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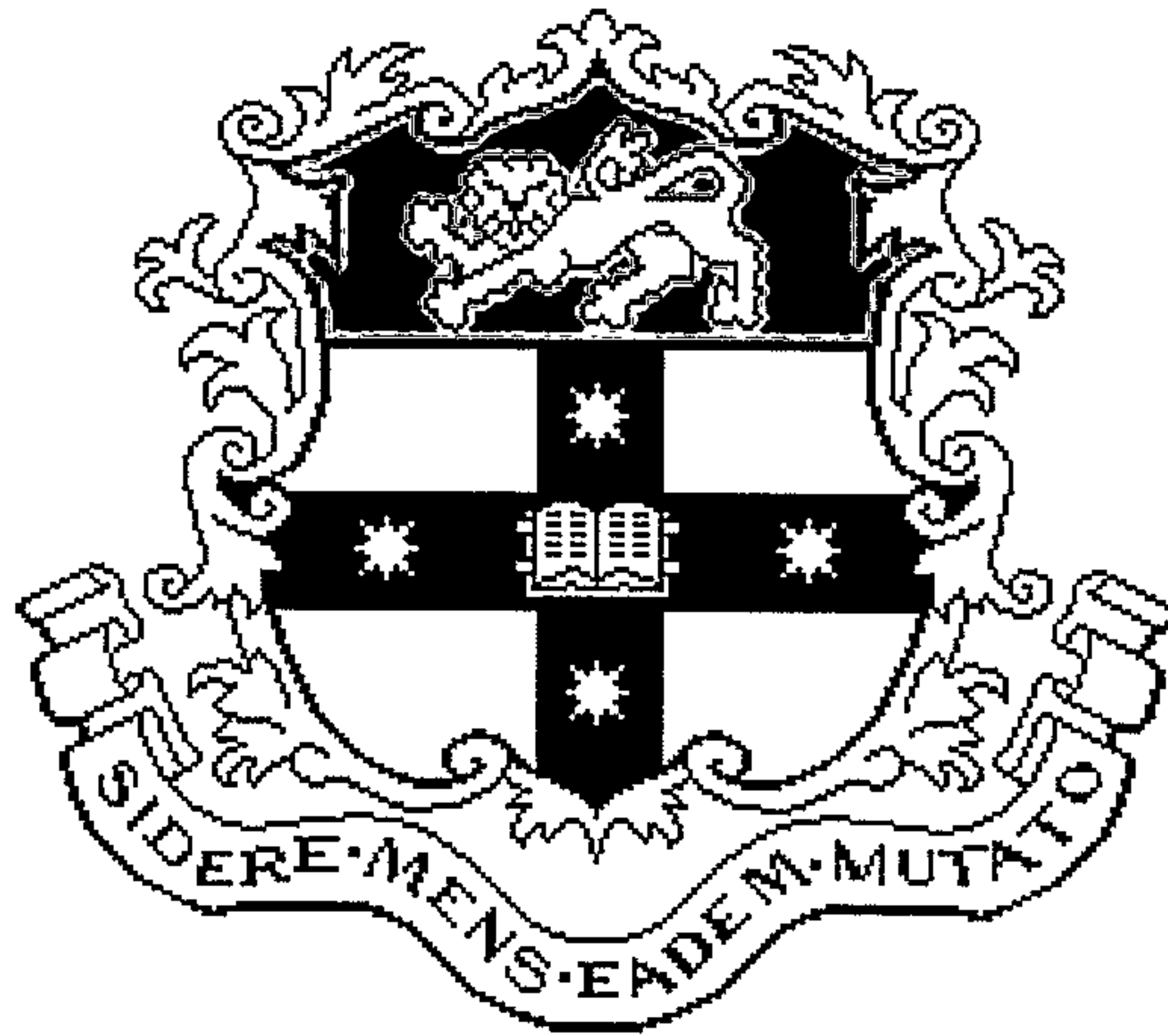
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**THE EXTENT OF ROOT RESORPTION AFTER THE
APPLICATION OF CONTINUOUS AND
CONTROLLED ORTHODONTIC FORCES FOR 12
WEEKS: A MICRO-CT SCAN STUDY**

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the degree of Master of Dental Science (Orthodontics)**

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DEDICATION

To all of those who are the wind beneath my wings.

To my family. Thank you for your support, encouragement and unconditional love. You show me that love has no frontier.

To Jam. Thank you for your love, patience, understanding and tremendous support. Without you I would not be able to come this far.

To Ajarn Somchai. Thank you for your words of wisdom to guide me through the darkness when no one was there.

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DECLARATION

CANDIDATE CERTIFICATE

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.

A. Paetyangkul.

Anchalee Paetyangkul

TABLE OF CONTENTS

- DEDICATION ii
- ACKNOWLEDGEMENTS iii
- DECLARATION v
- TABLE OF CONTENTS..... 1
- ABBREVIATIONS 4
- 1. INTRODUCTION 6
- 2. REVIEW OF THE LITERATURE..... 8
 - 2.1 CEMENTUM..... 8
 - 2.1.1 Definition and functions of cementum..... 8
 - 2.1.2 Classification of cementum..... 10
 - 2.1.3 Composition of cementum 12
 - 2.1.4 Development and distribution of cementum 14
 - 2.1.5 Cementum and Root Resorption 16
 - 2.2 ROOT RESORPTION 17
 - 2.2.1 Background 17
 - 2.2.2 Definition 17
 - 2.2.3 Prevalence 18
 - 2.2.3.1 Untreated Populations 18
 - 2.2.3.2 Orthodontically Treated Populations 19
 - 2.2.4 The Mechanism of Root Resorption 20
 - 2.2.5 Classification of Root Resorption 28
 - 2.2.6 Factors Associated with OIIR 34
 - 2.2.6.1 Biologic factors 34
 - 2.2.6.1.1 Individual susceptibility and genetic contribution 34
 - 2.2.6.1.2 Ethnicity 37
 - 2.2.6.1.3 Endocrine imbalance, alveolar bone density and bone turnover rate 37
 - 2.2.6.1.4 Asthma/ Allergy..... 39
 - 2.2.6.1.5 Nutrition 40
 - 2.2.6.1.6 Chronological age 41
 - 2.2.6.1.7 Stage of root formation 42
 - 2.2.6.1.8 Gender 42
 - 2.2.6.1.9 The presence of root resorption before orthodontic treatment 43
 - 2.2.6.1.10 Habits 43
 - 2.2.6.1.11 Tooth structure 44
 - 2.2.6.1.12 History of trauma 46
 - 2.2.6.1.13 Endodontically treated teeth..... 47
 - 2.2.6.1.14 Classification of malocclusion 48
 - 2.2.6.1.15 Specific tooth vulnerability to root resorption 50

