Volumetric analysis of root resorption craters after application of controlled orthodontic forces: A SEM study

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DEDICATION

To my wonderful mom and dad for your continual support, endless encouragement and absolute faith. Thank you for giving me this opportunity to pursue my utmost academic goal.

To my sister and my beloved niece Nicole for their support and love throughout these years.

DECLARATION

CANDIDATE CERTIFICATE

.....

(Eugene KM Chan, 2002)

This is to certify that the candidate carried out the work in this thesis in the Orthodontic Department, University of Sydney, and has not been submitted to any other University or Institution for a higher degree.

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TABLE OF CONTENTS

1	DEDICATION	2
2	DECLARATION	3
3	ACKNOWLEDGMENT	4
4	TABLE OF CONTENTS	6
5	ABSTRACT	7
6	INTRODUCTION AND AIMS	9
7	REVIEW OF LITERATURE	12
	• INTRODUCTION	12
	• STRUCTURE OF CEMENTUM	12
	• ROOT RESORPTION	27
	• ORTHODONTIC FORCES	53
	• SEM STUDIES	61
	• REFERENCES	66
8	MANUSCRIPT I	87
9	MANUSCRIPT II	149
10	MANUSCRIPT III	182
11	FUTURE DIRECTIONS	210

ABSTRACT

Root resorption has long been noted as an inevitable phenomenon in orthodontics. In previous studies, evaluation of the effects of different forces on root resorption has been limited. The technical difficulty in obtaining an accurate 3-dimensional quantitative volumetric analysis of root resorption craters has prevented the true understanding of this entity. Thirty-six upper and lower first premolar teeth from 16 patients (10 males, 6 females; mean age 13.9 years, range 11.7 – 16.1 years) requiring extractions for orthodontic treatment were collected. Speed brackets (Strite Industries, ON, CA) were bonded on the first premolars and first molars. ß-Titanium Molybdenum Alloy (TMA, Ormco, CA, USA) springs was used to activate the required forces. The right or left first premolars were randomly selected with an initial buccally directed light force of 25 grams (≈25cN) (Group 1), and a heavy force of 225 grams (≈225cN) (Group 2). Within the same patients, the contralateral sides served as controls. Premolars and molars were also bonded on the control side; but no spring was placed. After an experimental time of 28 days, the teeth were extracted and prepared for scanning electron microscope (SEM) imaging after bench drying and carbon coating. Stereo pairs of images were taken of all resorption craters at ±3° tilt and converted to 8-bit grayscale images for image analysis. 3-dimensional quantitative volumetric analysis was performed using *AnalySIS Pro 3.1** software (SIS, Münster, Ger.). This is an expanded version of a commercial software and was specially written for this study. The heavy force group demonstrated significantly greater volumetric resorption than control and light force groups ($p = 0.000$). Control and light force groups demonstrated no significant statistical difference in volumetric resorption although there was more volumetric resorption recorded in the light force

group. The mean volume of the resorption crater in light force group was 3.49-fold greater than the control group, and the heavy force group 11.59-fold more than control group. The heavy force group had 3.31-fold greater total resorption volume then light force group. All of the heavy force samples had resorption craters; however 66.6% of light force samples and only 16.6% of the control samples had resorption craters. Buccal cervical and lingual apical regions demonstrated significantly more resorption craters than the other regions ($p = 0.000$). This corresponds well to the tipping forces applied to the teeth. It is concluded that heavy orthodontic forces cause more root resorption than light forces after 28 days of force application.

* The authors have no commercial interest in Soft Imaging Systems (SIS).

INTRODUCTION

Root resorption appears to be an inevitable sequel to orthodontic tooth movement, (DeShields, 1969; Barber and Sims, 1981) occurring either apically (Kennedy, 1983; Kaley and Phillips, 1991) or along root surfaces in and around pressure zones (Reitan, 1964; Hemley, 1941; Vardimon, 1991). Nevertheless, it has been shown that roots of untreated permanent teeth also demonstrate sites of resorption, particularly on surfaces facing the direction of physiologic movement (Henry and Weinmann, 1951).

Although iatrogenic root resorption may seem to compromise the benefits of successful orthodontic outcome, most root loss due to orthodontics does not decrease the longevity or the functional capacity of the teeth involved (Brezniak and Wasserstein, 1993; Remingtion *et al.*, 1989; VonderAhe, 1973).

The type of treatment largely determines the location of resorption. In palatal expansion, resorption develops mainly in the cervical part of the mesiobuccal surfaces and furcation areas with only limited involvement of other areas (Vardimon, 1991). However, such cervical resorption generally remains undiagnosed unless it is extensive, whereas apical root resorption is often readily visible on radiographs (Barber and Sims, 1981; Wainwright, 1973; Harry and Sims, 1982).

Susceptibility to root resorption varies considerably. Teeth with radiographic signs of resorption prior to treatment have been reported to develop more extensive areas of resorption than initially intact teeth (DeShields, 1969; Zachrisson, 1976; Goldson and Henriksen, 1975). However in most cases, the outcome is very unpredictable.

The most commonly affected teeth (in decreasing frequency) are maxillary incisors, maxillary canines, mandibular incisors, mandibular first molars, mandibular second premolars and maxillary second molars (Brezniak and Wasserstein, 1993).

Whenever extensive areas of resorption occurs, predisposing factors have been proposed: vitality of the pulp (Spurrier and Hall, 1990), gender of the patient (DeShields, 1969), type and mechanics of force delivery (DeShields, 1969; Reitan, 1964; Goldson and Henrikson, 1975), bone density (Reitan, 1964; Wainwright, 1973), magnitude and duration of the force (DeShields, 1969; Kennedy and Joondeph, 1983; Reitan, 1964; Harry and Sims, 1982; Reitan, 1974) and systemic factors (*e.g.* endocrine disorders, asthmatics) (Becks 1939; McNab *et al.,* 1999).

The topography of tooth root surfaces has been examined using radiographs (Ketcham, 1927), light microscope (Reitan, 1974) and scanning electron microscope (SEM) (Jones and Boyde, 1972; Kvam, 1972a, 1972b). It has been reported that SEM provides enhanced visual and perspective assessment of root surfaces, and when recorded in stereo pairs, they provide resolution and detail not attainable with histological models reconstructed from serial sections (Reitan, 1974).

The aims of this study were 5-folds.

(i) To develop a protocol to allow volumetric measurement of root resorption craters on controlled samples of human premolar teeth;

(ii) To reproduce a digital 3-dimensional replica of root resorption craters;

(iii) To evaluate the effect of orthodontic force magnitude on volume of root resorption craters;

(iv) To identify the sites that may be predisposed to root resorption by volumetric measurement of root resorption craters; and

(v) To calibrate the commercial software *Analysis Pro 3.1* on accuracy of volumetric measurement.

REVIEW OF LITERATURE

INTRODUCTION

Apical root resorption has been reported to be a common idiopathic problem associated with orthodontic treatment. Loss of apical root material is unpredictable and when extending into dentine, is irreversible. Histological studies have reported high incidence while clinical studies have revealed a more varied finding. Extensive root resorption during orthodontics may compromise the benefits of an otherwise successful orthodontic outcome. However, most root loss resulting from orthodontic treatment does not decrease the longevity or the functional capacity of the involved teeth (Brezniak and Wasserstein, 1993).

Although most root resorption studies have attempted to investigate the aetiologic factors and predictability of this phenomenon, its origins remain obscure. Individual susceptibility, hereditary predisposition, systemic, local and anatomic factors associated with orthodontic mechanotherapy are commonly cited factors.

STRUCURE OF ROOT CEMENTUM

During orthodontic treatment, the movement of teeth would involve very much the remodelling of the dentoalveolus as well as the periodontium. The principle active biologic unit during tooth movement is the periodontium (Brezniak and Wasserstein, 1993). The only barrier to protect the cementum from resorptive attack of the osteoclast cells was thought to be the formative cell layer covering it (Tronstad, 1988;

Wesselnick *et al.*, 1988; Jones *et al.,* 1988). If there was a breach of this protective formative cell layer, the mineralized tissue and the periodontal matrix will come into direct contact (Jones *et al.*, 1988). This may also occur when the cementum is mechanically damaged (Tronstad, 1988).

Characteristics of Cementum

Cementum has been described as a non-uniform mineralized connective tissue. It has several morphological types in human. They differ with respect to structure, location, function, and rate of formation (Jones *et al.,* 1988). The function of cementum and its structure, in respect to the different types has been described in detail previously (Jones *et al.*, 1988; Bosshardt, 1997; Jones *et al.*, 1981; Schroeder, 1986, 1993).

Initial examination of cementum on the roots of human teeth was performed by Ringelmann in 1824 (Blackwood, 1957) followed by physiologist, Jan Evangelista Purkinje and his pupils Frankel and Raschkow in 1835 and later by the classic histologist Anders Adolf Retzius in 1837 (Schroeder, 1986).

Irrespective of the functional status of teeth (*i.e.* whether they are still erupting, totally erupted, in occlusion or impacted), root cementum is always present on some aspect of the tooth and develops with the growing root and, subsequently on established root surfaces. Cementum protects the dentine of the root, it adds to the size and volume of roots, and it fulfils the role of repair and regeneration. Unlike bone, cementum is not vascularized and does not undergo continuous mineral turnover. Cementum may be formed at any stage in the life of a tooth. It is an adaptable component which, by

means of apposition and patch-wise resorption, and may also respond to changing functional demands. Cementum is an essential component of the established periodontium, providing means of functional tooth support. It may also be an important element in tooth eruption, permitting adjusting movements of the tooth to occur in any direction (Schroeder, 1986).

Most of the data available for measurement of root surface area of the various types of teeth are derived from the application of the "membrane technique", or its modifications. This technique was first described by Brown in 1950. He poured latex solution onto extracted teeth and allowed it to set. It was then removed from the tooth and the surface area of the latex measured. The first permanent molars in both jaws have the largest root surface area, and, in decreasing order, are followed by second molars, canines, the premolars, and the central and lateral incisors. Root surface area estimated by other methods such as root shadow roentgenogram (Jepsen, 1963), benzene vapour absorption technique (Luthra *et al.,* 1974), Marconi Bridge apparatus (Despeignes, 1979) and computer aided digitization (Nicholls *et al.,* 1974; Levy and Wright, 1978; and Hermann *et al.*, 1983) compares favourably with those obtained by the "membrane technique" (Schroeder, 1986). The total root surface area of permanent molars is about 430 mm^2, premolars is about 250 mm^2, while incisor roots vary between 150 and 200 mm^2. This data has conceptual implications with regards to root surface areas remaining available for attachment after destructive phases of periodontitis or for tooth movement during orthodontic treatment.

Structure and Classification of Cementum

Cementum has been described as 'bonelike' (Ten Cate, 1994). As a mineralized substance, its composition is similar to bone. It is a specialized connective tissue, but unlike bone, it is avascular. It is the least mineralized of the three dental hard tissue components. Approximately 50 - 60% of cementum by weight is mineralised consisting of hydroxyapatite crystals, and the remaining proportions are organic constituents, predominantly collagen (approximately 25%) and water (approximately 15%).

At the cemento-enamel junction (CEJ), cementum is formed as a thin layer approximately 20-50 μm thick that widens to be approximately 150-200 μm at the apex (Ten Cate, 1994). The structure of the human CEJ may vary from animal models.

Frequently, the defining circumstances for overall genesis, distribution, accumulation, and thickness of cementum found at various sites of a particular human tooth specimen under investigation are unknown. For these reasons the structural aspects of the varying types of cementum have been used to classify the cementum as well.

Based on the classification adopted by Schroeder (1986), the structural features of the various types of root cementum can be examined according to their classification. Cementum has been classified several ways that often shadow each other but are recognized as distinct classifications. Early classification of cementum recognized

two basic types of cementum that were observed during the formation and eruption of the teeth. They are: primary and secondary cementum.

