ANALYSIS OF BONE AUGMENTATION WITH CORTICOTOMY-FACILITATED

DENTAL EXPANSION: A HISTOLOGIC & MICRO-CT STUDY

A Thesis

by

BRITNEY K. BARE

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

Chair of Committee,	Peter H. Buschang
Committee Members,	Phillip M. Campbell
	Marianela Gonzalez
Head of Department,	Phillip M. Campbell

May 2015

Major Subject: Oral Biology

ABSTRACT

The purpose of this study was to evaluate the effect of bone grafting when

performed in association with corticotomies. A randomized split-mouth design was

utilized in seven adult male beagle dogs. Corticotomies were performed with a

piezosurgery unit adjacent to the maxillary second premolars. The experimental

(Graft+) side additionally received bone grafting (demineralized freeze-dried bone graft,

Straumann USA, Andover, MA) with a resorbable collagen membrane. The premolars

underwent 9 weeks of archwire expansion, followed by 3 weeks of consolidation. Soft

tissues measurements, including probing depth, attachment loss, and recession were

obtained. Tooth movements were evaluated by intraoral, radiographic, and model

measurements. Microcomputed tomography was used to quantify the surrounding bone

and new bone formation was analyzed histologically using calcein and alizarin

fluorescent labels and hematoxylin and eosin stains.

Results of the experiment showed that the Graft+ and control (Graft-) second

premolars displayed similar amounts of expansion (~2.5 mm measured intraorally, and

~1.7 mm radiographically) and tipping. Bony dehiscences were visible on both the

Graft+ and Graft- sides, with significantly (p=0.038) more bone loss over the mesial root

on the Graft- than Graft+ side. New bone apposition was evident on the periosteal

surface of buccal bone and surrounding graft particles on the Graft+ side. Mineralized

particulate graft material was evident at the apical aspect of the roots. Histologically,

graft incorporation into host bone occurred along the buccal surface of the expanded

tooth root, with greater bone volume present apically than coronally. Bone material

density (mg HA/cm^3) was found to be significantly (p=0.028) greater on the grafted side.

No significant differences were found for any second premolar soft tissue measurement,

or for tooth and root heights between the Graft+ and Graft- sides.

Within the context of this study, we can conclude that while new bone formation

occurs after bone grafting in combination with corticotomies, it is mostly limited to the

more apical aspect of the tooth root. Although the soft tissue periodontium was not

detrimentally affected, bony dehiscence formation was not prevented with the bone

grafting procedure.

DEDICATION

       I dedicate this thesis to the most inspiring, motivating, and devoted people in my life: my parents. Mom and Dad, your unfailing support of my education and dreams has never gone unnoticed. You have both given so much for the betterment of your children and are truly an example to us all. I am honored to be your daughter.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

OVERVIEW

Tooth size to arch length discrepancy (TSALD), also known as crowding, is a common finding, with 39% of American adults exhibiting lower incisor crowding greater than 4 mm.[1] In order to alleviate a TSALD, space must be created either through removal of tooth structure, extractions, or expansion. In an attempt to avoid extraction, new expansion techniques have increased the popularity of nonextraction treatment.[2, 3] Distraction osteogenesis, dentoalveolar corticotomies, and other surgical interventions are other examples of potential solutions to this common problem.

An increase in space through expansion can come in two forms: orthopedic or orthodontic. Orthopedic expansion requires a growing individual and targets the skeletal base. Orthodontic expansion, conversely, does not require remaining growth potential and is achieved through movement of teeth through the alveolar complex. Despite claims from several bracket systems of having the ability to control tipping, clinical and animal studies have shown that all forms of non-surgical increases in the transverse dimension result in loss of torque control, leading to uncontrolled buccal tipping of the expanded tooth. It is this tipping that has detrimental effects on the surrounding periodontium.

With an ever-increasing number of adults seeking orthodontic treatment, attaining the optimal final result may be difficult and time consuming. This is in part

1

due to a greater potential for adults to present with a compromised periodontal status,[4, 5] slower cell mobilization, and slower collagen fiber conversion.[5] In order to satisfy the requests of this orthodontic population, new advances to decrease treatment time and maximize esthetic demands, all while maintaining periodontal health, are becoming more prevalent. One such treatment option that is being explored is the use of corticotomies to supplement traditional orthodontic modalities.

Corticotomies, also known as selective alveolar decortication (SAD), surgically assisted osteogenic orthodontics (SAOO), or periodontally accelerated osteogenic orthodontics (PAOO), involves linear and/or punctate perforations of the cortical bone surrounding the teeth to be moved. By definition, the cuts penetrate the entire thickness of the labial cortical layer of bone and extend just into the medullary bone. In 2001, the Wilcko brothers brought to light the notion of corticotomies with concomitant bone augmentation to further enhance the periodontal status of patients.[6] They believe that grafting the buccal surface of a moving tooth provides sufficient bone to fill pre-existing bony dehiscences and/or prevent future defects during orthodontic movement.

Currently, however, there is little experimental support for the grafting procedure presented by the Wilcko brothers. The fate of the grafting material remains unclear. Is it actually incorporated into useful vital host bone? Therefore, it is the goal of this study to validate or refute the need for alveolar bone augmentation in conjunction with the corticotomy procedure to facilitate orthodontic expansion and to better grasp the biological events that are occurring within the graft itself. The effects on both the teeth

and surrounding hard and soft tissues will be evaluated with histology, μCT, and study models.

The following review of the literature will expound on the corticotomy and bone grafting procedures and how they pertain to orthodontic expansion. First, a discussion of conventional orthodontic expansion and potential detrimental effects to this process will be covered. Next, a review of the corticotomy literature will be examined, followed by the combination of the previous two ideas to analyze the current literature on expansion in conjunction with the corticotomy procedure. Finally, a review of the bone augmentation procedure and its current use in corticotomies will be expounded upon.

LITERATURE REVIEW

Expansion

The Third National Health and Nutrition Examination Survey (NHANES III) collected data regarding the oral health of the United States population between the years 1988-1994. They found a significant need for some degree of orthodontic treatment for 57%-59% of the population.[1] Of the population, 15% displayed significant incisor irregularities that warranted major arch expansion or extraction due to esthetic or functional demands.[7]

The decision to extract or not has been a topic of debate in orthodontics for over a century. Edward Angle, the father of modern orthodontics,[8] advocated a full compliment of teeth.[9, 10] He resolved to eliminate any tooth size to arch length discrepancy through buccal expansion. A challenge to this thinking came in the 1950s

3

and 1960s when Charles Tweed demanded that the lower incisors be positioned upright over basal bone, which could be accomplished in the majority of cases only through extraction.[11] More recently, the pendulum has shifted back toward a marked reduction in the percentage of premolar extraction treatment. For example, O'Conner[2] conducted a national survey and discovered a reduction in extraction rates from 37.73% to 29.28% between 1988 and 1993.

Orthodontic literature supports the notion that both extraction and nonextraction treatment can result in satisfactory outcomes.[12-14] The decision to extract teeth, particularly in borderline cases, is often a difficult one to make. Some clinicians are critical of extractions due to the belief that excessive facial flattening and concave profiles may result.[15, 16] Previous studies have shown, however, that given the proper diagnosis, such fears are unsupported.[17-20] In fact, Boley et al[13] found that general dentists and orthodontists could not distinguish profiles of extraction and nonextraction treatment simply by looking at the face alone. Also, it has been found that extraction and nonextraction cases treated to similar positions of the mandibular incisors result in no long-term difference in facial profiles.[21] Still, in today's society, clinicians are more inclined toward a more conservative nonextraction approach[2], thus requiring expansion.

McNamara described three basic approaches to expansion: passive expansion, orthopedic expansion, and orthodontic expansion.[22] Passive expansion, such as with the lip bumper or Frankel appliance, is achieved when forces from buccal or labial musculature are removed. This disrupts the equilibrium, allowing the tongue to move the teeth in a labial direction. The next approach to expansion allows for bone

deposition at the midpalatal suture and is known as orthopedic expansion. This type of expansion, usually conducted with a jackscrew-type appliance such as with a rapid palatal expander (RPE), focuses forces on the underlying basilar bone rather than the dentoalveolar complex.[22-24] Unfortunately, this method of expansion is not feasible for all patients, as it must be conducted during sutural patency and while growth potential remains. Orthodontic expansion, the last method of expansion described by McNamara, utilizes archwires to move the dentoalveolar complex for space acquisition.

The Need for Expansion

Constriction of the maxilla often results in a narrow palatal vault and posterior dental crossbites, either unilateral or bilateral. The NHANES III reported that 9.1% of the United States population has a posterior crossbite involving two or more teeth.[1] They reported a prevalence of 8.5% for children between 8-11 years of age and 7.9% for those between 12-17 years.

Early treatment of crossbites involves opening of the midpalatal suture, resulting in the crossbite correction and possible improvement in other problems, such as skeletal asymmetries, mandibular shifts, and abnormal chewing patterns.[25-28] There is, however, minimal literature specifically addressing crossbite correction using archwires alone. Despite this, substantial literature exists on the transverse effects of archwire expansion. An evaluation of 27 patients treated with the Damon System by Vajaria et al[29] demonstrated significant changes in inter-premolar and inter-molar widths, amounting to 2.87 mm and 2.79 mm, respectively. These transverse changes, they asserted, produced a

positive effect on the esthetic result. Fleming et al[30] reported similar results in 2013 in their evaluation of passive and active self-ligating and conventional twin brackets. They found no difference in arch dimensional changes between the three groups after the alignment phase, with the Damon passive self-ligating group receiving an average of 1.97 mm, 4.51 mm, 3.96 mm, and 1.22 mm of expansion in the maxillary canines, first premolars, second premolars, and first molars, respectively.

In addition to alleviating crossbites and crowding, expansion is often utilized for esthetic broadening of the smile. In 2005, Moore et al [31] asked 30 adult laypersons to judge the desirability of smiles with varying amounts of buccal corridors. They found that, among both men and women, smaller buccal corridors were more attractive than larger buccal corridors. Martin et al [32] also evaluated the attractiveness of a smile based on buccal corridors. A smiling photograph was digitally altered to generate varying amounts of oral aperture fill. Eighty-two orthodontists and ninety-four laypeople evaluated the various smiles. They found that both groups of examiners rated smiles with large buccal corridors as being significantly less attractive than those with small or no buccal corridors.

An increase in arch perimeter after maxillary widening has also been well documented. Adkins et al,[33] in their study on 21 patients consecutively treated with the Hyrax appliance, found that for every millimeter of expansion in the maxillary first premolar area, the maxillary arch perimeter increased 0.7 mm. It is important to note that this perimeter gain is not solely due to premolar expansion, but also from expansion in the anterior.

The relationship between dental expansion using archwires and arch perimeter gain has been well documented. In 1991, Germane et al[34] created a mathematical study model to quantify perimeter gains during archwire expansion in the mandibular arch. Their results, which are presented in Table 1, show that significant amounts of posterior expansion are necessary for marginal gains in arch perimeter. Conversely, canine expansion and incisor flaring produce greater amounts of space.

Table 1: Perimeter Gain with Expansion in Mandibular Arch

Amount of expansion/flaring	Amount of increased arch perimeter
1st molar expansion of 1mm	0.27 mm
1st molar expansion of 5mm	1.72 mm
Canine expansion of 1mm	0.73 mm
Canine expansion of 5mm	5.34 mm
Incisor flaring of 1mm	1.04 mm
Incisor flaring of 5mm	6.03 mm

Dentoalveolar Anatomy

A thorough understanding of the dentoalveolar anatomy must be understood in order appreciate tooth movement and the effects of this movement. The dentoalveolar complex refers to the region that includes the teeth and their surrounding tissues. The tooth root is composed of an outer layer of cementum, intermediate layer of dentin, and inner pulpal tissue. Both the cementum and alveolar bone are calcified connective tissues made up principally of a fibrous matrix. Cementum, unlike the surrounding

7

alveolar bone, contains no blood vessels or innervation. The cemental surface undergoes resorptive and reparative processes during tooth movement.[35]

The tooth root is situated within its alveolar socket by means of the periodontal ligament (PDL). Fibroblasts, producing ground substance and extracellular fibers such as collagen and elastin, are the cells responsible for the creation and maintenance of the PDL. These fibroblast cells originate within the dental follicle during the development of the tooth. During remodeling and tooth movement, mitotic replication and local mesenchymal cells yield additional fibroblasts.[36] Collagen is the primary fibrous matrix of the periodontal ligament. This group of fibers attaches directly to the cementum of the tooth and the surrounding alveolar bone. The uncalcified collagen fibers that extend into the calcified bony socket are known as Sharpey's fibers.[36] The fibers of the PDL are oriented in various directions, thus allowing for absorption and distribution of forces (e.g. during mastication).

Dentoalveolar bone can be categorized based on its maturational stage into woven bone and lamellar bone. Woven bone is immature and poorly developed. It is found early in life, at ligament and tendon insertions, and in areas undergoing significant remodeling.[37] Eventually, woven bone matures into a highly organized and mineralized lamellar bone, which is the primary component of both trabecular and cortical bone. This process takes about one to four months. Lamellar bone can be further categorized as primary or secondary lamellar bone. It may take anywhere from one to four years for the primary lamellar bone to remodel into a more mature secondary lamellar bone.

The bone of the dentoalveolar complex is of three types: cribriform plate or alveolar bone proper, outer cortical bone, and inner trabecular bone. The first of these, the cribriform plate or alveolar bone proper, is the bone that makes up the socket adjacent to the tooth root and, as the name suggests, contains numerous small openings. The small openings allow for communication between the trabecular bone and the PDL by way of blood vessels, interstitial fluid, and nerves. The cribriform bone layer is composed of relatively compact, lamellar bone.[38, 39] Immediately surrounding the alveolar bone proper is spongy, trabecular bone. This bone is of the lamellar type and contains trabeculae that run inside bone marrow. Within the bone marrow are blood vessels, nerves, and fatty tissue. Lastly, the cortical bone makes up the outer lingual and facial plates of the alveolar bone. This bone is a dense, compact lamellar bone and under normal conditions is covered with periodontium and gingival tissues. In areas where the dentoalveolar complex is narrow, trabecular bone may be non-existent. In such cases, the cribriform plate and outer cortical plate, the third type of bone making up the dentoalveolar complex, are fused.[39, 40]

The two major cells responsible for bone development and remodeling are osteoblasts and osteoclasts. Osteoblasts, the bone synthesizing cells, are derived from preosteoblasts, a local osteoprogenitor cell. Preosteoblasts originate from mesenchymal stem cells within the periosteum and bone marrow.[36] Osteoclasts are responsible for bone resorption. They are multinucleated cells derived from hematopoietic stem cells. Since hematopoietic stem cells give rise to tissue macrophages and monocytes in the

peripheral blood, osteoclasts are also regarded as being of monocytic/macrophagic descent.[41]

The physiologic remodeling process differs between trabecular and cortical bone. Osteoblasts and osteoclasts communicate with additional cells such as osteocytes and the capillary blood supply to form the "Basic Multicellular Unit", or BMU, which is responsible for bone remodeling.[42] In highly vascular, low-density trabecular bone the BMU is able to act on a vast region of bone known as the resorptive front. In this region, osteoclasts on the trabecular surface resorb bone at a speed of approximately 25 μm per day. Following the osteoclasts is osteoblastic bone formation. Conversely, dense cortical bone forces the BMU to perform differently than it does in trabecular bone. Here, the BMU forms a cutting cone of osteoclasts to tunnel through the cortical bone in the direction of the load.[43] Behind the cutting cone come the osteoblasts to lay down new woven bone.[44] It is this difference in the remodeling process that explains the variance in speed of tooth movement through cortical and trabecular bone.

Biology of Orthodontic Tooth Movement

Orthodontic tooth movement is characterized as a disruption of physiologic equilibrium within the dentoalveolar complex by an external force.[10] The complex interaction between the tooth root, the surrounding periodontal ligament, and the alveolar bone involves different cell populations, each with distinct mechanisms of remodeling and adaptation to stress.[45] The complexity of the phenomenon has led to numerous proposed models of bone remodeling and tooth movement including pressure-

tension,[46-48] piezoelectric,[10] mechanotransduction,[49] microdamage,[48, 50] and molecular[51] theories. The actual method of tooth movement appears to be a composite of several models.

The first proposed model of orthodontic tooth movement, the pressure-tension theory, was introduced in the early 20th century with classic research conducted by Sandstedt,[52] Oppenheim,[48] and Schwartz.[53] It suggests that tooth movement occurs due to differential pressures placed on the dentoalveolar complex by orthodontic forces. Histology supports the notion that, as the tooth moves during force application, there is stretching and compression of the PDL.[54] Sandstedt observed bone deposition on the alveolar wall of the tension side and resorption on the pressure side, characterized by the appearance of osteoclasts within Howship's lacunae. With light pressure, osteoclasts are able to perform frontal resorption, where bone is removed on the margin immediately adjacent to the PDL. High compressive pressure, Sandstedt noted, led to localized vascular constriction, decreased oxygen levels, eventual cell death, and the development of a cell free, necrotic zone of "hyalinization".[52, 55] This hyalized tissue obstructs the path of osteoclastic activity. Multinucleated giant cells and mono-nucleated macrophage cells remove the necrotic tissue. Instead of invasion from the PDL side, osteoclasts are forced to re-route from the medullary bone toward the site of hyalinization. Also known as "undermining resorption", this ineffective form of resorption results in slower tooth movement.[56, 57]

The piezoelectric model of orthodontic tooth movement focuses on electric signals at the molecular level. In the early 1960s, Bassett and Becker purported that the

11

deformation of the crystalline structures within bone under mechanical stress respond by emitting electrical potentials which stimulate bone formation.[58] Many crystalline structures, such as hydroxyapatite, collagen, and fibrous proteins exhibit this phenomenon.[10, 51, 59] During orthodontic tooth movement, there is an observable electronegative charge on the tension side and an electropositive charge on the pressure side. This electrical potential could play a role in molecular communication during tooth movement.[60] However, the electrical potential generated is very brief and creates an equivalent signal in the opposing direction of the original.[10] Therefore, most researchers believe that the piezoelectric force is not the sole mechanism involved in tooth movement.

More recently, Henneman et al[61] described a four-step model for tooth movement involving tissue fluid flow. Step one includes fluid flow between the alveolar bone and the PDL due to an external force being applied. Osteocytes and PDL cells are then strained during the second phase as a result of the fluid flow. With this strain of the PDL comes a negative charge on the compression side and a positive charge on the tensional side with stretching of the collagen fibers. Melsen's studies reveal that the negative strain is due to the relaxation of the PDL fibers as opposed to the traditional idea of compression.[50] The relaxation of the PDL fibers lessens the amount of fluid flow within the canaliculi, or tiny channels that allow communication between osteocyte lacunae in the bone. With a reduction in fluid flow to the lacunae, apoptosis of osteocytes can occur. Osteocyte cell death stimulates osteoclast recruitment, leading to bone resorption. On the other hand, increases in fluid flow within the canaliculi on the side with positive

strain causes sheer stress on the osteocytes. The result is an upsurge in osteocyte activity.[62-64] Step three of the model, the increase or decrease in cellular activity, leads to the fourth step: remodeling.

Similar to the above model involving apoptosis of osteocytes is the microdamage principle. Baumrind[65] suggested that an external force on a tooth produces alveolar bone deflection. Strains occur in the teeth, PDL, and alveolar bone. The alveolar bone is more elastic and easily bent than the other tissues, incuding the tooth. Baumrind, along with other researchers, hypothesized that the displacement of the tooth leads to bone bending, fatigue and microcracks on the resorptive side of the alveolus.[66-68] Crack propagation may tear cell processes of the osteocytes, causing them to secrete molecules to trigger osteoclast recruitment.[69] Proponents of this model assert it is this microdamage that yields a cellular response and causes osteocyte apoptosis.[70]

In 1987, Frost furthered the idea of microstrain propagation and its effects on bone with his Mechanostat theory.[71] The Mechanostat describes bone adaptation as a consequence of applied strain. Adaptation allows the bone to adjust its mass and geometry to correspond to its functional needs. Below a level of 100-300 microstrains, removal of cortical-endosteal and trabecular bone mass occurs because bone strength is not needed. This range of remodeling is called the disuse window. In high stress level, between a range of 1500-3000 microstrains, an overall increase in cortical bone mass occurs. Between these two ranges, at 300-1500 microstrains, is the adapted window whereby bone is in a state of equilibrium with no observed overall apposition or resorption. However, in the pathologic overload window, where strain is greater than

3000 microstrains, microcracks occur in the bone. Beyond this range, damage accumulates and eventual pathologic fracture will occur.[72-74]

Detrimental Effects of Dental Expansion

Expansion makes it possible to improve smile esthetics, decrease crowding, and alleviate transverse discrepancies. Despite these positive effects, dental expansion has often been criticized because of the negative effects that may occur. In 1933, Dr. Charles H. Tweed brought some of these negative effects to the attention of orthodontists. After disappointments with some of the results of following Angle's treatment philosophy, Tweed reevaluated 70% of his own treated cases. He explained that the elimination of a TSALD through expansion often resulted in a protrusive, unaesthetic profile and concomitant dental instability.[10, 75, 76] After classifying his cases as successes or failures based on the objectives of stability, healthy tissue, function, and esthetics, Tweed found that over 80% were failures in at least one of the four objectives. Based on data obtained from the Bolton study, the norm for lower incisor position was determined to be within the range of 85 to 93 degrees.[77] Further analysis of Tweed's patients revealed that the position of the lower incisors in the failure causes were consistently proclined beyond this degree range. This provoked Tweed to retreat many of his patients and upright their incisors to a more suitable position. In 1940, Tweed brought the records of patients who had received nonextraction followed by extraction treatment to the American Association of Orthodontists meeting to verify the negative effects of excessive proclination with dental expansion.

Despite innovative materials since Tweed's time, one of the negative effects that still remains is uncontrolled tipping of teeth. Lundgren et al[78] used light continuous forces (50 cN) to expand the maxillary premolars. Their results showed palatal tipping of the apices ranging from 0.2 to 22.9 degrees in 49 of the 56 cases. Similar outcomes were observed by Paventy et al,[79] who evaluated archwire expansion with the Damon system on patients with 5 mm or more of crowding. Results showed effective arch expansion and consequential increased arch perimeter, but a significant amount of uncontrolled tipping. To better understand the biological processes that take place during archwire expansion with self-ligating brackets, Cattaneo et al[80] evaluated buccal bone modeling in the maxilla. Patients were treated with either passive (Damon 3MX) or active (In-OvationR) brackets. Using pre- and post-treatment cone beam CT scans they found that, in all but one patient analyzed, expansion was achieved through buccal tipping of the teeth (11.7 and 11.8 degrees tipping of the first premolar with the Damon and In-OvationR bracket, respectively). Kraus et al[81] used the foxhound model to evaluate the effect of archwire expansion on bone using a force system similar to the Damon system. They found that over 9 weeks of active expansion, 3.5 mm of transverse movement and 15.8 degrees of tipping occurred. They described a zone of reversal, where the pattern of bony apposition switched from the PDL side to the periosteal side of the buccal cortex, suggesting that active bone apposition is possible on the buccal aspect of an expanding tooth.

In addition to improper tooth position and uncontrolled tipping, it has been shown that archwire expansion and palatal expanders can produce buccal bone

dehiscences.[79] [82] With tipping, concentrated forces are exerted on the crestal bone.[83] If these forces exceed certain levels, detrimental effects can result. A significant decrease in the connective tissue level, as well as the buccal marginal bone level, was found with excessive labial tooth movements in experimental work on monkeys.[84] The previously described research conducted by Paventy et al[79] showed similar results, with statistically significant buccal bone height loss at the maxillary first premolars, mandibular first and second premolars, as well as mandibular first molars. Six months to one year later, J. Paventy re-evaluated 14 of the 19 subjects.[85] He noted that small amounts of bone height and width were recovered, but not to a statistically significant level. Cattaneo et al[80] also described buccal bone loss in their randomized clinical trial. They found 23% and 18% bone height losses with the Damon system on the right and left sides, respectively. With the In-Ovation bracket they noted 17% and 12% bone loss on right and left sides. Similarly, Kraus et al[81] showed average bone height reductions of 2.9 mm and 1.2 mm at the mesial and distal roots, respectively. They demonstrated that the rate of resorption of buccal bone appears to be greater than new bone apposition. It was concluded that, due to the amount of tipping that occurred, significant dehiscence of bone over the expanded tooth roots resulted. While new bone appears capable of being laid down lateral to an expanded tooth, as proven by the presence of osteoblasts on the periosteal side of the buccal bone, the negative side effects of archwire expansion will remain unless tipping can be controlled or bone can be augmented on the buccal surface.

Cortical Plate Encroachment & the Body's Ability to Respond

In 1982, Karring et al[86] sought to evaluate the effect of facial tipping on the left and right maxillary second and third incisors of beagle dogs. For five months, the teeth were tipped through the alveolar bone with orthodontic appliances in a labial direction. Afterwards, the mechanics were reversed on the left side, moving the teeth back to their original position over another five-month span. At the same time, the right side was held in their proclined positions. There was then an additional five months of retention prior to sacrifice. In all dogs, including controls, no soft tissue migration was apparent. In the control group, the average distance from the cementoenamel junction (CEJ) to the bone crest was 2.2 mm (± 0.5 mm). In the group where the incisors were retained in a proclined position, the average distance from the CEJ to bone crest was 4.1 mm (±2.1 mm). In the group where the incisors were tipped and subsequently returned to their original position, the distance was 1.8 mm (±0.4 mm). This study emphasizes that bone dehiscences can arise after labial tipping of teeth into the cortical bone, and that bone has a regenerative capability if teeth are placed back in their original position of equilibrium.

In a similar study in 1981 using Macaca nemistrina monkeys, Steiner et al[84] moved the central incisors a mean distance of 3.05 mm labially over 13 weeks. A flap was then reflected to evaluate the underlying tissues. Significant recession of the gingival margin, connective tissue level, and marginal bone was discovered. Eight months later, Engelking and Zachrisson[87] repositioned the teeth of the same animals lingually an average of 1.8 mm. After 5 months of retention, clinical and histologic analysis showed that marginal bone levels recovered coronally on average 2.5 mm for

the maxillary and 3.1 mm for the mandibular incisors. Like Kerring et al,[86] the authors concluded that vertical labial alveolar bone reapposition can occur over a dehiscence if the tooth is then repositioned to a more natural position.