2.2.6.2 Mechanical factors	51
2.2.6.2.1 Various appliances and different treatment modalities	51
2.2.6.2.2 Orthodontic movement type.....	52
2.2.6.2.3 Orthodontic force magnitude	53
2.2.6.2.4 Duration of the force application (Intermittent vs Continuous forces).....	54
2.2.6.2.5 Extent of tooth movement.....	55
2.2.6.2.6 Extraction and non-extraction.....	55
2.2.6.2.7 Treatment duration.....	56
2.2.7 Diagnosis.....	58
2.2.8 Clinical consequence of OIRR	59
2.2.9 Prevention and Management of root resorption.....	61
2.3 MICRO-CT SCAN	63
2.3.1 History and development	63
2.3.2 The SkyScan 1172 desktop X-ray micro-tomograph.....	68
2.3.3 X-ray micro-tomography of calcified tissues.....	70
3. REFERENCES.....	74
4. MANUSCRIPT	102
4.1 ABSTRACT.....	106
4.2 INTRODUCTION	108
4.3 MATERIAL AND METHODS	110
4.4 RESULTS	115
4.5 DISCUSSION	118
4.6 CONCLUSION.....	123
4.7 ACKNOWLEDGEMENTS	124
4.8 REFERENCES.....	124
4.9 LIST OF TABLES	131
4.10 LIST OF FIGURES	140
5. FUTURE DIRECTIONS	151
6. APPENDIX.....	152
Appendix 1: Four scanner generations (from Kalender, 2006) ¹⁹⁰	152
Appendix 2: Performance characteristics ^a of CT in a comparison from 1972 to 2005 (from Kalender, 2006) ¹⁹⁰	153
Appendix 3: Diagram for sample preparation.....	154
Appendix 4: Box-plot of the amount of tooth displacement in the light and heavy force groups	155
Appendix 5: Box-plot of the amount of tooth displacement for the maxilla and mandibular first premolars	156
Appendix 6A: Provisional Ethics Approval from the Human Research Ethics Committee, The University of Sydney	157
Appendix 6B: Ethic Approval from the University of Ondokuz Mayıs Medical Faculty Ethic Committee (English version).....	159
Appendix 6C: Ethic Approval from the University of Ondokuz Mayıs Medical Faculty Ethic Committee (Turkish version).....	160

Appendix 6D: Ethics Approval from the Human Research Ethics Committee, The University of Sydney (2006).....	161
Appendix 6E: Ethics Approval from the Human Research Ethics Committee, The University of Sydney (2007).....	162
Appendix 7A: Patient's Information Sheet.....	163
Appendix 7B: Guardian's Information Sheet	165
Appendix 8A: Consent form for Participant.....	167
Appendix 8B: Consent form for Parents/Guardian.....	168
Appendix 9: Raw data for root resorption volume	169
Appendix 10: Raw data for the distance of tooth movement.....	173

ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
AAC	Acellular afibrillar cementum
ANOVA	Analysis of variance
BMP	Bitmap
cAMP	Cyclic adenosine monophosphate
CEJ	Cemento-enamel junction
CMSC	Cellular mixed stratified cementum
EARR	External apical root resorption
FEM	Finite element model
FEO	familial expansile osteolysis
H&E	Haematoxylin and Eosin
HERS	Hertwig's epithelial root sheath
IC	Intermediate cementum
IL-1B	Interleukin-1 beta
Mp	Megapixel
OIRR	Orthodontically induced inflammatory root resorption
OPG	Orthopantomogram
PAEFC	Primary acellular extrinsic fibre cementum
PAIFC	Primary acellular intrinsic fibre cementum

PDB	Paget disease of bone
PDL	Periodontal ligament
RANK	Receptor activator of nuclear factor-kappa B
SCIFC	Secondary cellular intrinsic fibre cementum
SCMFC	Secondary cellular mixed fibre cementum
SEM	Scanning electron microscopy
TIFF	Tagged Image File Format
TNF ∞	Tumor necrosis factor- ∞
TNSALP	Tissue non-specific alkaline phosphatase
TRAP	Tartrate resistant acid phosphatase
XMT	X-ray micro-tomography

1. INTRODUCTION

Root resorption can be broadly divided into physiological and pathological resorption. Physiological resorption is a normal phenomenon that precedes the shedding of deciduous teeth. In contrast, pathological resorption occurs only under special circumstances, such as trauma, infection, orthodontic tooth movement and in certain systemic diseases.¹

Root resorption in traumatized teeth was first described by Bate in 1856,² but not until 1927 that Ketchum³ associated it with orthodontic tooth movement. The findings turned remarkable attention of dentists and orthodontists to the iatrogenic effects of biomechanical procedures.

External apical root resorption is referred to as an inevitable adverse effect of orthodontic tooth movement, however, this broad term does not implicate any specific etiology. The term orthodontically induced inflammatory root resorption (OIIRR) has been proposed by Brezniak and Wasserstein.⁴ It was defined as a sterile inflammatory process that is extremely complex and composed of various disparate components including forces, tooth roots, bone, cells, surrounding matrix, and certain known biologic messengers.

Most orthodontic patients experience some degree of root resorption.⁵ Fortunately, it is very rare that root resorption is severe enough to create a

clinical problem, and the benefits of esthetic and functional corrections of orthodontics far outweigh these normally minor side effects, however, in a small percentage of patient (5 – 10%) the degree of resorption exceeds acceptable levels and the longevity of the affected teeth may be compromised.⁶

There would be considerable clinical merit in being able to predict which patients are at risk of root resorption. A number of researchers attempted to determine the specific factors that could be implicated in root resorption. Various risk factors have been suggested both biologic and mechanical factors. Biologic factors include individual susceptibility, races, genetics, nutrition, chronological age and gender. Mechanical factors are the treatment associated factors, for instance, treatment mechanic, treatment duration, appliance used and type of tooth movement.

The challenging question still remains to verify the factors that enhance the root resorption or inhibiting the repair process after the application of the orthodontic force and, hopefully, this will be the key to the remedies for orthodontically induced inflammatory root resorption.

2. REVIEW OF THE LITERATURE

2.1 CEMENTUM

2.1.1 Definition and functions of cementum

Cementum is a non-uniform mineralized tissue covering the dentine of the tooth root. It is a specialized connective tissue that has many physical, chemical and structural features in common with compact bone.⁷ However, it differs from bone in that it contains no neural or vascular tissue, continues to grow in thickness throughout life and does not undergo remodelling or mineral turnover.⁸

Cementum is an element of the tooth itself, however, functionally it belongs to the dental attachment apparatus known as the periodontium.⁹ One of the key purposes of cementum is to provide support to the functioning tooth. It attaches the principal collagen fibres of the periodontal ligament to the root surface.

Cementum has essential adaptive and reparative functions. It is responsible for sustaining occlusal relationships and preserving the integrity of the root surface.

