evident approximately 0.8 mm from the MOP sites. Although accelerating orthodontics through minimally invasive approaches is desired, it appears that more invasive methods and faster rates of tooth movement are necessary to get clinically meaningful change in orthodontic tooth movement.

In order to understand the effects of more invasive methods to speed up tooth movement, bone healing must be considered. It is important to understand the limits of bone healing, how long the healing effect might last, and how long recovery might take. Berglundh et al[45] studied bone healing in the dog model using implants. They analyzed the bone between the threads of the implants. By sacrificing the dogs at different time points, they mapped the healing of new bone, finding mature bone had formed in 8 weeks. This timeline is in agreement with historical corticotomy research,[32] as well as the MOP research.[43] Currently, an active area of research is to lengthen the duration of the RAP.

Extending the RAP effect would likely result in faster tooth movement. However, even under acceleration of the RAP, conventional mechanics still produce tooth movement rates slower than desired. Wilko et al,[34] suggests the rate of tooth movement doubles to roughly 2 mm per month under these physiologic conditions. This is also supported in other studies.[40,41] They show two case reports of alveolar reshaping, which has since fallen under the name of "Wilckodontics" by the profession. A 24-year-old male patient and 17-year-old female patient, who were both class 1 molar malocclusion cases, underwent the alveolar reshaping procedure to accelerate tooth movement. Full thickness buccal and lingual flaps were laid and selective corticotomes with bone grafting and augmentation were performed before they surgically closed the site. The orthodontics then began immediately after the procedure to take advantage of the RAP effect and both cases were completed in less than seven months.

More recently, corticotomies have been expanded upon by incorporating corticectomies to increase the RAP effect. Ferguson et al[46] treated a sample of 118 patients who had 151 palatally impacted canines. 72 of the canines were treated with ostectomy-decortication, while the remaining 79 canines were treated with traditional corticotomies. Orthopantomograms were taken to assess the position of the palatally impacted canines prior to treatment. The canines were classified by the vertical position of their crowns and canine angulation in the palate. The control group was matched to the experimental based on these measures. In the ostectomy-decortication group, a full thickness flap was laid buccally and palatally to the canine position. Bone was removed around the crown of the canine as well as all of the bone between the crown of the canine and its desired final position of the in the arch. Corticotomies were also placed around the bone between the canine root and the desired final position of the root. Power chain then provided traction, which was immediately placed on the canines before surgical site closure. In the control group, the canines were exposed and bonded, and corticotomies were placed in the bone around the canine. As in the experimental group, traction was immediately applied to the arch following the procedure. In the ostectomy-decortication group, a significant difference between different starting positions of the canines in the palate and the time needed for forced eruption was reported. No significant difference between initial canine position and time needed for forced eruption was noted in the control group. However, there was a significantly shorter treatment time in the ostectomy-decortication group than the control group, of 6.6 months versus 21 months.

Ostectomies allow teeth to move faster, but even greater rates of tooth movement are needed to move teeth longer distances. In contrast to moving the tooth through the bone faster, one could imagine moving tooth along with the bone. This is known as distraction osteogenesis. Dr. Ilizarov, the father of modern distraction osteogenesis, lengthened limbs by slowly separating fractures at a rate of 1 mm/day. He found the bone could heal at this rate without prematurely fusing or resulting in non-union. This rate is 30 times faster than conventional movements in orthodontics. Further research out of Massachusetts General Hospital has shown that the bone can be moved in curves, and not just in straight lines in the jaw.[47] Moore et al[48] and Spencer et al[49] showed that the distraction of bony segments does not result in bony defects behind the teeth being moved in a beagle model.

Another distraction model, known as periodontal distraction utilizes bone removal in the path of desired tooth movement. The tooth is then distracted without the surrounding bone. The method of periodontal distraction is less invasive than moving the tooth within bone, known as dento-alveolar distraction. It however, moves teeth at slower rates and has been associated with increased root resorption, and increased technique sensitivity.[1]

Dento-alveolar Distraction

The growth of distraction led to the concept of dento-alveolar distraction (DAD). This approach has been recently studied as a way to produce enhanced tooth movement with surgical interventions.[5] This process involves cutting around a tooth leaving ~2-3 mm of surrounding bone, and sectioning it off the lingual cortex to produce the transport segment. An adjacent tooth is often extracted, and all bone other than the lingual cortex is removed up to the tooth transport segment in the path of desired movement. The transport segment is then moved rapidly at a rate of approximately 1 mm/day. The transport segment is then held in this new position to allow the bone to consolidate. This procedure allows for extremely rapid movement of teeth with minimal anchorage loss, as the tooth reaches its desired position prior to overcoming the lag phase in movement. Current studies suggest that movement of the distraction segment to the activation of the distractor is about 0.7:1, over the range of an extraction space.[1–3,5,6,50–53]

Dento-alveolar distraction (DAD) first came onto the scene in 2002, when Kisnisci et al[5] distracted 24 teeth. The procedure involved a buccal mucosal flap, cutting the cortical bone mesial and distal to the tooth, and 5 mm apical to the apex of the canine root. The trabecular bone around the tooth was then fractured with osteotomes, followed by fracturing the segment containing the tooth and surrounding bone (transport segment) off the lingual plate. The first premolar was then removed, additionally, the buccal plate and interfering bone between the transport segment and the desired final position of the segment was removed, which included exposing the sinus in many cases. Tooth movement was initiated immediately following the procedure without a latency period. All teeth were distracted until the space was closed to the second premolar. The authors noted that there was no appreciable anchorage loss, ankylosis, or root resorption, and that vitality testing of all the teeth had a normal response. However, in this paper, the authors do not provide information about the methodology used to evaluate post distraction tooth vitality.

The same group published two more papers in 2005. One analyzed the periodontal effects of dento-alveolar distraction based on 36 maxillary canines that underwent DAD in growing and adult patients an average age of 16.9 years.[6] They used the surgical procedure previously described by Kisnisci et al,[5] but added a latency period of up to 3 days. The distraction device was activated 0.4mm 2x/day (0.8 mm total) until space was closed, which took an average of 10.36 days. No specific data regarding the anchorage loss or the vitality state of the canines was reported. The authors stated that clinical evidence suggested minimal anchorage loss, and that no discoloration or radiographic signs of vitality loss were present. The 1-year follow up plaque index (measure of present plaque), gingival index (measure of bleeding to probing), pocket depth, and attached keratinized tissue width were not significantly different from the pre-surgical, recordings.

The second paper evaluated 20 canines in 10 16.5 year old patients who underwent dento-alveolar distraction.[50] Space closure from the first bicuspid extractions took an average of 10.1 days using the DAD protocol described in the Gurgan study. The outcome measures were tipping of the canines and anchor teeth, anchorage loss in the anchor teeth, and changes in the vertical dimension of the patient cephalometrically. An average of 0.2 mm anteroposterior and 0.5 mm vertical anchorage loss were found in the first molar. They also found an average of 13 degrees of canine tipping following DAD. There was a statistically significant change in the MPA of 0.67 degrees in the patient sample. In this study, they claimed that there were no complications. The teeth were also evaluated with electric pulp testing (EPT) pre treatment, post distraction, and throughout treatment with fixed appliances after DAD. The authors found no reliable results for tooth vitality through EPT at any time point after the procedure.

This group then wanted to determine whether DAD would lead to shorter treatment times in patients.[2] The experimental group began with an updated version of the DAD procedure, followed by fixed appliances with reciprocal closing mechanics for the maxillary lateral to opposite maxillary lateral segment. In the updated DAD procedure, a three-day latency was established, while the same distractor activation rate as prior, 0.8 mm/day, was used. The control group used reciprocal mechanics, first retracting the canines followed by the maxillary lateral to opposite maxillary lateral segment for space closure. For canine retraction, the experimental group averaged 12 days, while the canine retraction averaged 200 days in the control group. There was no significant change in the mandibular plane angle in the experimental group, compared to a one-degree increase found in the control group. The DAD group showed less than 1 mm of posterior anchorage loss AP, while approximately 2 mm of posterior anchorage loss was noted in the control group. Based upon the increased rate of canine retraction to that of conventional mechanics, the authors concluded that DAD would shorten treatment times. However, final treatment times were not given for either group. The author in 2018 submitted an author's response in reaction to questions about the paper. They emphasized that treatment began immediately following DAD, but still do not definitively conclude reduced treatment times.

Aside from this group, Sukurica et al[3] published a detailed study on the outcomes of DAD. 8 patients underwent first premolar extraction followed by dento-alveolar distraction of the canines (12 maxillary canines, and 8 mandibular canines). Cast analysis was used to assess anchorage loss, EPTs were used immediately and 6 months post distraction to assess tooth vitality, and tooth angulation was assessed through panoramic radiographs. The same surgical procedure was used as suggested by Kisnisci et al,[5] a 3-day latency period, and with a 0.5 mm/day of distractor activation schedule. Following DAD, 5.35 mm of canine distalization was achieved with 1.2 mm average anchorage loss over 14 days. 9.1 degrees of tipping in the canines was noted, with no appreciable tipping seen in the first molars. Six of the teeth were found to respond to EPT tests after 6 months, even though immediately following surgery, no teeth responded to the EPT.

Kharkar et al[1] looked to compare dento-alveolar distraction to periodontal distraction. Six patients were selected with dental bimaxillary protrusion. All four canines in each patient underwent distraction. One maxillary and one mandibular canine underwent periodontal distraction (PD), while the other two canines underwent DAD. There was no detail regarding how teeth were allocated into the PD and DAD groups. The same distraction device was used for all distractions. The PD group had no latency period, with a distractor activation rate of 0.5 mm/day. The DAD group had a 2-day latency period, and utilized the same distractor activation rate. The tooth movements were analyzed cephalometrically. Total space closure took an average of 1 week longer for PD compared with DAD, 19.5 days and 12.5 days respectively. Significant differences were also noted in canine tipping, PD averaged 15 degrees of tipping, 5 degrees more than DAD. Anchorage loss in the AP was statistically significantly different, although not clinically significant, being 0.25 mm vs 0.32 mm, favoring PD. In the vertical dimension, there was a statistically significant difference of 0.65 mm versus 0.55 mm favoring DAD. Root resorption was only noted in the PD group. Electronic pulp testing was performed prior to the surgery and again 1-year post distraction; all canines responded to EPT in the 6 studied patients. The authors note the difficulty of precision in the PD procedure, and importance of technique to avoid causing harm to the tooth to be distracted and to mitigate side effects. They conclude based on the results and surgical predictability, to find DAD superior to PD in rapid tooth movement.