Primary and Secondary Cementum

Cementum that is formed during the development and eruptive adjustment of the tooth has been described as primary cementum (Thoma and Goldman, 1939). Primary cementum is essentially hyaline and the course of Sharpey's fibres can be seen distinctly. It does not have cellular elements and is in immediate contact with the dentine, covering almost its entire surface (Held, 1951).

As the tooth erupts a certain amount of cementum may continue to form through apposition. This additional deposit of cementum is secondary cementum. Its structure resembles that of bone, containing lacunae in varying numbers. It is thicker than the primary cementum, and it is particularly abundant in the apical region (Held, 1951).

Excess apposition of secondary cementum is referred to as hypercementosis. Ten Carte (1994) reports that secondary cementum overlies primary cementum and may be either cellular or acellular. Historically, the primary and secondary classification of cementum was replaced by the cellular classification. Two types of root cementum (acellular and cellular) were later described (Schroeder, 1986).

Acellular and Cellular Cementum

The cells associated with cementum are cementoblasts and cementocytes (Ten Cate, 1994). Cementoblasts form cementum and line the root surface. These cells are interposed between bundles of periodontal ligament (PDL) fibres. A two-layered arrangement has been described (Berkovitz *et al.,* 1982) and differs between mammals. A primary layer of acellular cementum is present on all mammalian roots while the secondary layer of cellular cementum varies in thickness and distribution (Berkovitz *et al.,* 1982).

Acellular Afibrillar Cementum (AAC)

Acellular afibrillar cementum (AAC) contains neither cells nor extrinsic or intrinsic collagen fibres. It is simply a mineralized ground substance, believed to be a product of cementoblasts. In human it is found as coronal cementum covering the enamel surface and as part of acellular-extrinsic-fibre cementum. Its thickness ranges between 1 and 15 μm (Schroeder, 1986).

Acellular Extrinsic Fibre Cementum (AEFC)

Acellular extrinsic fibre cementum (AEFC) is composed almost entirely of densely packed bundles of Sharpey's fibres and lacks cells. It may be a co-product of fibroblasts and of cementoblasts providing the ground substance and may contain patches or layers of AAC. In human, it is primarily found on the cervical third of

roots but may also extend further apically. Its thickness ranges between about 30 and 230 μm (Schroeder, 1986).

Cellular, Mixed Stratified Cementum (CMSC)

Cellular, mixed stratified cementum (CMSC) is composed of extrinsic (Sharpey's) and intrinsic fibres, varying in proportion from one layer to the next, and may contain cells with uneven distribution and density. It is a co-product of cementoblasts and of fibroblasts. Its strata or layers are very irregular and patchy. They may be layers of AEFC and CIFC superimposed upon one another. In human, CMSC occurs primarily in the apical third of the root and the furcations. It forms the tip of the apex and accumulates in root surface concavities, extending coronally to a variable extent. Its thickness varies between 100 and 1000 μm or more (Schroeder, 1986).

Cellular Intrinsic Fibre Cementum (CIFC)

Cellular intrinsic fibre cementum (CIFC) contains cells but no collagen fibres that extend into the periodontal ligament; that is, all collagen fibres are intrinsic. It is a product of cementoblasts and, in the human, is found mainly as a substance formed in repair of resorption lacunae of the root. Its thickness varies with the depth of resorption.

CIFC is believed to be identical in structure to the intrinsic component of CMSC in that it resembles CMSC without Sharpey's fibres (Jones, 1981). CIFC is a common but inconsistently formed tissue. Its function is not for generating tooth support, although "the lack of extrinsic fibres may be only transitory" (Jones, 1981). CIFC is seen under conditions of repair following spontaneous or induced root resorption in deciduous and permanent teeth.

Fibrillar Classification of Cementum

Herbivores have demonstrated a cementum layer covering the enamel surface. The term "coronal cementum" describes this layer. This description is not ideal for all animals as those such as the rabbit, having continuous tooth eruption, do not permit a clear-cut anatomical division of crown and root (Listgarten and Kamin, 1969). Coronal cementum was therefore termed "afibrillar cementum" in contrast to "fibrillar cementum" which does contain collagen fibrils. Coronal cementum was later shown to include cellular and fibrillar portions (Listgarten and Kamin, 1969) and therefore coronal cementum may have a variety of different morphological characteristics, i.e. it may be cellular-fibrillar, acellular-fibrillar, and acellular-afibrillar.

Jones (1981) improved the description of Listgarten and Kamin (1969) by proposing a classification based upon the presence or absence of two main components of cementum; cells and Sharpey's fibres.

This was an even more detailed classification primarily based on the fibrillar component:

a. afibrillar (acellular)

b. extrinsic fibre (acellular)

c. mixed (extrinsic, intrinsic) fibre;

(i) acellular

(ii) cellular

d. intrinsic fibre (cellular)

For Jones (1981), the fibrillar component is the main functional component of cementum. She differentiated between collagen fibres formed outside the cementum (extrinsic) and fibres laid down in the plane of newly developing cementum layers (intrinsic). Extrinsic cementum is a product of fibroblasts of the dental follicle. It is attached to the periodontal ligament, which becomes incorporated as the Sharpey's fibres. They are roughly perpendicular to the developing cementum. Intrinsic cementum is believed to be a product of cementoblasts, unrelated to and not continuous with collagen fibres of the periodontal ligament.

Formation of Cementum

Cellular Types

Cementum is the product of cementoblasts, cementocytes, and fibroblasts of the periodontal ligament. All three cell-types originate as daughter cells from the ectomesenchymal cell population of the dental follicle proper (Schroeder, 1986).

Cementoblasts

Cementoblasts are found exclusively at the cementum-PDL interface. Resembling osteoblasts, they are cuboid in shape and their structure is similar to that of cells actively synthesising proteins and polysaccharide-complexes (Bevelander and Nakahara, 1968; Jande and Belanger, 1970; Furseth and Mjör, 1973). They may project a variable number of cytoplasmic processes and their actual shape depends on their position between collagen fibres (Schroeder, 1986).

Cementocytes

Cementocytes are derived from cementoblasts and are enclosed in the product they secrete. Structurally and functionally, they resemble osteocytes. They vary in distribution and density in Cellular Mixed Stratified Cementum (CMSC) and Cellular Intrinsic Fibrillar Cementum (CIFC). Young and mature cementocytes can be differentiated (Bevelander and Nakahara, 1968). With increasing maturation, cementocytes decrease in size, but their lysosomal bodies and autophagic vacuoles increase in number. Cementocytes located deep in the cementum often show signs of disintegration and shrinkage. They also exhibit the structural signs of vital cells of variable metabolic activity (Furseth, 1969, 1970). They have many long cytoplasmic processes of up to 15 μm in length. These processes project in all directions, but those approaching the cementum surface are longer and more numerous. Analogous to osteocytes, cementocytes can engage in "cementolytic' activity, which is parathyroid-hormone dependent and can respond to nutritional secondary

hyperparathyroidism and may contribute to regulating calcium phosphate metabolism (Henrickson, 1968; Jande and Belanger, 1970).

Fibroblasts and Cells of the PDL

The PDL consists of cells, connective tissue fibres, and interstitial tissue, with ground substance, blood and lymphatic vessels, and nerves. Fibroblasts found within developing or established PDL are a particular class of connective tissue cell.

Within the ligament there are four major types of cells described (Berkovitz and Shore, 1982):

a. connective tissue cells,
b. epithelial cells,
c. defence cells, and
d. cells associated with neurovascular elements

Connective tissue cells include various populations of fibroblasts, osteoblasts, cementoblasts, osteoclasts and dentoclasts. Epithelial cells occur in the form of strands and islands of the Rests of Malassez. Defence cells, such as macrophages, lymphocytes, granulated leucocytes, and mast cells, may be seen occasionally in the non-inflamed, healthy periodontal ligament.

The most common cell of the PDL is the fibroblast and it occupies approximately 50% of the volume of the densely collagenous portions within the PDL (Shore and Berkovitz, 1979). The majority of research about this cell is based on animal studies,

particularly the rodent. In human, PDL fibroblasts appear as ovoid or flattened cells (Schroeder, 1986). Generally, the shape of PDL fibroblasts varies with their orientation between connective tissue fibres. In regions where fibres and fibre bundles are densely packed and follow a straight course from bone to cementum, fibroblasts may appear elongated and are orientated along the fibre axis, while in the loose interstitial tissue associated with neurovascular elements the fibroblasts may be ovoid, spindle-shaped or elongated.

Root resorption, in the form of single, grouped or patch-like crater defects of varying size and depth, occur lateral and apical to the roots even when they are caries free and periodontally healthy (Massler and Malone, 1954; Harvay and Zander, 1959; Harry and Sims, 1982). Resorption, particularly in the periapical region and at mesial root surfaces is, observed facing the direction of physiological tooth movement (Henry and Weinmann, 1951; Massler and Malone, 1954). The number and extent of root resorption defects, including repaired defects, increases with age. The resorption potential also varies between individuals and the susceptibility to root resorption differs from tooth to tooth.

Henry and Weinmann (1951) found a number of resorption defects, but approximately 75%, are confined to the apical third of the root. Such resorption defects are rare in the cervical third of the root. In the mid-root and apical regions of mesial and buccal root surfaces, resorption defects are more numerous when compared to distal and lingual surfaces. Resorption defects are approximately 1 mm in diameter and about 100 μm in depth with mesial and buccal defects larger than distal and lingual defects. Most defects are limited to cementum, but about 30% penetrate into dentine (Henry

and Weinmann, 1951; Schroeder, 1986). In histological sections, the vast majority of resorption defects are demarcated by retained reversal lines and near completed anatomical repair. Thus the frequency of root resorption episodes may well approach 100% of the erupted, permanent teeth. Traumatic injuries and orthodontic treatment would increase the number and extent of resorption defects. This is particularly so in axially intrusive, horizontal movements and forces beyond physiological limits (Kronfeld, 1938; De Shields, 1969; Kvam, 1972c; Reitan, 1974; Rygh, 1977; Harry and Sims, 1982).

In all cases associated with trauma and treatment, external resorption of cementum and dentine is initiated in regions of a remodelling but previously disturbed, damaged, or partially necrotized periodontal ligament. Resorption usually starts from the periphery of such lesions (Rygh, 1977). Multinucleated giant cells with morphology identical to osteoclasts generate and drive this resorption.

Small defects approximating 15-20 μm in diameter and up to 10 μm deep may be caused by a single dentoclast, whereas larger craters result from groups of such cells acting in concert (Schroeder, 1986). It has frequently been stated that root cementum is more resistant to resorption than bone, and that this resistance is due to the presence of cementoid. Jones (1981) argued that a distinct layer of cementoid is particularly prominent in phases of active cementogenesis. Resorption would act during a resting phase, attacking both mineralized cementum and pre-cementum.

Lindskog and Hammarström (1980) demonstrated that like cartilage, dental cementum or PDL contained an anti-invasion factor, which acted as an inhibitor of proteases

such as trypsin and collagenase. Whether or not this factor prevents the root surface from being attacked under certain conditions is unknown.

The bottom of resorption craters, as seen with the scanning electron microscope (SEM) is scalloped and corresponds to a reversal line in histological sections. Under conditions of repair, it is first filled by CIFC and subsequently this CIFC may become coated with AEFC. Initially, a thin layer of CIFC lines the scalloped bottom of the crater and smoothens it while most of the AEFC still contains PDL tissue and numerous cells (probably cementoblasts) are laid down on the CIFC surface. In later stages most of the dentinal crater, up to the level of AEFC, becomes filled with CIFC.