At the cemento-enamel junction (CEJ), the cementum layer is relatively thin, generally ranging from 20 to 50 μm thick. At the apex it occurs in a thicker layer of approximately 150 to 200 μm .⁸

2.1.2 Classification of cementum

Cementum may be classified according to:

- Its timing of development: primary or secondary cementum.
- The presence or absence of cementocytes within its structure: cellular or acellular cementum.
- The origin of the collagenous fibres of the matrix: that is intrinsic fibres which result from cementoblast activity or extrinsic fibres which result from the incorporation of periodontal ligament (fibroblast formed) fibres.^{8,10,11}

Consequently, the following types of cementum have been described:^{8,10}

- Acellular Afibrillar Cementum (AAC) - This type of cementum is deposited in isolated patches over minor areas of enamel just coronal to the CEJ. It plays no role in tooth attachment and is considered to be a developmental anomaly.
- Primary Acellular Intrinsic Fibre Cementum (PAIFC) - This type of cementum extends 15-20µm at the most cervical region of the root. Its function is anchorage.
- Primary Acellular Extrinsic Fibre Cementum (PAEFC) – This cementum continues apically from the Primary Acellular Intrinsic Fibre Cementum to cover at least two thirds of the root and often more. Lacking cells, it is

composed almost entirely of densely packed bundles of Sharpey's fibres, reflecting its anchorage function. It is the most highly mineralized cementum.

- Secondary Cellular Intrinsic Fibre Cementum (SCIFC) – This cementum is located at the apical and inter-radicular regions of the root. It is the main reparative tissue in the restoration of root resorption defects.⁹
- Secondary Cellular Mixed Fibre Cementum (SCMFC) – This cementum has a highly variable distribution and quantity reflecting its adaptive function.
- Cellular Mixed Stratified Cementum (CMSC) – This cementum is found on the apex, the apical third of the root and the furcations. Its thickness varies between 100 and 1000 μm . It has both anchorage and adaptive roles.
- Intermediate Cementum (IC) – This type of cementum is a form of Secondary Cellular Intrinsic Fibre Cementum and is located only at the apex. It contains entrapped cellular debris either from the root sheath or the odontoblast layer. It is not involved in root attachment and appears to have no function.

2.1.3 Composition of cementum

Cementum consists of water, organic matrix and (inorganic) mineral. Volumetrically, its composition is on average 45% inorganic material, 33% organic and 22% water.¹² The relative amount of the mineral component however varies depending on the cementum type, location and root resorption activity. The inorganic material, like in bone, is calcium and phosphate in the form of hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$, with small amounts of amorphous calcium phosphates.⁹ The hydroxyapatite is not chemically pure as it also consists of ions that were taken up from the tissue fluid during the mineralization phase. The amount of these incorporated elements reflects their concentration in the tissue fluid that was present during this process. Following the initial formative process, the concentration of the various ions may change again by further incorporation or replacement with other ions.⁹ Fluoride found in cementum is by far the most concentrated of all mineralized tissues.^{13,14}

The organic matrix of cementum consists of approximately 90% type I collagen and 5% type III collagen.¹⁵ The major roles of collagen are structural and to provide a scaffold for mineralization.¹⁶

The non-collagenous proteins of cementum are composed of several glycoproteins, enamel-related proteins, proteoglycans and osteocalcin. The glycoproteins in cementum include bone sialoprotein, osteopontin, osteonectin and fibronectin.¹⁷

2.1.4 Development and distribution of cementum

The formation of cementum can be subdivided into a prefunctional and functional developmental stage. The prefunctional portion of cementum is formed during root development. On the other hand, the functional development cementum begins when the tooth is almost in occlusion.⁹ Cementum is secreted by cementoblasts onto the surface of root dentine or in some animals onto the crown enamel.¹⁸ Its formation begins following the onset of root formation and elongation. Hertwig's epithelial root sheath (HERS) guides the formation of the root. The HERS is a collar of epithelial cells resulting from the apical elongation of the enamel organ.⁸ Prior to cementogenesis, the HERS disintegrates and dental follicle cells penetrate the epithelial layer to access the root surface. Cementoblasts deposit the cementum and constitute a large number of these invading dental follicle cells.¹⁸

When cementum is formed slowly it is usually acellular (primary cementum). When it is formed rapidly, however, cementoblasts may become trapped in lacunae in the cementum and they are then known as cementocytes. This is similar to how osteocytes are in lacunae in bone. Cementum that contains cementocytes is cellular (secondary cementum). Both types of cementum are formed in layers throughout life in response to the physiological demands on the tooth. The first formed cementum is acellular. It is deposited onto the surface of

the dentine and is mostly found near the cemento-enamel junction (CEJ). Acellular cementum may cover the entire root from the CEJ to the apex, but it is often missing in the apical third. Cellular cementum is usually found in the apical region and progressively builds in thickness towards the apex.⁸

There are two separate cementoblast inhabitants according to the type of cementum formed. One cementoblast population produces primary (acellular) cementum and the other secondary (cellular) cementum.⁸ The phenotypes of the cells differ. This may be demonstrated by monoclonal antibody staining. A monoclonal antibody (E11) stains the cementoblasts and cementocytes of secondary cementum. The cementoblasts that cover primary cementum do not stain for this antibody. The cementoblasts differ in developmental origin: The cells of primary cementum arise from the dental follicle, whereas the cells associated with secondary cementum originate from a non-follicular population.⁸

The production of cementum continues throughout life unless upset by periodontal pathology.⁹ A linear relationship between the depth of the cementum and the age of the tooth has been found with an average thickness of 0.1 mm at age 20 years and 0.2 mm at age 55 years.¹⁹

2.1.5 Cementum and Root Resorption

The intact periodontal ligament and vital cementum are believed to have a protective effect on root resorption. Furthermore, the epithelial rests of Malassez which are remnants of Hertwig's epithelial sheath and lie close to the cementum seem to secrete a substance that prevents fusion of the cementum with the alveolar bone, and thus guard against root resorption.²⁰ Kronfield²¹ noted that the cementum was thinner in the areas of greater functional stress and Schwarz²² advocated that the optimal force level for tooth movement should be between seven and 26 g/cm². If the intensity and duration exceed the reparative capacity of the cementum, root resorption will ensue.

2.2 ROOT RESORPTION

2.2.1 Background

One of the unavoidable side effects of orthodontic therapy is root resorption. The first report of root resorption in permanent teeth was 150 years ago by Bates.² As early as 1941, Ottolengui²³ reported on apical root resorption caused by orthodontic treatment. Then in 1927, Ketcham³ was among the first persons who demonstrated root resorption on radiographic evidence as a consequence of orthodontic treatment, and since then it has been the subject of a substantial amount of research.

2.2.2 Definition

Becks and Marshall²⁴ defined the term of resorption as the destruction of formed tooth structure.

Root resorption is an undesirable effect during orthodontic movement; it is believed to take place when local areas of the periodontal ligament are overcompressed.²⁵

Brezniak and Wasserstien⁴ stated that root resorption is a universal term that describes a pathologic component engaged in the expression. Based on the actual process of the orthodontic root resorption, the term “orthodontically induced inflammatory root resorption” (OIIRR) was proposed. OIIRR is a sterile inflammatory process that is extremely complex and composed of various disparate components including forces, tooth roots, bone, cells, surrounding matrix, and certain known biologic messengers.

2.2.3 Prevalence

Root resorption has been found in both orthodontically treated and untreated populations.