In addition to Kharkar et al,[1] Kateel et al,[52] also used a split mouth study to compare PD to DAD. Eight patients received maxillary first bicuspid extraction. The right canines underwent periodontal distraction, and the left canines underwent DAD. The distractor was activated until space closure was complete at a rate of 0.8 mm/day. EPTs were performed immediately following distraction. 14.5 days were needed on average to close the space for DAD while 15.38 days were needed to close the space for PD. However, this wasn't statistically significantly different. Anchorage loss was 0.91 mm for PD and 0.84 mm for DAD, canine tipping was 14.94 degrees for PD and 14.88 degrees for DAD, and total canine movement was 6.6 mm for PD and 6.9 mm of canine movement was found for DAD. None of these findings were statistically significant, although it is mentioned that every measure favored DAD. EPTs were inconclusive as only 5/16 teeth responded, 2 in the PD group and 3 in the DAD group.

In response to the limited data on tooth vitality, Ersahan et al[4] utilized LDF to evaluate the pulpal vitality of teeth following DAD. The sample contained 20 class 2 div 1 malocclusion adults (mean age: 20.7) requiring extraction of the maxillary first bicuspids. 20 teeth in 10 patients underwent DAD as per Kharkar et al[1] protocol, with an altered latency period of four days. After distraction, a 4-week consolidation period was observed. Using acrylic splints and rubber dams to block out periodontal tissues, in conjunction with the removal of the distractor, LDF recordings of the canines were taken. The recordings were taken 1-week pre surgically, 4 days post operatively, 7 days post operatively, post distraction (11-14 days post operatively), and following 4 weeks of consolidation post distraction. Following each recording, the distractor was replaced. Average perfusion unit (PU) values were obtained over a 1-minute recording period. The average PU values were not significantly different between pre-surgical measurement, 7 days post-surgical measurements, and post-consolidation measurements. There was a temporary dip in PU measurement at the 4 days post operative recording that they noted. All teeth were classified as vital in the study.

Looking at the present literature on DAD, it appears effective in moving teeth with minimal periodontal and orthodontic side effects. However, there is limited data on tooth vitality in these studies. Pulp sensibility tests are most commonly reported, and with variable findings. One study utilized LDF in the maxillary jaw only. Although it had small sample of ten patients, it did show promising results of maintained vitality. Additionally, in the LDF study, the rate of movement was only 0.5 mm/day of distractor activation. Conclusions drawn from coloration of the teeth and radiographic appearance of the teeth are insufficient to determine tooth vitality. Given the limited vitality data, the safety of DAD for clinical use has not been established.

Tooth Vitality

In any procedure within the field of dentistry, tooth vitality is a primary measure of success. The Kisnisci group has shown non-significant changes in the periodontal health of teeth following DAD.[6] However, multiple DAD studies have looked at vitality, only as a secondary outcome measure, using pulp sensibility tests.[1,2,52,53] These have been shown to be inaccurate for teeth that have undergone trauma.[54] The closest correlation available is found in the oral surgery literature, in which the blood supply to the teeth is diminished orthognathic surgery, but returns following healing. The teeth do not respond to nerve pulp testing initially, however, sensation typically returns in time.[55,56] In particular, they noted that dramatic reductions in blood flow were seen in the canines. However, over the following 12-month period, blood flow in all teeth returned to near initial levels.

In order to gain a more accurate understanding of tooth vitality, recent endodontic research suggests that measuring a tooth’s blood flow is the gold standard for assessing vitality. This has been done utilizing Laser Doppler Flowmetry and Pulse Oximetry.[57,58] Another way to do so, would be harvesting the teeth and looking for blood vessels under microscopy.[59]

In 2009, Chen and Abbott reviewed the state of dental pulp testing. They identified two types of tests: pulp vitality tests such as Laser Doppler Flowmetry (LDF) and Pulse oximetry, and pulp sensibility tests, which include thermal testing and EPT.[58]

Vitality tests are an indication of blood flow within the tooth, while sensibility tests attempt to induce a response of the nerve within the tooth to stimuli. Thermal tests rely on the pain response, from cold or hot application, and the difference in the way the patient experiences the pain, to distinguish the health state of the tooth. There are concerns that sensibility tests may cause damage to teeth in a fragile pulp state. Due to relying on patient discomfort, and potential risks of pulpal damage to assess tooth vitality, a more accurate alternative, EPT, was developed. An EPT creates a current across the neural membrane within the pulp and releases an action potential. The probe is placed on the tooth with a conductive medium, such as toothpaste, between the probe and the tooth. The current is then increased until the pain threshold is reached, which often presents as a tingling sensation. There is no correlation for amount of applied current to tooth response. A tooth that is known to be healthy is used as the reference for a normal response, which is compared against the tooth in question. EPT suffers both from inherent variability in the teeth, and a high rate of false results. Like with thermal tests, EPT has been shown to be a poor predictor of tooth vitality in traumatized teeth, as well as teeth undergoing, and within, 9 months of orthodontic treatment. Actively necrosing pulp can have residual inflammation tissue that can elicit a response to EPT. Another issue is that the current can be conducted to adjacent teeth, creating false responses as well.

The second type of test described by Chen and Abbott, is the pulp vitality testing. They mention that pulse oximetry (PO) provides a significantly less costly test of pulp vitality than LDF. This method however, is less evaluated. Infrared light is scattered to detect the differences in oxygen saturated vs. unsaturated hemoglobin. The output results of teeth vary in the studies performed. Periodontal tissues present a significant scatter problem, which can lead to false or inflated results of vitality. Future research is indicated for the widespread use of pulse oximeters.

Like with Pulse oximetry, LDF is a non-invasive technique where a probe is placed on the tooth and aimed into the pulp cavity. A light source is emitted that will change frequency upon reflection with red blood cells. The detector will analyze the backscattered light into a signal. The signal is often reported arbitrarily as “PU” or perfusion units. The probe must be still for the most accurate measurement, as such, a splint is often made to hold the probe in a constant position. One complication is the scatter of light from other tissues, especially in larger wavelengths of light. The signal has been reported in many studies to have a pulsatile nature, and can be synchronized with an electrocardiogram taken at the same time. Only irregular fluctuations are noted in the recording of non-vital teeth. The main problem currently with LDF, is the inability to completely isolate other scattered light from non-pulp tissues that would register as a positive signal. This scatter is mainly from periodontal tissues, even when using the best splints and techniques to try and block out the periodontal tissue from the probe. Another drawback is that it is impossible to correlate the output values with blood flow, so absolute values of blood flow recorded by LDF should be considered cautiously. Any impedance to the light, such as restorations in the teeth, can cause LDF to be unusable on those teeth. There have been two main ways to interpret the results of LDF. Firstly, is to compare a contralateral tooth of the same morphology that is known to be healthy. There however, can be natural differences in the output values for healthy teeth in the same patient of the same morphology. Secondly, Fourier transforms, where the signal is matched to the patient's heart rate, is another common method being used to establish blood flow.

Nine years after this review, Mainkar and Kim[57] reexamined the methods of sensibility tests and vitality tests. This systematic review and meta-analysis evaluated three sensibility tests including cold tests, heat tests, and EPTs and two vitality tests including LDF and PO. Heat tests were the least reliable prediction of vitality, while cold tests generally showed high accuracy among sensibility tests. EPT was the best sensibility test for identifying vital teeth with a specificity of 93%; however, EPT has a low sensitivity of 72%, making it much less likely to correctly identify necrotic teeth. LDF and PO have higher scores for both sensitivity and specificity than the sensibility tests (LDF 98%/95%, PO 97%/95%). LDF also had a much tighter confidence interval for sensitivity than PO. The main drawbacks to LDF and PO are the high technique sensitivity, and the requirement for a tooth to have pulp that is accessible above the gingival margin.

Utilizing these pulp sensitivity tests, Naseri et al[59] correlated their clinical results with the histologic status of the pulp. 65 permanent teeth that were planned to be extracted for periodontal, prosthodontic, or orthodontic reasons, underwent sensibility testing. Following extraction, the teeth were sectioned and examined histologically. Sensibility tests were found to be more accurate in identifying untreatable pulp conditions than treatable pulp conditions. The accuracy to detect treatable vs. untreatable pulp for cold tests, hot tests, and EPT was 78%, 74%, and 62% respectively. Good correlation was found between the clinical result, the interpretation of the sensibility test, and the histologic analysis. In most cases, reversible vs. irreversible pulpitis was the least correlated. There is a need for better pulp testing methodology to distinguish between treatable and non-treatable teeth.

Lastly, in understanding the background of accelerated tooth movement, it is important to study an appropriate model. The bone structure is important when studying tooth movements, especially in dento-alveolar distraction. The rat model is insufficient because there are no osteons or marrow space between bone plates, as well as a differing PDL arrangement.[60] Another issue, is that small animals, such as rats, experience systemic reactions from damage that is sized for a human, and not properly scaled down.[61] The procedure delicacy and the appliance fabrication, make the amount of damage a major limitation in many acceleration studies. Additionally, for distraction accelerated tooth movements, the dog model is established.

In addition to showing a need for a non-rat model to study tooth movements, Ren et al[62] showed that dogs are effective to model human tooth movement. They combined tooth movement and force data, in both dogs and humans, into a mathematical model. This model predicts 0.29 mm per week of human canine retraction with 277g (135g - 471g) of force and 0.27 mm per week of mandibular second premolar movement in a dog with 253g (135g - 471g) of force. These were not significantly different, which led the group to conclude that human and dog tooth movements could be achieved over a wide range of forces with similar movement rates. This helps establish dogs as an optimum orthodontic model.