In the adjacent periodontal ligament, there is no preferential orientation of collagen fibres and they are not incorporated in CIFC. Eventually, with the fibres assuming proper alignment, a variably thick layer of AEFC may form on top of the CIFC (Henry and Weinmann, 1951; Jones, 1981).

The inorganic structural appearance of CIFC, formed in resorption lacunae of teeth moved orthodontically, is identical to that seen in deciduous teeth prior to their exfoliation (Schroeder, 1986). Eventual re-incorporation of Sharpey's fibres may occur either directly into superficial CIFC or indirectly by superimposition of AEFC. Periods of alternating resorption and repair may follow each other at a particular region. Thorough observation of retained and partially broken reversal lines and appositional lamellae, such phenomena can be detected in histological sections (Henry and Weinmann, 1951; Jones, 1981).

It has been noted that most external root resorption, once activated, is self-limiting. For this reason approximately 70% of all defects seen in old teeth are anatomically repaired (Henry and Weinmann, 1951).

Intermediate Cementum

In addition to the four 'major' types of cementum, there is an ill-defined layer, termed "intermediate cementum." The original research on cementum during mid 1800's demonstrated the existence of protoplasmic communications across the junction of cementum and dentine (Blackwood, 1957). Tomes (1914) stated that the cementum is connected to the dentine through the granular layer of dentine. This layer is external to the granular layer of Tomes and forms the apical part of the dentino-cemental junction, whereas in the coronal half of the root the hyaline, homogeneous layer of Hopewell-Smith (1920) forms this junction.

Bencze first introduced the term "intermediate cementum" in 1927 (Schroeder, 1986). This was in order to designate a peripheral, narrow layer including cellular remains, which is found between dentine and cellular root cementum in the apical half of the root. Both the layer of Hopewell-Smith and the intermediate cemental layer are not well defined (Schroeder, 1986).

ROOT RESORPTION

Definition

Historically, root resorption has been defined as destruction of formed tissue (Becks and Marshall, 1932). Surface root resorption may now be defined as the active removal of mineralized (and a thin layer of non-mineralized) cementum and dentine (Brudvik and Rygh, 1994). The loss of dental substance apically is often unpredictable and if destruction has extended into dentine, it may be irreversible. Although iatrogenic root resorption may seem to compromise the benefits of successful orthodontic outcome, most root loss due to orthodontics does not decrease the longevity or the functional capacity of the involved teeth (Brezniak and Wasserstein, 1993).

History

Bates first reported root resorption of permanent teeth in 1856. Ottolengui, in 1914, related root resorption directly to orthodontic treatment, and referred that Schwarzkopf in 1887 demonstrated resorbed roots in extracted permanent teeth. In 1927 root resorption was a subject of major concern to the orthodontic field. Ketcham (1927, 1929), demonstrated, with radiographic evidence, the differences between root shape before and after orthodontic treatment. He observed that root resorption occurred in every group of patients regardless of the method used to move their teeth. This was subsequently followed by a myriad of histologic, clinical, and physiologic research on root resorption and orthodontic treatment.

Classification

Phillips (1955), Reitan (1985), and Shafer *et al.* (1983) enumerated the various major factors causing root resorption of permanent teeth. Physiologic tooth movement, pressure from adjacent impacted tooth, periapical or periodontal inflammation, tooth implantation or re-implantation, continuous occlusal trauma, tumours or cysts, metabolic or systemic disturbances, local functional or behavioural problems, orthodontic treatment and idiopathic factors have all been implicated.

Andreasen (1988) defined three external root resorption types:

- Surface resorption, which is a self-limiting process, usually involving small outlining areas followed by spontaneous repair from adjacent intact parts of the periodontal ligament.
- Inflammatory resorption, where initial root resorption has reached dentinal tubules of an infected necrotic pulpal tissue or an infected leukocyte zone.
- Replacement resorption, where bone replaces the resorbed tooth material that leads to ankylosis.

According to Tronstad (1988), inflammatory resorption is related to the presence of multinucleated cells that colonise the mineralized or denuded cemental surface. He described two kinds of inflammatory resorption.

- Transient inflammatory resorption occurs when the stimulation to the damage is minimal and for a short period. This defect is usually undetected radiographically and is repaired and replaced by a cementum-like tissue.

- Progressive inflammatory resorption. If inflammation persist for a longer period of time, ankylosis may be the result of this extensive necrosis of the PDL with formation of bone onto a denuded area of the root surface. Since the tooth becomes a part of the bone, normal remodelling process will gradually lead to a complete destruction of the tooth by the bone (replacement resorption).

Root resorption after orthodontic treatment is often surface resorption (Andreasen, 1988) or transient inflammatory resorption (Tronstad, 1988). Replacement resorption is rarely if ever, seen after orthodontic treatment.

Incidence

Although this varies in different studies, most agree that idiopathic root resorption do occur in the untreated population. A high percentage (90.5%) of untreated permanent teeth display microscopic lesions of external root resorption (0.73 mm length and 0.10 mm depth). The most frequent site is at the apex, followed by mesial, buccal, distal and lingual surfaces. The differences between right and left sides or maxillary and mandibular teeth are negligible. However molars exhibited greater resorption areas as the total surface area was greater (Henry *et al.*, 1951). The numbers of incisors with root resorption increases from 15% (before treatment) to 73% (after treatment) (Lupi, 1996). In another study by Goldson *et al.* (1975), they reported an incidence raging

from 4% (before treatment) to 77% (after treatment). Factors affecting incidence include orthodontic movement, types of movements and amount and length of time. Root resorption usually does not start immediately but remains active once started until the end of treatment (Linge, 1993).

Root resorption process

Root resorption of the deciduous dentition is a normal, essential, and physiologic process. Usually it is a necessary precursor to the eruption of the permanent teeth (Cahill, 1988; Belanger, 1985; Sasaki, 1988a, 1988b; Ten Cate, 1989; Ngan, 1988a; Phillips, 1955). Some deciduous teeth undergo root resorption even with agenesis of the succedaneous teeth. Root resorption of the permanent teeth however, is a complex biologic process of which many aspects still remain unclear.

Root resorption has long been thought to result from the action of the odontoclasts, cells with similar cytological and functional characteristics of the osteoclasts (Ten Cate, 1998; Jones *et al.*, 1986, 1988; Lindskog *et al.,* 1987, 1988; Boyde *et al.*, 1985; Hammarström *et al.*, 1985). The osteoclast is a large pleomorphic multinucleated cell formed by fusion of mononuclear precursor. It is characterized by a ruffled border pointed towards the hard tissue surface (Jones *et al.*, 1988; Lindskog *et al.,* 1987; 1988; Hammarström *et al.*, 1985; Marks, 1983). There is a consensus that the osteoclasts are of haematopoietic in origin that originated from the bone marrow (Takahashi *et al.*, 1989; Marks, 1983; Osdoby *et al.*, 1982; Marks and Walker, 1981), and that the dissemination of their precursors is through the vascular system (Kahn, 1988).

Brudvik and Rygh (1994) used Tartrate Resistant Acid Phosphatase (TRAP) staining techniques as originally proposed by Cole and Walters (1987) to identify clast cells as well as their precursors. The level of enzyme tartrate resistant acid phosphatase activity expressed by TRAP positive staining reaction, on bone, root and in the PDL indicates the level of clast cell activity and hence the magnitude of the resorptive process. The origin of odontoclasts and osteoclasts may be similar. Osteoclasts arrive at the resorptive site via the bloodstream as mononuclear cells derived from haemopoietic precursors in the spleen or bone marrow (Pierce *et al.,* 1991). As a consequence, the proximity of blood vessels may be an essential factor in the resorption process. However, a local tissue contribution has not been ruled out (Andreasen, 1988; Marks, 1983; Roberts, 1975). Therefore alveolar bone osteoclasts may have precursors from both vascular and local sources.

Reitan (1974) suggested that when the surface cell layer was breached, the epithelial barrier may permit blood vessel access to the tooth surface and the resorptive process can begin. Resorption of the calcified dental tissues occurs when osteoclasts have access to the mineralized tissue through a breach in the formative cell layer covering the tissue (Tronstad, 1988; Jones and Boyde, 1988; Lindskog and Pierce, 1988). It can also occur if the pre-cementum is mechanically damaged or scraped off (Tronstad, 1988; Wesserlink and Beertsen, 1988) or when the mineral and matrix surfaces coincide (Jones and Boyde, 1988). The mineralized or denuded root areas attract hard tissue resorbing cells to colonize the damaged areas of the root (Brudvik and Rygh, 1993; Lindskog *et al.,* 1987). Alteration in levels of cytokines and growth factors may have modified cellular metabolism, which modulate the activity of both osteoblasts and osteoclasts (Centrella *et al.,* 1992).

Resistance to resorption is attributed to the innermost cellular layer of the periodontal ligament, which provides protective as well as a repair mechanism to the root surface (Andreasen, 1988). Although the precise mechanism is unknown, cells providing such action include cementoblasts, fibroblasts, osteoblasts, endothelial and perivascular cells. Small areas of surface resorption are repaired by the formation of new cementum and PDL fibres from adjacent vital parts of the periodontal ligament. Larger zones of damage are repaired by ankylosis by cells derived from the alveolar bone and bone marrow (Andreasen, 1988).

Jones and Boyde (1988) suggested that the cellular layer covering the root surface such as Sharpey's fibers, cementum, cementoid and Malassez epithelial cells might contribute to root surface protection. Uncalcified mineral tissues, osteoid, pre-cementum and pre-dentine have been reported to be resistant to resorption and prevent initial loss of root tissue (Reitan, 1985). However, continuous pressure will eventually lead to resorption of these areas (Tronstad, 1988; Reitan, 1985).

The resorption of the root requires the removal of both the organic and mineralized components from the cemental matrix. The removal of both these components is still not completely understood. According to Jones and Boyde (1988), the osteoclasts played a role for both demineralization of the calcified tissue and degradation of the organic matrix after demineralization.

The type of root resorption that occurs during orthodontic treatment is frequently preceded by hyalinization of the PDL (Rygh, 1977). During the remodelling process the necrotic hyalinized tissue and alveolar bone wall in the hyalinized zone are

removed by phagocytic cells such as macrophages, foreign body giant cells and osteoclasts (Rygh, 1974; Kvam, 1972a-b; 1973). As a side effect of the cellular activity during the removal of the necrotic PDL tissue, the cementoid layer of the root and the bone are left with raw unprotected surfaces in certain areas that can readily be attacked by resorptive cells. Root resorption then occurs around this cell-free tissue, starting at the border of the hyalinized zone (Rygh, 1977). Brudvik and Rygh (1994) implicated mononucleated non-clast cells in the initial removal of pre-cementum and mineralized acellular cementum in the periphery of the hyalinized zone. They further suggested that multi-nucleated giant cells (MNGC) without a ruffled border and mononucleated macrophage-like cells are responsible for removal of the necrotic tissue and also for resorption of the surface parts of root cementum. In the periphery zone, fibroblast-like and cementoblast-like cells perform phagocytosis of cellular remnants and adjacent fibrous components and remove unmineralized pre-cemental structures on the root surface by collagenolytic activity (Brudvik and Rygh, 1993).

Some studies demonstrated that the resorbing activity, as a response to mechanical or chemical stimuli by the cells of the periodontal ligament, is characterized by synthesizing prostaglandin E with concomitant increase in cAMP (Ngan *et al.*, 1988b). This process is regulated by hormones parathyroid (Takahashi, 1989; Ngan, 1988a) and calcitonin (Takahashi, 1988; Kess, 1988), neurotransmitters substance P (Nicolay *et al.*, 1988), vasoactive intestinal peptide (Patrone *et al.,* 1989), calcitonin gene related peptide (Davidovitch *et al.,* 1990), cytokines or monokines: interleukin-1 alpha (Takahashi, 1989; Davidovitch, 1988), interleukin-1 beta (Ngan, 1988a; Lynch, 1988), interleukin-2 (Davidovitch, 1989), tumour necrosis factor (Takahashi, 1989; Davidovitch, 1989) and interferon-gamma (Ngan, 1990). It has also been

suggested that the osteoclasts are controlled by osteoblasts in many ways (Jones *et al.*, 1988; Chambers, 1988).