2.2.3.1 Untreated Populations

Prevalences of 0-100% have been reported in untreated populations, depending on the source of data. Histological investigations involve progressive slices of roots, thus less detailed is missed, and the measurement are more accurate. Henry and Weinmann²⁶ reported 90% of the untreated individuals exhibited histological evidence of root resorption. Using radiographs, incidence ranged from 0²⁷-100²⁸%. The results of the histological surveys suggest that a certain amount of

apical root resorption may be a normal physiological process, perhaps related to continuous bone remodelling.²⁸

2.2.3.2 Orthodontically Treated Populations

Sectakof and Selnes⁵ stated that “Most patients who undergo orthodontic treatment experience a certain degree of apical root resorption, which may or may not present radiographically”. Fortunately, the severe apical root resorption is rare. Several clinical studies indicated that once active orthodontic treatment is stopped, root resorption ceases.²⁹⁻³¹

Moderate to severe apical root resorption (>2 mm and $< 1/3$ of the root length) has been reported. In a large study of more than 860 cases, Sameshima and Sinclair³² found 25% of the maxillary anterior teeth underwent > 2 mm of root resorption. Linge and Linge³³ examined the periapical radiographs of the maxillary incisors and reported that 16.5% of orthodontically treated patients had root shortening >2.5 mm in one or more maxillary incisors. Earlier, Killiany³⁴ reported external apical root resorption of >3 mm to occur at a frequency of 30%, with only 5 % of treated individuals found to have > 5 mm of root resorption. Excessive root resorptions ($>1/3$ of the root length) have been found in 1-5% of a treated population.^{35,36}

2.2.4 The Mechanism of Root Resorption

Orthodontic forces applied to the periodontal system exert similar pressures onto bone as to cementum via the periodontal ligament. If there were no differences in the biologic behaviour of these two tissues, both would resorb equally. It was thought that since cementum is more resistant to resorption when compared to the more vulnerable bone, applied forces usually cause bone resorption, which leads to tooth movement. However, resorption of the cementum and dentine may also occur.

The exact mechanism of root resorption is not yet fully known. Resorption of the calcified dental tissues occurs if osteoclast-like cells obtain access to the mineralized tissue by a breach in the formative cell layer covering these tissues.^{37,38} Resorption may also occur if the mineral and matrix surfaces contact,³⁸ or if the precementum is mechanically damaged or scraped off.³⁹ The mineralized or denuded root areas are attractants for colonisation by hard tissue resorbing cells.³⁹

Thilander *et al.*⁴⁰ elucidated the type of root resorption that occurs during orthodontic treatment frequently that is preceded by hyalinization of the periodontal ligament (PDL). During the remodelling process of the hyalinized zone the necrotic hyalinized tissue and alveolar bone wall are removed by

phagocytic cells such as macrophages, foreign body giant cells and osteoclasts. 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 surface 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.⁴¹

After application of force, it can take between 10 and 35 days for resorbed lacunae to appear.⁴²⁻⁴⁵ Clinically, this degree of resorption cannot be detected with radiographs, especially when occurring on the buccal and lingual surfaces.^{46,47}

Resorbed lacunae appear mainly on the pressure side,^{42,43,48-50} and rarely on the tension side.⁵¹ It has been claimed that root resorption during orthodontic treatment occurs in the same areas where physiologic root resorption originates.⁴² These areas may be more sensitive to local changes.

The application of orthodontic force induces a local inflammatory reaction.⁵² This inflammation is essential for tooth movement to occur, and is also induces the root resorption process.⁵³

When a prolonged orthodontic force of greater than 20-26 g/cm² ⁵⁴ is applied to a tooth, the loaded region of periodontal ligament will suffer over-compression and

undergo hyalinization (also known as sterile coagulation necrosis).^{43,55-58} These sterile tissue changes promote an inflammatory reaction in an attempt to remove the necrotic tissue and initiate tissue repair.⁵⁹⁻⁶² The inflammatory process involves both bone and cementum resorption as resorbed lacunae associated with hyalinized tissue elimination appear mainly on the pressure side 10 to 35 days after force application.⁴²⁻⁴⁴ When orthodontic pressure is below the optimal level of 20-26 g/cm², root resorption ceases but tooth movement is still possible.⁵⁴

The periodontal ligament yields in a two-step process: an initial morphometric change (compression) followed by biochemical changes. The histochemical changes seen in the periodontal ligament include: fibre coalescence; hyalinization;⁴⁹ degradation of connective tissue matrices by both an extracellular pathway (matrix metalloproteinases) and an intracellular phagocytic pathway (lysosomal enzymes);⁶³ and demineralisation of Sharpey's fibres.³⁸ Odontoclastic activity follows these changes.

Investigations into the histological changes in the tissues surrounding the zone of hyalinization have mainly been conducted on animal samples, particularly rats. During the process of bone remodelling, the surrounding osteoclasts show a high content of Tartrate-Resistant Acid Phosphatase (TRAP)^{64,65} and it is this content that can be stained positive for cells involved in orthodontic tooth movement and root resorption.⁶⁵⁻⁶⁷

Brudvik and Rygh investigated the processes of orthodontic root resorption and repair in rats and mice and published their results in a series of papers.^{25,68-71} The authors studied the histological changes seen under light microscopy of the molar teeth of animals that had undergone orthodontic tooth movement.^{68,69} The stains used in this study were TRAP and Haematoxylin & Eosin (H&E). They found that the first phase of root resorption involves the reactions of and penetration by adjacent healthy periodontal membrane TRAP-negative cells into unmineralized precementum. This first resorptive attack on the root surface occurred in the over-compressed zone. These invading periodontal cells were originally either stationary or blood borne. Root resorption occurred in the perimeter of the hyalinized tissue after 2 to 3 days in the rat samples. Prior to loss of root structure, mononucleated cells were observed proximal to or contacting the root surface. The authors suggested that it is these cells that start the resorption of the unmineralized cementoid and mineralized acellular cementum. They proposed that some of these cells were macrophages, fibroblasts or cementoblasts; which are all TRAP-negative.⁶⁹

In another study using transmission electron microscopy, Brudvik and Rygh studied in greater detail the penetration of cells into precementum and mineralized cementum.^{25,70} They confirmed that mononucleated non-clast cells

were found during the initial removal of precementum and mineralized acellular cementum at the periphery of the hyalinized tissue and also some distance from it. Macrophage-like cells phagocytosed necrotic tissue in the periodontal ligament after 6 hours and near the root surface after 24 hours. Fibroblast-like and cementoblast-like cells were involved in the resorptive process of precementum after 24 hours. Mononucleated cells removed the surface layers of mineralized cementum after 3 days. Multi-nucleated cells were seen in surrounding tissues but not usually near the mineralized cementum surface during the 5-day test period.⁶⁸