MATERIALS AND METHODS

Sample

Seven skeletally mature female mongrel hound dogs were purchased from a breeding facility, they were approximately 15-26 months of age and weighed between 68-86 pounds. Upon arrival, the dogs underwent physical examinations to ensure health and full eruption of dentition. Each dog received identifying tattoos. All dogs had fully erupted dentition and were determined to have completed adolescent growth. The dogs were quarantined for 10 days with no research activity. Of the seven dogs, one was used as a pilot dog. A soft food diet was maintained throughout the experiment to help prevent breakage of the orthodontic appliances. The dog model has been shown to be an effective model for studying bone remodeling and tooth movement and was chosen for this study.[62–64] The Institutional Animal Care and Use Committee at Texas A&M University College of Dentistry approved the housing, care, and experimental protocol (IACUC 2018-0257-CD0).

Appliance Design Preparation and Experimental Side Determination

After 12 hours of fasting, the dogs were sedated with an intramuscular injection of ketamine (2.2mg/kg IM) mixed with xylazine (0.22mg/kg IM) to perform dental prophylaxis with a Cavitron Select ultrasonic scaler (Dentsply, York, PA), irrigated with 0.12% chlorhexidine gluconate. Triad tray material (Dentsply, York, PA) was used to fabricate impression trays for each animal. Alginate impressions were taken and immediately poured in orthodontic die stone for study models. Periapical radiographs were taken of the mandibular left and right quadrants using a Planmeca Intra X-Ray unit (Planmeca USA, Roselle, IL) and size 3 film. They were used to determine the depth of cuts and root lengths of the teeth prior to surgery. (Figure 1) Experimental side was determined to be the opposite side that the periodontal distraction appliance was placed in the other jaw.

Appliance Design

Using the mandibular die stone impressions, orthodontic band material (Dentauram, Ispringen, Germany) was adapted to the mandibular canine, third premolar, and fourth premolar of the experimental side. A Herbst tube (Ormco, Orange, CA) of 0.072" diameter was aligned to the alveolar ridge on the buccal of the fourth premolar bands and soldered in place. A 12 mm mini rapid palatal expander (Forestadent, Pforzheim, Germany) was adapted to the canine and soldered to ensure the opened (minimally 7mm) jackscrew paralleled the alveolar ridge while fitting passively through the Herbst tube on the band of the fourth premolar. 0.45" stainless steel orthodontic wire was adapted to the arm of the RPE distal to the jackscrew and to the third premolar. (Figure 2) The appliance bands had small perforations placed to aid in retention.

Pre-surgical Preparation

Following a 12 hour fast, intramuscular injection of ketamine (2.2mg/kg IM) mixed with xylazine (0.22mg/kg IM) was administered. Each dog received an additional dental prophylaxis with the same ultrasonic scaler and irrigated with 0.12% chlorhexidine gluconate. Prior to intubation, atropine (0.05 mg/kg) was administered to prevent isoflurane-induced bradycardia. The dogs then received 1.5% isoflurane in oxygen at a rate of 1 L/minute. Baseline vitality readings of the mandibular third premolars were recorded bilaterally with a Laser Doppler Flowmeter (MoorVMS-LDF, Devon, UK). Small notches were placed in the teeth with a small round bur to help stabilize the probe. Two layers of nitrile gloves were used to 1) isolate the probe from outside light and 2) cover the gingival tissues around the tooth to reduce scatter. The operator stabilized the probe, and one-minute recordings were taken for the control and experimental tooth.

Surgery

Injection of 2% lidocaine with 1:100,000 epinephrine locally and for inferior alveolar block provided analgesia. Vital signs were monitored throughout the procedure. The mandibular 2nd premolar was hemisected, elevated, and delivered via forceps. The osteotomies used in this experiment were the similar to those outlined by Kurt et al.[2] A buccal mucoperiosteal flap was laid extending from the 4th premolar to the 2nd premolar. An outline corticotomy was performed using a 701 cross cut fissure bur. This cut went 5 mm below the apex of the roots, as determined by the periapical radiograph (Figure 1), and 2-3 mm mesial and distal to the roots of the tooth within the transport segment. The same fissure bur was used to make the coticotomy parallel to the alveolar ridge 1-2 mm below the crest on the lingual cortex. (Figure 3) All cuts were performed through the extraction site and buccal mucoperiosteal flap with the exception of the lingual corticotomy, which utilized minimal reflection of the soft tissue from the alveolar crest on the transport segment. Osteotomes were then utilized to fracture the transport segment from the attached trabecular bone, leaving the lingual cortex intact. Following mobilization of the transport segment, all bone mesial to the path of movement except for the lingual plate was removed for at least 7 mm, which was measured to verify adequate removal. (Figure 3, b) Careful attention was taken to minimize trauma to the inferior alveolar nerve during the operation. The procedure was performed only on the experimental side. Full mobility of the transport segment was established before closure of the surgical procedure with 3.0 Vicryl sutures.

Appliance Delivery

Prior to banding, the teeth were pumiced and rinsed, and then etched with 37% phosphoric acid for 15 seconds and rinsed again. 3M Glass Ionomer cement was mixed according to manufacturer instructions and applied to the band before cementation. Manual retraction with an air syringe provided a dry field. The appliance was then cured with the VALO cordless light (Ultradent Products Inc., South Jordan, UT) for 40 seconds. The distractor was turned forward and back three ¼ turns to ensure appliance bond and transport segment movement. A periapical radiograph was then taken to ensure seating of the appliance. (Figure 2)

Post-surgical preventative antibiotics and analgesics were administered to prevent infection and reduce pain. Ketaprofen (1mg/kg) was administered intramuscularly post-surgically. Clindamycin (11mg/ kg) and Nalbuphine (2mg/kg) were administered intramuscularly to the dogs 2x/day post-surgically for one week and as needed until sacrifice. Additionally 0.12% chlorhexidine gluconate rinses were given daily for 7 days post operatively.

Latency and Distractor Activation

Following a 5 or 7-day latency period Calcein Green injection (histologic bone marker) was administered for each dog. The third premolar was then distracted mesially with 1 mm/day activation for 6 days. Each day, the jackscrew of the distractor was turned one complete revolution, i.e. 1 mm. A Boley gauge was used to measure the distance between the ends of the jackscrew housing after each activation. The appliance was checked daily for breakages.

Alizarin Red was administered post distraction. There was a 3-week consolidation period to allow for bone remodeling. 3-4 days prior to sacrifice, Calcein Green was administered a second time as a histologic bone marker.

Euthanasia

On the day of sacrifice, the dogs were maintained nil per os and anesthetized with intramuscular injection of ketamine (2.2mg/kg IM) mixed with xylazine (0.22mg/kg IM). The bands were sectioned off of the teeth and the appliance was removed. Teeth were then polished to remove any excess cement with a fine diamond football, and flame shaped carbide bur using a high speed hand piece. Final records were then taken including intraoral photographs, periapical radiogrpahs, LDF vitality readings, and alginate impressions. Alginate impressions were taken last to ensure immediate pouring of the models in die stone to minimize distortion. The same Laser Doppler Flowmeter (MoorVMS-LDF, Devon, UK) and protocol used as the pre-surgical recordings was used to record the post-consolidation vitality.

Surgical plane anesthesia was confirmed by checking reflexes. Both common carotid arteries were exposed and cannulated and both external jugular veins were severed. 2cc of Beuthanasia-D was injected intracardially and cessation of heart function was confirmed with a stethoscope. The head was then perfused, through the cannulated carotids, with 1-2 liters of normal saline followed by 0.5-1 liter of the fixative, 4% paraformaldehyde solution. The paraformaldehyde solution began after the jugulars flowed clear liquid for ten seconds. The mandible was then harvested, split into left and right segments, and stored in 4% paraformaldehyde at 4° Celcius. The samples were then placed in 0.5% paraformaldehyde for microCT and histological analysis.

μCT Assessment of Bone Density

After sacrifice, the harvested mandible was sectioned. The section included the mesial 2-3 mm of the 4th premolar and extended mesially until 4 to 5mm mesial of the third premolar. (Figure 4) 30mm wide μCT tubes were used to hold the samples with the occlusal surfaces perpendicular to the long axis of the tubes. The tubes were filled with 0.5% paraformaldehyde and sealed with parafilm (Pechiney Plastic Packaging Company, Chicago, IL). The segments were scanned using the Scanco μCT 35 scanner (ScanCo Medical, Basserdorf, Switzerland) at 30 μm resolution, using 55 kVp, 145 μA and 800 ms integration time. Bone measurements were calculated with Analyze V12.0 software (AnalyzeDirect, Overland Park, KS). The same software was also used to complete 3D renderings of the segment, teeth, and areas of interest for bone analysis.

The quality of bone regenerate distal to the transport segment was determined by analyzing the bone in the middle 80% of the third premolar root as a 1 mm cylinder; the

10% above and below was no evaluated. (Figure 5) The lamina dura distal to the third premolar, including the same middle 80% of the root, as a rectangular prism section excluding the root, was also analyzed. (Figure 6) From these volumes of interest the Analyze V12.0 software was used to produce a report including bone material density, apparent density, trabecular number, trabecular thickness, and trabecular spacing. Additionally, full 3D renderings of the teeth and bone were made to measure the height and width of the alveolus. The level of resorption was qualitatively assessed by using the 3D root renderings. This was paired with periapical analysis of root length pre and post treatment.

Laser Doppler Flowmetry

The laser doppler readings taken during the procedure were analyzed through Fast Fourier Transform (FFT), as suggested by Yanpiset et al[65] FFT is an accepted method of LDF analysis and considered helpful when assessing individual teeth.[58,66] In order to run the FFT, the region of interest was taken from the two most representative 10-second intervals during the 1-minute LDF recordings taken prior. Two investigators independently agreed upon the areas over the one-minute recording period to be used for the FFT analysis. The Hz values used were based on the dogs' heart rates during the time of the LDF recording. A significant peak was then looked for at this particular Hz value. A strong peak in the FFT that synchronized with the recorded heart rates during the procedure served as an indication of vitality.[65] (Figure 7, 8) Both power values, one for each peak that matched the proper Hz for each of the two 10-second intervals, were recorded for statistical analysis. Two segments were used in order to limit the bias of a small window of time randomly containing a peak that could errantly be suggestive of vitality.