On the tissue level, histologic studies have revealed that during orthodontic treatment, force applied to a tooth will result in the surface being under pressure while the opposite surface will be under tension. On the compressive side, the PDL is strained and traumatized, displaying inflammatory changes, followed by healing process, and reorganization of the paradental tissues (Reitan, 1951; Storey, 1973; Rygh, 1974). An early occurrence following the application of orthodontic forces is increased blood flow in the dental pulp and alveolar bone (Kvinnsland *et al.,* 1989; McDonald and Pitt Ford, 1994; Vandevska-Radunovic *et al.,* 1994). Neuropeptides with vasoactive properties have been detected immunohistologically in the dental pulp and PDL during orthodontic tooth movement in rats (Kvinnsland and Kvinnsland, 1990) and cats (Saito *et al.*, 1991). These molecules include calcitonin gene-related peptide (CGRP), substance P (SP), and vasoactive intestinal peptide (VIP) (Davidovitch *et al.,* 1988). All these neuropeptides have been shown to cause vasodilation, plasma extravasation, and migration of leukocytes out of capillaries into the extravascular space.

In context of root resorption, the extravasation of plasma into the PDL in the early phases of orthodontic force application may be a crucial event. This plasma may contain significant amounts of inflammatory mediators. Upon entering the PDL, these molecules may attract cementoclast progenitors to the surface of the root, and activate these cells to resorb the root's cementum and dentine. This activation process may result from the action of these plasma-derived molecules alone, or in combination

with locally produced molecules such as cytokines, growth factors, colony stimulating factors, and cell adhesion molecules.

Brudvik and Rygh (1993) reported that after the application of the orthodontic force, the pressure surface demonstrates periodontal hyalinization, which is a sterile coagulation zone. This zone is a coagulation necrotic area of the PDL (Gaudet, 1970; Rygh, 1977; Kvam, 1972a; Brudvik and Rygh, 1993). This process of hyalinization usually precedes any form of root resorption associated with orthodontic tooth movement (Rygh, 1977). It takes approximately 10 to 35 days, after application of orthodontic forces, before resorption lacunae are noted on the tooth surfaces (Rygh, 1977). Three stages are described in the hyalinized zone: degeneration, elimination of destroyed products and re-establishment. Brudvik and Rygh (1993) suggested that the process of root resorption associated with the hyalinized zone have two areas of interest. The first is the peripheral zone at the circumference of the necrotic area. Here the cellular process of resorption precedes that of the second, central zone by 3-4 days.

Light and transmission electron microscopy have shown that root resorption occurs near the hyalinized zone in close proximity to a rich vascular network (Rygh, 1977). This has been verified by Brudvik and Rygh (1993), who showed occurrence of small craters in the cementum both at the coronal and apical peripheries of the hyalinized zone. Their results indicated an association between root resorption and active removal of the hyalinized necrotic tissue, showing the following consistent pattern:

1. The first sign of root resorption (initial phase) was defined as a penetration of cells from the periphery of the necrotic tissue where mononucleated fibroblast-

like cells, stained negatively by tartrate resistant acid phosphatase (TRAP), started removing the pre-cementum/cementum surface.

2. Root resorption beneath the main hyalinized zone occurred in a later phase during which multinucleated TRAP-positive cells were involved in both removing the main mass of necrotic PDL tissue and resorbing the outer layer of the root cementum. Further studies indicated that after the multinucleated TRAP-positive cells reached the subjacent contaminated and damaged root surface and removed the necrotic periodontal tissue, they continued to remove the cementum surface (Brudvik and Rygh, 1994).

When pressure is below optimal force (7-26g/cm² Schwarz, 1932 or 83 g/cm² Miura, 1975) or is removed, root resorption ceases.

Aetiology

Apical root resorption as a consequence of orthodontic treatment is considered a multifactorial problem and has been related to factors associated with biological variation (biological factors), treatment modalities (mechanical factors) combined biological and mechanical factors.

Biological factors

Individual susceptibility

Becks (1936) stated that orthodontically induced root resorption was not produced by mechanical force alone, but were the result of individual predisposition due to

endogenous factors. Degrees of root resorption vary among different people and on different teeth (Vlaskalic *et al.,* 1998; Rygh, 1977; Massler and Malone, 1952; 1954).

Genetics

Massler and Perreault (1954) and Newman (1975) have suggested a genetic component for shortened roots. Harris (1997) attributes hereditary as a cause for root resorption by affecting the amount and duration of force to correct malocclusion. An average hereditary of 70% for resorption was found. More variation exists between families than between siblings, thus siblings can be used as a gauge.

Hormonal Imbalance

The association between root resorption and endocrine problems such as hypothyroidism, hypopituitarism, hyperpituitarism and other diseases had been studied (Becks, 1939; Hemley, 1941). Hyperparathyroidism (Goultschin *et al.,* 1982), hypophosphatemia (Tangney, 1973), Paget's disease (Smith, 1978) have also been linked to root resorption. Poumpros *et al.* (1994) tested the effect of thyroxine on force-induced root resorption and found that in thyroxin-fed rat, fewer root resorption lesions were shown than in the control group. However on the other hand, Linge and Linge (1983) suggested that hormonal imbalance does not cause but influences the phenomenon.

Asthma/Allergy

Davidovitch *et al.* (1996) induced allergic asthma in guinea pigs and applied an orthodontic force against the maxillary molars. Although root resorption was not observed on these cementum-free and continuously erupting teeth, the number of

alveolar bone osteoclasts in areas of compressed PDL increased over the controls, suggesting that chemical mediators produced in the asthmatic state may influence cell populations and subsequently the resorption process.

McNab (1999) in a study of panoramic films, concluded a statistically significant increase in root resorption post-orthodontics in asthmatics when compared to non-asthmatics. However, this increase was only associated with grade 1 root blunting.

With a sample of 50 orthodontically treated individuals, Owman-Moll and Kurol (2000) analyzed factors that might be associated with orthodontically induced root resorption. The sample was divided into two groups: the high-risk and low-risk groups based on measurements of the magnitude of root resorptions. Results were suggestive of an association between allergy and the extent of root resorption, but no statistically significant difference was found in both groups.

Nutrition

Marshall (1929) advocated that malnutrition could cause root resorption. Becks (1936) demonstrated root resorption in animals deprived of dietary calcium and vitamin D. It was later suggested that nutritional imbalance is not a major factor in root resorption during orthodontic treatment (Linge and Linge, 1983).

Drug

Ong *et al.* (2000) examined the effect of prednisolone on orthodontic movement using an established rat model. Result showed that steroid had no significant effect in the magnitude of tooth movement, but had suppression effect on clastic activity.

Biological age

Thilander *et al.* (2000) suggested that adult patients experienced more root resorption after treatment than younger patients. Reitan (1954) observed that the adult alveolar bone surface was predominantly aplastic before the orthodontic treatment, indicating that the periodontal structures were in a state of rest. This was substantiated by the moderate number of cells and the fact that the fibrous tissue reacted more slowly. The turnover rate of collagen molecules is in general slower in adults than in growing children, a difference that is also reflected in the delayed onset of tissue changes in adults during tooth movement.

The apical third of the root is more firmly anchored in adult patients than in young patients. Hence, when an adult tooth is tipped over a short distance, comparatively the apical third of the root moves little. On the other hand, if the tipping is prolonged, the tooth begins to act as a two-armed lever. Apical resorption and destruction of the alveolar bone wall frequently follow.

Baumrind *et al.* (1996) analyzed the relationship in orthodontically treated adults between upper central incisor displacement measured on lateral cephalograms and apical root resorption measured on anterior periapical radiographs. They found that an average of 0.99 ± 0.34 mm of resorption was present in the absence of root displacement and an average of 0.49 ± 0.14 mm of resorption was implied per millimetre of retraction. Thus, a small portion of observed apical resorption could be accounted for by tooth displacement alone. Significant apical root resorption that was greater than 2.5 mm increases with age for all treatment variables. These included using of rectangular arch wires, class II elastics and open activators. Linge and Linge

(1983) also found that patients who started treatment before the age of eleven had less root resorption than those treated later. The age factor also carries information about root length development (Linge and Linge, 1991)

Recently, Sameshima and Sinclair (2001) examined the records of 868 patients who were treated with full fixed edgewise appliances (obtained from 6 private offices). Full-mouth periapical radiographs were used to accurately assess apical root resorption from first molar to first molar in both arches. The results showed that adult patients experienced more resorption than children; especially in the mandibular anterior segment.

Dental age

In the study of apical root resorption after fixed appliance therapy, Hendrix *et al.* (1994) found that posterior teeth showed that root shortening during active orthodontic treatment was independent of sex, age, extraction versus nonextraction therapy and the duration of active treatment. Teeth with incomplete root formation at onset of orthodontic treatment showed root lengthening during active treatment, but did not reach their "normal" tooth length. However, Rosenberg (1972) reported that incompletely formed roots still reached their normal root length and showed less resorption than those with completely formed roots. Roots that are partially formed appear to develop normally during orthodontic treatment although some may be stunted if treated vigorously during later childhood (Rudolph, 1936, 1940).

Gender

Gender generally has not been found to affect either incidence or severity of root resorption (Sameshima and Sinclair, 2001; Harris 1997), however, a statistically significant correlation has been suggested (Baumrind, 1996). Kjaer (1995) examined morphological factors in patients who had experienced severe resorption during orthodontic treatment. He reported that females were affected more often than males. The idiopathic root resorption ratio in females to males, according to Newman (1975), was 3.7 to 1. It was speculated that this difference might be due to a difference in root maturity between males and females (Dougherty, 1968a and 1968b).

The presence of root resorption before orthodontic treatment

The degree of root resorption before treatment (measured as root length) is a significant predictor. Roots already shortened by resorption are at risk of losing more substance during treatment than initially sound roots (Harris and Butler, 1992).

Habits

Habits exert forces on the teeth and have been shown to predispose the roots to resorption (Harris and Butler, 1992; Linge and Linge, 1991; Odenrick and Brattstrom, 1985; Newman, 1975). Finger sucking habit persisting beyond 7 years and lip or tongue dysfunction are significant risk factors for root resorption (Linge and Linge, 1991). Nail biting (Odenrick and Brattstrom, 1985), tongue pressure and tongue thrust have also been related to increased root resorption (Newman, 1975).

Tooth form and anomalies

Sameshima and Sinclair (2001) found that abnormal root shape was a significant factor of root resorption. In general, dilacerated teeth had the most resorption, followed by bottle-shaped and pointed teeth. This finding is in agreement with previous studies (Kjaer, 1995; Mirabella and Artun, 1995; Newman, 1975). No direct proof exists as to why an abnormal root shape would undergo resorption more easily; however, the deviant process that caused the abnormal shape in the first place has been suggested as a strong possibility. A genetic component to shape inheritance is also likely but not proved; disruption of the path of eruption has also been cited as another plausible cause (Sameshima and Sinclair, 2001).

Convergent apical root canal is considered to be an indicative of high root resorption potential (Kinsella, 1971). The degree of root resorption in teeth with blunt or pipette-shaped roots was significantly higher than in teeth with normal root form. The pipette-shaped root was shown to be the most susceptible root form to root resorption (Levander and Malmgren, 1988).

Kjaer (1995) and Becker *et al.* (1981) found that anomalies in the dentition such as ectopic eruption or agenesis were found frequently in patients who had experienced severe root resorption during orthodontic treatment. However, these patients may have required more extensive orthodontic therapy due to the anomaly, so those mechanical and duration factors probably played a part.