Brudvik and Rygh investigated further the resorptive processes beneath the main hyalinized zone.^{25,70} They found that the majority of cells involved in the removal of the hyalinized tissues and root resorption were multinucleated and TRAP-positive. The root surface adjacent to the hyalinized tissues underwent necrotic degenerative changes. They found that the cells involved in the removal of the main part of the necrotic periodontal membrane, as well as the damaged root surface tissue, differ from those involved during the initial phase. Twelve Wistar rats were studied and the results indicated that multi-nucleated TRAP-positive giant cells with non-ruffled borders were involved in the removal of necrotic tissues as well as damaged root surface. They hypothesized that after removal of damaged cementum the cells continued cementum resorption. Mono-nucleated giant cells with ruffled borders were never observed near the

remnants of necrotic tissue, but were found in the resorption lacunae of root and bone surfaces. Cementum fragments were not found inside these cells and they postulated that removal of cementum tissue occurred extra-cellularly. They also suggested that the multi-nucleated cells are derived from monocytes and macrophages that initially invaded the necrotic hyalinized tissues. These observations have since been supported by further publications.^{62,72}

In summary, Brudvik and Rygh concluded that orthodontic root resorption is a part of the hyaline zone elimination process. There are two stages in the removal of the hyaline zone: (1) Initially mononuclear TRAP-negative cells remove necrotic tissue in the periphery of the hyalinized zone as well as the surface layers of unmineralized cementum and mineralized acellular cementum, (2) After four days multinuclear and mononuclear, TRAP-positive cells remove central parts of the hyalinized zone and continues resorbing the damaged and undamaged mineralized cementum.

There are several existing theories explaining the resorption resistance of the dental tissues, especially cementum. After extensive research in this field, mainly with tooth replantation models, Andreasen related surface resistance to the innermost cellular layer of the periodontal ligament on the root surface.⁷³ He suggested that this layer supplies the protective mechanism to the root, as well as

the potential for repair. The cementoblasts, fibroblasts, osteoblasts, endothelial, and perivascular cells are included in the protective layer. Small areas of cell damage in which surface resorption occurs are fully repaired with new cementum and periodontal ligament fibres from the adjacent vital parts of the periodontal ligament. Larger zones of damage are repaired by alveolar bone and bone marrow derived cells, which leads to ankylosis. However, Andreasen disqualified the role of the peripheral part of the periodontal ligament; Sharpey's fibers, cementum, cementoid, and Malassez epithelial cells with regards to a possible role in the preventive resorption mechanism of the periodontal ligament.⁷³ This theory has been supported by Jones and Boyde.³⁸

It has been documented that the uncalcified mineral tissues, osteoid, precementum, and predentine are resistant to resorption and may initially prevent loss of root tissue.⁴⁹ However, continuous pressure will eventually lead to resorption of these areas.^{37,49} It has also been demonstrated that root resorption occurs even in teeth where deposition of mineralised material was prevented.⁷⁴

It has been found that resorption activity by the cells of the periodontal ligament, as a response to mechanical or chemical stimuli, is characterised by synthesising prostaglandin E with an associated increase in cAMP.⁷⁵ This process is regulated by hormones including parathyroid hormone^{76,77} and calcitonin.⁷⁶ There is also regulatory contributions from the neurotransmitter, substance P,⁷⁸ vasoactive intestinal peptide,⁷⁹ and calcitonin gene related peptide,⁸⁰ and cytokines or

monokines including interleukin- 1 alpha,^{76,81} interleukin-1 beta,^{77,82} interleukin-2,⁸³ tumour necrosis factor,^{76,83} and interferon-gamma.⁸⁴

If orthodontic forces are reactivated during active root resorption, the process will continue.⁴² It is believed that if active orthodontic forces are removed, but passive stress remains applied to the periodontal ligament with a retention appliance, root resorption will continue if necrotic tissue is close to the resorptive site.⁷⁰ It is not certain how long the rest period needs to be to allow time for the repair of root resorption cavities prior to the safe reapplication of orthodontic force.

2.2.5 Classification of Root Resorption

External root resorption has been classified differently according to different authors.

Andreason⁸⁵

- **Surface resorption:** Self-limiting process involving small outlining areas, followed by spontaneous repair from adjacent intact parts of the periodontal ligament.
- **Inflammatory resorption:** Initial root resorption has reached dentinal tubules of infected necrotic pulpal tissue or an infected leukocyte zone.
- **Replacement resorption:** Bone replaces the resorbed tooth material that leads to ankylosis.

Tronstad⁸⁶

- **Inflammatory resorption** occurs when the pre dentin or precementum becomes mineralized or, in case of precementum, is mechanically

damaged or scrapped off. There are two types of inflammatory resorption:

- *Transient inflammatory resorption* occurs when stimulation to the damage is minimal and for a short period. The defect is usually undetected radiographically and repaired by a cementum-like tissue.
- *Progressive inflammatory resorption* occurs when stimulation continues for a longer period. It is tissue-pressure related, thus if forces removed, resorption should stop. It is usually seen as apical resorption and shortening of roots in the radiographs.
- **Replacement resorption** when the tooth becomes a part of the bone, gradually leading to a complete destruction of the tooth by the bone. It occurs as a mistake because the cells involved in the remodelling of bone are not able to distinguish between root cementum, dentin and bone.

Ghafari⁸⁷

Post-orthodontic external root resorption:

- **Inflammatory resorption:** Inflammatory mediators and phagocytic cells colonise mineralised or denuded cemental surface and later dentinal

tubules or pulpal tissues. All resorptions result from an inflammatory response to stimuli.

- *Surface resorption.* External root resorption due to an inflammation in the outlining area of the root surface (cementum and possibly dentin and pulpal tissue). Usually transient followed by repair from adjacent intact parts of the periodontal ligament (and cementum) by a cementum-like tissue. Generally undetected radiographically. If aetiology is not removed, may progress further.

- *Progressive resorption with bone substitution.* Distinct change in the anatomy of the roots. Bone occupies space of the resorbed tooth substance and the resorption is detected radiographically. Ankylosis or replacement resorption may be the outcome.

- *Progressive resorption without bone substitution.* Progressive inflammation without substitution of the resorbed tooth substance by bone. May be cervical or peripheral. Not reported as a common outcome.

Trope⁸⁸

- **Root resorption:** Resorption affecting the cementum or dentin of the root of a tooth. On the basis of the site of origin of the resorption, it may be referred to as internal, external, or root end resorption.
- **External root resorption:** External root resorption can be divided into
 - Apical external root resorption
 - Lateral external root resorption
 - Cervical root resorption

Based on the anatomical region of occurrence, root resorption was described as⁸⁹

- 1) internal root resorption
 - 1.1 root canal (internal) replacement resorption
 - 1.2 internal inflammatory resorption
- 2) external root resorption
 - 2.1 cervical root resorption
 - 2.2 external apical root resorption

According to the clinical and histological characteristics external root resorption can be classified into four categories:⁸⁹

- 1) External surface resorption
- 2) External inflammatory root resorption
 - 2.1 Cervical root resorption with a vital pulp
 - 2.2 Cervical root resorption without a vital pulp
 - 2.3 External apical root resorption (EARR)
- 3) Replacement resorption
- 4) Ankylosis

In an extensive review by **Brezniak and Wesserstein (2002)**, the term “orthodontically induced inflammatory root resorption (OIIRR)” was coined. According to the histological process, they divided OIIRR in three degrees of severity:

1. **Cemental or surface resorption with remodelling.** Only the outer cemental layers are resorbed, and they are later fully regenerated or remodelled. This process resembles trabecular bone remodelling.
2. **Dentinal resorption with repair (deep resorption).** The cementum and the outer layers of the dentin are resorbed and usually repair the cementum material. The final shape of the root after this resorption and formation process may or may not be identical to the original form.