Statistical Analysis

All statistical analyses were performed using IBM SPSS® version 25 (IBM Corp., Armonk, NY). Normally distributed data was noted for tooth movements and microCT data, which described by means and standard deviations. For the vitality data non-parametric tests were used due to small sample size. Wilcoxon signed ranks test was used to compare experimental to control data.

RESULTS

Tooth Movement and Distractor Activation

Tooth movements were based on all 7 dogs or 5 dogs. Two dogs (E, F) were excluded from the average because their bands came loose at some point during consolidation. There was a statistically significant ($p<0.001$) between-group difference between the changes that occurred (Table 1, Figure 9). The experimental side moved an average of 4.1 mm. The control side did not move significantly.

The distraction device was activated at a rate of 1 mm/day according to the jackscrew specifications. The actual activation from the study measured on day six was 5.8 mm, (Table 2, Figure 10) indicating the teeth moved 70.7% of the amount of activation ($4.1/5.8 * 100 = 70.7\%$).

Root Resorption

In the periapical assessment of root length showed no significant differences in T2 root lengths (Figure 11). The control mesial and distal root lengths were not statistically significantly different from the experimental root lengths ($P = 0.31$ and 0.46 respectively). Qualitative assessments of root resorption showed no major differences between the control (Figure 12) and experimental (Figure 13) microCT 3D renderings.

MicroCT Bone Regenerate

Height and Width

There was no significant difference between the heights of the alveolar bone between the control and experimental sides (p=0.84). There was a significant difference in the widths of the alveolar bone with a means of 7.3 mm and 9.5 mm for the control and experimental sides respectively (p=0.01).

Regenerate Trabecular Bone

There were differences between the regenerate bone in the control and experimental groups (Table 4). Material density was significantly higher in the control (756.5 mg HA/ccm) than the experimental (658.6 mg HA/ccm) group. Apparent material density was not significantly different between groups. There also were statistically significant between-group differences in trabecular numbers (p=0.005) and trabecular spacing (p=0.002). Trabecular number was greater on the experimental side and trabecular spacing was greater on the control side. Trabecular thickness was higher on the control than experimental side, but the differences were not statistically significant.

Lamina Dura Bone

There were differences between the lamina dura bone in the control and experimental groups (Table 5). Material density was significantly higher in the control (817.4 mg HA/ccm) than the experimental (760.7 mg HA/ccm) group. Apparent material density was not significantly different between groups. There was also a statistically significant between-group difference in trabecular numbers (p=0.021) being higher in the experimental group. Trabecular spacing was not significantly different between groups. Trabecular thickness was higher on the control than experimental side, but the differences were not statistically significant.

Laser Doppler Flowmetry

Power of the Fourier transforms was greater on the experimental side initially and on the control side at the end of the experiment (Figure 15), but neither the initial (p=0.797) or end of consolidation (p = 0.261) differences were statistically significant. The experimental tooth of Dog G was left out of the statistical analysis as the pulp was exposed in the procedure and confirmed non-vital after pulpotomoy. The tooth did actively bleed when the pulp was exposed post consolidation during appliance removal. When evaluating the Fourier transform, it also has a noticeably different presentation. (Figure 8)

DISCUSSION

The movements of the tooth transport segment relative to distractor activation are similar, regardless of the activation rate. In the present study, which had an activation rate of 1 mm/day, the distractor efficiency for movement was 70.7%. Previous DAD studies using activation rates of 0.5 mm/day and 0.8 mm/day achieved device efficiencies of 73% and 67% respectively.[2,3] In other words, increasing the rate of activation to 1 mm/day does not appear to have any difference on the relative effectiveness of moving the teeth. Between the lack of rigidity in any appliance, and the give in the PDL and soft tissues, full expression of the jackscrew likely does not translate completely to the teeth. Additionally, the rates of 0.5 mm/day to 1 mm/day are likely at a force value that is within the threshold of these tissues to maintain the give.

Increased rates of DAD do not appear to have adverse effects on the roots. The present study showed no significant between side differences in root lengths post consolidation. The microCT qualitative evaluation of the roots also supports this finding as in comparison with periodontal distraction performed on the same animals, in which clear large resorptive lacunae could be seen, there was very slight if any difference seen in the DAD group. This is in line with past split mouth studies comparing PD to DAD, where some resorption, including apical resorption, was found in PD but not DAD subjects.[1,52] No apical resorption has been observed consistently in other DAD literature.[2,6,51] The ability to mitigate one of the more severe side effects of orthodontic treatment offers new options for patients, especially those that present at high risk for apical root resorption.

There was a statistically significant difference between the regenerate bone on the experimental group from the bone on the control side. Bone that has undergone surgical insult and healing has been shown to have an decreased material density.[37] Injured bone that has not yet matured, and is in the woven bone state, does not have the same density as mature bone. In the present study, this was also demonstrated by the greater trabecular number, decreased trabecular thickness, and decreased trabecular spacing compared with the bone on the control side. This is also consistent with previously reported data on remodeling bone, studying the response to full thickness flaps alone, full thickness flaps with corticomies, and bone damage alone.[37,39] In these studies the more damage to the bone the lower the density prior to at the same time point after bony insult prior to complete healing. Additionally, this is in accordance with other dento-alveolar distraction studies in dogs, in which a longer consolidation period was used than this study. The regenerate bone analysis in these studies, with a longer consolidation, thus showed more mature bone, than the regenerate bone in the present study.[48,49] This is the expected process and timeline during the complete healing of the bone.[45] This shows that both that new bone was produced, and that there is no pathologic change in the bone.

As well as the regenerate bone there was a significant difference between the lamina dura of the control and experimental teeth. There was a decrease in bone material density, trabecular number and trabecular thickness on the experimental side. This is consistent with the remodeling process previously reported.[37] It suggests that the total tooth movement by the end of the consolidation period is probably not solely due to the distraction segment, but also due to traditional orthodontic tooth movement within the segment. The force exerted on the tooth from the difference in activation of the distractor device and the total distance moved by the distraction segment, likely reduces through normal tooth movement and bone remodeling within the segment. Minimal anchorage loss has been reported in the literature with DAD. This is likely due to short distraction periods below that of the typical lag phase in undermining resorption orthodontic movement. DAD uses orthopedic level forces which would result in undermining resorption.[23–25] The consolidation phases typically extend beyond the time needed by the lag phase, and the over activated distractor being left in place could be a cause of some, albeit minimal, anchorage loss. Further studies are needed to determine whether passive rigid fixation of the transport segment following space closure could improve the side effect of rapid tooth distraction.

There was no loss in vitality of the teeth following DAD. In addition, no clinical signs of vitality loss, such as discoloration, were noted. The FFT data supported vitality of all of the teeth, with the exception of the one tooth that experienced a pulp exposure. This tooth was also noted at the end of consolidation to bleed following the exposure suggesting the tooth was likely vital as well. All teeth under the FFT analysis had significant peaks associated with the heart rate of the dog. There also was no significant difference between the power of the peak for the control vs experimental teeth prior to intervention, nor was there a difference between the control and experimental sides following DAD. This supports what has been suggested through clinical signs and the current limited LDF data on DAD.[1,4,51] DAD is a safe procedure to rapidly move teeth.

Dento-alveolar distraction has the potential to add alveolar bone in all three dimensions. Compared to the control side, the distraction segment appears to have not completely followed the alveolar ridge and has moved laterally up to 4 mm. The bone of the distraction segment however, has remained and does not have the appearance of remodeling bone. DAD has been previously utilized to augment the alveolar ridge.[48,49,67] This was done by removing a section of alveolar ridge, and moving a transport segment with DAD to close the defect with alveolar bone with full height and thickness. Bozkaya et al, in a case report, distracted a transport unit (containing only bone and no tooth) of a knife-edge ridge bucally.[67] The buccal increase in alveolar bone later was adequate for implant placement, which has remained stable for 8 years. This suggests stability in the extra alveolar arch width gained through DAD in the present experiment. This could play a major role in the future of orthodontics. Major surgical procedures such as surgically assisted rapid palatal expansion and orthognathic surgery are often implicated when tooth movement is limited by restriction of alveolar bone. DAD presents a more minor procedure which could increase arch perimeter decreasing the need for extractions, and decrease transverse and AP deficiencies allowing for bite correction in cases where it wasn't previously possible without major surgery. This would offer an important tool to the orthodontist, greatly expanding the possibilities of non-extraction and non-orthognathic surgery cases.