In addition to bony dehiscences, dental expansion has also been shown to increase root resorption.[88-90] Resorption may be caused by the limitation of the buccal and/or palatal cortices. The cemental root layer has been shown to resorb when excessive force is applied to the tooth. In 1996, Owman-Moll evaluated the effects of various orthodontic forces on tooth movement and root resorption.[89] In general, the greatest amount of resorption was seen at the roots' cervical and apical thirds. Similarly, Ballard et al[91] demonstrated with micro CT that areas of greatest resorption corresponded to those areas of greatest pressure.

Based on research conducted by Schwarz, it is thought that the optimal force for tooth movement is one that approximates the blood pressure in the capillaries so as to not compress vessels within the periodontium.[53] He suggested that the goal for favorable orthodontic tooth movement should be a light force to cause continuous resorption of alveolar bone without resorption of the root. This notion was later confirmed by Storey and Smith[92] and Reitan,[55] who advised avoiding or limiting hyalinization to achieve rapid tooth movement. Proffit has proposed a series of optimum forces (Table 2) for orthodontic tooth movement.[10] Light continuous forces should be used to avoid the detrimental effects of high strain.

Table 2: Optimal Force for Tooth Movements

Type of Movement	Force (gm)
Tipping	35-60
Bodily movement	70-120
Root uprighting/ torque	50-100
Rotation	35-60
Extrusion	35-60
Intrusion	10-20

Corticotomies

Regional Acceleratory Phenomenon

It is known that an increase in the rate of bone modeling and a decrease in bone density occurs as part of the body's natural healing process when bone is injured. This biological process is known as the regional acceleratory phenomenon, or RAP.[93-96] The RAP is described as a temporary state of accelerated healing, with a localized increased in cellular activity and bone remodeling at the site of injury through recruitment of osteoblasts and osteoclasts.[97] It involves an increase in vascular perfusion, an increase in bone turnover, and a decrease in bone density, or osteopenia.[95] The osteopenia is transient, however, and is quickly followed by rapid osteoblastic activity and bone modeling. Any noxious stimuli of sufficient magnitude can elicit the RAP. According to Frost, the greater the intensity of the injury, the greater a biological response.[98, 99]

The processes associated with corticotomies are not unlike those related to fracture healing. Three key phases of the healing process occur: the reactive phase,

reparative phase, and remodeling phase. The reactive phase begins immediately after

bony insult. Damage to the bone marrow and living bone, periosteum, and adjacent soft

tissue causes some cells to die and others to become sensitized for a better response to

local and systemic messengers.[100] During this phase, vascular constriction occurs to

alleviate bleeding. Within hours, a blood clot or hematoma forms. The main aspects of

the reactive phase are thought to have occurred within seven days of the injury. New

cells are produced which differentiate to provide fibroblasts, intercellular materials, and

supporting cells within a network of new blood vessels. Collectively, they make up

what is known as granulation tissue, which is interposed between the fragments of a

fracture or, in the case of a corticotomy, between the major fragments of osseous

removal. The formation of granulation tissue takes about two weeks. The next phase,

the reparative phase, includes the creation of chondroblasts and osteoblasts within the

granulation tissue. These cells form hyaline cartaliage and woven bone, which begin to

mineralize to form the callus.[101] Complete mineralization takes 1-4 months.[100] During

the final stage, the remodeling phase, bone is remodeled into mature lamellar bone,

which can take anywhere from 1 to 4 years. It is important to note that the rates of bone

healing depend on adequate stability and blood supply to the region.

   To determine how and why the RAP occurred, researchers in the field of

orthopedic surgery furthered Frost's investigations. Esterhai et al[102] measured bone

activity of patients with traumatic nonunion fractures using technetium scinigraphy. The

bone scan identified three specific patterns of radionuclide uptake at the fracture site: (1)

an intense, uniform increase in uptake at the nonunion site (69.5%), (2) a photo deficient

cleft (indicating very little or no bone activity and remodeling) between two intense areas of uptake (23.4%), and (3) an indeterminate pattern. Pattern number 2, or the presence of a "cold cleft" was closely associated with the discovery of synovial pseudarthrosis at surgery. This study supported the idea that an intensification of bone activity and remodeling, indicated by pattern number 1, or what Frost[98] referred to as the RAP, most often occurs during the healing process of fractures.

In a more recent publication in 2005, Akesson et al[103] sought to evaluate the short and long-term metabolic effects within the fracture site. They thought that if bone turnover occurs for extended periods of time after a fracture, it might be a potential confounder for clinicians when evaluating patients with osteoporosis. They collected pre-fracture baseline bone activity information on fourteen patients and compared it with their long-term results. A clinical fracture model of the proximal tibia was utilized, and postoperative samples were collected 6-9 weeks, 4-7 months, 9-13 months, and 14-17 months after the induced fracture. Bone formation was measured through serum samples by osteocalcin (OC), type 1 procollagen peptide (PICP), total alkaline phosphatase (ALP), and carboxy-terminal-telopeptide of type I collagen (ICTP). Deoxypyridinoline (Dpyr) was measured in the urine. More specifically, OC was measured using two-site immunofluorometric assays, both of which measured full-length and fragmented froms of OC (OC_{tot}) and one of which specifically assayed for the carboxylated form (OC_{cxy}). They found a peak in serum OC_{tot}, OC_{cxy}, and ALP 4-7 months post-fracture. After one year, bone formation had returned to baseline. Dpyr increased significantly, doubling at 6 weeks. ICTP increased by 73%. At 6 weeks, urine

OC increased to a maximum of 84%. Initially, the percentage increase of bone

resorption was greater than that of bone formation. They concluded that (1) bone

turnover as measured with biochemical markers is altered soon after fracture, (2) the

major changes occurred within 6 weeks to 6 months, but may continue for up to a year.

Bone Remodeling Rates and Density Effect Tooth Movement

The orthopedic literature has validated that the regional acceleratory

phenomenon occurs as a result of a noxious stimulus, such as a fractures or an electrical

current.[104] Literature within the orthodontic and dental community has also

demonstrated an association between increased bone turnover from the RAP and

increased tooth movement. Bone turnover, both resorption and apposition, is required

for tooth movement within the alveolar process. King et al[105] found that orthodontically

moved rat molars displayed evidence of bone resorption on the pressure side and

formation on the tension side when compared to untreated controls.

There is a correlation between bone density and the rate of tooth movement, with

accelerated movement through less dense bone. Goldie et al[106] confirmed this notion in

their study utilizing the rat model. Thirty-five adult female rats were divided into a

control group of non-lactating animals and a calcium-deficient, lactating group. The

maxillary molars were moved mesially with a 60-gram orthodontic force. Tooth

movement was evaluated at sacrifice by measuring the resulting space between the

maxillary molars. They found that the lactating animals exhibited decreased bone

density and significantly greater tooth movements, as well as a significant decrease in

22

bone mass. It was concluded that the increased tooth movements were correlated with decreased bone density.

In 1992, Ashcaft et al[107] sought to evaluate the effects of osteoporosis on orthodontic tooth movement. In sixteen New Zealand white rabbits, corticosteroids were given to decrease bone density and induce osteoporosis. After a 4-ounce force was placed on the maxillary left first molar, tooth movements were quantified by measuring the space distal to the first molar. It was found that the rabbits with corticosteroid-induced osteoporosis exhibited faster tooth movement.

The speed of tooth movement is also dependent upon bone remodeling rates. In 2000, Verna et al[108] divided 52 male Wistar rats into three groups: control, high bone turnover, and low bone turnover. The high and low bone turnover was brought about by induction of hyper- and hypothyroidism, accomplished by administering 0.003% L-T4 in the drinking water for four weeks of the high bone turnover group, and giving a semi-synthetic iodine-restricted diet with $KClO_4$ in the low bone turnover group. A constant, mesial force was then applied to the maxillary molars for three weeks. Their results showed accelerated rates of tooth movement in the group with high bone turnover and reduced rates of movement in the low bone turnover group.

A number of studies have been conducted to analyze tooth movement and remodeling rates. Collins and Sinclair's[109] work in cats, as well as Kawakami's[110] work in rats, revealed greater rates of tooth movement with localized injections of 1,25 dihydroxycalceferol (vitamin D) when compared to controls. Vitamin D is a potent stimulator of accelerated osteoclast activity. Through histologic examinations, the

researchers observed an increase in osteoclast recruitment and the presence of more Howship's lacunae on the pressure side of a moving tooth. Kale et al[111] found a statistically significant enhancement of tooth movement with local administration of prostaglandin E2 (PGE-2) and vitamin D in rats.

Just as tooth movement can be enhanced with localized mediators of osteoclastic activity, it can also be slowed. Bisphosphonates are a group of drugs designed to decrease bone turnover through direct inhibition of osteoclasts. They are commonly used for bone disorders such as Paget's disease and osteoporosis. Igarashi et al[112] have shown that a 40% decrease in tooth movements in rats occurred when they were given bisphosphonates systemically during orthodontic treatment. Similarly, after an injection with the bisphosphonate zoledronate into the extraction site of rats, Ortega et al[113] observed no significant movement of an adjacent tooth when compared to controls.

The induction of the RAP effect and its ensuing enhancement of bone turnover is the premise behind the popular minor alveolar surgical technique of corticotomies.

History of Corticotomies

The concept of surgically facilitated orthodontic therapy (SFOT) was first proposed in Europe by Cunningham at the end of the 19th century.[114] The concept remained largely in Europe during the first half of the 20th century. In 1921, Cohn-Stock reported removal of the palatal plate adjacent to maxillary teeth to enable their immediate repositioning and retrusion.[115] Similarly, Bichlmayr excised the buccal and lingual cortical plates at first premolar extraction sites in order to facilitate canine

retraction in bimaxillary protrusive patients over 16 years of age. He claimed the

procedure would accelerate tooth movement and reduce relapse potential.[116] Popularity

continued to rise in Germany, with others using a similar procedure that involved

vertical incisions of buccal or lingual cortices interdentally, also called a "septotomy",[117]

claiming a 20-25% reduction in treatment time.[118]

In 1959, Kole[119] first documented corticotomies in the United States. His

procedure, with some modern refinements such as the exclusion of a subacpical

osteotomy, is the basic technique that is employed today. With no empirical evidence to

support his claim, Kole proposed that disruption of the cortical layer of bone alone

would hasten tooth movement and prevent relapse. His method involved both buccal

and lingual decortication without disruption of the underlying medullary bone. Kole

theorized that the main resistance to orthodontic tooth movement was the cortical bone.

For this reason, his objective was to ensure that the tooth segments being moved were

only connected through softer medullary bone. He speculated that since the blood supply

from the mucoperiosteum was denuded when gaining access for the surgical cuts, the

vascularity from medullary bone would act as a nutritive supply to prevent necrosis.

With Kole's technique, teeth could either be moved in a segment or individually

to promote expansion and retraction. First, vertical cuts traversed the facial and lingual

cortices, extending just into the medullary bone.   These vertical cuts could be placed

interdentally or bordering a segment of teeth, depending on the movement required.

Following the vertical corticotomies, a horizontal osteotomy beyond the root apices

traversed the entire buccolingual width of the alveolus. The only site that Kole did not

advocate complete bicortical encroachment with a horizontal osteotomy was in the posterior mandibular region. Here, the horizontal cut only penetrated through the cortices so as not to damage the neural and vascular component of the jaw. In his original article, the majority of the appliances used to conduct tooth movement were removable, but were to only be taken out for cleaning. Kole reported a shortened time to case completion of only 12 weeks, as well as the lack of root resorption and devitalization, all of which were attributed to the block movement of teeth.

The latter half of the 20th century brought much naiveté with lack of empirical data to support claims of corticotomies.   Bell and Levy[120] published the first experimental study on corticotomies. Their surgical technique, however, differed from Kole's[119] suggested protocol. Working with *Macaca mulatta* monkeys, vertical interdental corticotomies were performed that should have been considered osteotomies. Buccal and palatal flaps were reflected and the cuts extended the entire width of the alveolus. The resulting block segment was mobilized with a chisel. Their conclusions were subjective and descriptive, vaguely noting a "destructive effect on the maxillary incisors", as well as ischemia. In 1975, Düker[121] replicated Kole's work in beagle dogs, moving the central incisors about 4 mm over 8-20 days. No control group was used, and he concluded that no significant injury to the periodontal attachment nor the dental pulps occurred with this procedure.

One of the greatest influences on today's standard for corticotomies occurred during the 1970s in Japan. Suya treated over 300 patients with nonextraction and corticotomies.[122] Essentially a refinement of Kole's surgery, Suya exposed the facial

and lingual cortical plates to gain access for vertical and horizontal cuts. Unlike Kole, the horizontal incision was not an osteotomy, but rather a buccal and lingual corticotomy that extended only through the labial cortex and connected the vertical interdental decortication. Suya reported completed orthodontic treatment within 10 weeks in 69% of his cases.

By the late 1990s, the Wilcko brothers began the integration of the corticotomy procedure into mainstream orthodontics with a series of case reports.[6, 123, 124] These case reports presented computed tomography scans of patients who had been treated with corticotomies. In contrast to the notion that the corticotomies were the result of bony block movement, the Wilckos were the first to suggest that the treatment effect was a consequence of the RAP effect. They did so because areas of the alveolus showed signs of demineralization and remineralization. The authors theorized that the transient osteopenia and resulting softer bone could be carried with the root during movement and later remineralized. Their technique, which originally involved both buccal and lingual full-thickness mucoperiosteal flaps, was the first to include the addition of bone grafting over the buccal corticotomies. By combining the corticotomy-facilitated orthodontic technique with alveolar augmentation, the Wilckos coined the procedure (periodontally) accelerated osteogenic orthodontics [(P)AOO]. Today, a more conservative approach is usually taken, whereby only the cortex is perforated from the buccal aspect to maintain an intact lingual blood supply.[125]

Specifics of "Wilckodontics"

PAOO as described by the Wilckos begins with careful flap reflection.[124] In the most coronal aspect of the flap, a full-thickness incision is made. In the more apical portions, a split-thickness dissection is performed to allow for minimal tension upon suturing. The periosteal layer is then elevated to expose the underlying alveolar bone. In order to decrease the need for a vertical releasing incision, the flap is extended both mesially and distally beyond the corticotomy area. The achievement of an esthetic outcome is of utmost importance. For this reason, the papilla between the teeth is not reflected and papilla preservation techniques are employed. In their early years when palatal decortication was still performed, retention of a palatal or lingual gingival collar of tissue maintained collateral blood supply to the papillary tissue.

Using a No. 1 or 2 round bur or piezoknife, vertical incisions are placed interdentally within the alveolar bone. These grooves extend just into the medullary bone to the point of bleeding, starting 2-3 mm apical to the crest of the bone and ending 2 mm beyond the root apices. The vertical corticotomies are then connected with a circular-shaped horizontal corticotomy. Pending adequate buccal bone thickness (i.e. greater than 1-2 mm thick), individual perforations may be placed over the radicular surface of the underlying teeth.

Lastly, particulate bone graft in the form of decalcified freeze-dried bone allograft, deproteinized bovine bone, or a combination of the two is placed over the areas that have undergone corticotomies. Clinical judgment as to the amount of graft material to be used is based on the direction of tooth movement, the pre-existing thickness of the

bone, and the expected amount of labial movement. Typically, this volume is about 0.25

mL to 0.5 mL per tooth.

Advantages of Corticotomies: Accelerated Tooth Movement

It is now well understood that the acceleration of tooth movement induced by

corticotomies is due largely to an increase in bone turnover.[126] Adjacent to corticotomy

sites, as much as a 5-fold increase in bone turnover has been reported,[127] with a 3-fold

increase in the number of osteoclasts and a 4-fold increase in the number of

osteoblasts.[128] In a recent publication by Wang et al,[129] the differences in cellular

response between corticotomy- and osteotomy-assisted tooth movement in a rat model

was described. Histological analysis revealed an increase in osteoclastic activity and

transient bony resorption adjacent to corticotomy sites, followed by a replacement and

mineralization phase of healing. Conversely, creating a completely mobile segment with

osteotomies resulted in a response similar to that of distraction osteogenesis, where no

stage of regional bone resorption was observed. These findings further support the

proposed notion by Wilcko et al[6] that corticotomy-assisted tooth movements are

dependent on a RAP effect.

Experimental and clinical work has established that the RAP brought about by

bony insult during corticotomies increases the rate of tooth movement.[6, 95, 96, 123, 130-137]

The majority of the corticotomy literature focuses on mesial-distal tooth movement,

which occurs within the alveolar trough and is mostly through more vascular and less

dense lamellar bone. Cho et al. performed a split-mouth study in two beagle dogs.[138]

Buccal and lingual "cortical activation" was preformed on the experimental side, while the contralateral side served as an untreated control. Cortical activation included the placement of 12 perforations around the tooth to which a mesializing force was placed with a 150-gram nickel titanium coil spring. It was found that approximately 440% more tooth movement occurred on the experimental side of the maxilla, and approximately 260% more on the experimental side of the mandible when compared to the control side. Micro CT analysis has revealed that the bone quality and quantity after mesial-distal corticotomy-facilitated tooth movement is similar to native bone.[93]

With conventional orthodontics, it has been estimated that teeth under a continuous force move 0.8 to 1.2 mm per month.[139] To shorten treatment time, particularly in adult patients, experimental evidence suggests that tooth movement enhanced by corticotomies can be completed in about half the time as compared with conventional orthodontics.[94, 138, 140, 141] Therefore, one can expect about 1.6 to 2.4 mm of tooth movement per month with corticotomies. It is important to note, however, that there is a narrow window of time available to take advantage of the RAP and its benefits on tooth movement. Experimental peak tooth movement with corticotomy treatment is documented at approximately 2-3 weeks.[94, 140, 141] Evidence indicates that the RAP effect in the canine model is limited to a maximum of 1-2 months.[142] Extrapolated to humans, the orthodontic advantages accompanying corticotomies are limited to about 2-3 months.

Further investigation by Cohen et al[143] in 2010 confirmed the additive effects of stimuli on the rate of tooth movement. Using a split-mouth design in ten foxhound dogs, they randomly assigned maxillary right and left quadrants into RAP and RAP+ groups.

The RAP group included extraction of the maxillary first premolar with subsequent osseous removal adjacent to the socket. The RAP+ group received additional injury through removal of the buccal plate extending from the canine to the second premolar. Statistically significant differences were observed in the amount of tooth movement between the two groups (RAP+ 2.9 mm vs RAP 1.8 mm). The authors concluded that increased surgical trauma increases the RAP effect and, therefore, the amount of tooth movement.

Advantages of Corticotomies: Soft Tissue Health

In addition to faster treatment time, corticotomy treatment has been promulgated as a means of attaining a healthier periodontium than would be achieved with traditional orthodontics. In their original article,[6] the Wilcko brothers claimed no significant apical root resorption and no periodontal pocketing despite the interdental osseous cuts and proclination of incisors that was performed to relieve crowding. They believe that a greater extent of movement can be achieved with corticotomies, thus reducing the need for extractions while providing increased support to the periodontium.[144] One of the first comments regarding the periodontium came from Düker[121] in 1975, when he performed vertical buccal corticotomies and horizontal bicortical osteotomies 5 mm apical to the maxillary roots of 6 beagle dogs. To minimize damage to the marginal periodontium, he stopped the vertical cuts shy of the alveolar crest. His work showed pulp vitality and healthy periodontium following 4 mm of tooth movement via thick elastics over an 8 to 20-day period.

In a later study, Gantes et al[145] sought to evaluate the periodontal status of the involved teeth after the corticotomy surgical technique was used in conjunction with orthodontic therapy. In five patients, plaque scores, probing depths, and probing attachment levels were recorded before and after treatment. Their conclusions were that minimal changes in the periodontal attachment apparatus developed following the corticotomy procedure.

Shoreibah et al[146] showed similar results in their 2012 publication. Twenty adult patients who presented with 3-5 mm of lower anterior crowding were equally divided into two groups. Group 1 treatment included corticotomy-facilitated orthodontic therapy alone, whereas group 2 treatment involved the addition of bone grafting to the corticotomy site. After a labial intracrevicular flap was reflected, vertical interdental grooves were made from mandibular canine to mandibular canine. The lingual periodontium was left intact and no horizontal subapical cuts were performed. Both groups were treated with labial movement of the lower incisors to relieve crowding. Pre-surgical, post-treatment (at debond), and 6 months post-treatment measurements of bone density and clinical probing depths were obtained for comparison. Their results demonstrated no significant difference in treatment time between the two groups (mean 17 weeks), as well as a significant reduction in probing depths in both groups from pre-treatment to 6 months post-retention (-1.4 ± 0.2 mm and -1.6 ± 0.2 mm in groups 1 and 2, respectively).

Advantages of Corticotomies: Increase in Alveolar Bone Width

With the augmentation of bone following corticotomies, a marked increase in labiolingual alveolar cortical width has been observed radiographically.[147-149] In general, studies show an overall increase in alveolar width at the level of the root apex from pre- to post-treatment which remains stable at two-years post-treatment. Proponents of supplemental bone grafting with corticotomies maintain that elimination of pre-existing fenestrations and dehiscences, as well as their prevention during labial tooth movement, necessitates its use.

Advantages of Corticotomies: Decreased Risk of Apical Root Resorption

Another often claimed advantage of corticotomy-facilitated orthodontic treatment is a decrease in apical root resorption. It has been hypothesized that the osteopenia induced by corticotomies allows for diminished osseous resistance to tooth movement. Therefore, less strain on the cemental surface of the root may result in a decreased incidence of root resorption. Interestingly, a diminished extent of hyalinization of the PDL occurs during tooth movement after corticotomies,[141] and hyalinization has been known to be a precursor to root resorption.[150]

To assess root resorption, Shoreibah et al[146] measured pre- and post-corticotomy treatment root length from the cementoenamel junction to the tooth apex on periapical films. Their results showed no significant root resorption in patients treated with corticotomies. However, the potential for magnification error and how they controlled for this error was not addressed. In another study, Machado et al[151] evaluated the

maxillary central incisors of non-extraction patients treated with (n=26) and without

(n=27) corticotomies. Using periapical radiographs taken with the paralleling technique,

it was shown that subjects in the conventional orthodontic treatment group exhibited

significantly greater root resorption than the corticotomy group. The corticotomy-

facilitated non-extraction orthodontic therapy resulted in half as much root shortening as

conventional orthodontics. These results are consistent with those reported by Wang et

al[152] who, using CBCT, found no significant difference in pre- and post-treatment root

length in their corticotomy group, but an average of 1.55 mm resorption in patients

treated with orthodontic therapy alone.

Advantages of Corticotomies: Enhanced Stability

Orthodontic stability is dependent on the ability of the periodontium to

regenerate, reorganize, and adapt to the final position of the teeth. Due to the increased

tissue turnover that occurs at the corticotomy site, researchers evaluated post-treatment

stability after PAOO.[153,154] Results indicate no relapse after 6 months of retention.

Similar results were attained by Oliveira et al[155] after proclining mandibular incisors a

minimum of 3 mm. They hypothesized that the lack of incisor relapse was due to

increased alveolar thickness from grafting and tissue memory after dramatic tissue

turnover. Unfortunately, no strong evidence for increased stability after corticotomies

exists. Prospective studies with matched controls, unlike the aforementioned studies,

must be conducted to make more definitive conclusions regarding the matter.

Orthodontic Application of Corticotomies

Table 3 shows the various uses of corticotomies that have been reported in the literature. Corticotomies have been used for the treatment of open bite, crowding, over-erupted molars, palatally impacted canines, accelerated space closure, and molar distalization to name a few. Note that, until recently, the majority of the orthodontic research was anecdotal, with case reports dominating the literature.

Table 3: Corticotomies in the Orthodontic Literature

Reference	Problem	Method	Study Design	Treatment Duration
Hwang and Lee[132]	Molar supereruption	Decortication and magnets	Case report	4 wks
Germec et al[156]	Lower incisor retraction after bicuspid extraction	"Conservative"—no lingual cuts	Case report	16 mos
Kole[119]	Rotations, distalization, Incisor proclination	Buccal & Lingual decortication + subapical osteotomy	Case report	6-12 wks
Moon et al[133]	Molar supereruption	Buccal & Lingual decortication + skeletal anchorage	Case report	2 mos
Anholm et al[157]	Narrow arches, unilateral class II	Buccal & Lingual decortication	Case report	11 mos
Oliveira et al[134]	Molar supereruption	Buccal & Lingual decortication	Case report	2.5-4 mos
Grenga et al[158]	Molar supereruption	Decortication + skeletal anchorage	Case report	6 mos
Aljhani and Zawawi[159]	Severe crowding, root resorption	Buccal & Lingual decortication+ Augmentation	Case report	11 mos
Fischer[131]	Bilateral impacted canines	Decortication perforations	Case control	11.5 mos
Aljhania and Aldrees	Anterior open bite	Buccal & Lingual decortication+ Augmentaiton	Case report	5 mos
Wilcko et al[6]	Crowding Posterior crossbite	Buccal & Lingual decortication+ Augmentaiton	Case report	6.5 mos
Nowzari et al[160]	Class II div 2 crowding	Buccal decortication +Augmentation	Case report	8 mos

Table 3 Continued

Reference	Problem	Method	Study Design	Treatment Duration
Kim et al[161]	Class III pre-surgical decompensation	Corticotomy+ Augmentation	Case report	5-8 mos
Iino et al[162]	Bimaxillary protrusion	Buccal & Lingual decortication	Case report	12 mos
Hassan et al[163]	Posterior cross bite, deepbite or open bite	Buccal & Lingual decortication+ Augmentation	Case reports	18-19 mos
Owen et al[164]	Mild anterior crowding	Corticotomy+ Invisalign	Case report	8 weeks
Ahn et al[165]	Class III pre-surgical decompensation	Corticotomy+ Augmentation	Case series	2.5 mos
Wang et al[152]	Class III pre-surgical decompensation	Corticotomy+ Augmentation	Case series	7.8 mos
Coscia et al[166]	Class III pre-surgical decompensation	Corticotomy+ Augmentation	Case series	8.23 mos
Aboul-Ela et al[167]	Class I, Div I canine retraction after bicuspid extraction	Decortication perforations+ MSIs	Case control	2-3 mos
Choo et al[168]	Maxillary or Bimaxillary protrusion	Buccal & Lingual Decortication + skeletal anchorage	Case series	20 mos

Of particular interest is the use of corticotomies to facilitate orthodontic expansion.