Lee *et al.* (1999) investigated the significance of dental anomalies as possible risk factors. Pre-treatment and post-treatment periapical radiographs of 84 patients with

presence of at least one dental anomaly and 84 patients without such anomalies were compared. They found that anomaly did not appear to increase the risk of root resorption.

Previous trauma

A history of trauma to the maxillary incisors has frequently been implicated as a contributing factor to the root resorption in orthodontic treatment. Brin *et al.* (1991) reported that incisors with a history of trauma and also had orthodontic treatment had more extensive resorption than incisors that had been traumatized without orthodontic treatment, or incisors that had orthodontic treatment without a history of trauma. Linge and Linge (1991) also agreed that trauma was a contributory factor of root resorption. Traumatized teeth without signs of resorption, however are not resorbed more than non-traumatized teeth (Malmgren *et al.*, 1982). Although traumatized teeth may not show any signs of root resorption, orthodontic treatment can initiate and possibly propagate this process (Andreasen, 1988). Treatment for traumatized teeth should be started with light, preferably intermittent forces; the clinician should aim at a limited goal in order to shorten treatment duration.

Endodontic treatment

A higher frequency and severity of root resorption in endodontically treated teeth during orthodontic treatment has been reported (Wickwire *et al.,* 1974). However, it has also been suggested that endodontically treated teeth are more resistant to root resorption because of an increased dentin hardness and density (Thilander *et al.*, 2000; Remington *et al.,* 1989).

It is recommended that teeth requiring root canal treatment during orthodontic movement be initially cleaned and shaped followed by the interim placement of calcium hydroxide (Andreasen *et al.*, 1994). This should be maintained throughout the active phases of tooth movement. The final canal obturation could be performed upon completion of orthodontic treatment. This approach is not recommended when a successful *gutta percha* filling is already in place prior to orthodontics.

Alveolar bone density

More resorption occurs with dense alveolar bone than in less dense alveolar bone where a greater number of resorptive cells are associated with decreased marrow spaces (Reitan, 1985). According to Reitan (1974), a strong continuous force on less dense alveolar bone causes the same root resorption as a mild continuous force on highly dense alveolar bone.

Malocclusion

Although VonderAhe (1973) did not find a correlation between root resorption and the types of malocclusion, some investigators (Hendrix *et al.,* 1994; Harris and Butler, 1992; Linge and Linge, 1991) noted that both increased overjet and the amount of root movement during treatment correlated positively with the extent of root resorption. Kaley (1991) showed that there were significantly more Class III patients among the severe resorption cases than would have been expected. Risk indicators for resorption that were related to treatment procedures included approximation of the maxillary incisor roots against the lingual cortical plate, maxillary surgery, and root torque. Ghafari (1994) proposed that orthognathic surgery influenced root resorption by affecting the blood supply to the PDL, bone and/or cementum. This precipitates

the ageing changes associated with adults. Harris *et al.* (1997) demonstrated greater ANB values and low angle cases were commonly associated with greater external root resorption.

Individual tooth suspectibility

According to severity the most frequently affected teeth are maxillary lateral incisors, maxillary central incisors, mandibular incisors, distal root of mandibular first molars, mandibular second premolars and maxillary second premolars (Brezniak and Wasserstein 1993; Kaley and Phillips, 1991; McFadden *et al.,* 1989; Kennedy *et al.*, 1983; Newman, 1975; Becks, 1936)

However, Sameshima and Sinclair (2001) reported maxillary teeth were more severely affected than mandibular teeth. The most severely resorbed teeth were maxillary lateral incisors, followed by maxillary central incisors, maxillary canines, mandibular canines, mandibular central incisors, and mandibular lateral incisors. The maxillary lateral incisors demonstrated the highest percentage of abnormal root shapes. They are also the third most commonly missing tooth; after third molars and lower second premolars. Other developmental anomalies include dens invaginatus. Brin *et al.* (1993) found that the erupting canine often resorbed the lateral root from the palatal direction; this resorption was usually not visible on conventional radiographic examination.

Loss of root length

Loss of marginal attachment is more detrimental than loss of an equivalent amount of root length by apical root resorption. 3mm of apical root resorption is approximately

equivalent to 1mm of crestal bone loss. An incisor with 5mm of apical root resorption will still have 75% of its periodontal attachment remaining (Kalkwarf *et al.*, 1986).

Mechanical factors

The particular treatment regimens and techniques, and the time in active treatment have been suggested as risk factors for root resorption.

Appliances

It is often stated that the degree of root damage is related to the type of appliance used. Several studies have investigated the effect of different appliance and root resorption.

(i) Standard edgewise and straight-wire edgewise techniques: Mavragani *et al.* (2000) found that apical root resorption was decreased in the straight-wire group compared to the standard edgewise group. This may be due to the more efficient force control.

(ii) Fixed and Removable appliances: Linge and Linge (1983) compared root resorption resulting from fixed and removable appliances and concluded that fixed appliances are more detrimental to the roots. Stuteville (1937) on the other hand, suggested that the jiggling forces caused by removable appliances are more harmful to the roots.

(iii) Begg and Edgewise techniques: It is often stated that the light wire Begg technique causes less root resorption than Edgewise (Kinsella, 1971). Malmgren *et al.* (1982) suggested that there is no difference between these techniques, but found that the frequency of root resorption was significantly higher (48%) in traumatized maxillary incisors when intruded by the Begg technique compared with edgewise technique (43%). Beck and Harris (1994) examined the degrees of in-treatment root resorption and found no difference between the Begg and Tweed techniques. Parker and Harris (1998) also found no statistical difference in average external apical root resorption between Tweed standard edgewise technique, Begg lightwire technique, and Roth-prescription straightwire technique.

(iv) Speed and Edgewise techniques: no statistical difference in the amount of root resorption reported (Blake *et al.,* 1995).

(v) Sectional and Continuous mechanics: Alexander (1996) found no significant difference between continuous and sectional archwire mechanics.

(vi) Intermaxillary elastics: Linge and Linge (1983) found significantly more root resorption on the side where elastics were used and suggested that jiggling forces which resulted from function combined with elastics were responsible for the incisors' root resorption. Linge and Linge (1991) concluded that treatment with fixed appliances, rectangular arch wires, and the use of Class II elastics, showed risk factors for root resorption. It was

reported that Class III elastics used for anchorage preparation increased mandibular first molar distal root resorption (Rudolph, 1940).

(vii) Maxillary expansion: Thilander *et al.* (2000) found that using rapid palatal expansion, premolars and molars are pressed in a buccal direction against the thin cortical plate with risk of root resorption. These finding supported the studies by Odenrick *et al.,* 1991; Vardimon *et al.,* 1991; Hill, 1987. However, Handelman *et al.* (2000) on the other hand, found minimal amount of root resorption from rapid maxillary expansion in adults. Sameshima and Sinclair (2001) proposed that there was no significant difference for transverse treatments of rapid, slow expansion or no treatment.

(viii) Slot size and archwire type: there was no significant difference between 0.018" and 0.022" slot or steel and titanium for all anterior teeth (Sameshima and Sinclair, 2001).

(ix) Edgewise and activator: In comparing edgewise with activator-only patients, Linge and Linge (1991) found no resorption in the activator group. They also concluded that open activators, plates with clasps and vertical elastics had a very low correlation with single-root resorption.

Direction of movement

Of the several modes of tooth movement, pressure from intrusive forces seems the most likely to cause external apical root resorption (Thilander *et al.*, 2000; Beck and

Harris, 1994; Reitan, 1974). Parker and Harris (1998) also showed that incisor intrusions with increase in lingual root torque together were the strongest predictors of external apical root resorption. In contrast, distal bodily retraction, extrusion, or lingual crown tipping had no discernible effect. According to Thilander *et al.* (2000), the stress distribution along the roots during bodily movement is less than that during tipping. Therefore the risk of root resorption during bodily movement should be less than tipping. DeShields (1969) and McFadden and colleagues (1989), however, found no significant associations between vertical movement of the root apex and root resorption.

Force magnitude

Harry and Sims (1982) found the distribution of resorbed crater was directly related to the amount of stress on the root surface and the rate of lacunae development was more rapid with increasingly applied forces. They concluded that higher stress causes more root resorption. Exceeding the optimal force can cause periodontal ischaemia leading to root resorption (Brezniak and Wasserstein, 1993). According to Schwartz (1932), applied force exceeding the optimal level of 7 to 26 gm/cm^2 causes periodontal ischemia, which can lead to root resorption. Levander and Malmgren (1994) evaluated the effect of a treatment pause on teeth in which apical root resorption was discovered. The amount of root resorption was significantly less in patients treated with a pause than in those treated without interruption. On the other hand, Hall (1978) found that intermittent forces had been linked in detrimental effects to the jiggling forces generated.

Treatment duration

Several previous studies reported that the severity of root resorption was directly related to duration of treatment (Vlaskalic *et al.,* 1998: Baumrind *et al.,* 1996; Brezniak and Wasserstein, 1993; Linge and Linge, 1991; Goldin, 1989; Levander and Malmgren 1988; Sharpe *et al.,* 1987; Goldson and Henrikson, 1975; Reitan, 1974). The total duration of treatment is considered to be more crucial factor than magnitude of the force (Thilander *et al.,* 2000). Linge and Linge 1991 showed that time of treatment with rectangular arch wires significantly contribute to apical root resorption. An apical root loss of 0.9 mm per year during labial root torque had been reported by Goldin (1989). Levander and Malmgren (1988) found that 34% of examined teeth showed apical root resorption after 6-9 months of treatment with fixed appliances.

Relapse

Sharpe *et al.* (1987) examined the relationship of post-orthodontic treatment relapse to root resorption. The subjects in the relapse group had undergone longer periods of treatment and exhibited a greater prevalence of root resorption than that observed in the non-relapse group. The distances that teeth were translated seemed to affect the extent of root resorption Root resorption after treatment is mostly related to causes other than active treatment itself, such as occlusal trauma, active retainers and others (Dougherty, 1968a, 1986b).

Causal factors

Ghafari (1994) summarized factors, which caused root resorption:

- Physiological and orthodontic tooth movement
- Pressure from impacted teeth, tumours or cysts.
- Periapical or periodontal infection
- Tooth implantation or re-implantation
- Occlusal trauma
- Metabolic, systemic and idiopathic factors

Fuhrman (1996) included risk factors of root resorption:

- Small alveolar process
- Thin buccal or lingual bone plates
- Eccentric position of teeth
- Basally extended maxillary sinus
- Progressive alveolar bone loss

Diagnosis

Radiographs are commonly used as a diagnostic aid for root resorption. Radiographic detection of apical root shortening requires a certain degree of resorption. Tooth movement makes it more difficult to assess the exact amount of root loss especially when the tooth is torqued or tipped. Commonly used radiographs are ineffective in assessing buccal and lingual root resorption. Radiographs used include periapical paralleling, orthopantomogram (OPG), cephalogram, and lamiogram.

All radiographs are often difficult to standardize and to compare the same tooth at different times when teeth have moved.

- Periapical radiographs taken yearly (Ghafari, 1994) or OPG every 6-9 months (Levander and Malmgren, 1988).
- If resorption is detected, an additional radiograph taken in 3 months to monitor. May need to reassess goal, accept compromised results and modify force (Ghafari, 1994).
- Decrease treatment duration – accept compromised results (Brezniak and Wasserstein, 1993).
- Lighter forces – avoid intermaxillary elastics to decrease jiggling and occlusal trauma (Linge and Linge, 1991).
- Pause in treatment with intermittent forces to allow the resorbed cementum to heal (Acar *et al.,* 1999).
- Limit movement associated with increased risks – intrusion and torque (Parker and Harris, 1999).