CONCLUSION

DAD: Does not cause loss of bone

DAD: Does not cause loss of vitality in dense mandibular bone

DAD: Does not cause significant root resorption

DAD: Is an effective way to rapidly move teeth

DAD: Has potential to gain alveolar width and should be further evaluated to increase arch length

DAD: Can produce implant quality bone

DAD: Can preserve anchorage

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APPENDIX A

FIGURES

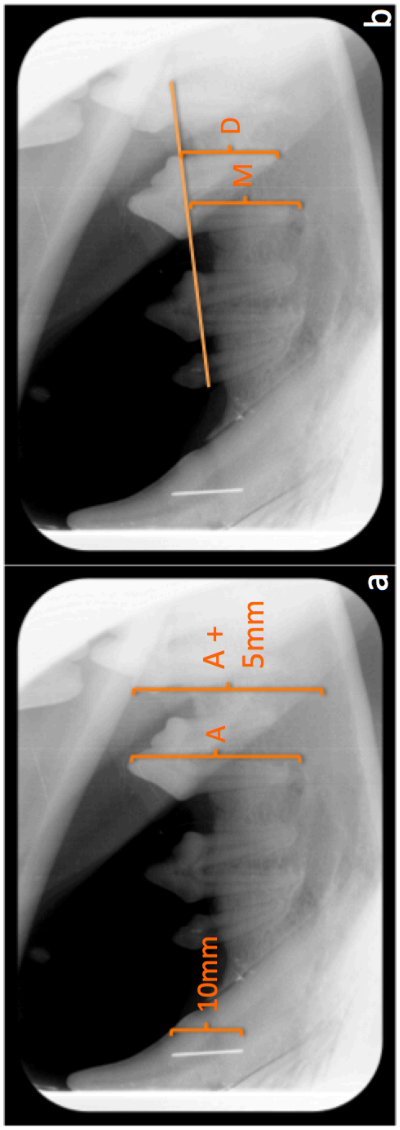

Figure 1: Radiographic measurements pre surgery. a) calibrated wire to 10mm, A is root length, A+ 5 mm is depth used to guide surgical cut b) reference line from CEJ of 1st premolar to furcation of 4th premolar to measure Mesial and Distal root length (same measurement also used post consolidation)

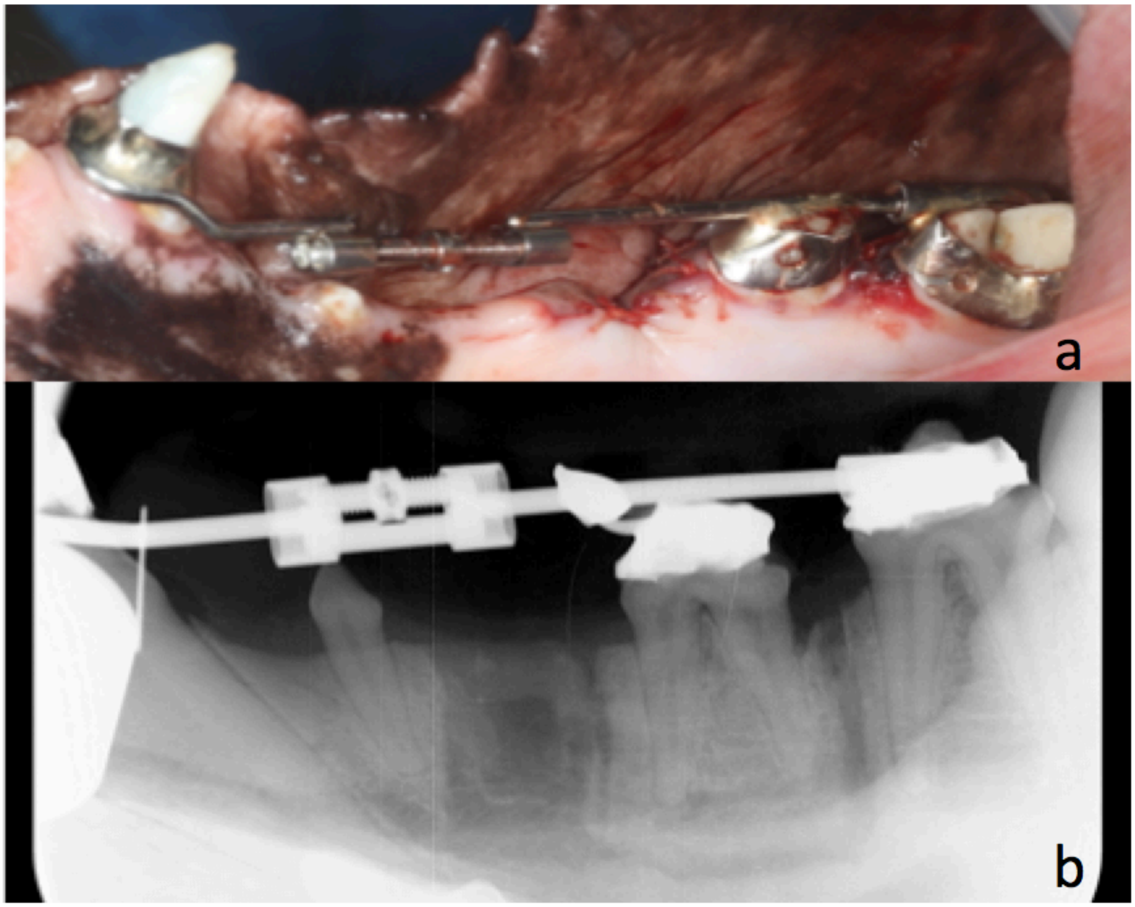

Figure 2: Distractor device. a) post surgical cementation lingual view b) post surgical cementation radiographic view

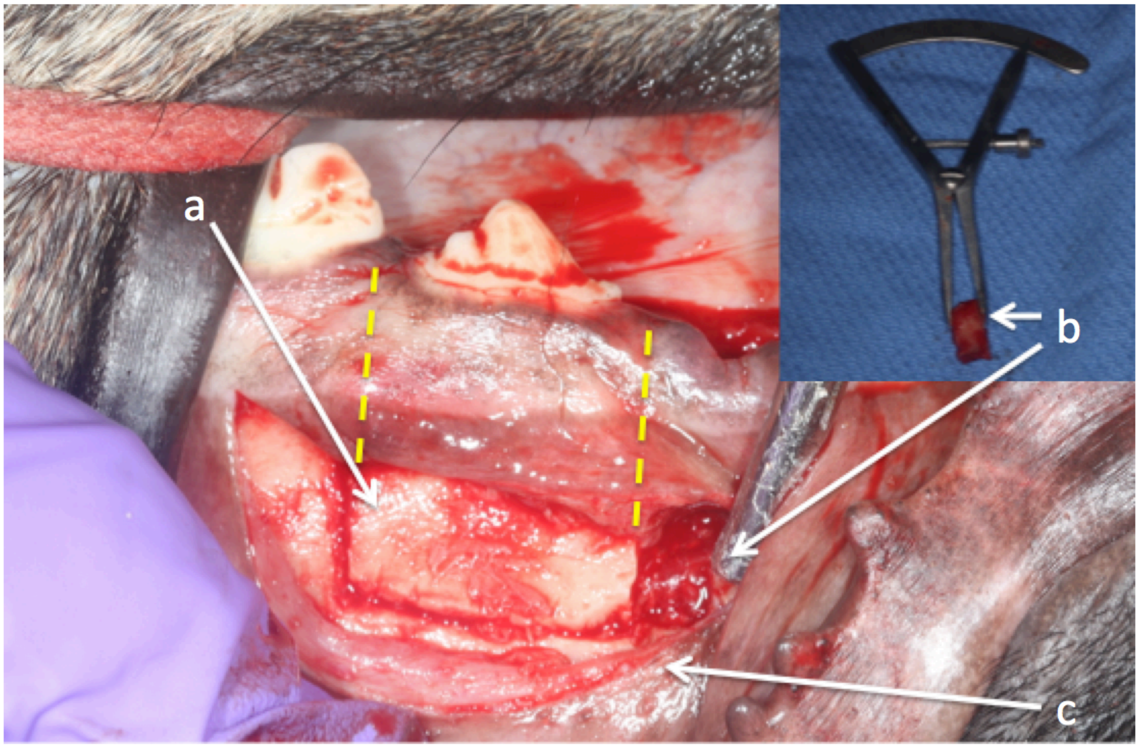

Figure 3: Surgical Procedure. a) Mobilized transport segment, the dotted lines indicate the cuts extend through the top of the alveolus b) measured bone removed mesial to the transport unit to ensure minimum 7mm of clearance for distraction segment c) mucoperiosteal flap

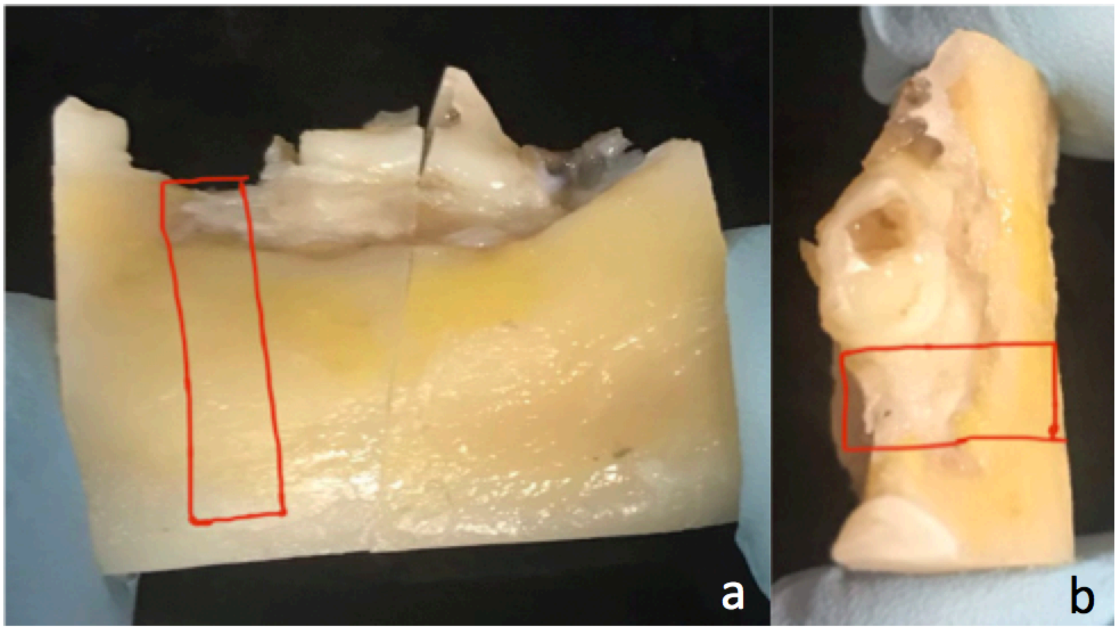

Figure 4: Harvested MicroCT Sample. Estimates of the regenerate, which are distal to experimental tooth marked. a) buccal view of sample with regenerate bone region drawn b) Occlusal view of sample with regenerate bone region drawn