Expansion and Corticotomies

Corticotomies have been reported to aid in arch expansion by facilitating tooth movements through demineralized cortical bone. The demineralized bone is thought to more readily follow the expanded tooth, allowing for less dehiscence formation.[169] The

use of corticotomies to specifically address the need for expansion was first documented in a case report on two adult patients with unilateral posterior crossbites by Hassan et al.[163] As adults with mature midpalatal sutures, they would not benefit from jackscrew palatal expansion because their malocclusions were unilateral in origin, and because of the dental tipping this appliance would produce. Therefore, expansion was achieved with a heavy labial bar and corticotomies on the affected side. No assessment of the surrounding hard or soft tissue status, amount of tipping, or long-term stability was conducted in this case report.

In addition to transverse discrepancies, corticotomies may also be used to assist in pre-orthognathic surgery dentoalveolar decompensation. Kim et al,[161] for instance, described two adults with class III skeletal malocclusions and subsequent dental compensations, including retroclined mandibular incisors, thin facial alveolar bone, and accompanying dehiscences. Alveolar decortication surgery was performed and one patient received particulate bone grafting with a non-resorbable membrane. After rapid labial tooth movement to idealize the position of the lower incisors before surgery, post-treatment cone beam computed tomography revealed an unspecified amount of augmentation of the alveolar bone in both patients. The problem with cone beam CT scans, however, is that large voxel size may not permit adequate evaluation of bone volume addition, nor does it allow one to determine whether the grafted material has been incorporated into new bone or whether it remains discretely separated from the patient's pre-existing bone.

Following in their footsteps, Ahn et al[165] sought to quantitatively evaluate labial alveolar bone in a group of 15 class III dentoalveolar compensated patients who were planned for two-jaw orthognathic surgery. Augmented corticotomies were performed, followed by an average of 10.45 degrees of lower incisor labial decompensation. Using lateral cephalograms, pre- and post-treatment measurements of alveolar bone thickness at the root apex and B-point were compared. Statistically significant increases in mean bone thickness occurred at both the root apex (1.56 mm) and B-point (1.98 mm). They reported no gingival recession for any of the patients, irrespective of the degree proclination of the mandibular incisors. Shortcomings of this study include a lack of controls, small sample size, and evaluations based on lateral cephalograms. There are inherent problems associated with the use of lateral cephalograms to measure alveolar bone thickness, such as ambiguity of landmark identification and difficulty identifying structures, as well as image magnification and distortion. To sufficiently confirm their results and ensure no presence of dehiscences or fenestrations, particularly at the cervical margin, histological and/or μCT evaluation would need to be performed.

In 2013, Wang et al[152] used cone beam CT scans as a better means of analyzing labial alveolar thickness in class III pre-surgical patients. CBCT provides advantages over lateral cephalograms including excellent tissue contrast, submillimeter spatial resolution, and removal of tooth overlap. Despite the enhanced image, cone beam CT does not allow one to adequately assess the quality and quantity of the bone in question. In their study, twenty-six subjects were allocated to group 1 and received augmented corticotomies. Orthodontic activation for decompensation in this group occurred every

two weeks. Group 2 served as a control and consisted of 30 patients receiving conventional orthodontic treatment with adjustments every four weeks. Their results led to the following conclusions: (1) Augmented corticotomies resulted in a more adequate decompensation of lower incisors relative to the mandibular plane (10.64° for group 1 vs. 5.06° for group 2), and (2) better periodontal preservation was achieved with augmented corticotomies (average increase in labial alveolar thickness at the apex of 3.11 mm in group 1 vs. -0.88 mm in group 2). However, vertical bone loss of similar amounts occurred in both groups. These results are consistent with those of a similarly conducted study by Coscia et al,[170] except no mean vertical loss in alveolar bone was observed.

Corticotomies and Grafting

Various types of bone graft material exist. These include autografts which are derived from the host, allografts which are taken from an individual of the same species as the host, xenografts which are derived from another species, and alloplasts which are synthetic materials used to replace human bone. Historically, autogenous bone is considered the gold standard for critical size defects of the craniofacial region.[171] It possesses the potential for three biological processes: osteogenesis, the formation of new bone from osteocompetent cells, osteoinduction, the formation of new bone from osteoprogenetor cells, and osteoconduction, the formation of new bone along a scaffold of osteocompetent cells at the recipient site.[172] Autogenous bone can be harvested from a number of intraoral and extraoral sites such as the iliac crest, tibia, rib, calvarium,

mandibular ramus, chin, and maxillary tuberosity. Since a smaller volume of bone

grafting material is necessary for corticotomies, if autogenous bone is to be used,

intraoral sites are generally harvested as opposed to extraoral sites to decrease donor site

morbidity. Cortical bone, such as that collected from the calvarium, has fewer

incidences of resorption but a slower revascularization rate for the graft than cancellous

bone.[172]

Allografts are most frequently used today during corticotomy procedures due to

ease of use, accessibility, and elimination of donor site morbidity. Despite having only

osteoconductive and potential osteoinductive properties, studies in the orthopedic and

oral surgery literature document positive outcomes with the use of allografts. Allografts

are usually harvested from human cadaveric bone, but may also be derived from live

human donors and can be prepared as fresh, frozen, freeze-dried, mineralized, and

demineralized. Following harvesting, grafts are processed via different means such as

physical debridement, ultrasonic washing, ethylene oxide or gamma irradiation

treatment, antibiotic washing, and freeze-drying to ensure no diseases are transferred to

the recipient. The manner in which the graft is processed determines the extent of its

osteoinductive properties. For example, demineralization of the freeze-dried bone more

readily exposes bone morphogenic proteins, or BMPs, within the bone.   BMPs are the

group of factors responsible for bone formation. They promote recruitment of

mesenchymal cells, chondroblast differentiation, cartilaginous formation, vascular

invasion, and finally bone formation.[173] Therefore, freeze-dried bone (FDB) is primarily

osteoconductive, whereas demineralized freeze-dried bone (DFDB) provides

osteoinduction in addition to an osteoconductive scaffold.[174, 175] For this reason, the most commonly used type of allograft for the post-corticotomy augmentation procedure is demineralized freeze-dried bone allograft (DFDBA).

Xenografts are derived from the inorganic portion of bone of a genetically different species than the host. The most commonly used xenograft is bovine bone. After being harvested, this bone undergoes complete deproteination by high temperature processing (1000°C), thus eliminating all risk of eliciting an immune response by the recipient.[172] The resulting crystalline structure closely matches human cancellous bone. In 1992, a study by Klinge et al[176] was conducted to analyze bovine graft incorporation at the grafting site. By 14 weeks, total resorption of the graft had taken place with subsequent new bone formation in its place.

Alloplasts are synthetic variants used as bone substitutes and include various combinations of hydroxyapatite and β-tricalcium phosphate, bioactive glasses, porous hydroxyapatite, calcium sulfate, and calcium carbonate. Since these materials contain no bioactive proteins, only osteoconductive properties are available for new bone growth.[171] The main disadvantage of alloplasts is the lack of osteoinductive power offered by autografts and certain allografts.

The physical and chemical properties of graft materials play an important role in the rate of resorption and replacement by new bone.[177] Bone grafts are expected to be incorporated into the recipient site. This first involves the bony union between the edges of the graft and native bone segments followed by the gradual resorption of the graft material itself with concomitant replacement by new bone.[178,179] The time to and

41

amount of incorporation into host bone depends on numerous variables. Factors such as graft type, particle size, porosity, crystallinity, element impurities, processing method, and the pH of surrounding tissues all play a role in the resorption rate. For instance, the larger the particle size, the longer the material will remain at the site of augmentation. Also, a cortical graft may never be fully resorbed due to incomplete vascular penetrance into the tightly packed lamellar bone. Because of the great variability in grafting materials, it is difficult to definitively define an exact time to full graft resorption and bone replacement. One study showed that within 8 weeks, most of the graft has been remodeled.[180] However, another study reported the presence of grafting granules even after 44 months.[181] Despite the range in numbers, most of orthopedic and dental literature agrees that the majority of cancellous bone graft replacement occurs in 3-4 months.

The process of incorporation of new bone within the implanted grafting material is biologically similar to that of normal bone healing, with a reactive, reparative, and remodeling phase. Like long bone healing, adequate blood supply and stability are crucial for graft survival, and periosteal preservation has been documented to enhance incorporation of the graft.[182] Urist first described the five stages of graft incorporation in 1976.[183] Stage one, the inflammatory stage, immediately follows bone grafting. A blood clot forms to stop the bleeding. Necrosis of the graft occurs and a subsequent inflammatory response is established. During the second stage, the osteoblast stage, platelet derived growth factor attracts lymphocytes, plasma cells, osteoblasts, and polynuclear cells. Granulation tissue then forms with an ingrowth of capillary buds

bringing macrophages and mesenchymal cells. A fibrovascular stroma develops with an influx of osteogenic precursors and blood vessels. Osteoblasts and osteoclasts are stimulated and the osteoclasts initiate graft resorption. Stage three is the osteoinductive stage, whereby mesenchymal cells differentiate into osteoblasts and new bone is laid down by endochondral ossification. Next is the osteoconduction stage, during which the graft serves as a passive template for ingrowth of vascular and cellular activity. Lastly, stage five is the remodeling stage where final incorporation and remineralization occurs. It is important to recognize that these final three stages are closely entwined and occur simultaneously during graft healing.

In the grafting procedure known as guided bone regeneration, a resorbable or non-resorbable membrane is used as a mechanical barrier to stabilize particulate graft material while simultaneously maintaining space around the bony defect to discourage in-growth of soft tissue at the osseous healing site. A graft has the potential to lose up to 25% of its volume after 4 months when a membrane is not used.[184] In general, both resorbable and non-resorbable membrane materials are equally effective in attaining adequate bony defect fill, but the use of a resorbable membrane does not require a second removal surgery.[185, 186] In a systematic review of bone replacement grafts used in the treatment of intrabony periodontal defects, increases in bone level and in clinical attachment levels, as well as decreases in probing depths were found, when compared to simply open flap.[187] Additionally, when compared to grafting alone, grafting with a barrier membrane increases clinical attachment level and decreases probing depth.[187]

Traditionally, particulate bone grafts are used in dentistry to fill bony defects or gain additional bone height and/or width. Jensen and Terheyden[188] reported a mean increase in horizontal and vertical dimensions of 2.6 mm and 3.6 mm, respectively, following the guided bone regeneration technique. There is no consensus in the literature, however, on the biological events that take place after grafting with DFDBA. Smukler et al[189] demonstrated the presence of residual DFDBA particles within a network of newly bone formation. They concluded that it may take many months or years for complete particulate resorption and total replacement by new bone. Scheyer et al,[190] however, used guided tissue regeneration to preserve alveolar ridge width after tooth extraction. Bone core samples were histologically analyzed at weeks 6, 12, and 24 after bone augmentation. While localized woven bone and nonmineralized osteoid was present at week 6, they observed mostly regenerated new woven bone by week 12 with continued maturation at week 24.

In 2001, Wilcko et al. introduced the notion of using the afore-mentioned particulate bone grafts following a corticotomy procedure.[6] The case report described a patient with severe maxillary transverse constriction whose premolars were expanded over 3 mm. The authors claimed an increase in the buccolingual thickness of the cortical bone. A bone biopsy taken two years post-retention qualitatively revealed the presence of lamellar bone. Later, in 2008, Nowzari et al[191] published the first case report using autogenous particulate bone as the grafting material after a corticotomy procedure. One year after treatment was complete, the surgical sites were reentered and a visual report of both resorption and remodeling of the particulate material grafted from the patient's

mandibular ramii and lingual exostoses was described. They claimed no loss in alveolar height.

Since the Wilckos' first augmentation procedure with corticotomies, many others are also using bone grafting to supposedly build bone. To date, Shoreibah et al[146] has conducted the only study comparing corticotomies with and without bone augmentation. One aim of their study was to evaluate the effect of bone grafting on the periodontium. Using bioactive glass as their grafting material of choice, they sought to assess bone density in patients receiving either corticotomies or corticotomies with bone grafting. Measurements of bone density were obtained through calculation of mean gray value with DBSWIN software in an area of interest on periapical radiographs. As expected, they found a mean decrease in bone density following the corticotomy surgery. By 6 months post-treatment, a significantly greater percent increase in bone density was discovered in the group receiving bone augmentation. When comparing the groups from the start of orthodontic treatment and six months into retention, however, no significant differences in bone density changes could be noted. Again, using periapical radiographs to measure bone density is not accurately quantified, nor does it provide clear information on the condition of the grafted bone.

No studies have analyzed the biological results of bone grafting with corticotomies to assess the amount of new bone formation and incorporation of vital host bone into the grafted site, if any, after expansion has been performed. Grafting of this type is unique in that it is not typically used to fill a current defect, but rather prevent a defect from occurring in the form of a dehiscence. It is crucial to understand what is

happening within the graft itself. Is there actual host-graft union? Is there blood flow into the graft, creating viable tissue that is usable by the orthodontist? Or is the increase in density simply due to the presence of osseous material that is discontinuous from the host?

SIGNIFICANCE

Orthodontic research in the area of corticotomies has been driven by current clinical treatment instead of sound research leading to proven treatment modalities. No studies to date have assessed slow, buccal archwire expansion after flap elevation and corticotomies using histology and micro-computed tomography. Nor have there been any studies analyzing the effects of additional grafting over the corticotomy sites. Micro-CT is advantageous over other methods in assessing the quality and quantity of newly formed bone because it allows for a more complete, non-destructive three-dimensional representation of the specimen.[192] An understanding of the biological processes that occur during corticotomy-facilitated slow dental expansion with and without osseous grafts will provide knowledge and insight on current expansion techniques, as well as influence future treatment protocol. This will allow information and research to guide the advancement of clinical orthodontic techniques.

The popularity of corticotomies as an adjunct to traditional archwire expansion has given rise to a number of questions. Are there similarities between expansion with archwires alone and that produced with archwires and corticotomies? If detrimental

effects do occur during archwire expansion with corticotomies, does the inclusion of additional grafted bone aid in limiting these deleterious effects?

Therefore, the purpose of this study is to compare corticotomy treatment with and without grafting material to illuminate regional differences in bone maturation with micro-computed tomography, histology, and histomorphometry. In addition, we will analyze buccal tooth movement biomechanics to elucidate unsubstantiated claims about more bodily tooth movement through bone with corticotomy procedures, as well as assess the outcome on surrounding soft tissues.

CHAPTER II

ANALYSIS OF BONE AUGMENTATION WITH CORTICOTOMY-FACILITATED

DENTAL EXPANSION: A HISTOLOGIC & MICRO-CT STUDY

INTRODUCTION

With an ever-increasing number of adults seeking orthodontic treatment,

attaining the optimal final result may be difficult and time consuming. This is in part

due to a greater potential for adults to present with a compromised periodontal status,

slower cell mobilization, and slower collagen fiber conversion. [4, 5] In order to satisfy the

requests of this orthodontic population, new advances to decrease treatment time and

maximize esthetic demands, all while maintaining periodontal health, are becoming

more prevalent. One such treatment option that is being explored is the use of

corticotomies to supplement traditional orthodontic modalities.

Currently, however, there is little experimental support for the grafting procedure

presented by the Wilcko brothers. The fate of the grafting material remains unclear. Is

it actually incorporated into useful vital host bone? Or is the increased alveolar width

after grafting due to the presence of osseous material that is discontinuous from the

patient, and therefore is unusable by the orthodontist?

Therefore, it is the goal of this study to validate or refute the need for alveolar bone augmentation in conjunction with the corticotomy procedure to facilitate orthodontic expansion and to better grasp the biological events that are occurring within the graft itself. The effects on both the teeth and surrounding hard and soft tissues will be evaluated with histology, µCT, and study models. An understanding of the biological processes that occur during corticotomy-facilitated slow dental expansion with and without osseous grafts will provide knowledge and insight on current expansion techniques, as well as influence future treatment protocol. This will allow information and research to guide the advancement of clinical orthodontic techniques.

MATERIALS AND METHODS

Seven skeletally mature male beagle dogs, each between 9 and 12 months of age and weighing 21-25 lbs, were used in this experiment. The canine model was chosen because its periodontal ligament, tooth, root, and alveolar bone qualities are similar to those of humans.[193] The dog maxilla was used because its natural lateral concavity allows for the generation of a buccal force system. Housing, care, and experimental protocol were approved by and performed in accordance with the guidelines set forth by the Institutional Animal Care and Use Committee (IACUC) at Texas A&M University Baylor College of Dentistry. All of the animals were in good overall health with no systemic compromises, periodontally healthy, and had sound maxillary teeth.

Initial Records

Using a random number table generated electronically, each animal's maxilla was randomly divided into an experimental side (Graft +) and a control side (Graft -). Following 10 days of quarantine, initial records were taken and bone markers were placed. After 12 hours of fasting, animals were sedated with an intramuscular injection of Ketamine (8-24 mg/kg IM) mixed with Xylazine (0.22 mg/kg IM). The animals then received a dental prophylaxis using an ultrasonic scaler irrigated with 0.12% chlorhexidine gluconate. Two 6 mm long Imtec miniscrew implants (3M Unitek, Monrovia, CA) were placed in the midline of the palate just mesial and distal to the 2nd premolars to serve as stable references for superimposing radiographs and measuring tooth movements. After placement, the heads of the miniscrews were removed with a

metal cutting bur to the level of the palatal tissue for animal comfort. Inter-miniscrew

distance was measured with digital calipers and recorded for future radiographic

calibration.

Right and left periapical radiographs, as well as an occlusal radiograph, were

taken using a size 4 film. A holder was customized to stabilize both the film and the x-

ray tube at reproducible angulations and distances. To ensure repeatable caliper

measurements, small notches were drilled in the cusp tip of the canine, 2nd premolar, and

4th premolar using a mosquito shaped micro diamond bur (Brasseler USA, Savannah,

GA). Pre-treatment periodontal measurements were recorded, including probing depths

at the mesial, middle, and distal aspect of the buccal and lingual surfaces, as well as

gingival recession and attachment levels. Lastly, an alginate impression of the maxilla

was taken with a custom Triad TruTray (Dentsply Intl, York, PA) tray and the model

was poured using dental stone for appliance fabrication.

Appliance Design

Using the impressions and resulting models, appliances were designed based on

an established protocol.[194] Orthodontic band material (Dentaurum, Ispringen, Germany)

was custom formed and welded to fit the maxillary canines, 2nd premolars, and 4th

premolars. The inner surfaces of the bands were micro-abraded with 60-micron alumina

particles and several small perforations were made with a 0.25 round bur to aid in

retention. Molar brackets with a 0.022" slot size were welded and then soldered to the

bands. The 4th premolar bracket (3M Unitek, Monrovia, CA) had a 10° distal offset, -

14° torque, and a 0.045" headgear tube. The canine bracket had a 0° offset, 0° torque, and a 0.051" headgear tube. Damon Q maxillary premolar brackets (Ormco, Orange, CA) with a 0° offset and -11° torque were used on the 2nd premolar bands. Due to the more buccal position of the canine and 4th premolar, a buccal force vector was produced on the 2nd premolar when the archwire was engaged (Figure 1A&B).

Surgical Protocol

Following initial sedation with the Ketamine and Xylazine cocktail, the dogs were intubated and given 1%-1.5% Isoflurane in oxygen at 1 L per minute. Vital signs were monitored throughout. Local anesthetic was administered at the surgical sites via buccal and palatal regional infiltration of 2% Lidocaine with 1:100,000 epinephrine (Patterson Dental, St. Paul, MN). All procedures were performed under sterile conditions.

Corticotomies were performed on both sides of the maxilla. A full-thickness vestibular incision was made, extending from the mid-root level of the 3rd premolar to the mid-root level of the 1st premolar. Periosteum was removed apically to about 4 mm beyond the root apex and coronally to about 2 mm from the alveolar crest, resulting in a pocket for access for osseous cuts, bone graft material, and membrane placement (Figure 2A). Following flap reflection, a surgical pencil was used to demarcate the desired ossous cuts, and decortication was performed mesial and distal to the 2nd premolar. Using a piezsurgery unit (Piezosurgery Inc, Columbus, OH) equipped with a 0.55 mm thick OT7 osteotomy tip insert (Piezosurgery Inc.), vertical cuts were made mesial and

distal to the 2nd premolar roots, beginning 1-2 mm apical to the alveolar crest and extending about 2-3 mm apical to the root apex. A horizontal corticotomy connected the two vertical cuts at their apical extent (Figure 2B). All cuts extended through the buccal cortical bone and just into the medullary bone, so as to induce bleeding. Copious irrigation with sterile saline was utilized throughout the surgical procedures to avoid bone heating and necrosis.

Following the corticotomy procedure, the experimental side (Graft+) received bone grafting and a resorbable membrane was placed. The grafting material, 0.05 cc of demineralized freeze-dried human cortical bone allograft (Straumann USA, Andover, MA) with a particle size ranging from 250-1000 microns, was rehydrated as per manufacturer's protocol, placed and packed directly over the 2nd premolar root (Figure 2C). Care was taken to ensure that the grafting material was extended to the bordering corticotomies. Lastly, a Cytoplast RTM resorbable collagen membrane (Osteogenics Biomedical, Lubbock, TX) was measured to size and positioned over the graft (Figure 2D). Single interrupted 4-0 vicryl sutures were used to close the flap without excessive tension.

The dogs then received a single post-operative dose of Ketoprofen (1mg/kg IM). They were also given Nalbuphine (2mg/kg IM) once daily for two weeks, with additional doses given if needed for pain beyond two weeks. For prevention of post–operative infection, Clindamycin (11mg/kg IM) was administered twice daily for two weeks. Until the gingiva was healed, the dogs were given a daily rinse with 0.12%

53

chlorhexidine gluconate beginning the day of surgery. They were maintained on a soft diet for the duration of the experiment in order to prevent appliance breakages.

Appliance Placement

A twelve-fluted carbide bur was used to remove calculus and debris from the teeth and a retention groove was placed in each of the banded teeth with a 330 carbide bur. After etching with 37% phosphoric acid for 15-30 seconds, the appliance was cemented with light-cured RelyX Unicem (3M ESPE, St. Paul, MN) resin cement. Excess cement was removed with a scaler to prevent gingival irritation. A 0.045" stainless steel wire was placed passively through the headgear tubes of the canines and 4th premolars to protect the appliances. A 0.016" x 0.022" CuNiTi straight wire (Ormco, Orange, CA) was inserted in the archwire slots of the canine and 4th premolar brackets and then engaged into the depth of the lateral maxillary concavity into the 2nd premolar slot (Figure 1B). The ends of both wires were cinched, roughened, and bonded with composite for retention and comfort.

Expansion Protocol

After four weeks, the 0.016" x 0.022" CuNiTi straight wire was replaced with a 0.019" x 0.025" CuNiTi straight wire, which was maintained for an additional five weeks. After a total of nine weeks of active expansion, a 0.019" x 0.025" stainless steel wire was bent passively to ensure that no additional expansive forces would be

transmitted to the 2nd premolar. Passive consolidation with this stainless steel wire was continued for three additional weeks.

Fluorescent Bone Labels, Final Records and Sacrifice

To identify regions of bone remodeling, fluorochrome bone labels were administered intravenously at weeks 4 (Calcein, 10mg/kg; MP Biomedicals, Santa Ana, CA), 7 (Alizarin complexone, 20mg/kg; Alfa Aesar, Ward Hill, MA), and 10 (Calcein). All dyes were prepared immediately before use. After 12 weeks, the animals were injected with the previously described Ketamine and Xylazine cocktail and final records were obtained, including occlusal and periapical radiographs, caliper measurements, archwire force measurements, periodontal measurements, and impressions. Surgical plane anesthesia was then confirmed by checking reflexes. The animals were sacrificed by cannulating both common carotid arteries, severing the external jugular veins and injecting 2 cc Beuthanasia-D intracardially. Following cessation of heart function, 1.5 liters of saline followed by 1 liter of 70% ethanol was flushed through the cannulas. The maxilla was then harvested and stored in 70% ethanol.

Data Collection and Analysis

Data was collected by one investigator on five occasions: pre-surgically, on the day of surgery, and at weeks 4, 9, and 12 post-surgically (Figure 3).

Intraoral Measurements

At each occasion, three intraoral measurements were taken using the afore-mentioned notches on the teeth, including intercanine width, inter-2nd premolar width, and inter-4th premolar width, with a digital caliper (General Tools, New York, NY). Intraclass correlation of nine replicate measurements of intercanine, inter-2nd premolar, and inter-4th premolar width measurements ranged from 0.997 to 0.999.

Force levels at the 2nd premolar were also recorded after new archwire placement with a Correx force gauge (Haag-Streit, Switzerland). Each measurement was taken three times and averaged. Replicate analysis (n=20) for force produced an intraclass correlation of 0.996, indicating excellent reliability.

Radiographic Measurements

Occlusal radiographs were imported into ViewBox 4 (dHAL Software, Kifissia, Greece) and calibrated for size based on the known inter-miniscrew distance. A sagittal reference line was extrapolated, passing midway between the midpalatal implants. From this reference line, the perpendicular distances to experimental and control canines, 2nd premolars, and 4th premolars were measured. For the canines, the measurement was taken at the intersection of the band with the most medial aspect of the root. The 2nd premolars were measured at the intersection of the band with the most coronal part of the furcation, and the 4th premolars were measured at the intersection of the band with the middle of the pulp canal of the mesial root (Figure 4A). An intraclass correlation of 0.962 was observed for replicated (n=36) radiographic measurements.