Repair

Repair of resorbed craters is seen after 35 to 70 days after force application (Harry *et al.,* 1982; Stenvik *et al.*, 1970). Craters extending into cementum only becomes fully anatomically reconstructed. Whereas deep dentinal craters are repaired by a thin cemental layer. This results in an irregularly shaped root morphology (Andreasen, 1988). After both types of repair, the PDL width is usually normal. During repair, there is migration of cementoblasts over the resorbed surface. These cells compete for

available surfaces and excludes the existing osteoblasts and cementoblasts (Jones *et al.*, 1988).

ORTHODONTIC FORCES

Magnitude of force

The "optimal force" theory was first introduced by Storey and Smith (1952). They showed that there was a range of pressure, 150-200 g (equivalent to 150-200 cN) on the tooth-bone interface, which produced the maximum rate of tooth movement for distalization of maxillary canines in man. For pressures below this range, movement was limited due to the ability of the soft tissue to function as a shock absorber. If the force is increased beyond this optimum, the displacement is reduced due to tissue necrosis of the periodontal membrane, *i.e.* hyalinization.

This theory was critically reviewed by Boester and Johnston (1974), who found that the amount of space closure after premolar extraction was about the same if the applied force was 5, 8 or 11 ounces (140g, 225g and 310g) but significantly less if only 2 ounces (55g) was used. A similar opinion has been presented by some other researchers who suggested that tooth displacement is the same even if the applied force is increased (Reitan, 1960; Burstone and Groves, 1961; Maltha *et al.*, 1996; Owman-Moll *et al.*, 1995).

On the other hand, some investigations demonstrated a more linear relationship between force magnitude and tooth movement; *i.e.* the heavier the applied force, the

greater the rate of tooth movement (Andreasen and Johnson, 1967; Hixon *et al.*, 1969, 1970; Andreasen and Zwanziger, 1980).

In the early 1970's two reports, one on human (Hixon *et al.*, 1970) and one on cats (Mitchell *et al.*, 1973) presented a large variation in tooth movement in response to applied force magnitude. This was further confirmed by Maltha *et al.* (1996) in an investigation in dogs. They reported that bodily tooth movement seemed to be related more to individual factors than to the magnitude of the force.

It has been demonstrated that a light continuous force could be applied to move teeth orthodontically with drum springs (DS). The magnitude of force is constantly maintained throughout movement of the teeth without any force decay. Re-activations were not required and retraction of canines into first premolar extraction spaces was demonstrated to be more rapid than conventional space closure with elastomeric chains. (Darendeliler *et al.*, 1997)

A series of studies by Owman-Moll *et al.* in 1995 performed on 144 adolescents and 200 premolar teeth showed that tooth movement increased gradually over time during the experimental period with a continuous force of 50g. However, there were no differences regarding tooth movement when the applied force was doubled to 100g. But when the force was increased 4 times to 200g, tooth movement increased 50% on average. It was also noted that tooth movement was more effective with a continuous force than with an interrupted continuous force of the same magnitude. The occurrence and severity of root resorption in histological sections increased markedly after the 2^{nd} week when a continuous force of 50g was applied. Deep root resorptions,

reaching half way to the pulp in the apical 3rd of the root, were recorded after only 3 weeks. After 7 weeks of 50g force application, the mean resorbed root contour on 3 bucco-lingual orientated histological sections was 6.7% on average. It was also demonstrated that root resorptions do not seem to be very force-sensitive. There was no significant difference in the occurrence and severity of root resorptions when the force increased 4 times from 50g to 200g. While continuous force of 50g was more efficient than interrupted continuous forces on moving teeth, the occurrence of root resorptions was unaltered. It was concluded that there was no significant correlation between root resorption and magnitude of tooth movement.

Root shortening caused by external root resorption is a well-known side effect after orthodontic tooth movement. Reitan (1964,1974,1985) has always advocated the use of light orthodontic forces in order to increase the cell activity in the surrounding tissues and reduce the risk of root resorptions. This was later confirmed by King and Fischlschweiger in 1982. He found, in an investigation in rats, that light forces produced insignificant root resorptions, whereas intermediate or heavy forces resulted in substantial cratering. This result was in agreement with earlier findings, both in animals (Kvam, 1967; Dellinger, 1967) and in human (Harry and Sims, 1982).

Contradicting findings were reported by Stenvik and Mjör (1970) in a study concerning premolar intrusion in human. They observed that root resorptions increased after application of light forces, 35g when compared to heavy forces, 250g.

Due to the fact that different types of orthodontic appliances were utilized, *e.g.* frictionless sectional arch (Storey and Smith, 1952; Boester and Johnston, 1974),

Kloehn-type headgear (Andreasen and Johnson, 1967), full fixed appliance (Andreasen and Zwanziger, 1980), latex elastics (Mitchell *et al.*, 1973), sliding mechanics (Hixon *et al.*, 1970; Maltha *et al.*, 1996) and different magnitudes of forces applied in the above mentioned studies, 25 g to 1515 g, the comparisons of the effects on tooth movement were difficult. Moreover, the direction of tooth movement varied in different investigations. Some investigators (Storey and Smith, 1952; Hixon *et al.*, 1970; Maltha *et al.*, 1996) moved teeth mesiodistally in spongy bone. Other authors used techniques for tooth intrusion (Stenvik and Mjör, 1970) or extrusion (Reitan, 1974). Reitan also investigated the effect of root tipping, applying torque technique, (1964) or crown tipping (1974).

Type of force

Another factor to consider when evaluating orthodontic treatment is the type of applied force. A continuous force may be interrupted by brief or extended periods of rest, *i.e.* interrupted continuous type of force or intermittent force. The latter type of force is mainly used in connection with removable appliances.

Most investigations concerning tooth movement and tissue reactions are based on continuous force application. However, a continuous force is not necessary to produce tooth movement. It is well known that tooth movement is effectively performed with functional appliances (Chateau *et al.*, 1983; Graber *et al.*, 1985) as well as headgear (Andreasen and Johnson, 1967; Boecler *et al.*, 1988) with less than full time wear. It has been suggested that an interrupted continuous force with periods of rest may favourably affect cell proliferation in the supporting tissues,

which in turn might promote further tooth movement (Reitan, 1985). In a study done by Levander *et al.* (1994), the effect of interrupted and continued treatment on initially resorbed maxillary incisors was compared. Intraoral, standardized radiographs revealed less root resorption when the force was discontinued.

Using rabbit incisors, Proffit and Sellers (1986) reported that light forces used to oppose eruption for 50% of the time, produce approximately the same effect as continuous forces. However, when forces were activated for a smaller percentage of time showed a considerably decreased effect.

Tooth movement has been characterized in three phases: initial, lag and post-lag phase (Storey, 1973; King and Fischlschweiger, 1982; Burstone, 1985; King *et al.*, 1991). The initial phase is a reflection of stretch and compression of the PDL and lasts only for a short period of time. The lag phase is characterized by only little or no tooth movement at all, and areas of hyalinization are a common finding in histological sections. During the post-lag phase, tooth movement is continued, and resolution of hyalinized tissue combined with frontal or undermining bone resorption has been reported histologically. Reitan (1951) showed that, during the first 24 hours of tooth movement, an interrupted type of force caused less reduction in cellular activity in areas of compression than did a continuous force. In a subsequent study, the Bimler appliance was used (Reitan, 1957) to generate an intermittent tipping force of 70g to 100g at an undetermined frequency. The rate of tooth movement showed that the lag phase, which was so characteristic of continuous forces, was almost missing. These findings indicate that interrupted continuous forces seem to compromise the nutrient supply of the PDL to a lesser degree than do continuous forces.

Oates *et al.*, (1978) presented a case report on a dog, indicating that a pulsating force of 60g with a frequency of 3 pulses per minute and duration of 3 seconds and a continuous force of the same magnitude were equally effective in producing tooth movement. These findings agree well into those of Reitan (1951), who showed histological similarities between continuously and interrupted continuously moved teeth in dogs. The interrupted continuous forces of 180g to 200g were of 10 minutes or 2 hours duration with intervals of 20 seconds and 2 minutes, respectively.

In a 23-year old Caucasian woman contralateral maxillary molars were distalized using a continuous force of 18 ounces (500g) as a control on one side and a pulsating force of 30 ounces peak (average 20 ounces = 560g) as a test on the other side (Shapiro *et al.*, 1979). The tooth loaded with a pulsating force for 24 hours showed an increased rate and an increased magnitude of tooth movement compared with the tooth moved with a continuous force.

A Modern fixed appliance system is based upon a continuous type of force from the arch wire, and its influence on the efficiency of tooth movement and related root resorptions should be elucidated. Earlier investigations concerning the effect of short-term forces have generally dealt with forces of pulsating type (Reitan, 1951; Oates *et al.*, 1978; Shapiro *et al.*, 1979) and may not be fully compared with interrupted continuous forces.

Duration of force

The total duration of force, often equivalent to treatment time, is considered in some investigations to be a more critical factor than the magnitude of force with regards to adverse tissue reactions during orthodontic treatment (Stenvik and Mjör, 1970; Harry and Sims, 1982).

After 10 days of force application (50g) Kvam (1972a) recorded small, round root resorption cavities in human teeth using SEM. The amount of root resorption increased with time. After 25 days the resorption had reached the dentine and showed a characteristic honeycomb appearance. This positive association between duration of force and root resorption has later been confirmed in rats (Williams, 1984) as well as in human (DeShields, 1969; McFadden *et al.*, 1989). However, other reports have not been able to verify these findings (VonderAhe, 1973; Lilja and Odenrick, 1982; Linge and Linge, 1980, 1983; Dermaut and De Munck, 1986).

In some investigations the force control has been insufficient, and this may affect the result. Although "continuous forces" were applied, the magnitude was measured only at the start of the experiment (Kvam, 1972a), although the experimental periods were 35-76 days; or only at the start and end of the experiment (Stenvik and Mjör, 1970). Another investigation was carried out with slow maxillary expansion with a quadhelix appliance (Lilja and Odenrick, 1982). This makes force measurements difficult as the applied force is distributed among teeth, surrounding tissues and elastic sutures.

Reparative potential

Root resorption seems to be a common finding after orthodontic treatment. It has been suggested that the healing process may start as soon as the applied orthodontic force is discontinued or reduced to below a certain level (Reitan, 1974, 1985; Rygh 1977, 1985). In fact, it has been noted that root resorption and repair with secondary cementum may occur simultaneously (Stenvik and Mjör, 1970; Barber and Sims, 1981; Harry and Sims, 1982).

Several studies have been carried out to elucidate the reparative process during retention after rapid maxillary expansion (Barber and Sims, 1981; Langford and Sims, 1982; Odenrick *et al.*, 1991), and they all agreed that repair seemed to increase with retention time.

It has been hypothesized that all resorptions will be repaired once the cause of root resorption has ceased (Rygh, 1977; Reitan, 1985). However, Vardimon *et al.* (1993) claimed that all resorptions would heal provided that the total resorbed surface area does not exceed the unresorbed areas.

Studies concerning the reparative potential with time have been carried out after rapid palatal expansion, when the applied force is both higher and more difficult to measure and the strain in the surrounding tissue probably higher compared with conventional treatment with a fixed appliance.

SEM STUDIES ON ROOT RESORPTION

Previous root resorption studies done with SEM focused on several aspects. Rygh (1977) studied the organic changes in Wistar rats and human. In the animal group, 67 Wistar rats of both sexes were used. One maxillary first molar in each animal was moved buccally with a fixed appliance. This appliance was activated to provide a force of 5, 10 or 25 grams. The experimental periods were 2, 6, 12, 24, 48 and 60 hours and 5, 15 and 28 days. The human material consisted of 11 premolar teeth that were moved by means of a fixed appliance for periods between 2 and 50 days. The experimental forces were 70, 100, 120 and 240 grams. He examined these specimens under both light and electron microscopes. There was no attempt at quantitative analysis in this study. He described the nuclear remnants of occluded blood vessels with contents and compressed fibrils remaining together with more amorphous filamentous material after compression for 3-4 days in rats and 21 days in human.