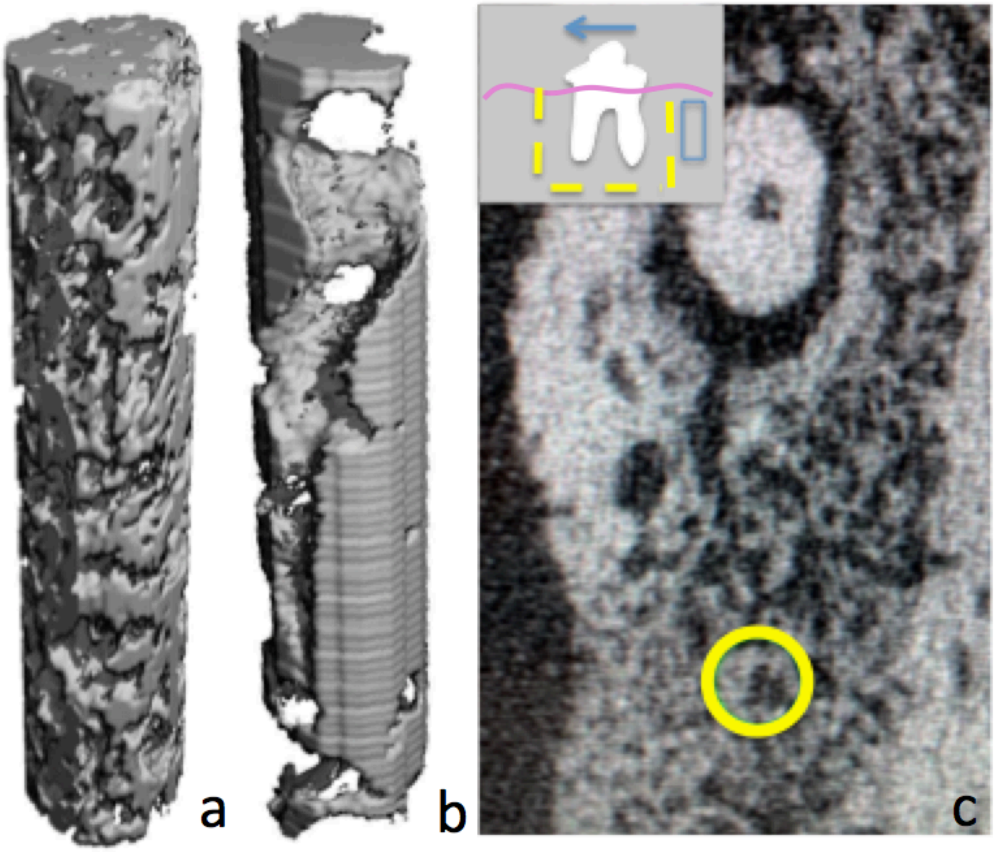

Figure 5: Regenerate Bone. a) average representative control regenerate bone rendering for the middle 80% of bone on the root b) average representative experimental regenerate bone rendering c)example of contour drawn for samples c) example of contour drawn for samples and diagram to visualize area of bone

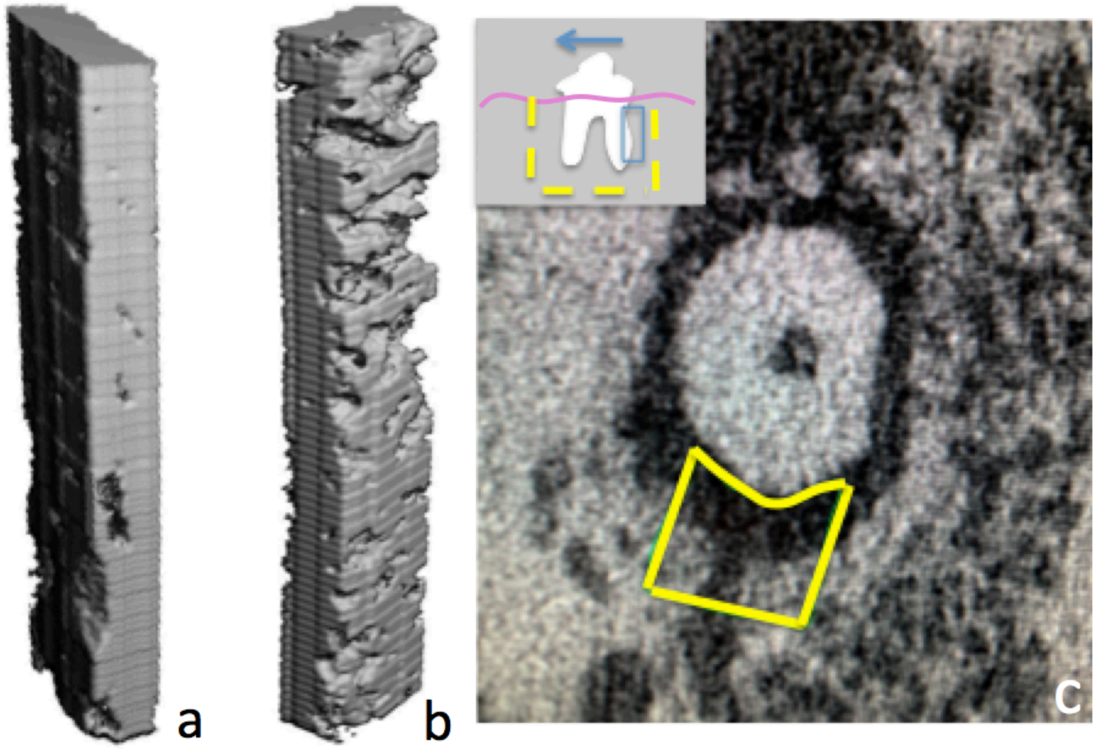

Figure 6: Lamina Dura Bone. a) average representative control lamina dura rendering for the middle 80% of bone on the root b) average representative experimental lamina dura rendering c) example of contour drawn for samples and diagram to visualize area of bone

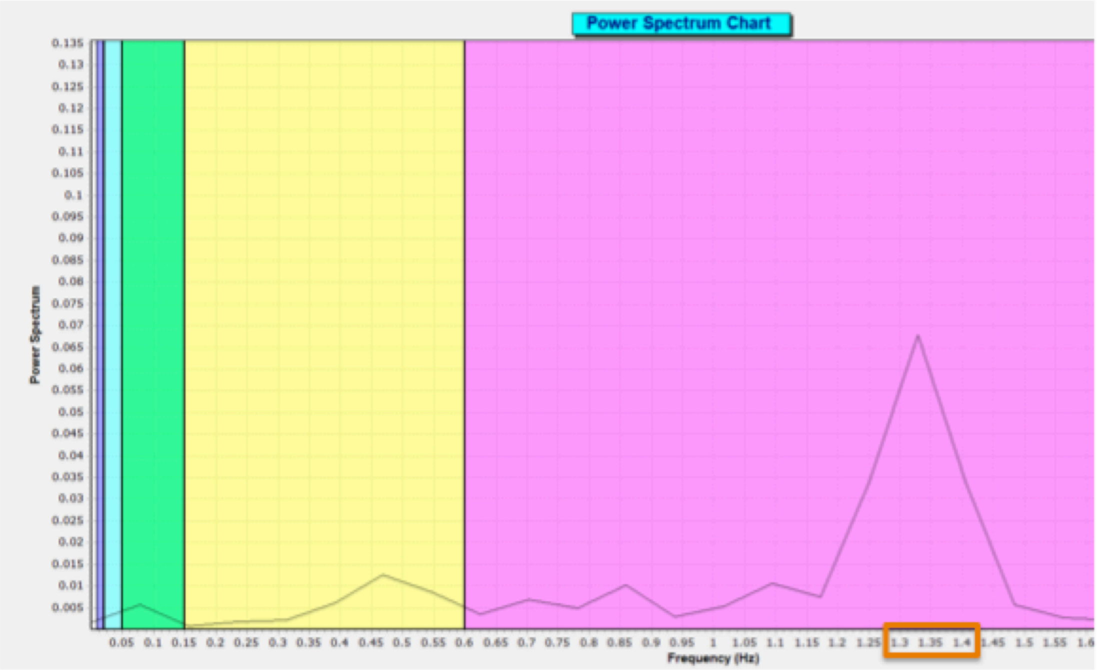

Figure 7: Vital Tooth FFT. Heart rate of dog correlates with 1.3-1.4 Hz with significant peak present in addition to the power spectrum value of 0.68

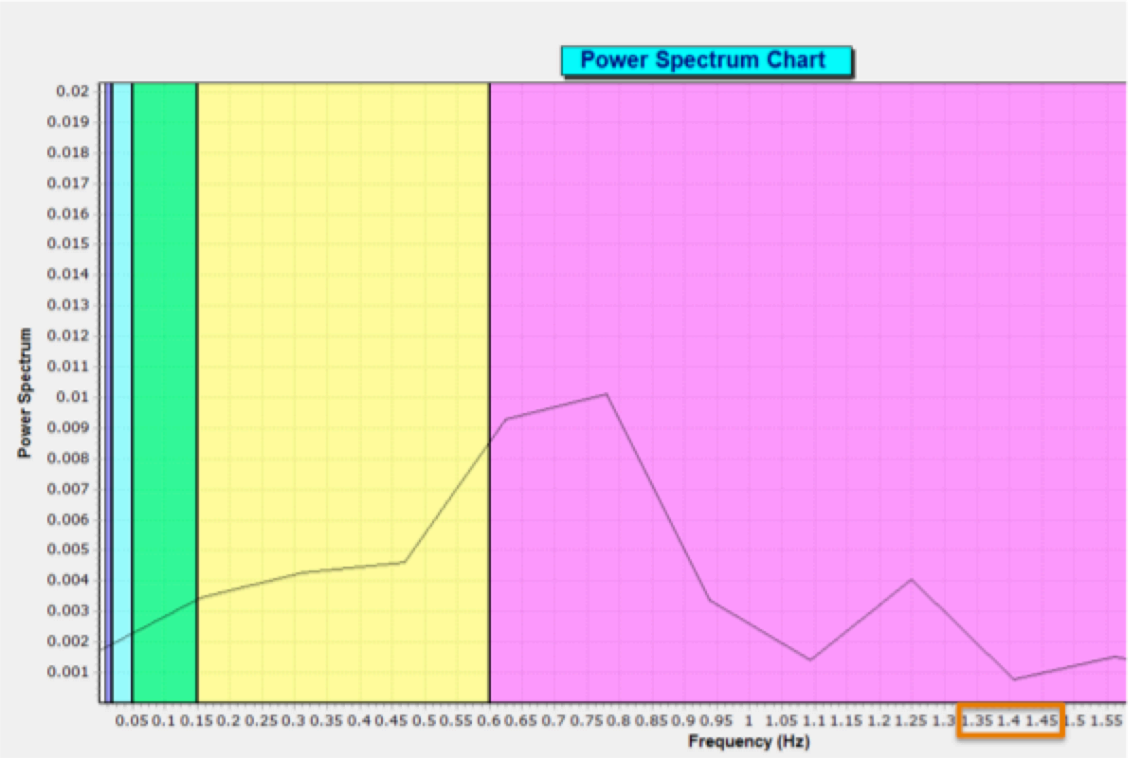

Figure 8: Non-Vital Tooth FFT. (Dog G experimental post consolidation). Heart rate of dog correlates with 1.35-1.45 Hz while no significant peak is present in addition to the low power spectrum value of <0.002