To quantify tipping, the intital and final models were scanned using Ortho Insight 3D laser scanner and software (Motionview Software LLC, Hixson, TN). On each model, three landmarks were digitized bilaterally on 2nd premolars, including (1) the most occlusal midline point on the palatal rugae adjacent to the tooth of interest, (2) the most cervical point on the palatal aspect of the tooth of interest, taken at its mesiodistal center, and (3) the cusp tip of the tooth of interest. The angles formed after connecting the three points were recorded on both the pre- and post-movement models (Figure 4B), and tipping was calculated as their angular difference. All points and angles were plotted and measured twice on two separate days, then averaged. Replicate analysis (n=12) for tipping resulted in a strong intraclass correlation of 0.996.

Micro CT

The overlying soft tissue was removed and the maxilla was sectioned to produce blocks of bone approximately 27 mm wide that included the 1st, 2nd, and 3rd premolars. Vertically, these blocks were approximately 19 mm high, including at least 4 mm of bone beyond the apices of the teeth. Two blocks of bone were placed, apical sides first, into micro-CT tubes with an internal diameter of 27 mm. The specimens were separated and stabilized with foam, immersed in 70% ethanol, and firmly sealed with Parafilm (Pechiney Plastic Packaging Company, Chicago, IL) to prevent dehydration. The tubes were loaded into the Scanco Micro-CT 35 scanner (ScanCo Medical, Bassersdorf, Switzerland) and scanned at 30 μm resolution, 55 kVp voltage, 145 μA current, and 600 ms integration time.

Micro-computed tomographic scans were utilized to evaluate bone quality and quantity. Three-dimensional reconstructions of the block specimen, as well as two-dimensional slices (30 μm thick) were generated and analyzed using the Scanco Micro-CT v.6.0 software. In order to quantify the amount and density of bone, an additional 1 mm thick occluso-apically region of interest adjacent to the 2nd premolar was isolated and segmented. The region included the buccal cortical bone extending from 1 mm to 2 mm apical to the mesial root's apex. The segments ranged in length from 10 to 12 mm, depending on the mesial-distal width of the 2nd premolar. After the volumes of interest were defined, the grayscale images were smoothed by a Gausian filter with a sigma value of 0.9 and support value of 1. The threshold boundaries for the scans were set between 270 and 1,000 Hounsfield units for all specimens. Bone quantity was measured as material density (bone mass per unit volume, minus voids) and percent bone volume (ratio of number of bone voxels to total number of voxels within a specific region of interest).

The following linear measurements were derived from 2-D slices of both the Graft+ and Graft- 2nd premolars:

1. Buccal bone height (BBH), a measure of dehiscence, taken from the most lingual aspect of buccal bone at the level of the apex to the beginning of the dehiscence at the cervical margin of both the mesial and distal root.

2. Total tooth height (TTH), a measure of root resorption, taken from the cusp tip to root apex.

3. Total root height (TRH), a measure of root resorption, taken from the middle of each root from the level of the furcation to the apices.

Each measurement was performed twice on different days and averaged. Intraclass correlation for microCT measurements (n=12) was 0.99.

Histology

For histological analysis, the 1st and 3rd premolars were removed from the block specimens. Experimental (Graft +) and control (Graft -) 2nd premolars were evaluated as follows: specimens from two dogs (C and D) were submitted for analysis with fluorescence microscopy using an coronal orientation, specimens from one dog (E) was submitted for fluorescence microscopy using an axial orientation, and specimens from two dogs (F and G) were evaluated using traditional hematoxylin and eosin (H&E) stains sliced in a coronal orientation (Table I).

The specimens analyzed with fluorescence microscopy were fixed in 70% ethanol, dehydrated in graded alcohol, embedded in methyl methacrylate and allowed to polymerize. They were sectioned with an IsoMet diamond saw (Beuhler; Houston, TX) along the specified axis at a thickness of approximately 150 μm, then hand-ground to a thickness of 75-100 μm. After polishing, the slides were analyzed with a Nikon Eclipse 80i microscope at a magnification of x10 for evidence of fluorochrome triple labeling surrounding the 2nd premolar.

Specimens evaluated histologically with H&E were decalcified in EDTA, dehydrated in graded alcohol, cleared with xylene, then infiltrated and embedded in

paraffin. After sectioning the block with a microtome in the standardized orientation to a thickness of 5-10 μm, the sections were mounted to glass slides and stained with hematoxylin and eosin.

Statistical Analyses and Determination of Significance

Statistical analyses were performed using SPSS® 22.0 software (SPSS Inc.; Chicago, IL). With the exception of dental tipping, the data was normally distributed. Central tendencies and dispersions were therefore described with means and standard deviations. Due to a small sample size, nonparametric Wilcoxon signed rank tests were used for group comparisons to test for statistical significance. Significance was set at $p<0.05$.

RESULTS

Immediately following surgery, healing progressed normally with no significant swelling or tissue damage in any of the dogs. Five of the seven dogs had appliance failures during the 12-week experiment, with equal numbers of failures on the experimental (n=7) and control (n=7) sides. All necessary repairs were performed within 24 hours of appliance breakage (Table II).

Tooth Movements and Forces

Caliper measurements showed that inter-2nd premolar width significantly increased 5.24 mm (p=0.002) during the 9 weeks of active expansion, and decreased 0.24 mm during the consolidation period, for a total of 5.0 mm expansion (Figure 5). Inter-canine width decreased 2.04 mm during active expansion, and decreased an additional 0.69 mm during consolidation, for a total decrease of 2.73 mm (p=0.001). Inter-4th premolar width decreased 0.18 mm, followed by a 0.39 mm increase during consolidation, resulting in a total expansion of 0.57 mm (p=0.017).

Radiographically, the canines on the Graft+ and Graft– sides constricted 0.58 mm (p=0.009) and 0.79 mm (p=0.004), respectively, by the end of consolidation (Figure 6A). Graft+ and Graft- 2nd premolars were laterally displaced 1.66 mm (p=0.002) and 1.65 mm (p=0.001), respectively (Figure 6B). Graft+ 4th premolars constricted 0.56 mm (p>0.05), while the Graft– 4th premolars expanded 0.26 mm (p>0.05) (Figure 6C). At the end of consolidation, no significant differences in expansion were observed between Graft+ and Graft– sides for the canines, 2nd premolars, or 4th premolars (Table III). The

peak rate of 1.2 mm/week of tooth movement occurred at week 4. Over the 12 weeks,

the Graft+ and Graft- 2nd premolars tipped 1.7° and 3.7°, respectively, with no

significant difference between the two sides (Figure 7).

The initial force applied by the 0.016" x 0.022" CuNiTi archwire to the 2nd

premolar was 138 ± 12.38 grams. By 4 weeks, this force derogated to 68 ± 8.02 grams,

at which time the 0.019" x 0.025" CuNiTi was placed, delivering a force of 170 ± 9.7

grams. The average force at the end of active expansion was 75 ± 8.2 grams.   The final

0.019 x 0.025" ss archwire was bent passively into the archwire slot of the 2nd premolar

so that no force was applied during consolidation (Figure 8).

Periodontal Measurements

No pre-treatment differences existed between Graft + and Graft – sides for any of

the periodontal measurements, including recession, probing depth, or clinical attachment

level. Most of the pre- to post-experimental periodontal changes showed no significant

changes between sides. The distolingual probing depth on the canine showed the only

significant (p=0.038) side difference (Table IV).

MicroCT

The 3-dimensional reconstructions showed dehiscences over both the mesial and

distal roots of the 2nd premolars on all 14 specimens (Figure 9). The dehiscences on the

Graft+ side were generally less extensive (i.e. did not extend the entire mesiodistal width

of the tooth root) than those on the Graft– side. The mesial roots on the Graft+ side had

significantly (p=0.038) greater buccal bone heights (BBH) than the mesial roots on the Graft- side (2.3 ± 2.5 mm vs 0.1 ± 0.2 mm, respectively). The BBHs of the distal roots for the Graft+ (0.75 ± 1.25 mm) and Graft− (0.51 ± 1.17 mm) sides were not significantly different (p=0.5) (Table III). The Graft+ side showed significantly (p=0.029) more buccal bone loss over the distal root than mesial root; the Graft− side showed no differences.

Post-experimental total tooth height (TTH) and total root height (TRH) showed no statistically significant differences between the Graft+ and Graft− sides, indicating no significant difference in the amount of apical root resorption (Table III). However, lateral root resorption, especially on the buccal root surfaces, was evident on both Graft+ and Graft− sides (Figures 10A-B, 15A-B).

Mineralized particulate graft material was visible along the root surface of 6 of the 7 Graft + specimens (Figure 9). Bone on the Graft+ side was significantly (p=0.028) more dense (mg HA/cm^3) than the bone on the Graft− side. There was no statistically significant side difference in cortical bone volume fraction (BV/TV) (p=0.6) (Table III).

Histology

H & E sections showed the presence of graft material from the most coronal extent of buccal bone to beyond the apex of the Graft+ 2nd premolar roots (Figures 11A-B). Particles were surrounded by host bone, and buccal bone thickness was greatest at the apical aspect of the root, where larger graft particles were visible. The remnants of graft particles appeared as compact bone with empty lacunae where osteocytes once were (Figure 12A).

Immediately adjacent to the graft, new woven bone had been laid down and osteocytes were evident within the calcified tissue. The buccal bone had osteoblasts lining the periosteal surface and mature multinucleated osteoclasts on the endosteal, or PDL surface (Figure 12B). Within the PDL, collagen fibers appeared stretched and disrupted on both the apical aspect of the buccal bone and the coronal aspect of the lingual surfaces, with numerous Sharpey's fibers insertions. Despite these areas of tension, the width of the PDL remained constant along its corono-apical extent.

The Graft– side demonstrated minimal to no buccal bone, only gingival fibers running parallel to the tooth root (Figures 13A-B). The lingual aspect of the Graft – sides showed islands of new bone and no major osteoclastic activity (Figure 13C). On both the Graft+ and Graft– sides, sites of dehiscence were characterized by a merging of collagen fibers and fibroblasts of the PDL and periosteum.

The Graft+ side showed more fluorescence, indicating a greater rate of bone turnover, than the Graft– side. New buccal bone formation was visible along the grafted region (Figure 14A). Distinct and consistent calcein and alizarin label lines were evident

on the periosteal surface buccal to the tooth roots, extending along the entire length of buccal bone. At the most buccal surface, concentric rings of fluorescence, indicating calcification, surrounded graft particles. An area of mixed, indistinct fluorescence was evident on the periosteal surface where graft was being incorporated (Figure 14B). Bone deposition was also clearly evident as wide bands of fluorescence on the PDL side of the lingual cortical bone at the most coronal 3/4 of the alveolus; the apical ¼ showed minimal to no bone turnover.

Root resorption was evident on both Graft+ and Graft– sides. The location of the root resorption was consistent, occurring predominantly at the mesiodistal center and in the apical 2/3 of the roots (Figures 15A-B).

DISCUSSION

The overall amount of archwire expansion that occurs with corticotomies is not affected by the presence of particulate graft material, despite having an added volume of bone for the tooth to travel through. After the 12-week experiment, both the Graft+ and Graft– 2nd premolars were buccally displaced similar amounts, whether measured radiographically or intraorally. The finding that newly formed bone does not impede tooth movement supports animal studies investigating mesiodistal orthodontic tooth movement through grafted bony defects.[195-197] Two studies have reported significantly greater tooth movements immediately adjacent to the graft site than on the non-grafted side of induced defects after immediate force application.[198, 199] In contrast, augmentation after corticotomies is separated from the moving tooth by host medullary and cortical bone. The pre-existing bone could be the determining factor in expansion, not the presence or absence of graft material.

The rates of tooth movement were slightly greater than expected. Peak rates of 1.2 mm per week were observed. Previous dog studies demonstrate slower rates of tooth movement with conventional orthodontics, ranging from approximately 0.75 mm[140] to 1 mm[138,141] per month for mesiodistal tooth movements, and 1 mm per month for lateral tooth movements.[194] These studies, however, did not include corticotomies. The majority of studies evaluating corticotomies in dogs have reported a 2-4-time increase in mesial-distal tooth movements.[94, 138, 140, 141] On that basis, approximately 2-4 mm of

tooth movement per month, or 0.5-1 mm per week would be expected. In a recent investigation of flapless corticotomies using the same appliance design, the peak rate of tooth movement was 1.3 mm per week, which is comparable to the amount attained in the present study.[200]

Peak rates of lateral tooth movements appear to occur later than peak rates of mesiodistal movements. Peak rates were observed around week 4 in the present study, which is somewhat later than the 2-3 week peaks described for traditional corticotomies.[94, 140, 141] The difference is probably related to the type of bone that the teeth are being moved through. As opposed to mesiodistal tooth movements through medullary bone, expanded teeth encounter greater resistance from the more dense and less vascular cortical buccal bone.[201, 202] Therefore, modeling would be expected to occur at a slower rate, causing peak tooth movements to occur later. It is also possible that the RAP effect on the buccal bone was not as pronounced as in previous studies due to the location of the surgical cuts. During mesiodistal tooth movement, the root travels directly through the corticotomy site and may have resulted in a more pronounced osteopenic response and sooner peak tooth movement. Rusó et al,[200] who also moved teeth in a buccal direction, showed that peak rates occurred at week 5. The one-week difference in peaks (4 weeks vs. 5 weeks) may be due to their lack of flap elevation. Since their study indicated less of an effect on tooth movement when compared to corticotomies performed with a full-thickness flap, and since the magnitude of a RAP effect is proportional to the amount of the surgical insult,[143] it is possible that the flap

elevation of our study attributed to a slightly sooner peak in tooth movement.

Although corticotomies enabled greater amounts of archwire expansion initially, the overall amount of expansion that occurred post-treatment was not greater than archwire expansion obtained without corticotomies. In the present study, the majority of tooth movements occurred during the first 4 weeks of active expansion, when the 16x22 CuNiTi wire was in place. The force level from this wire decreased from 138 grams to 68 grams, and about 2.1 mm of expansion occurred per side. The subsequent 5 weeks of active expansion with the 19x25 CuNiTi resulted in insignificant amounts of tooth movement. This pattern is different than the one observed without corticotomies. For example, Kraus et al[194] showed that the majority of expansion occurred with the 19x25 CuNiTi between weeks 4-9. They found only approximately 1 mm of tooth movement during the first month of expansion. This suggests that corticotomies increased the initial velocity of lateral expansion. However, the overall amount of expansion post-treatment was not greater and may be accounted for by the archwires. Once deflection has been fully expressed, no additional tooth movement can be achieved, regardless of treatment with or without corticotomies.

It is important to note that efforts were made to minimize uncontrolled tipping of the 2nd premolars. A 19x25" wire in brackets with -11° torque was utilized, and the application of force was as close to the center of resistance as possible. This partially explains why only limited and statistically insignificant amounts of tipping occurred.

Histology showed a relatively uniform band of calcein, administered at week 4 (i.e. during the greatest rate of tooth movement), along the coronal ¾ of the lingual surface of the expanded premolar root. When teeth have been tipped, apposition is usually only evident at the cervico-palatal trailing edge of the tooth.[194] Tipped teeth also exhibit abundant osteoclasts at the apico-palatal aspect of the tooth,[194] which was not the case in the present study. Substantially greater amounts of tipping (7°-15.8°) usually occur in self-ligating systems.[194,80,203] One study using beagle dogs showed buccal tipping of premolars between 16-27°.[204] Even with full-size rectangular wires, some tipping is inevitable due to the inability to approximate the center of resistance within the bone and the existence of working tolerances between the bracket slot and archwire (approximately 12° with a 19x25" wire in a 0.022" slot size). However, since treatment with corticotomies evokes a period in which bone density is less,[205] it is possible that the decreased amount of tipping in this study was partially due to the decreased resistance of buccal bone.

Dental expansion with continuous forces after corticotomies, whether performed with or without bone augmentation, increases the risk of lateral root resorption. Apical cemental repair and lateral root resorption were evident on both sides of the maxilla (Figure 14). Root resorption is a process that occurs in response to hyalinized areas within the periodontal ligament.[206] The resorptive lesions in this study were found almost exclusively in the mesiodistal middle 1/3 of the buccal root surfaces. The PDL is thinnest in this area, which explains the increased hyalinization.[207] Buccal lateral root

resorption similar to that found in the present study has also been documented in past animal studies, both with and without corticotomies.[143, 194, 195, 208, 209] Interestingly, while the magnitude of force does not have an effect on the amount of root resorption, the type of force does.[208, 210] Having periods of inactivation, intermittent forces can prevent the formation or allow for reorganization of hyaline within the periodontal tissues, thus reducing root resorption. Continuous forces, like those used in this study, produce more severe root resorption than intermittent forces.

Bone augmentation in conjunction with corticotomies resulted in less dehiscence formation than corticotomies alone, despite similarities in the amounts of tooth movement and tipping that occurred. There was approximately three times as much root coverage by bone on the Graft + than Graft - side. Unfortunately, the available literature on dehiscence elimination via hard tissue grafting primarily pertains to defects that have already formed. For example, inadequate alveolar bone width often results in dehiscence-type defects in the buccal bone after implant placement. Successful reduction of close to 90% of these defects has been reported after treatment with bone grating and resorbable membranes.[211-213] While case reports support the use of guided tissue regeneration to reduce or eliminate bony defects in post-orthodontic patients,[214-216] little evidence exists regarding pretreatment augmentation to prevent dehiscence formation. In the context of the present study, alveolar bone augmentation decreased the potential for dentoalveolar deficiency during lateral tooth displacement.

Although the graft material aided in reinforcing the buccal bone during lateral expansion, it did not eliminate dehiscence formation. Buccolingual tooth movements beyond the confines of the alveolar housing, whether accidental or planned, can lead to bony dehiscence.[217] Once the expanded root surface is denuded of cortical bone, repair will occur if the tooth has been moved back into cancellous bone.[218] To prevent dehiscence formation, Wilcko et al[169] hypothesized that corticotomies with bone augmentation induce a state of transient demineralization, whereby buccal bone can be carried along with an expanded tooth root, a process known as "bone matrix transportation", thus allowing for the root to exceed the anatomical limit of the alveolar cortex. A recent study by Lee et al,[204] however, suggests that it is the augmentation procedure itself that actually builds new bone beyond the resorbed cortical bone to prevent dehiscences. Remarkably, the development of buccal bone defects does not seem to be a factor of the amount of expansion, as the animal with the most tooth movement (7.5 mm inter-premolar change) also demonstrated the greatest amount of bone apposition.

Loss of particulate graft may have played an integral role in the dehiscence formation. In the present study, greater amounts of new bone were evident at the apical than coronal region of the tooth. Past research has demonstrated that soft tissue compression can lead to graft displacement and a decrease in the volume of the membrane-protected area.[219-222] Pitaru et al,[223] for example, reported bone graft material loss due to relatively rapid degradation of the coronal portion of the collagen membrane.

This can occur from breakdown of the material after the immediate post-surgical inflammatory response, or from salivary enzymes. It is therefore possible that the collagen membrane used in the present study did not provide sufficient rigidity to withstand concomitant pressure from the tipping tooth and the attached gingiva in the coronal region. Investigation into the use of an alternative membrane, such as a resorbable reinforced membrane, to maintain the space for bone regeneration after corticotomies should be conducted.

Perhaps most importantly, the present study is among the first to demonstrate new bone growth along the buccal cortex after corticotomy-assisted orthodontics. Histology showed that the demineralized freeze-dried cadaveric particulate graft was incorporated into woven and mature lamellar bone on the periosteal surface of buccal bone. Similarly, fluorochrome labeling demonstrated substantial bony apposition adjacent to the graft sites over the 2nd premolar roots. Buccal bone apposition has previously been shown to occur in both canine[194] and human[31] models with conventional orthodontic force application. MicroCT evaluation of the buccal bone overlying adjacent, untouched teeth in the present study revealed that it was quite thin and did not exceed 1 mm. Given that the 2nd premolar was expanded well beyond 1 mm, any bone remaining during the post-treatment evaluation would have either been due to alveolar bone bending, new bone growth, or a combination thereof. While it is clear in the present study that graft particles themselves allowed for osteoconduction, with concentric rings of bone having been laid down, apposition may have also been, in part,

due to alveolar bone bending.[65, 68] DeAngelis[224] suggested that alveolar distortion stimulates a cascade of biological processes, including alteration of the electric environment attributed by piezoelectricity of the bone. As a result of the localized stresses, microstrains levels may rise to an optimal level that promotes bone maintenance, or even growth.[71, 74] Future research must be conducted to investigate whether the origin of the newly formed buccal bone discovered in the present study is from the graft material alone, or whether inherent bone growth as a result of orthodontic stimulation also plays a role.

Bone density is greater when corticotomies are supplemented with bone grafting than when performed alone. Besides radiographic evaluation,[161] no direct quantification of bone density after grafting with corticotomies has been previously documented. The presence of grafting material in the present study had a direct effect on bone density; significantly greater material density of cortical bone was evident in the region of interest on the grafted than the non-grafted side. There was no difference in bone volume fraction (BV/TV). Compared to adjacent native bone, core samples of grafted bone have been shown to exhibit a lower bone volume fraction, but no significant difference in bone density.[225] The difference could be due to the combination of host bone with graft material. By 12 weeks, mature lamellar bone forms in the graft site, [226] and bone mineral density continues to steadily increase for at least 52-weeks.[227] Since corticotomies induce less BV/TV and less bone density when compared to native bone,[200, 228] it can be assumed from the present study that bone augmentation plays a role

in increasing the bone density after corticotomies.

Corticotomies performed with and without bone grafting do not have a detrimental effect on the surrounding soft tissues. While osseous defects were created, no corresponding periodontal attachment loss occurred around the 2nd premolar. Lee et al[204] also reported maintenance of periodontal tissue integrity after corticotomies with bone grafting, with only a 0.4 mm increase in pocket depths. Although statistically significant, this minimal increase was not regarded as clinically relevant. The probing depths and levels of the gingival margin did not reflect the underlying osseous destruction in the present study. Similarly, a sample of patients evaluated by Löst[229] had an average dehiscence depth of 5.43 mm, and probing depth of only 1.38 mm. The normal probing depth is attributed to the presence of a long junctional epithelial attachment to the root's cementum. Additionally, animal studies conducted in both monkey[230] and dog[231] models suggest a link between maintenance of periodontal attachment levels and orthodontic tooth movement through intrabony defects when inflammation is well controlled. In the present study, strict plaque-control regiments were followed to ensure no damaging effects to the gingiva after corticotomies.

Clinical Implications

Many patients seeking orthodontic treatment are pre-disposed to buccal bone defects. Anthropologic data shows a positive correlation between thin alveolar bone and the presence of dehiscences and/or fenestrations.[232] In fact, Evangelista et al[233] found that over 50% of all teeth exhibit some degree of dehiscence before orthodontic

treatment is even initiated. Hyperdivergent patients, in particular, have a greater

predilection towards pre-treatment dehiscences.[234]

The procedure used in this experiment was designed to preserve the surrounding

periodontium while increasing the clinical efficacy of buccal tooth movement.   While it

is clear that new buccal bone growth is possible after corticotomies in conjunction with

bone augmentation, the volume of new bone was not necessarily adequate to compensate

for the extent of tooth movement and many unknowns still remain. Previous studies

have indicated the possibility for buccal bone apposition over an expanded tooth,

whether performed with or without corticotomies.[194, 200, 235] However, a significant

limitation of the present study was due to the amount of dehiscences, contributing to the

inability to perform sufficient histologic comparisons. It is possible that there was

apposition on the periosteal side of the Graft- buccal cortex, but it occurred at a slower

rate than the tooth was displaced. The same concept can be applied to a lesser degree

the Graft+ side, whereby the expanding tooth root outpaced much of the new bone

formation. We may, therefore, need to reconsider immediate tooth movement until the

graft is able to fully integrate. Doing so, however, would not take full advantage of the

RAP effect. Additionally, a lesser force than was used may be necessary to achieve

expansion of the maxillary 2nd premolars with no bone loss. Until there is a more

thorough understanding of the optimal force system, grafting technique, membrane

material, and biological mechanisms involved, the positive outcome of new bone growth

and maintenance of attachment level must not be misinterpreted as a justification for clinical utilization of the augmented corticotomy technique for buccal expansion. Additional research is needed to determine the requirements for adequate graft incorporation so that the negative consequences of the procedure (ie dehiscence formation) can be prevented.

Furthermore, long-term follow-up studies of patients treated with this procedure must be performed. It may be that there is an inherent inability to form and maintain new bone, regardless of graft placement, because the patient's alveolar process is in a state of physiologic equilibrium. Since the stress and strains placed on the bone determine the morphologic characteristics of the bone, and since placement of a graft does not alter the patient's function (i.e. no changes in masticatory forces occur), one might expect that building new buccal bone cannot be maintained due to disuse.

CHAPTER III

CONCLUSIONS

From the present study, we can conclude that:

1. Archwire expansion after corticotomies resulted in similar amounts of tooth movement, whether grafting was or was not performed.

2. Although tipping was controlled, all of the teeth demonstrated bony dehiscence over both roots, with ~30% less bone loss occurring in the Graft+ than Graft- group.

3. Corticotomies with bone augmentation was associated with more dense buccal bone than corticotomies alone.

4. After corticotomy-facilitated dental expansion, grafted bone was evident within host bone, with more new bone formation occurring apically than coronally.

5. Soft tissue was not detrimentally affected by corticotomies.

6. Resorption of the tooth roots occurred at the portion in closest proximity to the cortex during expansion.

REFERENCES

1.   Proffit WR, Fields HW, Jr., Moray LJ. Prevalence of malocclusion and orthodontic treatment need in the United States: estimates from the NHANES III survey. Int J Adult Orthodon Orthognath Surg 1998;13:97-106.

2.   O'Connor BM. Contemporary trends in orthodontic practice: a national survey. Am J Orthod Dentofacial Orthop 1993;103:163-70.

3.   Weintraub JA, Vig PS, Brown C, Kowalski CJ. The prevalence of orthodontic extractions. Am J Orthod Dentofacial Orthop 1989;96:462-6.