Kvam (1972a) looked at human premolars under the SEM after application of 50 grams of force for 5, 10, 15, 20, 25, 30, 45 and 76 days. He sectioned the apex of the tooth and divided the rest of the tooth into the buccal and lingual sides. The samples were dehydrated in graded solutions of ethyl alcohol and ether and were mounted on metal holders with silver colloidium. These were then coated with gold-pallidium under continuous tilting and rotation and studied in the SEM. The control group demonstrated peripheral principal fibre bundles interlaced with thin fibre that covered the root surface. Vessels of varying sizes and nerve fibres were observed. In the pressure side of the experimental group, the organic tissue was markedly altered. The thin fibers of the principal fibre bundles had lost the periodic striations and had fused

into a homogenous substance. Resorption craters were often covered by organic tissue and in order to record the incidence of resorption, these organic tissue components has to be removed. It was found that resorption initiated as small cavities with diameters measuring about 6μm. Marginal root resorption began at 10 days and the number of small, round and thin walled craters increased and then merged into extensive and shallow excavations. Initially, the cervical root portion was most frequently affected but subsequently, the middle root portion was also marked by craters. In sites of active resorption, the resorption surface consisted of latticed fibers indicating that the inorganic minerals were removed prior to the collagen component of dentine and cementum. All teeth that had been moved for a period longer than 15-20 days showed marginal root resorption, and in cases observed longer than 25 days, the resorption extended into dentine. Frequently, resorption occurred beneath tissue that had been compressed and in addition, the craters were most extensive when they were found near hyalinzed zones.

Harry and Sims (1982) studied the topography of human root resorption under levels of continuous intrusive forces of varying magnitude and duration. They found that loss of root length could occur within 35 days with forces as light as 50 grams. After 70 days with mean activations ranging from 50 to 200 grams, progressive apical resorption was accompanied by regions of cellular cementum repair.

Barber and Sims (1981) looked at 9 patients that required rapid maxillary expansion (RME) as part of their orthodontic treatment. They also subsequently required removal of premolars as part of their treatment as well. Activation was performed till correction of cross bite is achieved. The correction was held by tying the RME

appliance till time of extraction. The crowns were removed and the roots were sectioned into buccal and lingual portions. Specimens were treated with sodium hypochlorite prior examination under the SEM. The surfaces of the root were photographed under low and high magnifications and a digitizer was used to calculate the resorption-affected areas in the buccal profile. Generally, they found no resorption on the control teeth. The experimental teeth that were expanded and retained for a short time had small areas of active resorption and repair confined mainly to the cervical regions of their buccal root surfaces. Experimental teeth that were expanded and retained for 20, 33 or 36 weeks showed large resorption bays scattered along their entire buccal surfaces. Usually the cervical and middle third regions were involved. Actively resorbing surfaces were characteristically smooth and multilocular in appearance and were delineated by a rim of relatively sheer and undermined cementum. However, resorbing dentine was easily distinguished from resorbing cementum due to the presence of minute surface openings marking sites previously occupied by odontoblastic processes. The morphology of the repairing surfaces was also described.

Acar *et al.* (1999) compared the effects of continuous and discontinuous forces on root resorption. 100 grams of tipping force was applied to 22 human first premolars from 8 patients with elastics. One side served as the continuous group (24 hours of wear per day) while the contralateral side the discontinuous group (12 hours of wear per day). The teeth were extracted after 9 weeks, prepared and viewed under the SEM. Composite electron micrographs of the buccal surface of each specimen were digitized and area affected by resorption were measured. Although his results were up

for debate, he concluded that there was less resorption and apical blunting was less severe with discontinuous force.

Malueg *et al.* (1996) looked at external root resorption of human teeth affected by periapical infection under the SEM. He described the phenomenon of funnelling resorption extending from the anatomical apex of the tooth outwards; present in teeth diagnosed with a necrotic pulp and acute apical abscess.

Sismanidou and Lindskog (1995) described the spatial and temporal pattern of repair of induced root resorption craters on teeth after palatal expansion. 2 spatial patterns of repair of orthodontic surface resorption patches were observed with cementum deposition proceeding either from the periphery or starting somewhere in the centre of the resorbing areas. The onset of reparative cementum mineralization appears to follow within two weeks after the release of force, involving initially only acellular cementum formation. However, the pattern of formation changes gradually to a slow deposition of cellular cementum at more advanced stages of healing.

Hellsing and Hammarström (1996) looked at rat molars after application of an initial force of 250 mN with a fixed buccal expander. The animals were sacrificed after 1, 3, and 7 days of treatment and also at 1, 2, 3, 4, 5, and 6 weeks after force application has ceased. The specimens were studied under both light and scanning electron microscopes. A hyaline zone was identified on the pressure side as early as one day after the initiation of treatment. However, after longer treatment periods, these hyaline zones were lost at extraction or during the preparation for the SEM. After 1 week of treatment, resorption in the cementum was noticed. The resorption extended to the

dentine and dentinal tubuli were seen. Formation of reparative cementum started two weeks after treatment. Changes in the cementum surface as well as root resorption cavities could be seen for as long as six weeks after the cessation of orthodontic forces.

Despite the depth and extent of the literature in root resorption studies, none have made attempts at quantifying the extent of root resorption by volumetric analysis of the resorption craters; and correlating the extent of root resorption by volumetric analysis to the magnitude of force used, as well as to the region of the root surfaces.

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MANUSCRIPT I

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Volumetric analysis of root resorption craters after application of light and heavy orthodontic forces: A SEM study.

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ABSTRACT

Root resorption has long been noted as an inevitable phenomenon in orthodontics. In previous studies, evaluation of the effects of different forces on root resorption has been limited. The technical difficulty in obtaining an accurate 3-dimensional quantitative volumetric analysis of root resorption craters has prevented the true understanding of this entity. Thirty-six upper and lower first premolar teeth from 16 patients (10 males, 6 females; mean age 13.9 years, range 11.7 – 16.1 years) requiring extractions for orthodontic treatment were collected. Speed brackets (Strite Industries, ON, CA) were bonded on the first premolars and first molars. ß-Titanium Molybdenum Alloy (TMA, Ormco, CA, USA) springs was used to activate the required forces. The right or left first premolars were randomly selected with an initial buccally directed light force of 25 grams (≈25cN) (Group 1), and a heavy force of 225 grams (≈225cN) (Group 2). Within the same patients, the contralateral sides served as controls. Premolars and molars were also bonded on the control side; but no spring was placed. After an experimental time of 28 days, the teeth were extracted and prepared for scanning electron microscope (SEM) imaging after bench drying and carbon coating. Stereo pairs of images were taken of all resorption craters at ±3° tilt and converted to 8-bit grayscale images for image analysis. 3-dimensional quantitative volumetric analysis was performed using *AnalySIS Pro 3.1* software (SIS, Münster, Ger.). This is an expanded version of a commercial software and was specially written for this study. The heavy force group demonstrated significantly greater volumetric resorption than control and light force groups ($p = 0.000$). Control and light force groups demonstrated no significant statistical difference in volumetric resorption although there was more volumetric resorption recorded in the light force

group. The mean volume of the resorption crater in light force group was 3.49-fold greater than the control group, and the heavy force group 11.59-fold more than control group. The heavy force group had 3.31-fold greater total resorption volume then light force group. All of the heavy force samples had resorption craters; however 66.6% of light force samples and only 16.6% of the control samples had resorption craters. Buccal cervical and lingual apical regions demonstrated significantly more resorption craters than the other regions ($p = 0.000$). This corresponds well to the tipping forces applied to the teeth. It is concluded that heavy orthodontic forces cause more root resorption than light forces after 28 days of force application.

KEY WORDS: premolars, light forces, heavy forces, root resorption, resorption craters, SEM, 3-dimensional volume measurement.

INTRODUCTION

Root resorption appears to be an inevitable sequel to orthodontic tooth movement, [1,2] occurring either apically [3,4] or along root surfaces in and around pressure zones. [5,6,7] However, it has also been shown that roots of untreated permanent teeth also demonstrate sites of resorption, particularly on surfaces facing the direction of physiologic movement. [8] Although iatrogenic root resorption may seem to compromise the benefits of a successful orthodontic outcome, most root loss due to orthodontics does not decrease the longevity or the functional capacity of the teeth involved. [9]

The type of treatment largely determines the location of resorption. In palatal expansion, resorption develops mainly in the cervical part of the mesiobuccal surfaces and furcation areas with only limited involvement of other areas. [7] However, such cervical resorption generally remains undiagnosed unless it is extensive, whereas apical root resorption is often readily visible on radiographs. [2,10,11]

Susceptibility to root resorption varies considerably. Teeth with radiographic signs of resorption prior to treatment have been reported to develop more extensive areas of resorption than initially intact teeth. [1,12,13] However in most cases, they could be very unpredictable. The most commonly affected teeth (in decreasing frequency) are: maxillary laterals, maxillary canines, mandibular incisors, mandibular first molars, mandibular second premolars, maxillary second molars. [9]

Whenever extensive areas of resorption occurs, predisposing factors have been proposed: vitality of the pulp, [14] gender of the patient, [1] type and mechanics of force delivery, [1,5,13] bone density, [5,10] magnitude and duration of the force [1,3,77,11,15] and systemic factors (*e.g.* endocrine disorders, asthmatics). [16,17]

The extent of root resorption has been examined using radiographs, [18] light microscope [15] and scanning electron microscope (SEM). [19,20,21] It has been reported that SEM provides enhanced visual and perspective assessment of root surfaces, and when recorded in stereo pairs, they provide resolution and detail not attainable with histological models reconstructed from serial sections. [15]

SEM studies on root resorption.

Previous root resorption studies done with SEM focused on several aspects. Rygh [22] studied the organic changes in Wistar rats and human teeth. A fixed appliance applied a buccally directed force of 5, 10 and 25 g in the rats and 70, 100, 120 and 240 g in the human subjects. He examined these specimens under both light and scanning electron microscopes. There was no attempt at quantitative analysis of resorption in this study. He described the nuclear remnants of occluded blood vessels with contents and compressed fibrils remaining together with more amorphous filamentous material after compression for 3-4 days in rats and 21 days in humans.

Kvam [21] looked at human premolars under the SEM after application of 50 grams of force for 5, 10, 15, 20, 25, 30, 45 and 76 days. He sectioned the apex of the tooth and divided the rest of the tooth into the buccal and lingual sides. The samples

were dehydrated in graded solutions of ethyl alcohol and ether and were mounted on metal holders with silver colloidium. These were then coated with gold-palladium under continuous tilting and rotation and studied in the SEM. The control group demonstrated peripheral principal fiber bundles interlaced with thin fibre that covered the root surface. Vessels of varying sizes and nerve fibers were observed. On the pressure side of the experimental group, it was found that resorption initiated as small cavities with diameters measuring about 6μm. Marginal root resorption began at 10 days and the number of small, round and thin walled craters increased and then merged into extensive but shallow excavations. The cervical root regions were most frequently affected initially; but subsequently, the middle root regions were also marked by craters. In sites of active resorption, the resorption surface consisted of latticed fibers indicating that the inorganic minerals were removed prior to the collagen component of dentine and cementum. All teeth that had been moved for a period longer than 15-20 days showed marginal root resorption. In cases observed for longer than 25 days, the resorption had extended into dentine.

Harry and Sims [11] studied the topography of human root resorption under levels of continuous intrusive forces of varying magnitude and duration. They found that loss of root length could occur within 35 days with forces as light as 50 g. After 70 days with mean activations ranging from 50g to 200g, progressive apical resorption was accompanied by regions of cellular cementum repair.