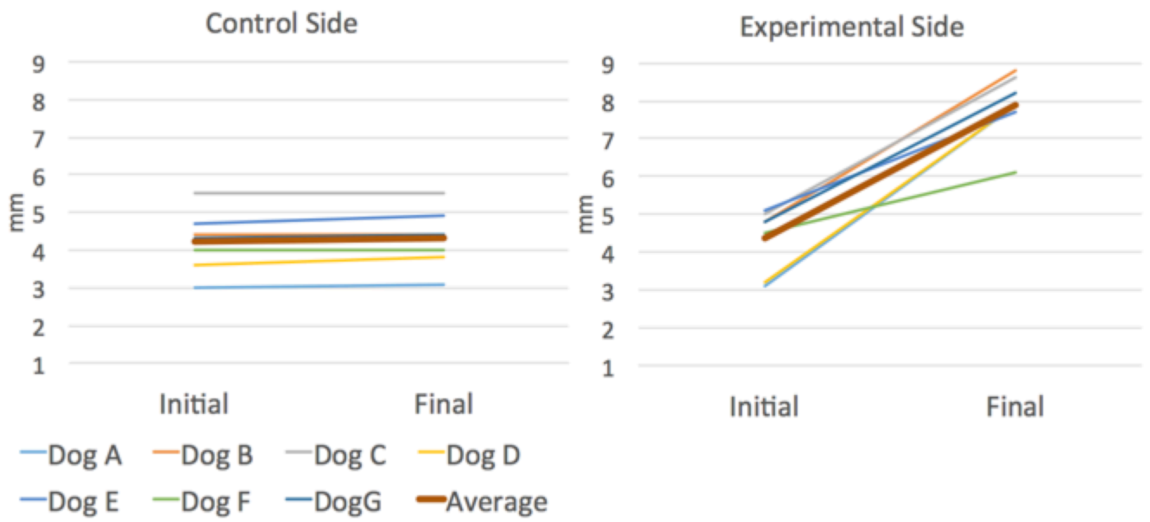

Figure 9: Cast tooth movements. Initial to final movements for control and experimental groups were significantly different $p < 0.001$

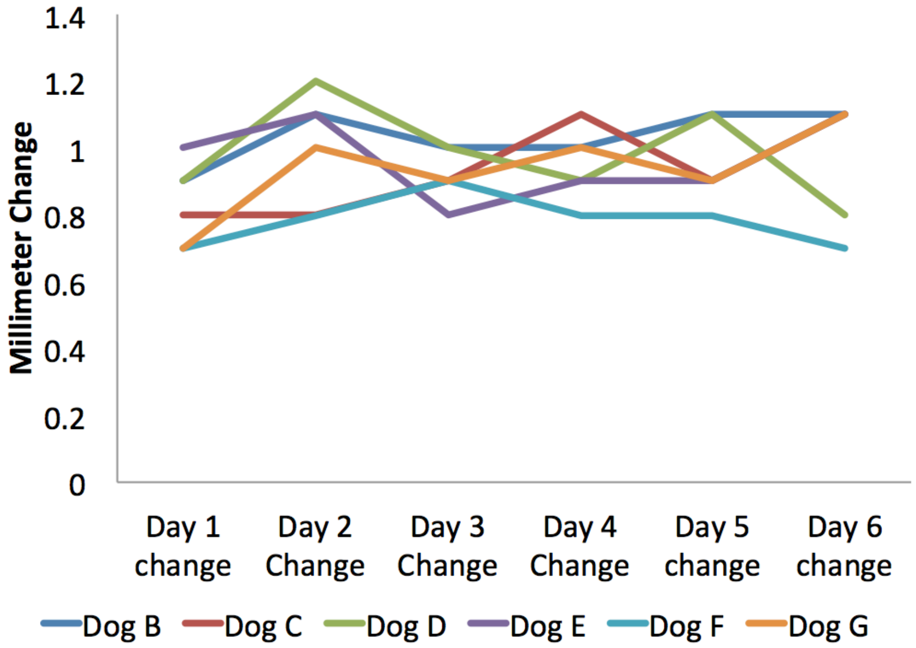

Figure 10: Distractor jackscrew changes. Daily change following the activation

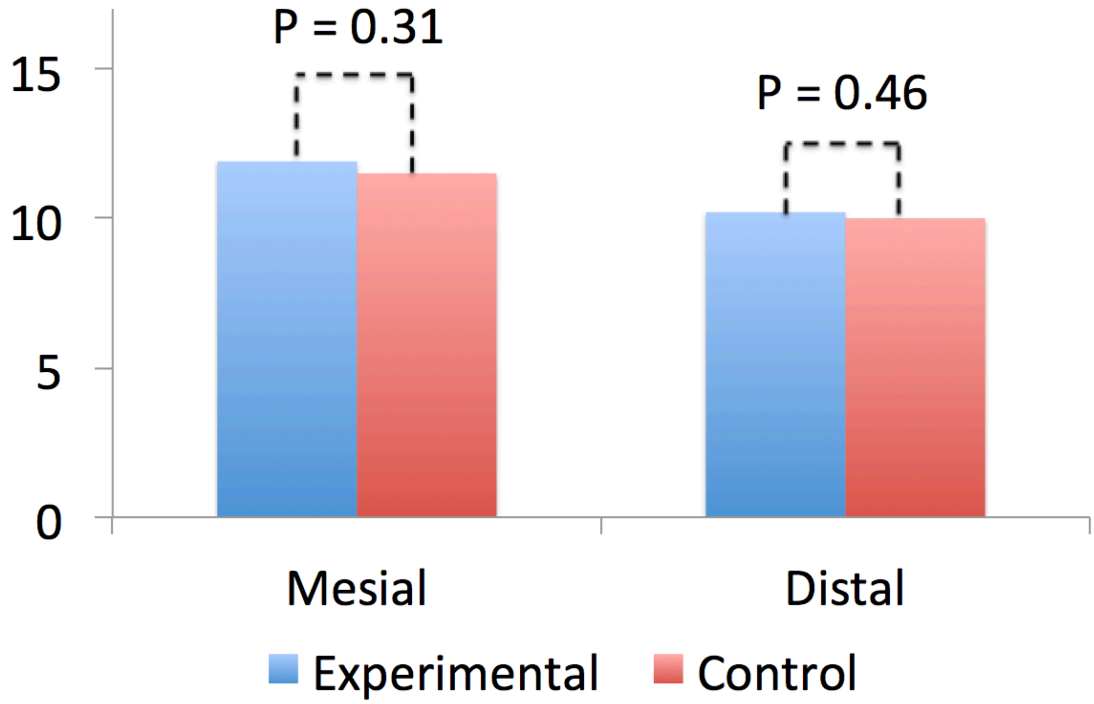

Figure 11: Periapical Root Length. Average length of mesial and distal tooth roots post consolidation from periapical analysis

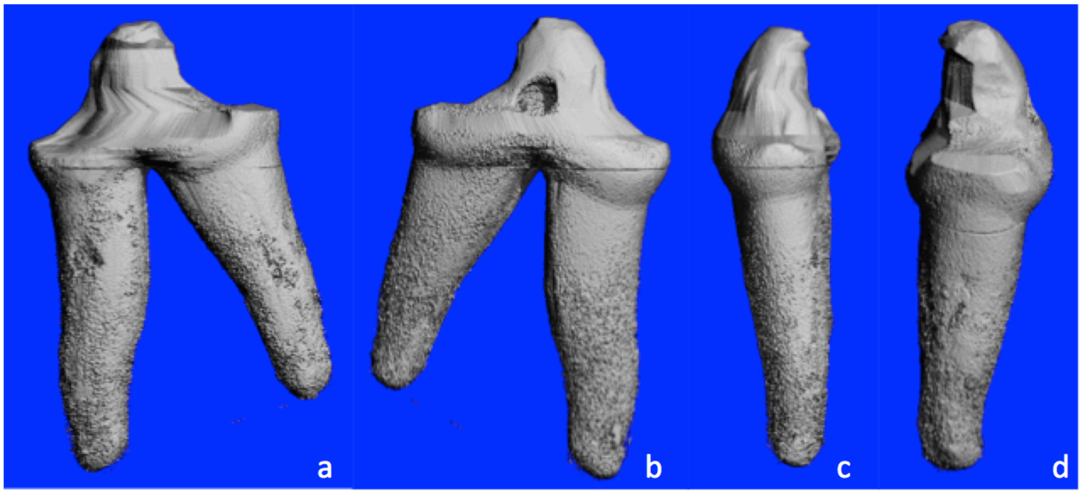

Figure 12: Experimental Tooth Rendering. MicroCT 3D rendering of an experimental 3rd premolar representing no significant resorption or resorptive lacunae a) Lingual b) Buccal c) Mesial d) Distal