4.   Matthews D, Kokich VG. Managing treatment for the orthodontic patient with periodontal problems. Seminars in Orthodontics 1997;3:21-38.

5.   Ong MM, Wang HL. Periodontic and orthodontic treatment in adults. Am J Orthod Dentofacial Orthop 2002;122:420-8.

6.   Wilcko WM, Wilcko T, Bouquot JE, Ferguson DJ. Rapid orthodontics with alveolar reshaping: two case reports of decrowding. Int J Periodontics Restorative Dent 2001;21:9-19.

7.   Brunelle JA, Bhat M, Lipton JA. Prevalence and distribution of selected occlusal characteristics in the US population, 1988-1991. J Dent Res 1996;75 Spec No:706-13.

8.   Peck S. A biographical portrait of Edward Hartley Angle, the first specialist in orthodontics, part 1. Angle Orthod 2009;79:1021-7.

9.   Peck S. So what's new? Arch expansion, again. Angle Orthod 2008;78:574-5.

10.   Proffit WR, Fields HW, Jr., Sarver D. Contemporary Orthodontics, Fourth Edition. St. Louis, Missouri: Mosby Elsevier; 2007.

11.   Tweed CH. The diagnostic facial triangle in the control of treatment objectives. Am J Orthod 1969;55:651-7.

12.   Johnson DK, Smith RJ. Smile esthetics after orthodontic treatment with and without extraction of four first premolars. Am J Orthod Dentofacial Orthop 1995;108:162-7.

13.	Boley JC, Pontier JP, Smith S, Fulbright M. Facial changes in extraction and nonextraction patients. Angle Orthod 1998;68:539-46.

14.	Rushing SE, Silberman SL, Meydrech EF, Tuncay OC. How dentists perceive the effects of orthodontic extraction on facial appearance. J Am Dent Assoc 1995;126:769-72.

15.	Dewel B. The Case-Dewey-Cryer extraction debate: a commentary. Am J Orthod 1964:220-30.

16.	Witzig J, Spahl T. The clinical management of basic maxillofacial orthopedic appliances. Littleton, Mass: PSG Publishing; 1986.

17.	Drobocky OB, Smith RJ. Changes in facial profile during orthodontic treatment with extraction of four first premolars. Am J Orthod Dentofacial Orthop 1989;95:220-30.

18.	Luppanapornlarp S, Johnston LE, Jr. The effects of premolar-extraction: a long-term comparison of outcomes in "clear-cut" extraction and nonextraction Class II patients. Angle Orthod 1993;63:257-72.

19.	James RD. A comparative study of facial profiles in extraction and nonextraction treatment. Am J Orthod Dentofacial Orthop 1998;114:265-76.

20.	Conlin RT. Finished cases and their faces. J Clin Orthod 1989;23:751-5.

21.	Stephens CK, Boley JC, Behrents RG, Alexander RG, Buschang PH. Long-term profile changes in extraction and nonextraction patients. Am J Orthod Dentofacial Orthop 2005;128:450-7.

22.	McNamara J. Orthodontics: Current Principles & Techniques. St. Louis, Missouri: Elsevier Inc; 2005.

23.	Haas AJ. Palatal expansion: just the beginning of dentofacial orthopedics. Am J Orthod 1970;57:219-55.

24.	Haas AJ. Long-term posttreatment evaluation of rapid palatal expansion. Angle Orthod 1980;50:189-217.

25.	Brin I, Ben-Bassat Y, Blustein Y, et al. Skeletal and functional effects of treatment for unilateral posterior crossbite. Am J Orthod Dentofacial Orthop 1996;109:173-9.

26. Kluemper GT, Beeman CS, Hicks EP. Early orthodontic treatment: what are the imperatives? J Am Dent Assoc 2000;131:613-20.

27. Pirttiniemi P, Kantomaa T, Lahtela P. Relationship between craniofacial and condyle path asymmetry in unilateral cross-bite patients. Eur J Orthod 1990;12:408-13.

28. Piancino MG, Talpone F, Dalmasso P, et al. Reverse-sequencing chewing patterns before and after treatment of children with a unilateral posterior crossbite. Eur J Orthod 2006;28:480-4.

29. Vajaria R, BeGole E, Kusnoto B, Galang MT, Obrez A. Evaluation of incisor position and dental transverse dimensional changes using the Damon system. Angle Orthod 2011;81:647-52.

30. Fleming PS, Lee RT, Marinho V, Johal A. Comparison of maxillary arch dimensional changes with passive and active self-ligation and conventional brackets in the permanent dentition: a multicenter, randomized controlled trial. Am J Orthod Dentofacial Orthop 2013;144:185-93.

31. Moore T, Southard KA, Casko JS, Qian F, Southard TE. Buccal corridors and smile esthetics. Am J Orthod Dentofacial Orthop 2005;127:208-13; quiz 61.

32. Martin AJ, Buschang PH, Boley JC, Taylor RW, McKinney TW. The impact of buccal corridors on smile attractiveness. Eur J Orthod 2007;29:530-7.

33. Adkins MD, Nanda RS, Currier GF. Arch perimeter changes on rapid palatal expansion. Am J Orthod Dentofacial Orthop 1990;97:194-9.

34. Germane N, Lindauer SJ, Rubenstein LK, Revere JH, Jr., Isaacson RJ. Increase in arch perimeter due to orthodontic expansion. Am J Orthod Dentofacial Orthop 1991;100:421-7.

35. Brudvik P, Rygh P. Transition and determinants of orthodontic root resorption-repair sequence. Eur J Orthod 1995;17:177-88.

36. Ten Cate A. Oral Histology: Development, Structure, and Function. 5th ed. St. Louis, MO: Mosby-Year Book, Inc; 1998.

37. Weinmann J, Sicher H. Bone and bones: Fundamentals of Bone Biology. British Journal of Surgery 1955;43:224-24.

38. Moss-Salentijn L, Hendricks-Klyvert M. Dental and Oral Tissues, an Introduction. 3rd edition. Philadephia: Lea and Febiger; 1990.

39.   Avery J. Oral Deveolpment and Histology. 3rd edition. Los Angeles: Lippincott Williams and Wilkins; 1994. 13:226-242.

40.   Melfi R, Alley K. Perman's Oral Embryology and Microscopic Anatomy. 9th edition. Los Angeles: Lippincott Williams & Wilkins;1994.

41.   Bar-Shavit Z. The osteoclast: a multinucleated, hematopoietic-origin, bone-resorbing osteoimmune cell. J Cell Biochem 2007;102:1130-9.

42.   Kular J, Tickner J, Chim SM, Xu J. An overview of the regulation of bone remodelling at the cellular level. Clin Biochem 2012;45:863-73.

43.   Petrtyl M, Hert J, Fiala P. Spatial organization of the haversian bone in man. J Biomech 1996;29:161-9.

44.   Parfitt AM. Osteonal and hemi-osteonal remodeling: the spatial and temporal framework for signal traffic in adult human bone. J Cell Biochem 1994;55:273-86.

45.   Meikle MC. The tissue, cellular, and molecular regulation of orthodontic tooth movement: 100 years after Carl Sandstedt. Eur J Orthod 2006;28:221-40.

46.   Schwarz A. Tissue changes incident to orthodontic tooth movement. Int J Orthod 1932;18:331-52.

47.   Bister D, Meikle MC. Re-examination of 'Einige Beitrage zur Theorie der Zahnregulierung' (Some contributions to the theory of the regulation of teeth) published in 1904-1905 by Carl Sandstedt. Eur J Orthod 2013;35:160-8.

48.   Oppenheim A. Tissue changes, particularly of the bone, incident to tooth movement. Eur J Orthod 1911;29:i2-i15.

49.   Burger EH, Klein-Nulend J. Mechanotransduction in bone--role of the lacuno-canalicular network. FASEB J 1999;13 Suppl:S101-12.

50.   Melsen B. Tissue reaction to orthodontic tooth movement--a new paradigm. Eur J Orthod 2001;23:671-81.

51.   Masella RS, Chung P-L. Thinking Beyond the Wire: Emerging Biologic Relationships in Orthodontics and Periodontology. Seminars in Orthodontics 2008;14:290-304.

52.   Sandstedt C. Einige beiträge zur theorie der zahnregulierung. Nord Tandlaeg Tidskr 1904;5:236-56.

53.   Schwarz A. Tissue changes incidental to orthodontic tooth movement. Int J Oral of Orthodontia, Oral Surgery, and Radiography 1932;18:331-52.

54.   Krishnan V, Davidovitch Z. Cellular, molecular, and tissue-level reactions to orthodontic force. Am J Orthod Dentofacial Orthop 2006;129:469 e1-32.

55.   K R. Clinical and histologic observations on tooth movement during and after orthodontic treatment. Am J Orthod 1951;53:721-45.

56.   Yee JA, Kimmel DB, Jee WS. Periodontal ligament cell kinetics following orthodontic tooth movement. Cell Tissue Kinet 1976;9:293-302.

57.   Kardos TB, Simpson LO. A new periodontal membrane biology based upon thixotropic concepts. Am J Orthod 1980;77:508-15.

58.   Bassett CA, Becker RO. Generation of electric potentials by bone in response to mechanical stress. Science 1962;137:1063-4.

59.   Gross D, Williams WS. Streaming potential and the electromechanical response of physiologically-moist bone. J Biomech 1982;15:277-95.

60.   Davidovitch Z, Finkelson MD, Steigman S, et al. Electric currents, bone remodeling, and orthodontic tooth movement. II. Increase in rate of tooth movement and periodontal cyclic nucleotide levels by combined force and electric current. Am J Orthod 1980;77:33-47.

61.   Henneman S, Von den Hoff JW, Maltha JC. Mechanobiology of tooth movement. Eur J Orthod 2008;30:299-306.

62.   Burger EH, Klein-Nulend J, Smit TH. Strain-derived canalicular fluid flow regulates osteoclast activity in a remodelling osteon--a proposal. J Biomech 2003;36:1453-9.

63.   Tan SD, Kuijpers-Jagtman AM, Semeins CM, et al. Fluid shear stress inhibits TNFalpha-induced osteocyte apoptosis. J Dent Res 2006;85:905-9.

64.   Aguirre JI, Plotkin LI, Stewart SA, et al. Osteocyte apoptosis is induced by weightlessness in mice and precedes osteoclast recruitment and bone loss. J Bone Miner Res 2006;21:605-15.

65.   Baumrind S. A reconsideration of the propriety of the "pressure-tension" hypothesis. Am J Orthod 1969;55:12-22.

66.   Verna C, Dalstra M, Lee TC, Cattaneo PM, Melsen B. Microcracks in the alveolar bone following orthodontic tooth movement: a morphological and morphometric study. Eur J Orthod 2004;26:459-67.

67.   Zander HA, Muhlemann HR. The effect of stresses on the periodontal structures. Oral Surg Oral Med Oral Pathol 1956;9:380-90.

68.   Grimm FM. Bone bending, a feature of orthodontic tooth movement. Am J Orthod 1972;62:384-93.

69.   Hazenberg JG, Freeley M, Foran E, Lee TC, Taylor D. Microdamage: a cell transducing mechanism based on ruptured osteocyte processes. J Biomech 2006;39:2096-103.

70.   Taylor D, Lee TC. Microdamage and mechanical behaviour: predicting failure and remodelling in compact bone. J Anat 2003;203:203-11.

71.   Frost HM. Bone "mass" and the "mechanostat": a proposal. Anat Rec 1987;219:1-9.

72.   Frost H. Bone "mass" and the "mechanostat": a proposal. Anat Rec 1987;219:1-9.

73.   Frost H. A determinant of bone architecture. The minimum effective strain. Clin Orthop Relat Res 1983;175:286-92.

74.   Frost H. Bone's mechanostat: a 2003 update. Anat Rec A Discov Mol Cell Evol Biol 2003;275:1081-101.

75.   Tweed CH. A philosophy of orthodontic treatment. Am J Orthod Oral Surg 1945:74-103.

76.   Tweed CH. Indications for the extraction of teeth in orthodontic procedure. Am J Orthod Oral Surg 1944;42:22-45.

77.   Margolis HI. A basic facial pattern and its application in clinical orthodontics; the maxillofacial triangle. Am J Orthod 1947;33:631-41.

78.   Lundgren D, Owman-Moll P, Kurol J. Early tooth movement pattern after application of a controlled continuous orthodontic force. A human experimental model. Am J Orthod Dentofacial Orthop 1996;110:287-94.

79.   Paventy A. Nonextraction treatment using the Damon system: A CBCT evaluation. Thesis, Univ of Oklahoma; 2009.

80.   Cattaneo P, Treccani M, Carlsson K, al. e. Transverseal maxillary denoalveolar changes in patients treated with active and passive self-ligating brackets: a randomized clinical trial using CBCT-scans and digital models. Orthod Craniofac Res 2011;14:222-33.

81.   Kraus CD, Campbell PM, Spears R, Taylor RW, Buschang PH. Bony adaptation after expansion with light-to-moderate continuous forces. Am J Orthod Dentofac Orthop 2014;145:655-66.

82.   Garib DG, Henriques JF, Janson G, de Freitas MR, Fernandes AY. Periodontal effects of rapid maxillary expansion with tooth-tissue-borne and tooth-borne expanders: a computed tomography evaluation. Am J Orthod Dentofacial Orthop 2006;129:749-58.

83.   Quinn R. A reassessment of force magnitude in orthodontics. Am J Orthod Dentofacial Orthop1985;88.

84.   Steiner J, Ainamo J. Changes of the marginal periodontium as a result of labial tooth movement in monkeys. J Periodontol 1981;52.

85.   Paventy J. A CBCT Evaluation of Posterior Facial Alveolar Bone in Nonextraction Treatment Using the Damon System. Thesis, Univ of Oklahoma; 2010.

86.   Karring T, Nyman S, Thilander B, Magnusson I. Bone regeneration in orthodontically produced alveolar bone dehiscences. J Periodontal Res 1982;17:309-15.

87.   Engelking G, Zachrisson BU. Effects of incisor repositioning on monkey periodontium after expansion through the cortical plate. Am J Orthod 1982;82:23-32.

88.   Brezniak N, Wasserstein A. Root resorption after orthodontic treatment: Part 2. Literature review. Am J Orthod Dentofacial Orthop 1993;103:138-46.

89.   Owman-Moll P, J K, D L. Effects of a doubled orthdontic force magnitude on tooth movement and root resorptions. An inter-individual study in adolescents. Eur J Orthod 1996;18.

90.   Sameshima GT, Sinclair PM. Predicting and preventing root resorption: Part II. Treatment factors. Am J Orthod Dentofacial Orthop 2001;119:511-5.

91.   Ballard D, Jones A, Petocz P, Darendeliler M. Continuous vs intermittent controlled orthodontic forces on root resorption. A microcomputed-tomography study. American Journal of Orthodontics and Dentofacial Orthopedics 2009;136:e1-8.

92.   Storey E, Smith RJ. Force in orthodontics and its relation to tooth movement. Aust Dent J 1952;56:11-18.

93.   Lee W, Karapetyan G, Moats R, et al. Corticotomy/Osteotomy-assisted tooth movement microCTs differ. J Dent Res 2008;87:861-67.

94.   Mostafa Y, Mohamed Salah Fayed M, Mehanni S, ElBokle N, Heider A. Comparison of corticotomy-facilitated vs standard tooth-movement techniques in dogs with miniscrews as anchor units. Am J Orthod Dentofacial Orthop 2009;136:570-77.

95.   Sebaoun JD, Kantarci A, Turner JW, et al. Modeling of trabecular bone and lamina dura following selective alveolar decortication in rats. J Periodontol 2008;79:1679-88.

96.   Iino S, Sakoda S, Ito G, et al. Acceleration of orthodontic tooth movement by alveolar corticotomy in the dog. Am J Orthod Dentofacial Orthop 2007;131:448 e1-8.

97.   Yaffe A, Fine N, Binderman I. Regional accelerated phenomenon in the mandible following mucoperiosteal flap surgery. J Periodontol 1994;65:79-83.

98.   Frost H. The regional accelerated phenomenon. Orthop Clin N Am 1981;12:725-6.

99.   Frost HM. The regional acceleratory phenomenon: a review. Henry Ford Hosp Med J 1983;31:3-9.

100.   Frost HM. The biology of fracture healing. An overview for clinicians. Part I. Clin Orthop Relat Res 1989:283-93.

101.   Brighton CT, Hunt RM. Histochemical localization of calcium in the fracture callus with potassium pyroantimonate. Possible role of chondrocyte mitochondrial calcium in callus calcification. J Bone Joint Surg Am 1986;68:703-15.

102.   Esterhai JL, Jr., Brighton CT, Heppenstall RB, Alavi A, Desai AG. Detection of synovial pseudarthrosis by 99mTc scintigraphy: application to treatment of traumatic nonunion with constant direct current. Clin Orthop Relat Res 1981:15-23.

103.   Akesson K, Kakonen SM, Josefsson PO, et al. Fracture-induced changes in bone turnover: a potential confounder in the use of biochemical markers in osteoporosis. J Bone Miner Metab 2005;23:30-5.

104.   Paterson D. Treatment of nonunion with a constat direct current: a totally implantable system. Orthop Clin N Am 1984;15:47-59.

105.   King GJ, Keeling SD, Wronski TJ. Histomorphometric study of alveolar bone turnover in orthodontic tooth movement. Bone 1991;12:401-9.

106.   Goldie RS, King GJ. Root resorption and tooth movement in orthodontically treated, calcium-deficient, and lactating rats. Am J Orthod 1984;85:424-30.

107.   Ashcraft MB, Southard KA, Tolley EA. The effect of corticosteroid-induced osteoporosis on orthodontic tooth movement. Am J Orthod Dentofacial Orthop 1992;102:310-9.

108.   Verna C, Dalstra M, Melsen B. The rate and the type of orthodontic tooth movement is influenced by bone turnover in a rat model. Eur J Orthod 2000;22:343-52.

109.   Collins MK, Sinclair PM. The local use of vitamin D to increase the rate of orthodontic tooth movement. Am J Orthod Dentofacial Orthop 1988;94:278-84.

110.   Kawakami M. [Effects of local application of 1,25 (OH)2D3 on experimental tooth movement in rats]. Osaka Daigaku Shigaku Zasshi 1990;35:128-46.

111.   Kale S, Kocadereli I, Atilla P, Asan E. Comparison of the effects of 1,25 dihydroxycholecalciferol and prostaglandin E2 on orthodontic tooth movement. Am J Orthod Dentofacial Orthop 2004;125:607-14.

112.   Igarashi K, Mitani H, Adachi H, Shinoda H. Anchorage and retentive effects of a bisphosphonate (AHBuBP) on tooth movements in rats. Am J Orthod Dentofacial Orthop 1994;106:279-89.

113.   Ortega AJ, Campbell PM, Hinton R, Naidu A, Buschang PH. Local application of zoledronate for maximum anchorage during space closure. Am J Orthod Dentofacial Orthop 2012;142:780-91.

114. Cunningham G. Methode sofortiger regulierung von Anomalenz. Oesterreichisch-Ungarische. Vierteljahrsschrift Zahnheilkd 1894;10:455-57.

115. Cohn-Stock G. Die chirurgische immediatregulierung der Kiefer speziell die Chirurgische Behandlung der Prognathie. Vierteljahrsschrift Zahnheilkd 1921;1921:320-54.

116. Bichlmayr A. Ckirurgische Kieferothopaedie und das verhalten des Knochens und der Wurzelspitzen nach derselben. Dtsch Zahnaerztl Woschenschrift 1931:835-42.

117. Skogsborg C. The use of septotomy in connection with orthodontic treatement. Int J Orthod 1931:1044-57.

118. Ascher F. Spaetbehandlung der prognathie des oberkiefers. D. Zahnarztly 1947;2:218-26.

119. Kole H. Surgical operations on the alveolar ridge to correct occlusal abnormalities. Oral Surg Oral Med Oral Pathol 1959;12:515-29 concl.

120. Bell WH, Levy BM. Revascularization and bone healing after maxillary corticotomies. J Oral Surg 1972;30:640-8.

121. Duker J. Experimental animal research into segmental alveolar movement after corticotomy. J Maxillofac Surg 1975;3:81-4.

122. Suya H. Corticotomy in orthodontics: mechanical and biological basis in orthodontics. Heidelberg, Germany: Huthig Buch Verlag; 1991.

123. Wilcko WM, Ferguson DJ, Bouquot JE, Wilcko MT. Rapid orthodontic decrowding with alveolar augmentaiton: case report. World J Orthod 2003:197-205.

124. Murphy KG, Wilcko MT, Wilcko WM, Ferguson DJ. Periodontal Accelerated Osteogenic Orthodontics: A Description of the Surgical Technique. J Oral and Maxillofac Surgery 2009;67:2160-66.

125. Murphy NC, Bissada NF, Davidovitch Ze, et al. Corticotomy and Tissue Engineering for Orthodontists: A Critical History and Commentary. Seminars in Orthodontics 2012;18:295-307.

126. Pham-Nguyen K. Micro-CT analysis of osteopenia following selective alveolar decortication and tooth movement. Thesis, Boston Univ; 2006.

127.   Bogoch E, Gschwend N, Rahn B, Moran E, Perren S. Healing of cancellous bone osteotomy in rabbits--Part I: Regulation of bone volume and the regional acceleratory phenomenon in normal bone. J Orthop Res 1993;11:285-91.

128.   Sebaoun JD, Kantarci A, Turner JW, Carvalho RS, Van Dyke TE. Modeling of trabecular bone and lamina dura following selective alveolar decortication in rats. J Periodontol 2008;79:1679-88.

129.   Wang L, Lee W, Lei D, et al. Tissue responses in corticotomy- and osteotomy-assisted tooth movements in rats: histology and immunostaining. Am J Orthod Dentofacial Orthop 2009;136:770.e1-70.e11.

130.   Midgett RJ, Shaye R, Fruge JF, Jr. The effect of altered bone metabolism on orthodontic tooth movement. Am J Orthod 1981;80:256-62.

131.   Fischer TJ. Orthodontic treatment acceleration with corticotomy-assisted exposure of palatally impacted canines. Angle Orthod 2007;77:417-20.

132.   Hwang HS, Lee KH. Intrusion of overerupted molars by corticotomy and magnets. Am J Orthod Dentofacial Orthop 2001;120:209-16.

133.   Moon CH, Wee JU, Lee HS. Intrusion of overerupted molars by corticotomy and orthodontic skeletal anchorage. Angle Orthod 2007;77:1119-25.

134.   Oliveira DD, de Oliveira BF, de Araujo Brito HH, de Souza MM, Medeiros PJ. Selective alveolar corticotomy to intrude overerupted molars. Am J Orthod Dentofacial Orthop 2008;133:902-8.

135.   Lee JK, Chung KR, Baek SH. Treatment outcomes of orthodontic treatment, corticotomy-assisted orthodontic treatment, and anterior segmental osteotomy for bimaxillary dentoalveolar protrusion. Plast Reconstr Surg 2007;120:1027-36.

136.   Spena R, Caiazzo A, Gracco A, Siciliani G. The use of segmental corticotomy to enhance molar distalization. J Clin Orthod 2007;41:693-9.

137.   Lee W, Karapetyan G, Moats R, et al. Corticotomy-/osteotomy-assisted tooth movement microCTs differ. J Dent Res 2008;87:861-7.

138.   Cho K, Cho S, Oh C, al. e. The effect of cortical activation on orthodontic tooth movement. Oral Dis 2007;13:314-19.

139.   Iwasaki LR, Haack JE, Nickel JC, Morton J. Human tooth movement in response to continuous stress of low magnitude. Am J Orthod Dentofacial Orthop 2000;117:175-83.

140.   Sanjideh PA, Rossouw PE, Campbell PM, Opperman LA, Buschang PH. Tooth movements in foxhounds after one or two alveolar corticotomies. Eur J Orthod 2010;32:106-13.

141.   Iino S, Soakoda S, Ito G, et al. Acceleration of orthodontic tooth movement by alveolar corticotomy in the dog. Am J Orthod Dentofacial Orthop 2007;131:448.e1-48.e8.

142.   Buschang PH, Campbell PM, Ruso S. Accelerating Tooth Movement With Corticotomies: Is It Possible and Desirable? Seminars in Orthodontics 2012;18:286-94.

143.   Cohen G, Campbell PM, Rossouw PE, Buschang PH. Effects of increased surgical trauma on rates of tooth movement and apical root resorption in foxhound dogs. Orthod Craniofac Res 2010;13:179-90.

144.   Wilcko W, Wilcko MT. Accelerating tooth movement: The case for corticotomy-induced orthodontics. Am J Orthod Dentofacial Orthop 2013;144:4-12.

145.   Gantes B, Rathbun E, Anholm M. Effects on the periodontium following corticotomy-facilitated orthodontics. Case reports. J Periodontol 1990;61:234-8.

146.   Shoreibah EA, Ibrahim SA, Attia MS, Diab MM. Clinical and radiographic evaluation of bone grafting in corticotomy-facilitated orthodontics in adults. J Int Acad Periodontol 2012;14:105-13.

147.   Twaddle B. Dentoalveolar bone density changes following accelerated osteogenesis. Thesis, St Louis Univ Dept of Orthod; 2002.

148.   Twaddle B. Dentoalveolar bone density changes following accelerated osteogenesis. J Dent Res 2002;81.

149.   Twaddle B, Ferguson DJ, Wilcko MT, Wilcko WM, Lin CY. Dentoalveolar bone density changes following corticotomy facilitated orthodontics. J Dent Res 2002;80:301.

150.   Brudvik P, Rygh P. The initial phase of orthodontic root resorption incident to local compression of the periodontal ligament. Eur J Orthod 1993;15:249-63.

151.   Machado I, Ferguson DJ, Wilcko MT, Wilcko WM, Alkahadra T. Root resorption following orthodontics with and without alveolar corticotomy. J Dent Res 2002:301.

152. Wang B, Shen G, Fang B, Yu H, Wu Y. Augmented corticotomy-assisted presurgical orthodontics of class III malocclusions: a cephalometric and cone-beam computed tomography study. J Craniofac Surg 2013;24:1886-90.