Barber and Sims [2] looked at 9 patients that required rapid maxillary expansion as part of their orthodontic treatment. They also subsequently required removal of premolars as part of their treatment. Activation of the expander was performed until

the correction of crossbite was achieved. Specimens were treated with sodium hypochlorite prior examination under the SEM. The surfaces of the root were photographed under low and high magnifications and a digitizer was used to calculate the resorption-affected areas in the buccal profile. Generally, they found no resorption on the control teeth. The experimental teeth that were expanded and retained for a short time had small areas of active resorption and repair confined mainly to the cervical regions of their buccal root surfaces. Experimental teeth that were expanded and retained for 20, 33 or 36 weeks showed large resorption bays scattered along their entire buccal surfaces. Usually the cervical and middle third regions were involved.

Acar *et al.* [23] compared the effects of continuous and discontinuous forces on root resorption. 100 g of tipping force was applied to 22 human first premolars from 8 patients with elastics. The upper premolars had interproximal contacts trimmed away to eliminate interferences. A two-by-four passive intrusion arch was set up with the elastics running from a buccal button on the tooth to the stainless steel wire in a bucco-gingival direction. One side served as the continuous group (24 hours of wear per day) while the contralateral side served as the discontinuous group (12 hours of wear per day). The teeth were extracted after 9 weeks, prepared and viewed under the SEM. Composite electron micrographs of the buccal surface of each specimen were digitized and area affected by resorption were measured. Although their paper has been put up for debate, [24] the authors concluded that there was less resorption and apical blunting was less severe with discontinuous force.

Hellsing and Hammarström [25] looked at rat molars after application of an initial force of 250 mN with a fixed buccal expander. The animals were sacrificed

after 1, 3, and 7 days of treatment and also at 1, 2, 3, 4, 5, and 6 weeks after force application has ceased. The specimens were studied under both light and scanning electron microscopes. A hyaline zone was identified on the pressure side as early as one day after the initiation of treatment. However, after longer treatment periods, these hyaline zones were lost at extraction or during the preparation for the SEM. After one week of treatment, resorption in the cementum was noticed. The resorption extended to the dentine and dentinal tubuli were seen. Formation of reparative cementum started two weeks after treatment ceased. Changes in the cementum surface as well as root resorption cavities could be seen for as long as six weeks after the cessation of orthodontic forces.

Despite the depth and extent of the literature in root resorption studies, none have made attempts at quantifying the degree of root resorption by volumetric analysis of the resorption craters; and correlating root resorption to the magnitude of force used, as well as to the region of the root surfaces.

The aims of this study were 4-folds. To develop a protocol to allow volumetric analysis of root resorption craters on controlled samples of human premolar teeth, to reproduce digital 3-dimension replica of root resorption craters, to evaluate the effect of orthodontic force magnitude on volume of root resorption craters and also to identify the sites that may be predisposed to root resorption by volumetric analysis of root resorption craters.

MATERIALS AND METHODS

Sample collection

This study was approved by the Ethics Committee of the Central Sydney Area Health Service (Ethical approval: Project 5/98 CSAHS Human ethics review committee UDH). All subjects completed a written informed consent. A sample of thirty-six teeth from sixteen patients (ten males, six females mean age 13.9 years, range 11.7 - 16.1 years) requiring at least bilateral first premolar extraction for orthodontic treatment was collected. They all complied with a strict selection criterion. [26] The samples had no previously reported or observed dental treatment, no previously reported or observed trauma, no previously reported orthodontic treatment, no past history or present signs and symptoms of periodontal diseases, no signs and symptoms of bruxism, no medical history that would affect the dentition, no abnormality concerning the craniofacial and dentoalveolar complexes and had completed apexogenesis. All information of the patients' fluoride consumption was also obtained. Speed brackets (Strite Industries, ON, CA) were bonded on the first premolars and first molars (Figs. 1, *A-C*). ß-Titanium Molybdenum Alloy (TMA) (Ormco, CA, USA) springs were used to activate the required forces. The clinical setup for application of forces was similar to a previous study. [27] The right or left first premolars were randomly selected with an initial buccally directed light force of 25g (≈25cN) (Group 1), and a heavy force of 225g (≈225cN) (Group 2) applied. Within the same patients, the contralateral sides served as controls. Premolars and molars were also bonded on the control side; but no spring was placed. [26] After an experimental time of twenty-eight days, the premolars were extracted by one operator. After sterilization and debridement, the samples were mounted on a stainless steel

diamond coated high-speed long shank chamfer bur secured with Glass ionomer cement (GIC) (Transbond 3M, CA, USA) (Fig. 2). [26] They were then stored in Milli-Q (de-ionized water) at 23 ± 1°C until due for testing. [28] The teeth were prepared for SEM imaging after bench drying and carbon coating.

SEM

All samples were bench dried for at least 48 hours prior to coating. The samples were carbon coated with the sputter technique [29] at for a thickness between 250Å to 300Å, using Edwards Coating System E306A. The Scanning electron microscope (Phillips XL30) was used to obtain the images of each crater on the buccal and lingual surfaces. These surfaces were viewed under the SEM at approximately zero degrees to the horizontal. To overcome the nature of the curved surface of the root surface, a motorized rotational stent was constructed to enable the near absolute horizontal imaging (Fig. 3). This 360° motorized rotating mounting stent was also used to enable the sample to be rotated within the vacuum chamber of the SEM without constant and time-consuming venting and pumping. All images were focused at eucentric point at 15kV, corresponding to approximately 200nm and saved as TIFF (tagged image file format) images.

Image Processing

Stereo imaging principle

To produce a stereo pair, two SEM images of the specimen with ±3° tilt were collected. This difference in perspective is introduced by tilting the specimen along

the z plane in the SEM. One image was collected with the specimen tilted to a positive angle and one to a negative angle. In general, the amount of tilt required will depend on the roughness of the surface. The smoother the surface the greater the tilt required; and the greater the tilt the greater the 3 dimensional (3-D) effect.

Parallax has been described as the perception of objects by the eye; taking into account the binocular imaging of the lenses. This parallax (P) of the craters measured from their respective stereo pairs is directly related to the height (h) of the object (in this case depth) where $h = P/[2\sin(Ø/2)]$ where Ø is the total tilt angle (Fig. 4). A series of images were obtained with different levels of tilt to test the stereo effect of images. As the depth of the craters ranged within 20 to 250μm, to obtain the optimal stereo imaging effect in this study, ±3° tilt was used.

AnalySIS Pro 3.1 (SIS, Oxford Instruments)

The expanded version of the *Analysis Pro 3.1* (SIStereo imaging, Münster, Germany) was developed exclusively for this project. This version allowed volumetric measurement of irregular open craters by exploring the z-dimension generating the depth profile of the craters. An 8-bit grayscale replica of the crater was then created (Figs. 5, *A-B*). Calibration of this software was performed using known pyramidal indentations on solid metallic cylinders. [32]

The plane of the surface of the craters has to be absolutely parallel to the horizontal for accurate depth profiles to be generated. Although we obtained an approximate zero degrees horizontal imaging, the innate mild curvature of the

cementum surface did not allow for absolute parallelism. To overcome this problem, three `hot spots' points on the SEM image were selected and a shading correction was performed [31] (Figs. 6, *A-B*). This shading correction negated the tilt error of the curved surfaces and allowed accurate volume measurements.

Using the stereo pair and the angle of tilt, the software calculates surface characteristics over the selected crater area. Once measured, the magnitude of the parallax was used to calculate the depth profile of the crater and to generate the volume of the prescribed crater. [31]

When a stereo pair was loaded into the software, the images were coded red and green and superimposed to form an anaglyph as shown on figure 7, *A*. The 8-bit grayscale image (Fig. 5, *B*) could also be superimposed on the anaglyph to create another 3-D view (Fig. 7, *B*). These craters can now be viewed in 3-D with a pair of red-green 3-D glasses.

Images of the total buccal and lingual surfaces of the premolars were also taken and saved as TIFF images. The flat horizontal surface of the buccal surface was placed parallel to a jig with a marked line parallel to horizontal acting as reference (Fig. 8). The `straight-on' buccal and lingual surfaces (Fig. 9) were than imaged with the SEM using similar settings. Using the *Analysis Pro 3.1*, the surface areas of the regions 11, 12, 13, 21, 22 and 23 were demarcated and measured (Fig. 10). Each process was repeated 3 times and a mean value obtained. The volume of resorption per unit area was than obtained.

RESULTS

Initial test crater

To test the variability of the imaging and image processing results, one test crater was imaged three times with three stereo pairs of images captured. Each pair of image was then processed another three times to test the variability of the results. The variance component between different images was 0.098 while variance component between the processes within each image was 0.051. The variance between images was about twice the variance between processes within images. Hence one crater was imaged four times with four stereo pairs of images. Each pair of image processed twice with the analysis software. Each crater had eight readings.

Univariate Analysis of variance (one-way ANOVA) was performed by Statistical Package for Social Sciences (SPSS for Windows, version 10.0, SPSS Inc, Chicago, Ill). During statistical evaluation, the raw data were adjusted for the residual plots to conform to normality. The cube root of the volumetric readings was used to create the full model for statistical analysis.

Comparison of volumetric analysis of resorption craters between groups

In the full model comparing control to light and heavy force groups, a linear increasing trend was observed from control to light to heavy group (Table I). Contrast value was 1.33, the standard error was 0.314, t value was 4.23 on 181 df (degrees of freedom) and $p = 0.000$ (Table II, Figure 11).

Comparison of volumetric analysis of resorption craters between regions

The buccal and lingual sides were divided into three equal regions for analysis. The buccal cervical, middle and apical regions were labeled 11, 12 and 13 respectively. On the lingual side, the lingual cervical, middle and apical regions were labeled 21, 22 and 23 respectively (Fig. 12).

Looking at the experimental teeth of the light and heavy groups, the buccal cervical and lingual apical regions had significantly more resorption then the other regions (Fig. 13). Contrast value was 7.096, standard error was 1.295, t value was 5.48 on 85 df and $p = 0.000$ (Table III).

Cross comparison of regions in groups

In the control (baseline) group, the buccal cervical region (11) had no resorption while the lingual apical (23) demonstrated mild resorption (Table IV). As the force increased to 25g (light group), regions 11 and 23 increased significantly when compared to the other regions. When the force increased further to 225g (heavy group), resorption at region 11 increased 2.66 times while resorption at region 23 had no significant change. Resorption at the other regions (except region 12 in the light group) remained almost as baseline throughout the increase in forces (Table IV). This trend could clearly be seen in figure 11 as well.

Mean volume of resorption per tooth

The mean volume of resorption per tooth is described as the graph in figure 14. The control group had 16.77 x 10^6 μm^3, light force group had 58.69 x 10^6 μm^3 and heavy force had 194.58 x 10^6 μm^3. The mean volume of the resorption crater in light force group was 3.49-fold greater than control, and the heavy force group 11.59-fold more than control group. The heavy force group had 3.31-fold greater total resorption volume then light force group.

Mean volume per unit area of tooth surface

The mean volume of root resorption for each region of the root surface was calculated (Table V). Although the buccal cervical region (11) demonstrated more resorption than the lingual apical region (23), there was no significant difference in the amount of resorption between these two regions ($p = 0.180$) (Table VI). The mean area per region was obtained (Table VII). On both the buccal and lingual regions, there was a trend demonstrating a greater area at the cervical to the apical regions (Fig. 15). The mean volume per unit area of tooth surface was then obtained (Table VIII). Regions 11 and 23 demonstrated more resorption per unit area than the other regions (Fig. 16). Although there was more resorption at region 23 than 11, it was not statistically significant ($p = 0.258$) (Table IX).