3. **Circumferential apical root resorption.** Full resorption of the hard tissue components of the root apex occurs, and root shortening is evident. Different degrees of apical root shortening are possible.

2.2.6 Factors Associated with OIIRR

Root resorption is a universal term that describes a pathological process for which no single etiologic component is engaged in the expression. Factors affecting root resorption can be divided into biologic and mechanical factors

2.2.6.1 Biologic factors

2.2.6.1.1 Individual susceptibility and genetic contribution

Individual susceptibility is considered a significant factor in determining root resorption potential with or without orthodontic treatment. Rygh⁴¹ stated that the root resorption process seems to vary among persons and within the same person at different times. According to Owman-Moll *et al.*,^{90,91} individual reactions may even be more important than the increase in amount of force or length of the experimental period on both the tooth movement achieved and occurrence of root resorption. Some individuals appear to be intrinsically endowed with resistance to apical resorption under the stress of mechanotherapy and some, at the other extreme, are prone to experiencing severe resorption under the same regime. McFedden *et al.*⁹² reviewed the cases with the most severe root shortening in his study and found that there are persons with high resorptive potential in whom

root shortening occurs in both the mandible and the maxilla when applying intrusive force.

Several studies strongly suggest a genetic component for shortened roots. Direct evidence for a genetic component was recently demonstrated with use of the sib-pair model and estimated the heritability to be 70%. Although no definite genetic conclusion was found, autosomal dominant, autosomal recessive, and polygenic modes of inheritance are possible.

Gene candidates for external apical root resorption that have been studied include interleukin-1B (IL-1B),⁹³ TNFRSF11A,⁹⁴ tissue non-specific alkaline phosphatase (TNSALP)⁹⁴ and tumor necrosis factor- α (TNF α).⁹⁴

IL-1 genes were investigated because they encode cytokines known to be involved in the bone resorption (IL-1 cytokine) accompanying orthodontic tooth movement. The study done by Al-Qawasmi *et al.*⁹³ indicated that the IL-1B polymorphism accounts for 15% of the total variation of maxillary incisor external apical root resorption. Persons homozygous for the IL-1B allele 1 have a 5.6 fold increased risk of external apical root resorption greater than 2 mm as compared with those who are not homozygous for the *IL-1 β* allele 1.

Decreased IL-1 β production in the case of IL-1B (+3953) allele 1 may result in prolonged stress concentrated in the root of the tooth, triggering a cascade of

fatigue-related events leading to root resorption.⁸⁹ This supports the hypothesis that excessive root resorption associated with orthodontic tooth movement may be mediated through a decreased rate of catabolic bone remodelling in prolonged stress and strain of the tooth root against the alveolar bone.⁹³ Furthermore, the idea of increased bone turnover and decreased bone density allowing for faster tooth movement and less root resorption is supported by the other several studies.^{95,96}

In another linkage disequilibrium study, three possible linkages of OIIRR, including TNSALP, TNF α , and TNFRSF11A gene loci, were investigated.⁹⁴ The TNFRSF11A gene codes for the receptor activator of nuclear factor-kappa B (RANK). This gene maps to the same region as do familial expansile osteolysis (FEO) and a form of familial Paget disease of bone (PDB).⁹⁷ TNSALP plays a crucial part in mineralization and cementum formation. Mice lacking a functional TNSALP gene have defective acellular cementum formation along the molar roots and delayed tooth eruption.⁹⁸ TNF α levels are elevated during orthodontic tooth movement in human gingival sulcus.⁹⁹ They found no association between OIIRR and the TNF α and TNSALP genes. Only the TNFRSF11A locus is related to OIIRR.⁹⁴

2.2.6.1.2 *Ethnicity*

An ethnic dichotomy has been reported that Caucasian and Hispanic patients are more vulnerable than Asian patients to OIIRR.³² The authors stated that ethnic differences were known to exist in shape and size of teeth, therefore it was plausible that the developmental processes were not the same as well. However, this study was criticized that their samples came from six different orthodontic practices and five of six orthodontic practices tended to have a dominant attending racial group which may result in biased outcomes. One practice with a more balanced distribution of the three racial groups had no significant difference between the groups. Moreover, there was no attempt to adjust for treatment factors. Thus the finding that Asians have less root resorption may not be associated to race *per se*; it may instead be a reflection of certain treatment modalities incurred in Asian patients.¹⁰⁰

2.2.6.1.3 *Endocrine imbalance, alveolar bone density and bone turnover rate*

The effects of endocrine imbalance to the bone density have gained more attention in recent studies. Endocrine systems which regulate general bone metabolism influence the degradative activity and bone resorption.¹⁰¹ Consequently, they affect the rate of tooth movement and root resorption.

In an experimental animal study, Poumpros *et al.*⁹⁶ tested the effect of L-thyroxine on force-induced root resorption. They found that in thyroxine-fed rats, fewer root resorption lesions were presented than in the control group. They suggested that the administration of thyroxine should be considered in some patients, particularly in those who show beginning root resorption, or those who have low thyroid function. This has been supported by a report of three patients who received low dose thyroid supplement during the active course of orthodontic treatment.¹⁰² All patients had indications for progressive root resorption. They stated that none of the patients exhibited any clinical side effects from low dose thyroid and all appeared to benefit from the thyroid supplement.

Goldie and King¹⁰³ demonstrated decreased bone density as a result of secondary hyperparathyroidism leading to increased tooth movement and significantly less OIIRR.

In a rat model,⁹⁵ high and low bone turnovers were created by inducing hyper- and hypothyroidism. They found that low bone turnover associated with a significantly greater amount of OIIRR in the absence of the orthodontic loads. On the other hand, the high bone turnover group showed faster rate of tooth movement.