153. Nazarov AD, Ferguson DJ, Wilcko WM, Wilcko MT. Improved retention following corticotomy using ABO objective grading system. J Dent Res 2004;83.

154. Hajji Ss. The influence of the accelerated osteogenic response on mandibular decrowding. J Dent Res 2001;30:180.

155. Oliveira K, Ferguson DJ, Rajaei O, Wilcko WM, Wilcko MT. Thesis, Boston Univ; 2006.

156. Germec D, Giray B, Kocadereli I, Enacar A. Lower incisor retraction with a modified corticotomy. Angle Orthod 2006;76:882-90.

157. Anholm JM, Crites DA, Hoff R, Rathbun WE. Corticotomy-facilitated orthodontics. CDA J 1986;14:7-11.

158. Grenga V, Bovi M. Corticotomy-enhanced intrusion of an overerupted molar using skeletal anchorage and ultrasonic surgery. J Clin Orthod 2013;47:50-5; quiz 64.

159. Aljhani AS, Zawawi KH. Nonextraction treatment of severe crowding with the aid of corticotomy-assisted orthodontics. Case Rep Dent 2012;2012:694527.

160. Nowzari H, Yorita FK, Chang HC. Periodontally accelerated osteogenic orthodontics combined with autogenous bone grafting. Compend Contin Educ Dent 2008;29:200-6; quiz 07, 18.

161. Kim SH, Kim I, Jeong DM, Chung KR, Zadeh H. Corticotomy-assisted decompensation for augmentation of the mandibular anterior ridge. Am J Orthod Dentofacial Orthop 2011;140:720-31.

162. Iino S, Sakoda S, Miyawaki S. An adult bimaxillary protrusion treated with corticotomy-facilitated orthodontics and titanium miniplates. Angle Orthod 2006;76:1074-82.

163. Hassan AH, AlGhamdi AT, Al-Fraidi AA, Al-Hubail A, Hajrassy MK. Unilateral cross bite treated by corticotomy-assisted expansion: two case reports. Head Face Med 2010;6:6.

164. Owen AH, 3rd. Accelerated Invisalign treatment. J Clin Orthod 2001;35:381-5.

165. Ahn HW, Lee DY, Park YG, et al. Accelerated decompensation of mandibular incisors in surgical skeletal class III patients by using augmented corticotomy: a preliminary study. Am J Orthod Dentofacial Orthop 2012;142:199-206.

166. Coscia G, Coscia V, Peluso V, Addabbo F. Augmented Corticotomy Combined With Accelerated Orthodontic Forces in Class III Orthognathic Patients: Morphologic Aspects of the Mandibular Anterior Ridge With Cone-Beam Computed Tomography. J Oral Maxillofac Surg 2013;71:1760.e1-60.e9.

167. Aboul-Ela SMBE-D, El-Beialy AR, El-Sayed KMF, et al. Miniscrew implant-supported maxillary canine retraction with and without corticotomy-facilitated orthodontics. Am J Orthod Dentofac Orthop 2011;139:252-59.

168. Choo H, Heo H-A, Yoon H-J, Chung K-R, Kim S-H. Treatment outcome analysis of speedy surgical orthodontics for adults with maxillary protrusion. Am J Orthod Dentofac Orthop 2011;140:e251-e62.

169. Wilcko MT, Wilcko WM, Bissada NF. An Evidence-Based Analysis of Periodontally Accelerated Orthodontic and Osteogenic Techniques: A Synthesis of Scientific Perspectives. Seminars in Orthodontics 2008;14:305-16.

170. Coscia G, Coscia V, Peluso V, Addabbo F. Augmented Corticotomy Combined With Accelerated Orthodontic Forces in Class III Orthognathic Patients: Morphologic Aspects of the Mandibular Anterior Ridge With Cone-Beam Computed Tomography. J Oral Maxillofac Surg 2013.

171. Costantino PD, Hiltzik D, Govindaraj S, Moche J. Bone healing and bone substitutes. Facial Plast Surg 2002;18:13-26.

172. Bagheri S, Bell RB, Khan H. Current Therapy in Oral and Maxillofacial Surgery. St. Louis, MO: Elsevier; 2012.

173. Khoury F, Antoun H, Missika P. Bone Augmentation in Oral Implantology. New Malden, United Kingdom: Quintessence Publishing Co, Ltd; 2007.

174. Wikesjo UM, Sorensen RG, Kinoshita A, Wozney JM. RhBMP-2/alphaBSM induces significant vertical alveolar ridge augmentation and dental implant osseointegration. Clin Implant Dent Relat Res 2002;4:174-82.

175. Kubler N, Reuther J, Kirchner T, Pressnitz B, Sebald W. Osteoinductive, morphologic and biomechanical properties of autolyzed, antigen-extracted, allogenic human bone. J Oral Maxillofac Surg 1993;51:1346-57.

176.   Klinge B, Alberius P, Isaksson S, Jonsson J. Osseous response to implanted natural bone mineral and synthetic hydroxylapatite ceramic in the repair of experimental skull bone defects. J Oral Maxillofac Surg 1992;50:241-9.

177.   Misch CE, Dietsh F. Bone-grafting materials in implant dentistry. Implant Dent 1993;2:158-67.

178.   Elsalanty ME, Genecov DG. Bone grafts in craniofacial surgery. Craniomaxillofac Trauma Reconstr 2009;2:125-34.

179.   Bauer TW, Muschler GF. Bone graft materials. An overview of the basic science. Clin Orthop Relat Res 2000:10-27.

180.   Virolainen P, Perala M, Vuorio E, Aro HT. Expression of matrix genes during incorporation of cancellous bone allografts and autografts. Clin Orthop Relat Res 1995:263-72.

181.   Skoglund A, Hising P, Young C. A clinical and histologic examination in humans of the osseous response to implanted natural bone mineral. Int J Oral Maxillofac Implants 1997;12:194-9.

182.   Thompson N, Casson JA. Experimental onlay bone grafts to the jaws. A preliminary study in dogs. Plast Reconstr Surg 1970;46:341-9.

183.   Friedlaender G. Current Concept Reviews: Bone Grafts. J Bone Joint Surg Am 1987;69A:786-90.

184.   Zitzmann NU, Naef R, Scharer P. Resorbable versus nonresorbable membranes in combination with Bio-Oss for guided bone regeneration. Int J Oral Maxillofac Implants 1997;12:844-52.

185.   Simion M, Trisi P, Piattelli A. Vertical ridge augmentation using a membrane technique associated with osseointegrated implants. Int J Periodontics Restorative Dent 1994;14:496-511.

186.   Simion M, Dahlin C, Blair K, Schenk RK. Effect of different microstructures of e-PTFE membranes on bone regeneration and soft tissue response: a histologic study in canine mandible. Clin Oral Implants Res 1999;10:73-84.

187.   Reynolds M, Aichelmann-Reidy M, Branch-Mays G, Gunsolley J. The efficacy of bone replacement grafts in the treatment of periodontal osseous defects. A systematic review. Ann Periodontol 2003;8:227-65.

188.   Jensen S, Terheyden H. Bone augmentation procedures in localized defects in the alveolar ridge: clinical results with differenct bone grafts and bone-substitute materials. Int J Oral Maxillofac Implants 2009;24:218-36.

189.   Smukler H, Landia L, Setayesh R. Histomorphometric evaluation of extraction sockets and deficient alveolar ridges treated with allograft and barrier membrane: a pilot study. Int J Oral Maxillofac Implants 1999;14:407-16.

190.   Scheyer E, Schupbach P, McGuire M. A histologic and clinical evaluation of ridge preservation following grafting with demineralized bone matrix, cancellous bone chips, and resorbably extracellular matrix membrane. Int J Periodontics Restorative Dent 2012;32:543-52.

191.   Nowzari H, Yorita F, Chang H-C. Periodontally accelerated osteogenic orthodontics combined with autogenous bone grafting. Compend Contin Educ Dent 2008;29:2000-06.

192.   Tjia J, Moghe P. Analysis of 3-D microstructure of porous poly(lactide-glyoxide) matrices using confocal microscopy. J Biomed Mater Res 1998;43:291-9.

193.   Aerssens J, Boonen S, Lowet G, Dequeker J. Interspecies Differences in Bone Composition, Density, and Quality: Potential Implications for in Vivo Bone Research. Endocrinology 1998;139:663-70.

194.   Kraus CD, Campbell PM, Spears R, Taylor RW, Buschang PH. Bony adaptation after expansion with light-to-moderate continuous forces. Am J Orthod Dentofac Orthop 2014;145:655-66.

195.   Oltramari PV, de Lima Navarro R, Henriques JF, et al. Orthodontic movement in bone defects filled with xenogenic graft: an experimental study in minipigs. Am J Orthod Dentofacial Orthop 2007;131:302 e10-7.

196.   Sheats R, Strauss R, Rubenstein L. Effect of a resorbable bone graft material on orthodontic tooth movement through surgical defects in the cat model. J Oral Maxillofac Surg 1991;49:1299-303.

197.   Araujo M, Carmagnola D, Berglundh T, Thilander B, Lindhe J. Orthodontic movement in bone defects augmented with Bio-Oss. J Clin Periodontol 2001;28:73-80.

198.   Seifi M, Ghoraishian S. Determination of orthodontic tooth movement and tissue reaction following demineralized freeze-dried bone allograft grafting intervention. Dent Res J 2012;9:203-09.

199. Ahn HW, Ohe JY, Lee SH, Park YG, Kim SJ. Timing of force application affects the rate of tooth movement into surgical alveolar defects with grafts in beagles. Am J Orthod Dentofacial Orthop 2014;145:486-95.

200. Ruso S, Campbell PM, Rossmann J, et al. Bone response to buccal tooth movements-with and without flapless alveolar decortication. Eur J Orthod 2014;36:613-23.

201. Chen N, Glowacki J, Bucky L, et al. The roles of revascularization and resorption on endurance of craniofacial onlay bone grafts in the rabbit. Plastic and Reconstructive Surgery 1994;93:714-22.

202. Shapiro F. Cortical bone repair. The relationship of the lacunar-canalicular system and intercellular gap functions to the repair process. The Journal of Bone and Joint Surgery 1988;American Vol 70:1067-81.

203. Jackson A. The effects of crowding on buccal tipping comparing the Damon Bracket System and a straight-wire orthodontic appliance. Thesis, St. Louis University, Dept of Orthodontics 2008.

204. Lee KB, Lee DY, Ahn HW, et al. Tooth movement out of the bony wall using augmented corticotomy with nonautogenous graft materials for bone regeneration. Biomed Res Int 2014;2014:347508.

205. Lee W, Karapetyan G, Moats R, et al. Corticotomy-/osteotomy-assisted tooth movement microCTs differ. J Dent Res 2008;87:861-65.

206. N B, A W. Root resorption after orthodontic treament: Part 2. Literature review. Am J Orthod Dentofacial Orthop 1993;103:138-46.

207. Nanci A, Somerman M. Ten Cate's Oral Histology: Development, Structure, and Function. St. Louis: Mosby Inc; 2003.

208. Deguchi T, Seiryu M, Daimaruya T, et al. Decreased alveolar bone turnover is related to the occurrence of root resorption during experimental tooth movement in dogs. Angle Orthod 2014.

209. Kawamoto T, Motohashi N, Kitamura A, et al. Experimental tooth movement into bone induced by recombinant human bone morphogenic protein-2. Cleft Palate Craniofac J 2003;40.

210. Kameyama T, Matsumoto Y, Warita H, Soma K. Inactivated periods of constant orthodontic forces related to desirable tooth movement in rats. J of Orthodontics 2003;30:31-37.

211. Nemcovsky C, Artzi Z. Comparative study of buccal dehiscence defects in immediate, delayed, and late maxillary implant placement with collagen membranes: clinical healing between placement and second-stage surgery. J Periodontology 2002;73:754-61.

212. Chen ST, Darby IB, Adams GG, Reynolds EC. A prospective clinical study of bone augmentation techniques at immediate implants. Clin Oral Implants Res 2005;16:176-84.

213. Hockers T, Abensur D, Vanlentini P, Legrand R, Hammerle C. The combined use of bioresorbable membranes and xenografts or autografts in the treatment of bone defects around implants. A study in beagle dogs. Clin Oral Implants Res 1999;10:487-98.

214. Bonacci F. Hard and soft tissue augmentation in a postorthodontic patient: a case report. Int J Periodontics Restorative Dent 2011;31:18-27.

215. Toygar H, Kircelli B. Regeneration of multiple adjacent bone dehiscences with guided tissue regeneration after orthodontic proclination: a corrective treatment approach. Int J Periodontics Restorative Dent 2010;30:345-53.

216. Naaman N, Chaptini E, Taha H, Mokbel M. Combined bone grafting and orthodontic treatment of an iatrogenic periodontal defect: a case report with clinical reentry. J Periodontol 2004;75:316-21.

217. Yared KF, Zenobio EG, Pacheco W. Periodontal status of mandibular central incisors after orthodontic proclination in adults. Am J Orthod Dentofacial Orthop 2006;130:6 e1-8.

218. Wainwright W. Faciolingual tooth movement: its influence on the root and cortical plate. Am J Orthod 1973;64:278-302.

219. Buser D, Dula K, Hirt HP, Schenk RK. Lateral ridge augmentation using autografts and barrier membranes: A clinical study with 40 partially edentulous patients. J Oral Maxillofac Surg 1998;54:420-32.

220. Sandberg E, Dahlin C, Linde A. Bone regeneration by the osteopromotion technique using bioresorbable membranes: An experimental study in rats. J Oral Maxillofac Surg 1993;51:1106-14.

221. Dahlin C, Alberius P, Linde A. Osteopromotion for cranioplasty: An experimental study in rats using a membrane technique. J Neurosurg 1991;74:487-91.

222.   Donos N, Kostopoulos L, Karring T. Alveolar ridge augmentation using a resorbable copolymer membrane and autogenous bone grafts. Clin Oral Implants Res 2002;13:203-13.

223.   Pitaru S, Tal H, Soldinger M, Grosskopf A, Noff M. Partial regeneration of periodontal tissues using collagen barriers. Initial observations in the canine. J Periodontol 1988;59:380-6.

224.   DeAngelis V. Observations in the response of alveolar bone to orthodontic force. Am J Orthod 1970;58:284-94.

225.   Huang HL, Hsu JT, Chen MY, et al. Microcomputed tomography analysis of particular autogenous bone graft in sinus augmentation at 5 months: differences on bone mineral density and 3D trabecular structure. Clin Oral Investig 2013;17:535-42.

226.   Chen ST, Wilson TG, Hammerle C. Immediate or early placement of implants following tooth extraction: review of biologic basis, clinical procedures, and outcomes. Int J Oral Maxillofac Implants 2004;19 Suppl:12-25.

227.   Lee CY, Prasad HS, Suzuki JB, Stover JD, Rohrer MD. The correlation of bone mineral density and histologic data in the early grafted maxillary sinus: a preliminary report. Implant Dent 2011;20:202-14.

228.   McBride MD, Campbell PM, Opperman LA, Dechow PC, Buschang PH. How does the amount of surgical insult affect bone around moving teeth? Am J Orthod Dentofacial Orthop 2014;145:S92-9.

229.   Löst C. Depth of alveolar bone dehiscences in relation to gingival recessions. J Clin Periodontol 1984;11:583-89.

230.   Polson A, Caton J, Polson AP, et al. Periodontal response after tooth movement into intrabony defects. J Periodontol 1984;55:197-202.

231.   Wennstrōm J, Stokland B, Nyman S, Thilander B. Periodontal tissue response to orthodontic movement of teeth with infrabony pockets. Am J Orthod Dentofacial Orthop 1993;103:313-9.

232.   Rupprecht R, Horning G, Nicoll B, Cohen M. Prevalence of dehiscences and fenestrations in modern american skulls. J Periodontol 2001;72:722-29.

233.   Evangelista K, Vasconcelos Kde F, Bumann A, et al. Dehiscence and fenestration in patients with Class I and Class II Division 1 malocclusion assessed with cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2010;138:133 e1-7; discussion 33-5.

234.   Enhos S, Uysal T, Yagci A, et al. Dehiscence and fenestration in patients with different vertical growth patterns assessed with cone-beam computed tomography. Angle Orthod 2012;82:868-74.

235.   Capps C. Evaluation of Transverse, Bodily Tooth Movement and its Effects on the Surrounding Hard Tissue. Thesis, Texas A&M Univ Baylor College of Dent Dept of Orthod ; 2014.

Dog	Side	Histology Type	Orientation
A	Graft +	NE	NE
A	Graft -	NE	NE
B	Graft +	NE	NE
B	Graft -	NE	NE
C	Graft +	Fluorescence	Coronal
C	Graft -	Fluorescence	Coronal
D	Graft +	Fluorescence	Coronal
D	Graft -	Fluorescence	Coronal
E	Graft +	Fluorescence	Axial
E	Graft -	Fluorescence	Axial
F	Graft +	H&E	Coronal
F	Graft -	H&E	Coronal
G	Graft +	H&E	Coronal
G	Graft -	H&E	Coronal

Table AI. Histologic Designations. Summary of bilateral specimen histologic allocations and corresponding orientations. *H&E,* Hematoxylin and eosin; *NE,* not evaluated.

Dog	Week	Description of Breakage	Correction
A	4	4th premolar band debonded	Rebonded
A	10	4th premolar bracket sheared from band	Re-welded, re-soldered
B	3	2nd premolar band debonded	Remade & Rebonded
C	3	Canine band debonded	Remaded & Rebonded
C	8	2nd premolar band debonded	Remade & Rebonded
E	9	4th premolar bracket sheared from band	Re-welded, re-soldered
G	6	4th premolar bracket sheared from band	Re-welded, re-soldered

Table AII. Appliance Breakages. Summary of appliance breakages during the 12-week experimental duration.

	Variable	**Experimental (Graft +)**		**Control (Graft -)**		**Diff Prob**
		Mean	S.D.	Mean	S.D.	
Tooth Movements: Radiographic	Canine	-0.57	0.40	-0.79	0.45	NS
	PM2	1.66	0.84	1.65	0.69	NS
	PM4	-0.56	1.32	0.26	1.09	NS
MicroCT	BBH — Mesial Root	2.31	2.51	0.086	0.20	0.038
	BBH — Distal Root	0.75	1.25	0.51	1.17	NS
	TRH — Mesial Root	8.54	1.01	8.45	1.05	NS
	TRH — Distal Root	6.18	0.86	6.22	0.63	NS
	TTH — Mesial Root	13.81	1.45	13.98	1.18	NS
	TTH — Distal Root	11.45	1.33	11.75	0.69	NS
	Material Density (mgHA/cm^3)	798.74	18.29	789.63	22.17	0.028
	BV/TV	0.44	0.13	0.51	0.08	NS

Table AIII. Descriptive Statistics. Descriptive statistics for pre- and post-experimental changes and comparisons.

Measurement		Experimental (Graft +)			Control (Graft -)			Diff Prob
		Mean	S.D.	Sig	Mean	S.D.	Sig	
Canine	MF	0.21	0.27	NS	0.29	0.39	NS	0.56
	F	0.14	0.69	NS	0.07	0.45	NS	0.66
	DF	0.0	0.58	NS	0.07	0.19	NS	0.66
	ML	0.36	0.85	NS	0.29	0.57	NS	0.92
	L	0.57	0.61	NS	0.36	0.94	NS	0.40
	DL	-0.21	0.57	NS	0.36	0.75	NS	0.04*
PM2	MF	0.07	0.45	NS	0.14	0.24	NS	0.56
	F	0.14	0.38	NS	0.07	0.19	NS	0.66
	DF	-0.36	0.48	NS	0.07	0.19	NS	0.11
	ML	0.0	0.0	NS	0.36	0.38	NS	0.06
	L	0.0	0.29	NS	0.21	0.39	NS	0.28
	DL	-0.07	0.19	NS	0.0	0.0	NS	0.32
PM4	MF	-0.21	0.76	NS	0.0	0.58	NS	0.32
	F	0.0	0.29	NS	0.36	0.48	NS	0.13
	DF	-0.07	0.45	NS	0.42	0.45	NS	0.13
	ML	-0.43	0.53	NS	-0.07	0.61	NS	0.26
	L	0.29	0.49	NS	0.29	0.39	NS	1.0
	DL	0.21	0.39	NS	0.14	0.38	NS	0.67