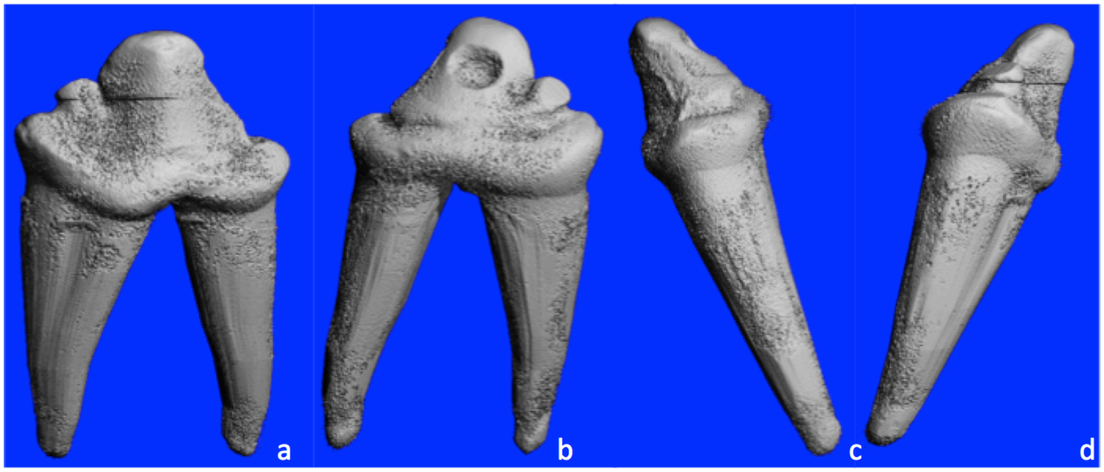

Figure 13: Control Tooth Rendering. MicroCT 3D rendering of a representative control 3rd premolar representing no significant resorption or resorptive lacunae a) Lingual b) Buccal c) Mesial d) Distal

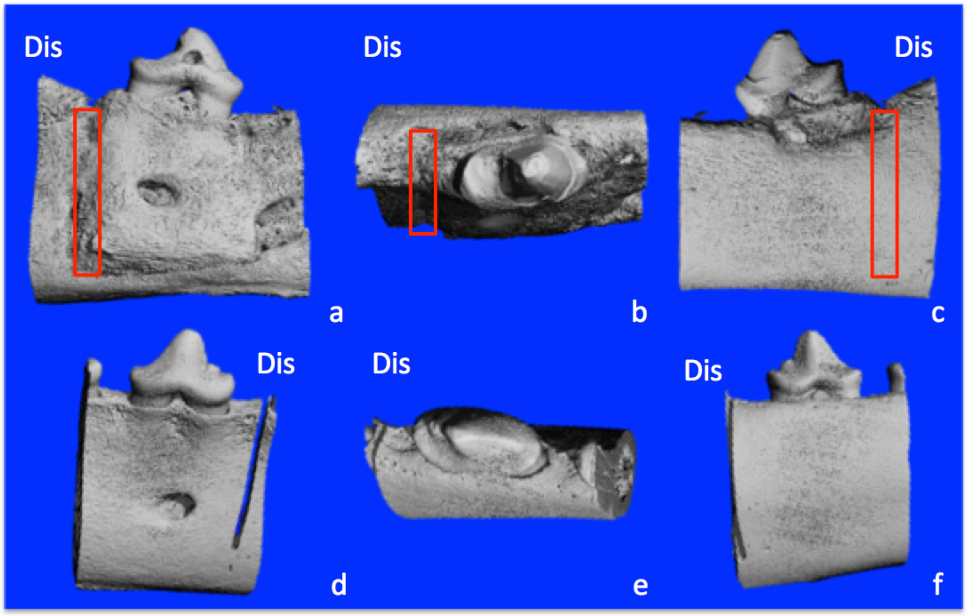

Figure 14: Control and Experimental MicroCT Sample Rendering. MicroCT sample, red boxes approximate regenerate bone, distal labeled as "Dis" a) MicroCT experimental rendering of buccal b) MicroCT experimental rendering of occlusal c) MicroCT experimental rendering of lingual d) MicroCT control rendering of buccal e) MicroCT control rendering of occlusal f) MicroCT control rendering of lingual

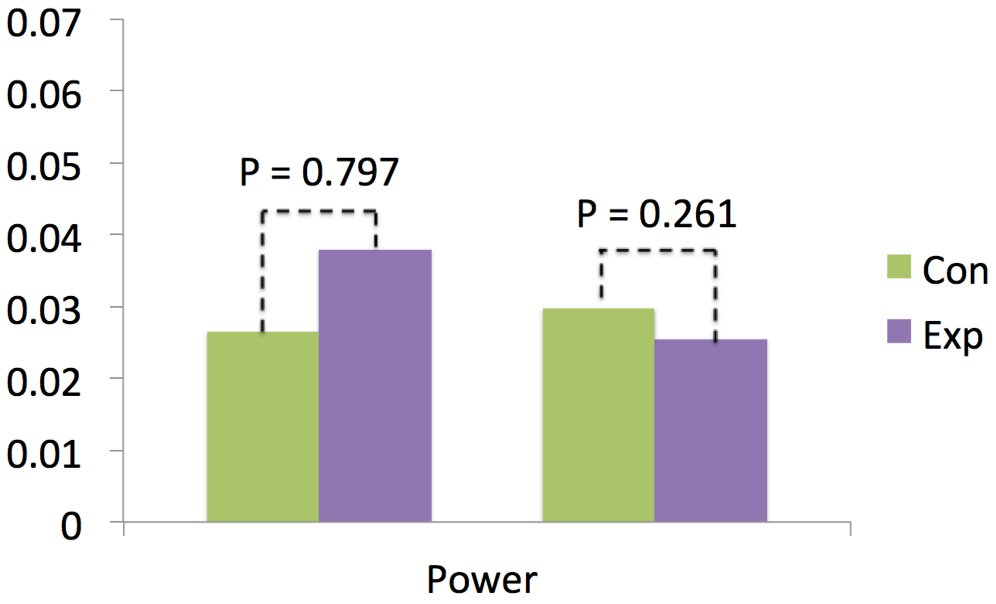

Fig 15: Control vs. Experimental LDF Analysis. Median power values from FFT depicting no significant difference in the control vs. experimental teeth both initially and after consolidation

APPENDIX B

TABLES

Table 1: Cast tooth movements. The tooth movements (mm) measured on the cast models post consolidation. Average excludes dogs E and F. *Bands noted off of tooth at sacrifice visit, bands were actively on tooth and checked during distraction

	Experimental		Control		Changes	
Animal	T1	T2	T1	T2	Experimental	Control
Dog A	3.1	7.9	3.0	3.1	4.8	0.1
Dog B	4.8	8.8	4.4	4.4	4.0	0.0
Dog C	5.0	8.6	5.5	5.5	3.6	0.0
Dog D	3.2	7.9	3.6	3.8	4.7	0.2
Dog E	5.1	7.7	4.7	4.9	2.6*	0.2
Dog F	4.5	6.1	4.0	4.0	1.6*	0.0
Dog G	4.8	8.2	4.3	4.4	3.4	0.1
Average (excluding E, F)					4.1	0.1
Average (including E, F)					3.5	0.1

Table 2: Distractor jackscrew activation. The activation of the distractor jackscrew (mm) applied through the full tern of the screw each day. Average excludes dog F. *Dog F was noted to have difficulty turning the appliance, often needing to turn forward and back to get movement. Cross threading was thought to have possibly been occurring.

Animal (mm)	Initial	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Total
Dog A	18.3	17.4	16.3	15.3	14.3	13.2	12.1	6.2
Dog B	16.7	15.9	15.1	14.2	13.1	12.2	11.1	5.6
Dog C	16.1	15.2	14	13	12.1	11	10.2	5.9
Dog D	18.1	17.1	16	15.2	14.3	13.4	12.3	5.8
Dog E	16.9	16.2	15.4	14.5	13.7	12.9	12.2	4.7
Dog F*	17.6	16.9	15.9	15	14	13.1	12	5.6
Dog G	18.3	17.4	16.3	15.3	14.3	13.2	12.1	6.2
Average								5.82

Table 3: Alveolar heights and widths. Width measured at the mid point from CEJ to apex of the root length of the tooth. Height measured from coronal bone level to 3mm below the apex of the tooth.

	Control		Experimental		Prob	
	Height	Width	Height	Width	Height	Width
Dog A	15.3	7.6	15.2	8.8		
Dog B	14.8	7.3	14.4	10.6		
Dog C	12.1	7.0	12.1	7.4		
Dog D	14.1	7.4	14.0	9.2		
Dog G	15.0	7.2	14.8	11.3		
Average	14.3	7.3	14.1	9.5	0.84	0.01

Table 4: Regenerate bone characteristics. Represents the bone values of the regenerate bone under microCT.

		Experimental		Control		Difference
Measurement	Units	Mean	SD	Mean	SD	Prob
Material Density (mg HA/cm^3)		658.6	34.5	756.5	54.4	0.007
Apparent Density (mg HA/cm^3)		408.5	71.0	312.6	146.7	0.253
Trabecular Number (n/mm)		5.63	1.31	2.62	0.73	0.005
Trabecular Thickness (mm)		0.13	0.015	0.23	0.10	0.058
Trabecular Spacing (mm)		0.21	0.087	0.50	0.19	0.002

Table 5: Lamina dura bone characteristics. Represents the bone values of the lamina dura bone under microCT.

	Experimental		Control		Difference
Lamina Dura Section	Mean	SD	Mean	SD	Prob
Material Density (mg HA/cm^3)	760.7	43.8	817.4	24.7	0.006
Apparent Density (mg HA/cm^3)	562.3	136.1	643.5	73.5	0.234
Trabecular Number (n/mm)	5.58	0.93	5.11	0.71	0.021
Trabecular Thickness (mm)	0.237	0.059	0.300	0.044	0.090
Trabecular Spacing (mm)	0.157	0.074	0.147	0.063	0.721