2.2.6.1.4 Asthma/ Allergy.

Inflammation is a necessary process of the orthodontic tooth movement. In this process, immune cells migrate out of the capillaries in the periodontal ligament and interact with locally residing cells by elaborating a large array of signal molecules. Osteoclasts originate in the immune system, and their myeloid progenitor cells are derived from the monocyte/ macrophage lineage.¹⁰⁴ Odontoclasts are osteoclastlike, multinucleated and are most likely also derived from the immune system. Consequently, it can be concluded that cells derived from the immune system are directly responsible for the resorption of alveolar bone that promotes tooth movement and the excessive root resorption that sometimes accompanies the force-induced tissue remodelling.¹⁰⁵ It has been suggested that the inflammatory mediators produced in an asthmatic episode may enter the periodontal ligament and act synergistically to enhance root resorption.¹⁰⁶

Nishioka *et al.*¹⁰⁵ analysed the records of 60 Japanese orthodontic patients and 60 pair-match controls. They concluded that allergy and asthma may be considered high-risk factors for the development of excessive root resorption during the course of orthodontic treatment in a Japanese population. The same conclusion was reached in a histological study that amongst many possible contributing factors only subjects with allergy showed an increased risk of root resorption, but no statistically significant result was found.¹⁰⁷

Using orthopantomograms (OPGs), McNab *et al.*¹⁰⁶ compared 99 healthy with 44 asthma individuals. The results showed that the incidence of external apical root resorption was elevated in asthmatics compared to non-asthmatics. However, the prevalence of external apical root resorption was higher in the asthmatic group, both asthmatics and healthy patients showed comparable numbers of teeth with moderate and severe resorption.

2.2.6.1.5 Nutrition

Malnutrition was advocated as a cause of root resorption.¹⁰⁸ Becks¹ demonstrated root resorption in animals deprived of dietary calcium and vitamin D.

On the other side, Goldie and King¹⁰³ deprived lactating rats of dietary calcium and phosphorus. They found that despite a greater amount of tooth movement and loss of bone mass in the dietary deficient group, the root resorption craters were actually smaller than the control group.

In orthodontic patients, regular alcohol consuming may increase the risk of OIIRR through vitamin D hydroxylation in the liver.^{6,109} In these individuals, the force-induced plasma extravasation may transfer ethanol and its metabolites into the PDL, where they can act synergistically with cytokines produced by local cells to evoke initiation and rapid progression of root resorption, as part of a

general effort to maintain calcium⁶ homeostasis. Reducing or eliminating this root resorptive risk can, therefore, be accomplished by ceasing the alcohol habit. Administration of ethanol to bone cells *in vitro* had profound inhibitory effects on matrix formation and proliferative activities.¹¹⁰

2.2.6.1.6 Chronological age

A number of parameters have been reported that encourage higher prevalence of root resorption in adults.^{92,111-113} Increasing with age, the periodontal membrane becomes less vascular, aplastic, and narrow, the bone more dense, avascular and aplastic, and the cementum wider. Massler and Malone² claimed that even without orthodontic treatment, the incidence of root resorption increase with age.

Brezniak and Wasserstein¹¹⁴ reviewed the early articles regarding the effects of age to the OIIRR and indicated that only a few studies showed no relationship between OIIRR and patient age at orthodontic treatment. However, they later reviewed more recent studies and found the opposite. Sameshima and Sinclair³² examined the records of 868 patients who were treated with edgewise appliances. It was concluded that adult patients experienced more resorption than children did in the mandibular anterior segment only. In their further case-control study,¹¹⁵ they did not find a positive correlation between the severity of OIIRR and the age of the patients with severe OIIRR. These finding are consistent with that of Baumrind *et al.*¹¹⁶

2.2.6.1.7 Stage of root formation

Incomplete root formation has been found to be a preventive factor for OIIRR.^{28,113} Although the teeth with partially formed roots were exhibited further elongation during orthodontic treatment, Hendrix *et al.* postulated that these roots were shorter than expected root length compared with the untreated individuals.^{111,117} This investigation was questioned by Vlaskalic *et al.*²⁸ because they did not make adjustment for the radiographic projection difference between pretreatment and post-treatment OPG.

2.2.6.1.8 Gender

In many studies, no correlation between gender and root resorption has been found.^{2,32,92,118-121} However, other studies^{113,116,122-125} suggested that females were affected more often than males.

Newman¹²⁴ found that the idiopathic root resorption ratio was 3.7:1 females to males, respectively. It was postulated that the result may be due to the difference in the stage of root development of the male, it is chronologically less than that of the female, and the male roots are less susceptible to the traumatic effects of orthodontic stress.^{113,122}

Although the effect of gender upon OIIRR of the maxillary lateral incisors was reported, such correlation was not found in the maxillary central incisors.¹²⁶

Interestingly, the direction of the differences was reversed in the experiment by Baumrind *et al.*¹¹⁶ In the adult patients, they observed more OIIRR in male subjects than in female subjects.

2.2.6.1.9 The presence of root resorption before orthodontic treatment

Harris and Butler¹²⁷ found a significant relationship between the degree of root resorption pre and post orthodontic treatment. Earlier studies had shown that an orthodontically moved tooth often undergoes some degree of root resorption, with more occurring in individuals who experienced root resorption before orthodontic treatment.²

2.2.6.1.10 Habits

Pressure from habits has been shown as a contributing factor of the apical root resorption. Nail biting,¹²⁸ tongue thrust and digit sucking have been statistically related to increased root resorption.¹²⁴

Severe nail-biters exhibited a significant higher degree of root resorption before and after orthodontic treatment compared with matched controls without the habit. This may implicate that the nail biting *per se* caused EARR.¹²⁸

Harris and Butler¹²⁹ demonstrated that the open bite subjects experienced higher degree of EARR before and after orthodontic treatment. They speculated that the pressure from tongue exerts to the anterior teeth in open bite cases causing cementoclasts to breach into the traumatized region, leading to the EARR.

Even though, in 1983, Linge and Linge did not find a positive relationship between previous or persisting habits and the average change in incisor root length,¹¹¹ their consecutive study demonstrated that finger sucking habits persisting beyond the age of 7 years and lip or tongue dysfunction are significant risk factors for root resorption.³³

2.2.6.1.11 *Tooth structure*

Teeth with abnormal root shape (pipette, pointed, or dilacerated) showed greater potential of root resorption.³² A common belief is that teeth with relatively short roots before orthodontic therapy tend to undergo more root resorption during orthodontic treatment.^{1,2,124,125,130,131} However, there are some studies indicated that teeth with blunt roots had less resorption.^{32,132} The latter finding may be related to longer teeth needing stronger forces to be moved and the fact that the

displaced root apex of the longer tooth is moved in the larger distance during orthodontic correction.⁸⁹ A strong connection between dental anomalies such as invaginations^{125,131} and taurodontic roots¹²⁵ and OIIRR was also reported. Harris *et al.*¹³³ indicated that the crown-root angle did not significantly associate with the apical root resorption pre and post-orthodontic treatment.