Table AIV. Periodontal Probing Statistics. Pre-treatment to post-treatment group differences for periodontal probing depths. *MF:* mesiofacial; *F:* straight facial; *DF:* distofacial; *ML:* mesiolingual; *L:* straight lingual; *DL:* distolingual; *p<0.05
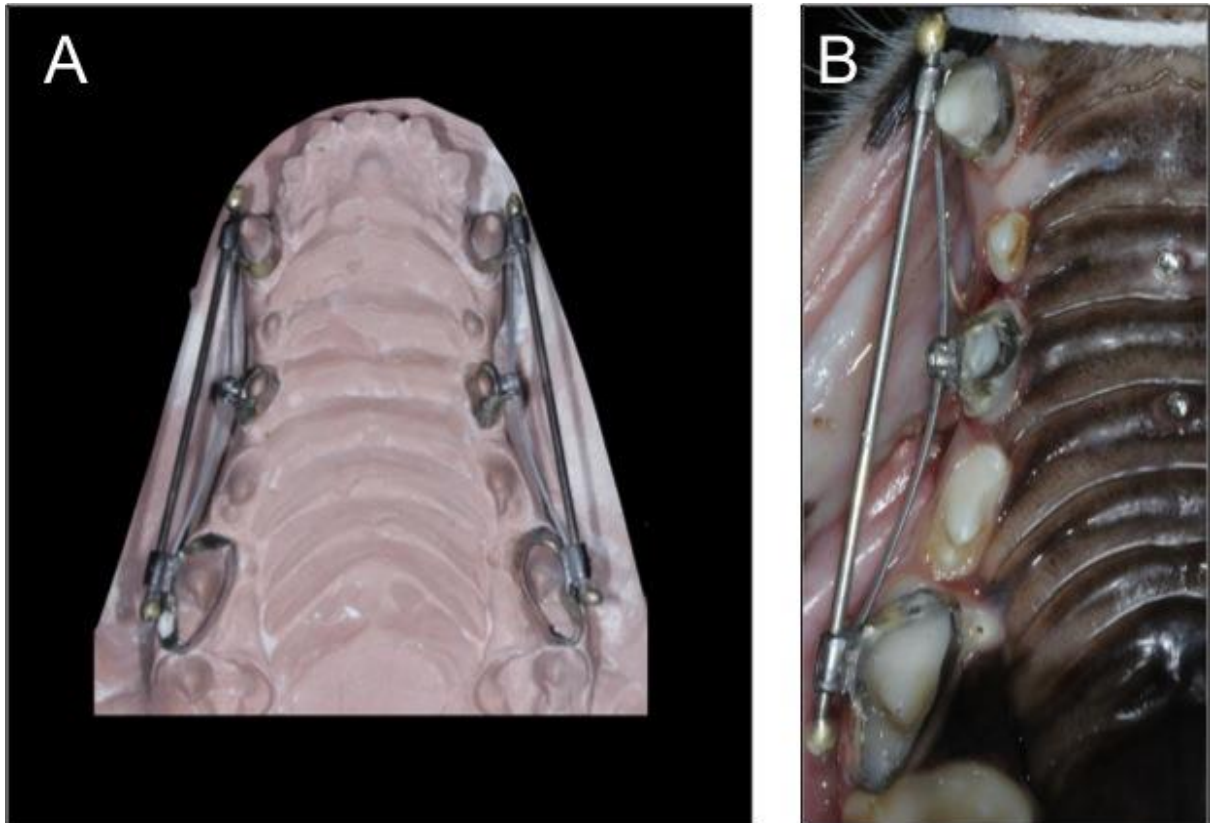
Figure 1. Appliance Design. Occlusal view of the appliance after fabrication on the cast (**A**) and after delivery and cementation (**B**). Bands were cemented to maxillary canines, 2nd premolars, and 4th premolars. A 0.045" ss protective archwire was placed through the headgear tubes.
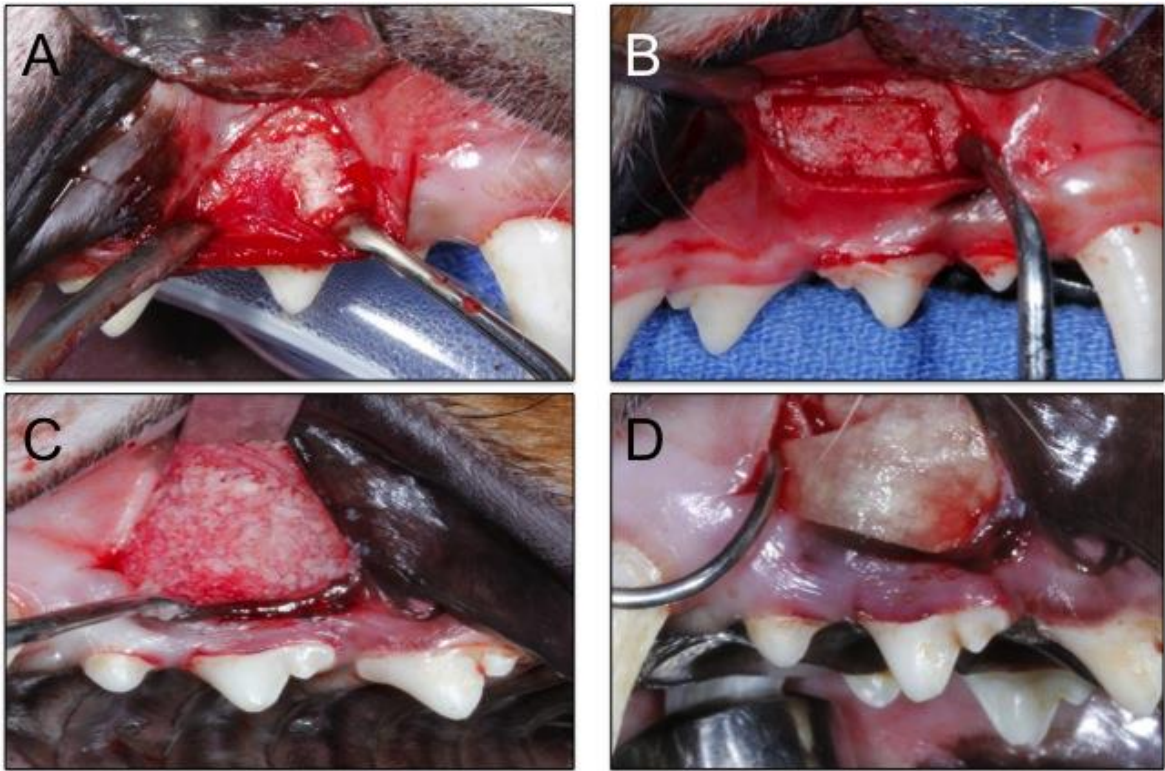
Figure 2: Surgical Procedures. (**A**) View of vestibular flap with periosteum removed at surgical site, (**B**) Corticotomies performed mesial, distal, and 2-3 mm apical to the 2nd premolar roots, (**C**) 0.05 cc of demineralized freeze-dried human cortical bone allograft placed over the 2nd premolar and adjacent corticotomies, (**D**) Resorbable collagen membrane positioned over the graft.
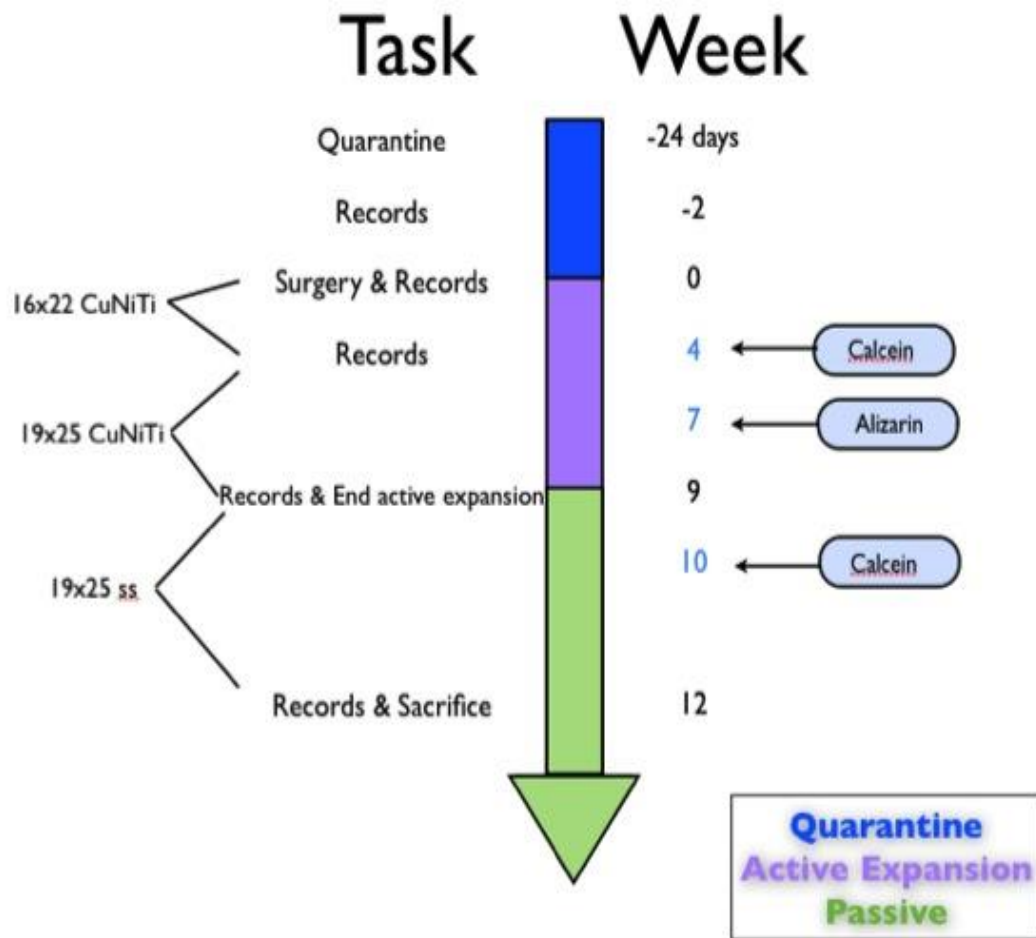
Figure 3. Experimental Timeline. Animals were quarantined for 10 days, followed by records acquisition (blue). Active expansion of the 2nd premolar (purple) included 4 weeks with a 16x22 CuNiTi wire, followed by 5 weeks with a 19x25 CuNiTi wire. A consolidation period of 3 weeks was observed whereby a 19x25 ss wire was made passive (green). Total experimental duration was 12 weeks.
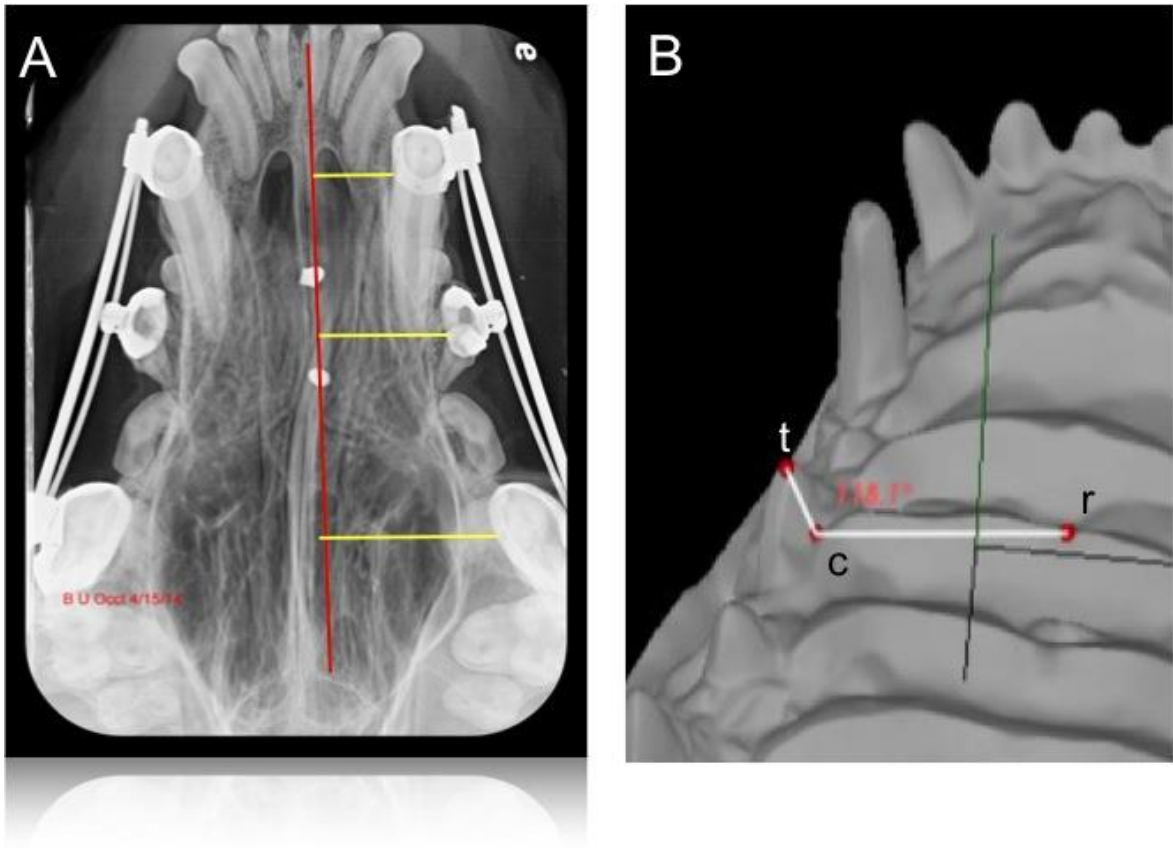
Figure 4. Radiographic Expansion and Dental Tipping Images. (A) Radiographic measurements of expansion: A reference line connecting the two palatal miniscrews was extrapolated. From this line, the perpendicular distance to the most lingual aspect of the bands of the canine, 2nd premolar, and 4th premolar was measured. **(B)** Dental casts used to evaluate tipping of the 2nd premolars, calculated as the angular difference between pre- and post-experimental measurements. Angles were defined by connecting the points **r**, the most occlusal midline point on the palatal rugae adjacent to the tooth of interest, **c**, the most cervical point on the palatal aspect of the tooth of interest, taken at its mesial-distal center, and **t**, the cusp tip.
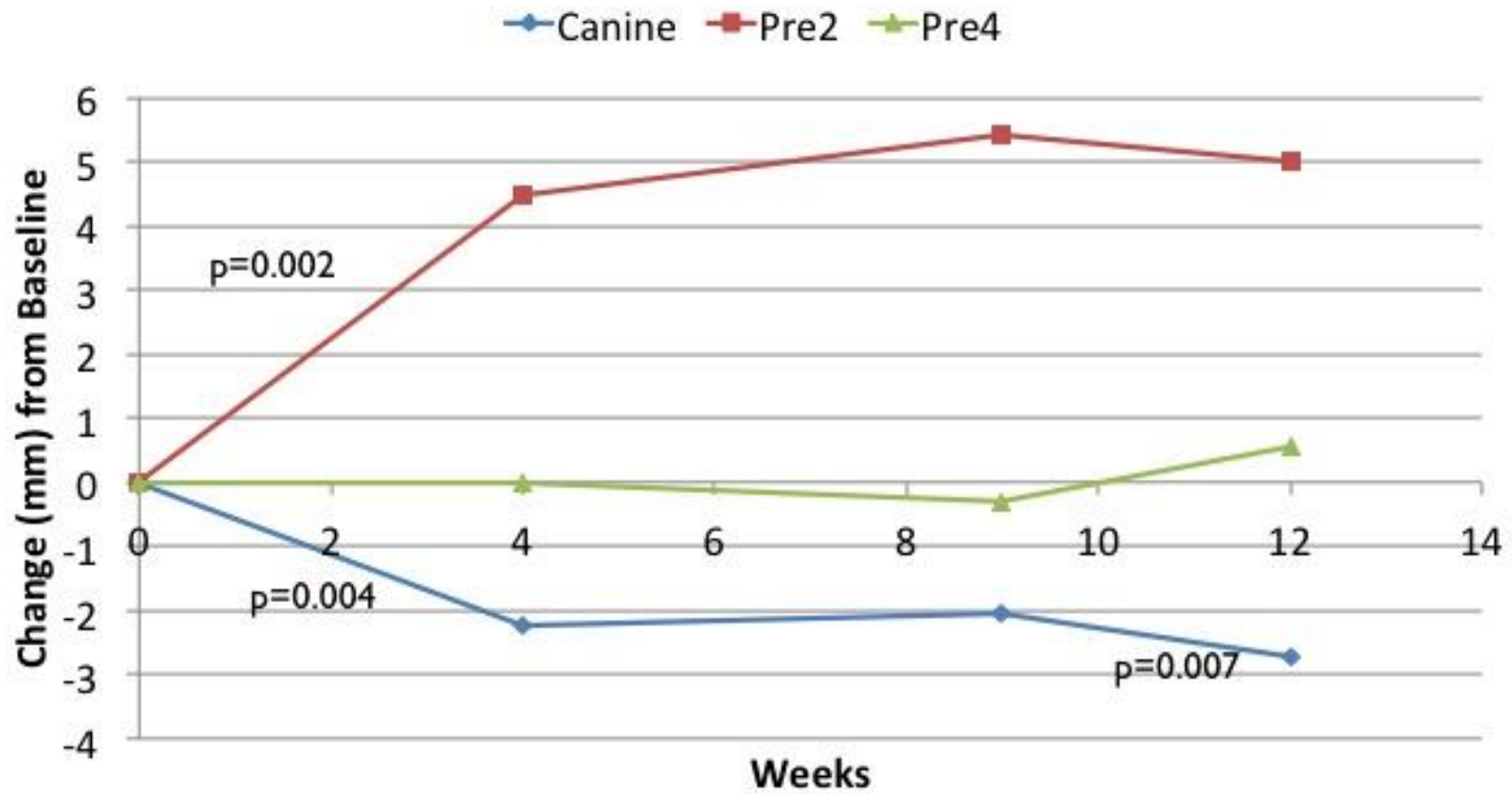
Figure 5. Intraoral Measurements of Tooth Movement. Interdental caliper measurements showing overall significant expansion of the 2nd premolars (p<0.001), no significant change at the 4th premolar, and constriction of the canine.
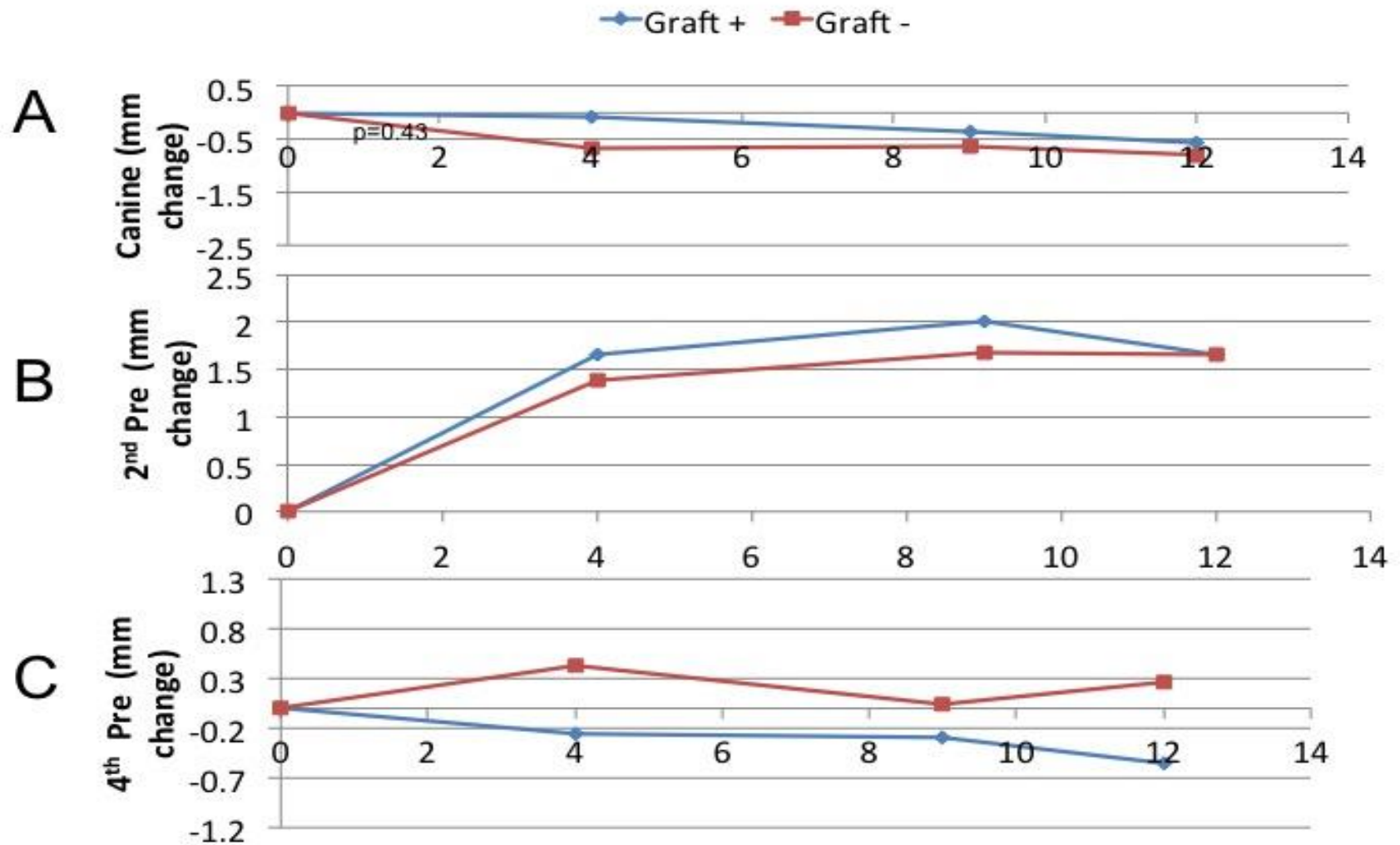
Figure 6. Radiographic Measurements of Tooth Movement. Millimeter changes in pre- and post- experimental widths of the Graft + and Graft – canine (**A**), 2nd premolar (**B**), and 4th premolar (**C**), measured from midsagittal reference line (Figure 4A).

107
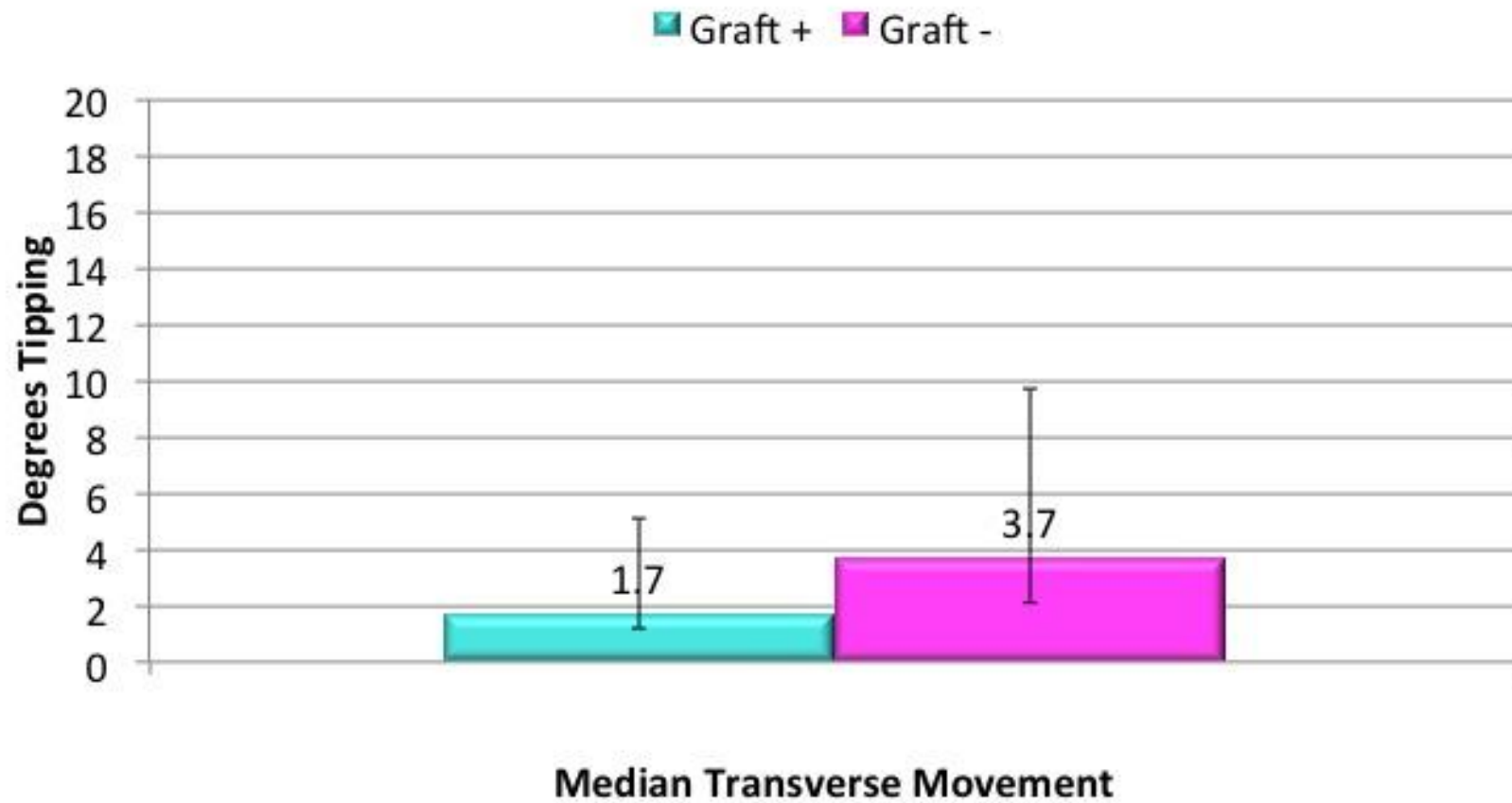
Figure 7. Tipping Measurements. Medians and interquartile ranges of dental tipping on the Graft + and Graft – sides.
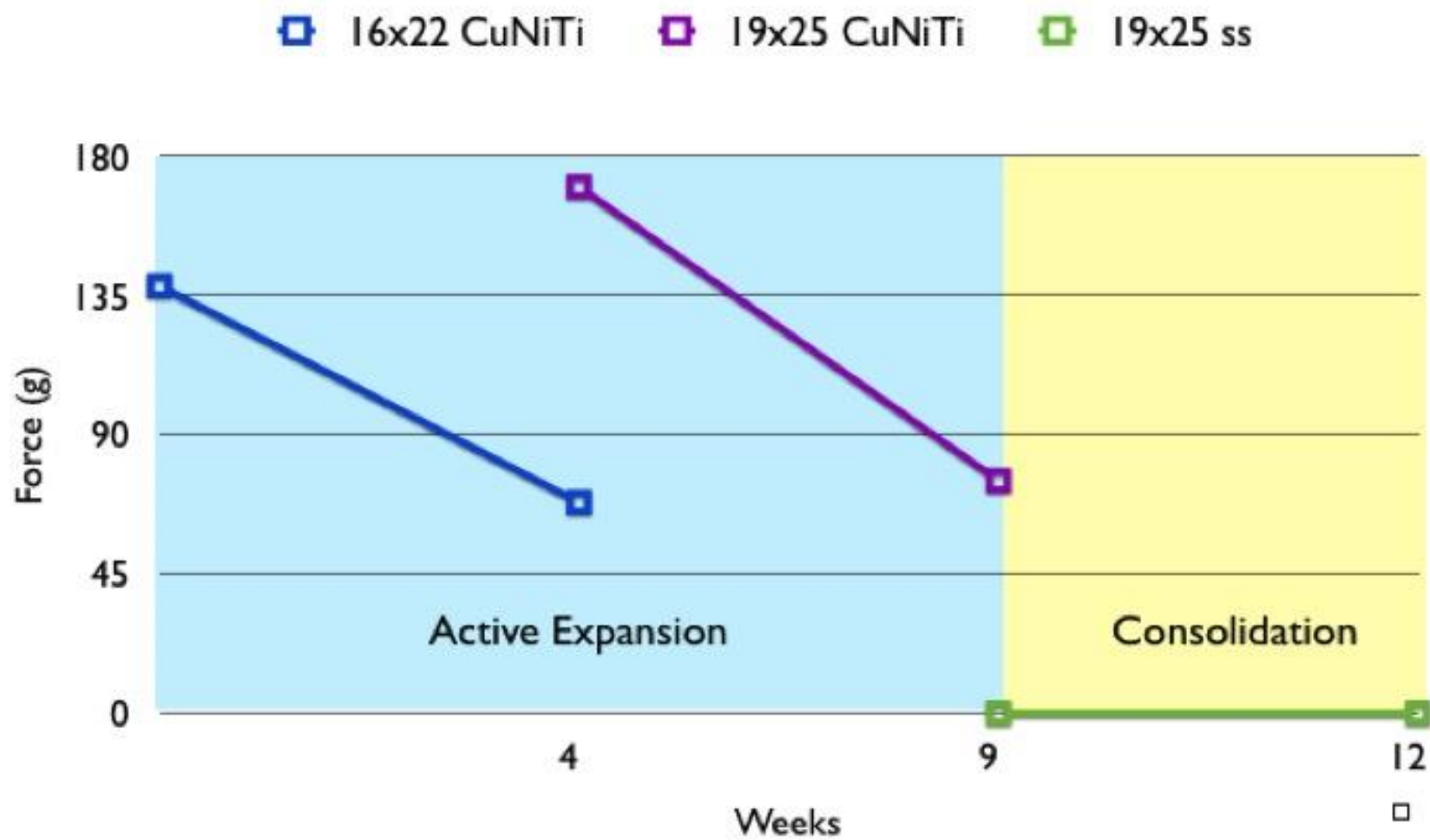
Figure 8. Force Measurements. Force, in grams, exerted by each archwire.
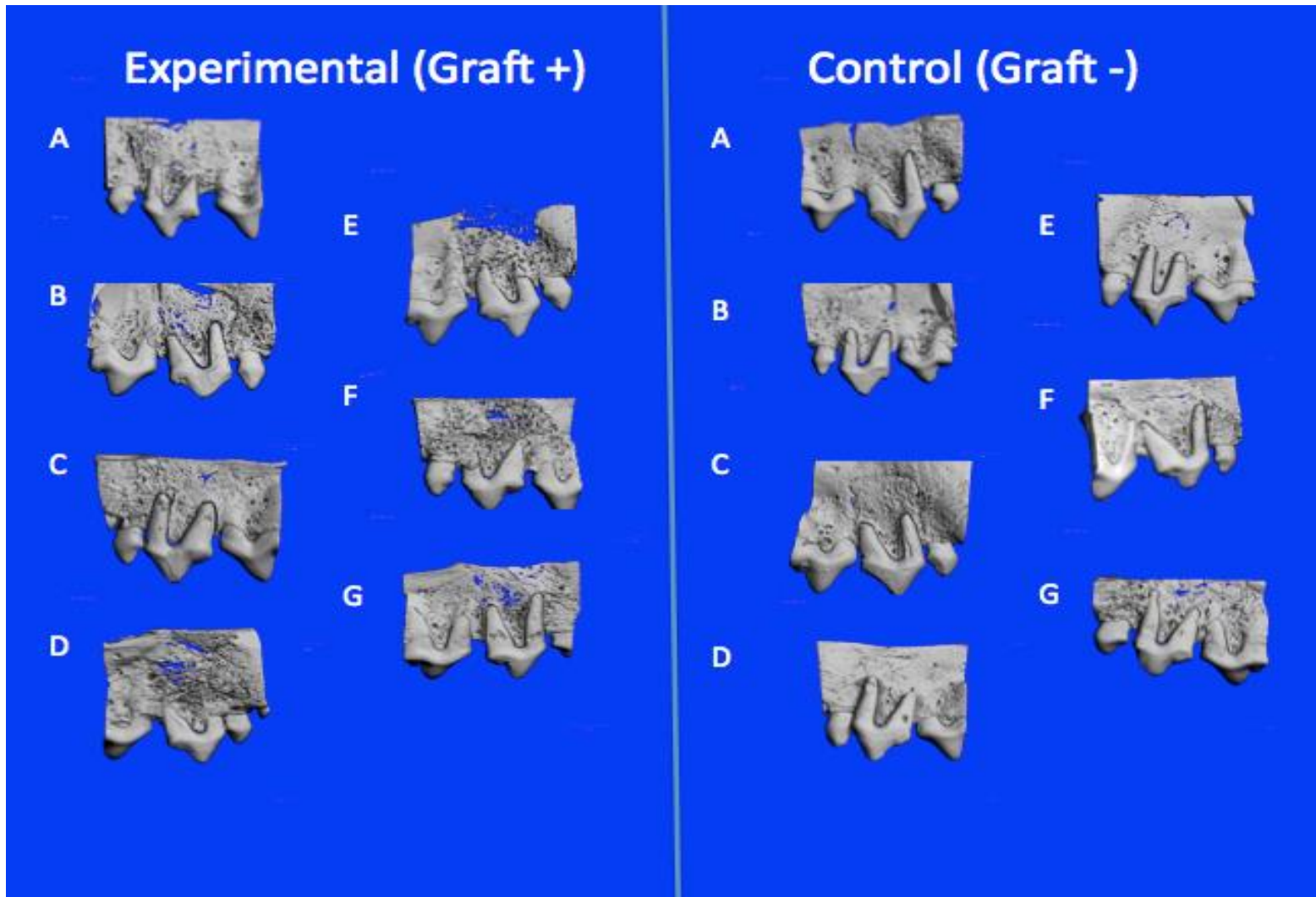
Figure 9. Three-Dimensional Micro-CT Reconstructions: Buccal View. Block sections of animals A-G. Note the severe dehiscences in the Graft – group, with generally less bone loss in the Graft + group.
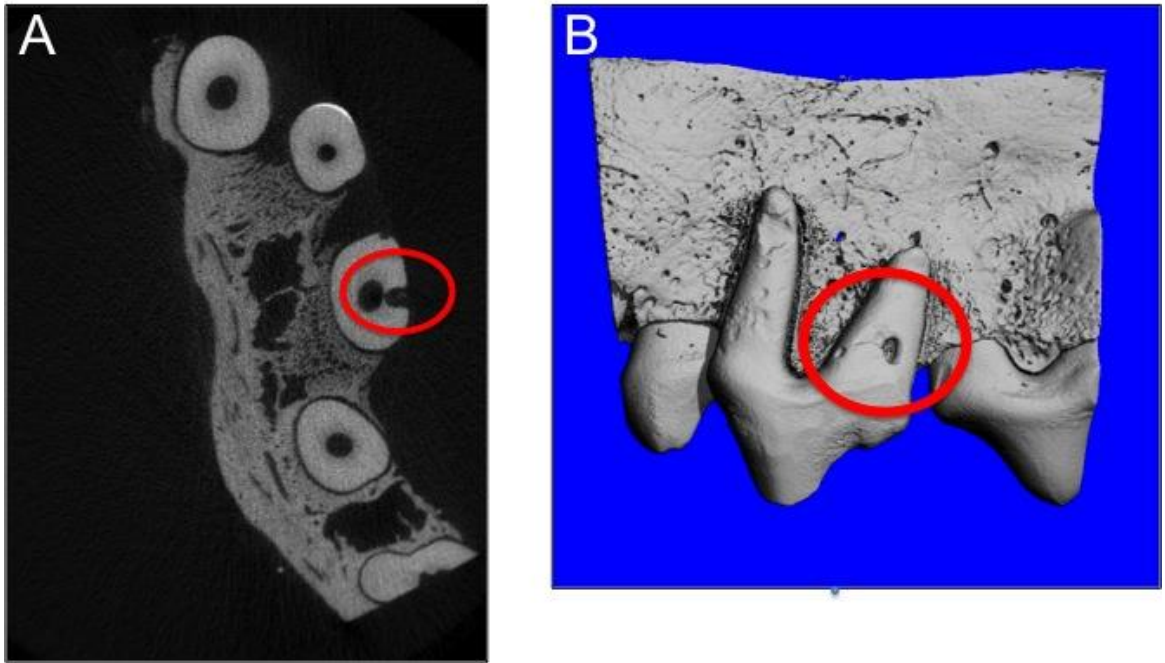
Figure 10. Two- and Three-Dimensional Micro-CT Images of Root Resorption. Two dimensional (**A**) and three dimensional (**B**) microcomputed tomographic images of dog D, depicting areas of lateral root resorption (*circled)* on the distal root of the Graft – side.
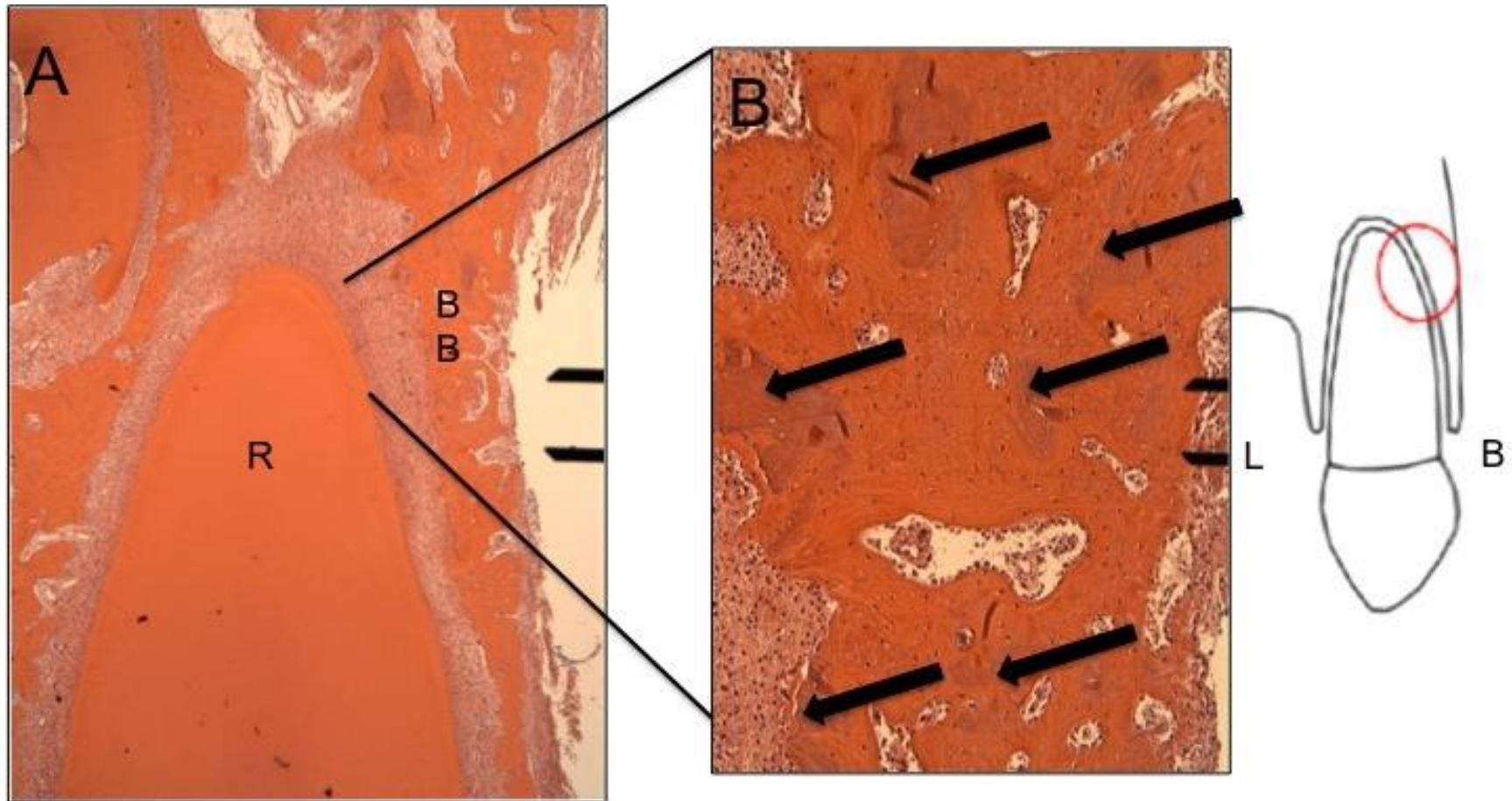
Figure 11. H&E Sections: Graft+ Side Graft Incorporation. Hematoxylin and eosin sections magnified 2.5 times (**A**) and 10 times (**B**) showing bone graft particles (*arrows*) along the buccal surface of the Graft + side. (*BB,* Buccal bone; *R,* root)
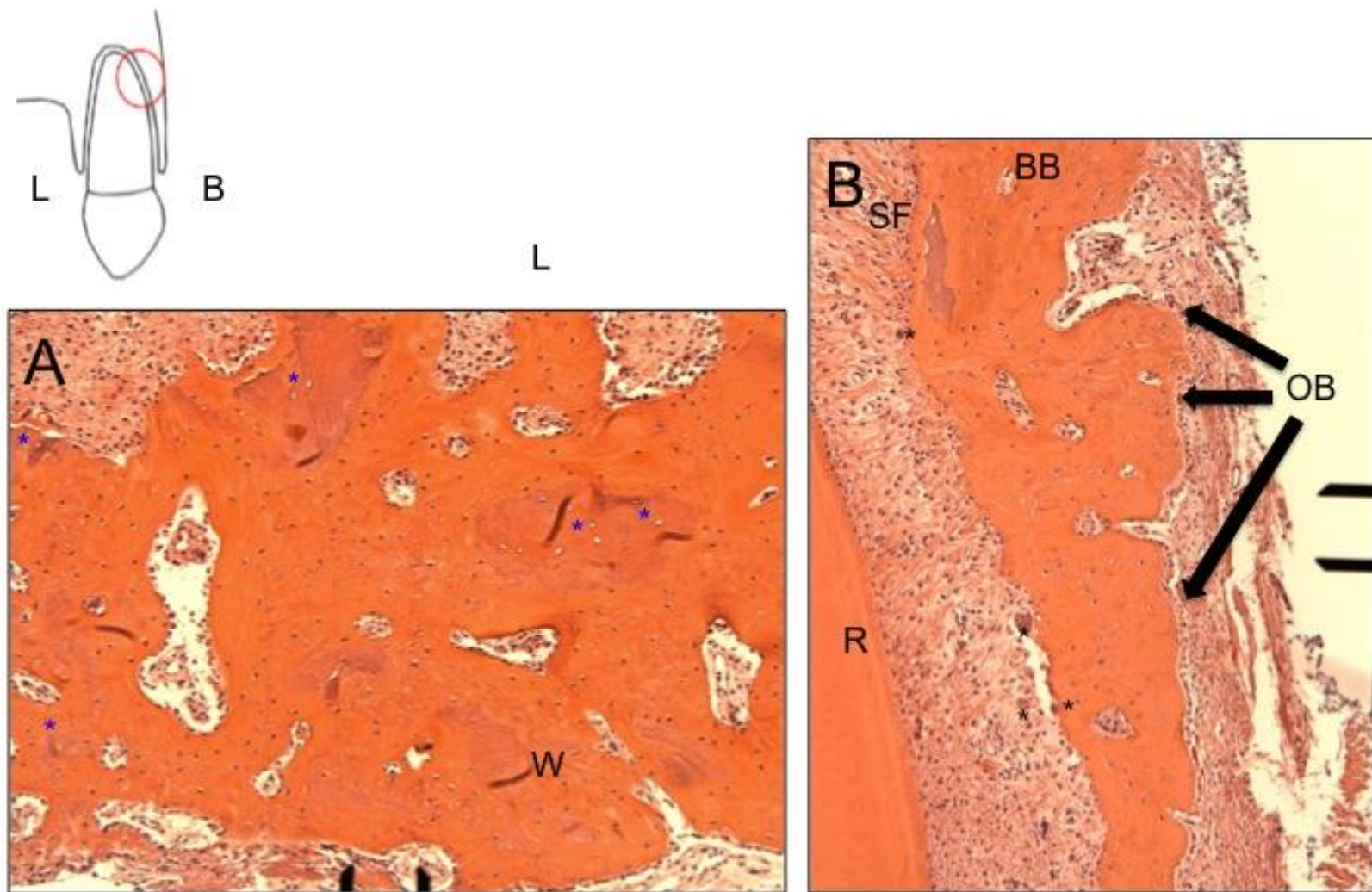
Figure 12. H&E Sections: Graft + Side Cellular Activity. Sample photomicrographs of Graft + specimens. **(A)** Note that new woven bone has been laid down adjacent to remaining graft material. Empty lacunae which previously housed osteocytes are evident within the graft particles (*blue asterisks*). **(B)** Osteoblasts (*arrows*) lined the periosteal surface of buccal bone and mature multinucleated osteoclasts (*black asterisks*) were found on the endosteal surface of buccal bone, indicating active remodeling. (*BB*, buccal bone; *W*, woven bone; *R,* root; *OB*, osteoblasts; *SF*, Sharpey's fibers)
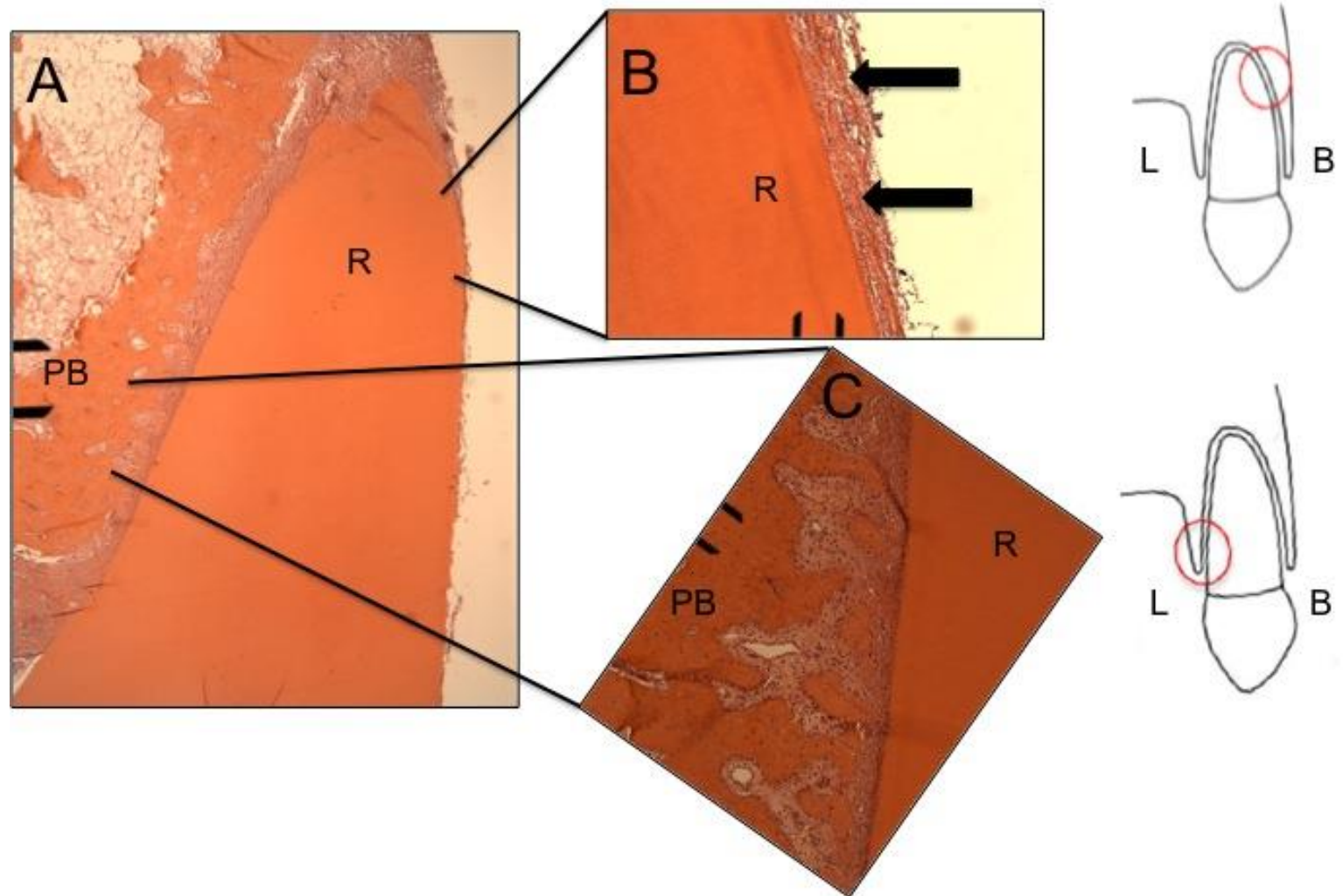
Figure 13. H&E Sections: Graft- Side. Hematoxylin and eosin sections of Graft – specimen at 2.5 times magnification **(A)**. At 10 times magnification of the buccal surface **(B)**, no bone is present until the apical 1/3; only gingival fibers (*arrows*) cover the root surface. **(C)** 10 times magnification of the palatal surface showing new islands of bone growth behind the buccally moving tooth. (*R,* root*; PB,* palatal bone)
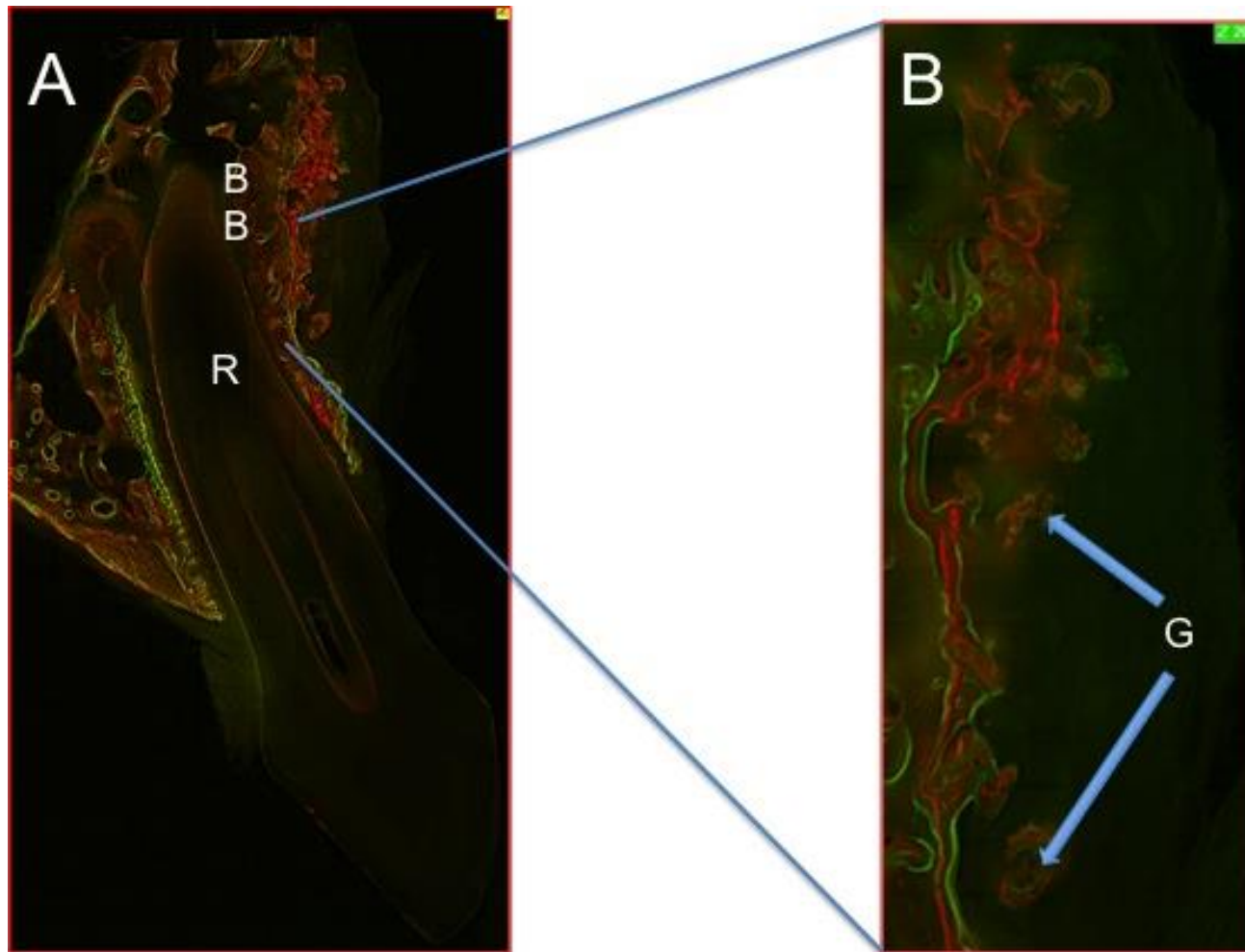
Figure 14. Fluorescence Microscopy: Graft+ Side. Vital staining with calcein (green) and alizarin (red) bone labels was performed at weeks 4, 7, and 10. **(A)** 2.5 times magnification of the Graft + side. From the palatal aspect, a uniform band of calcein and alizarin extends to the apical ¼ of the root, indicating very little tipping and more of a translatory movement. New bone formation is evidenced by distinct label lines on the periosteal surface of buccal bone in the region of graft placement. At higher magnification **(B,** *20x magnification),* regions of mixed, indistinct label lines are present where graft incorporation is occurring. (*G,* graft; *R,* root; *BB*, buccal bone)
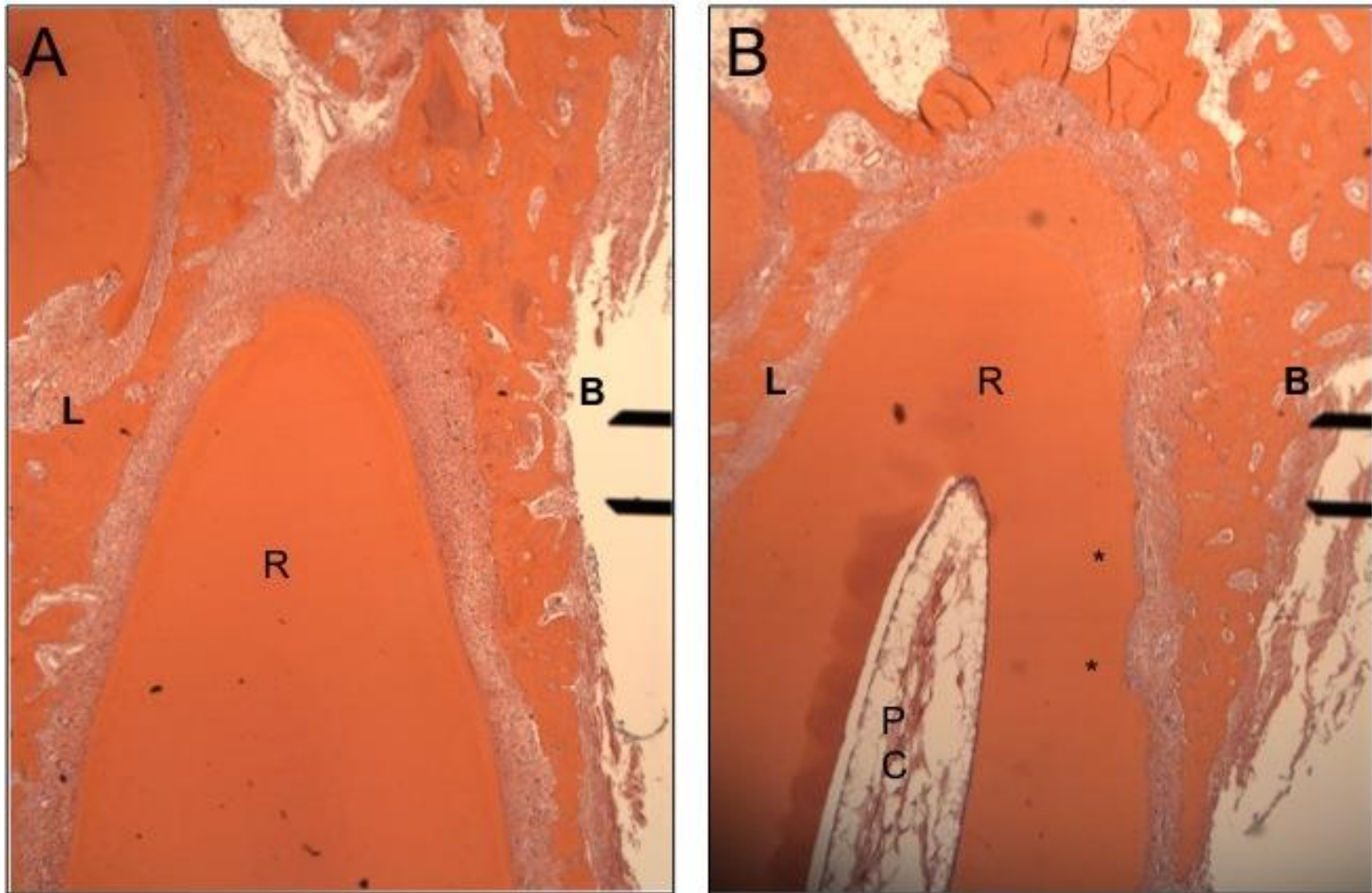
Figure 15. H&E Sections: Lateral Root Resorption. Lateral root resorption was commonly observed on both the Graft + and Graft – sides, but only at the most central aspect of the tooth in the mesial-distal direction. **(A)** Dog G Graft + section at the mesial aspect of the mesial root, depicting no severe lateral resorption. **(B)** Dog G Graft + sectioned more at the mesial root's height of contour. Here, lateral root resorption is evident (*asterisks*). (*B*, buccal; *L*, lingual; *R*, root; *PC,* pulp canal)