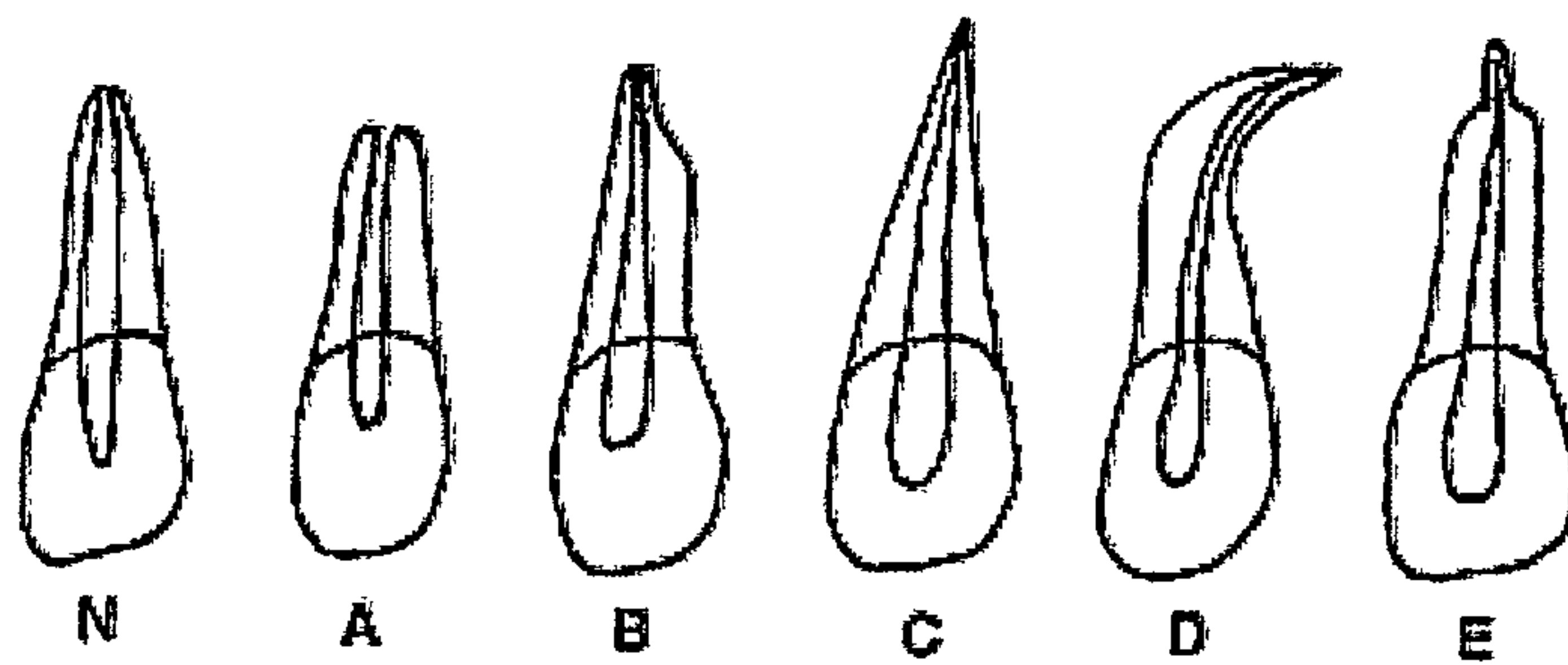


Figure. 1. Various root forms: normal(N), blunt(A), eroded(B), pointed(C), bent(D), bottle shaped(E). (*From Mirabella and Årtun 1995*)¹³²

An association between abnormal root forms and severity of OIIRR was observed by Smale *et al.*¹³⁴ The results suggested that long, narrow, pointed, deviated roots were risk factors for root resorption of the maxillary incisors.

Nishioka *et al.*¹⁰⁵ discussed in their article that when similar force is applied to the teeth, the distribution of the stress is different according to the types of root anatomy and the dental root with pointed or bent shape may be exposed to greater stress than roots with normal morphological features. These increased

stresses may traumatize the apical PDL, followed by an inflammatory repair process, which progresses to resorption of the root apex.

A recent study¹³⁵ of deviated root shapes used finite element models(FEMs) to demonstrate the stress distribution at the root. Five three-dimensional FEMs of different root morphology had been constructed and were applied with forces in an intrusive and lingual direction. It appeared that the short, bent and pipette-shaped roots had a significant higher stress concentration around the root apex compared to normal and blunt-shaped root.

A number of investigations advocated the increased prevalence of dental anomalies with apical root resorption. Kjær¹²⁵ reported a strong association between some dental morphological characteristics, such as invagination and taurodontism, and the tendency to root resorption during orthodontic treatment. This is supported by Mavragani *et al.*¹³⁶ who found significant difference in the severity of apical root resorption between invaginated and non-invaginated maxillary lateral incisors. In contrast, Lee *et al.*¹³⁷ did not find increased apical root resorption in 84 orthodontic cases exhibiting at least one dental anomaly, compared with 84 matched control samples.

2.2.6.1.12 History of trauma

A history of trauma has been associated with root resorption generally due to tissue changes very near the root surface.³³ Traumatized teeth can exhibit

external root resorption without orthodontic treatment.⁸⁵ It has been reported that a combination of trauma with orthodontic forces can aggravate the resorptive process.^{33,111,138} However, traumatized teeth without signs of resorption are not resorbed more than non-traumatized teeth provided the orthodontic tooth movement was started 4 to 5 months after trauma.^{139,140} Treatment for traumatized teeth should be light intermittent forces to avoid prolonged tipping.

2.2.6.1.13 Endodontically treated teeth

There is inconclusive evidence regarding severity and frequency of OIIRR in endodontically treated tooth.

Remington *et al.*³¹ suggested that endodontically treated teeth were more resistant to root resorption because of increased dentin hardness and density. This finding was supported by Mirabella and Årtun,¹³² who confirmed that endodontic treatment was a preventive factor for lateral incisors and canines.

Spurrier *et al.*¹⁴¹ examined the periapical radiographs of 43 orthodontic patients who had at least one endodontically treated incisor. In each patient the vital contralateral incisor served as a control. The results indicated that vital incisors resorbed to a significantly higher degree than endodontically treated incisors. However, a mean difference between two groups was only 0.77 mm which may be not considered as clinically significant. Seventeen year later, Esteves *et al.*¹⁴²

repeated the work of Spurrier *et al.*¹⁴¹ and found that there was no significant difference in OIIRR in endodontically treated and untreated teeth.

In contrary, Wickwire *et al.*¹⁴³ concluded that there was a greater frequency of OIIRR in non-vital teeth compared to their vital controls. However, their samples involved teeth that were treated endodontically after trauma. Teeth with an active inflammatory process from infected pulpal tissue, or from trauma, may be more subject to apical root resorption than vital teeth as orthodontic tooth movement itself creates an inflammatory response that may increase the resorptive process.¹⁴⁴ A successful endodontically treated tooth, with healthy surrounding tissues, in the absence of inflammation, would be no more susceptible to resorption than a normal tooth.^{31,144}

In a review of literature, Hamilton and Gutmann¹⁴⁴ recommended that if a tooth required root canal treatment during orthodontic movement, the root canal should be cleaned, shaped and an interim dressing of calcium hydroxide be placed. The tooth should be sealed occlusally to prevent bacterial leakage. Canal obturation is, then, accomplished upon the completion of orthodontic tooth movement.

2.2.6.1.14 Classification of malocclusion

Some initial malocclusions were reported as a risk factor for OIIRR e.g. open bite, overjet, Class II and Class III malocclusion. However, VonderAhe,²⁹ and

Mirabella and Artun¹³² found negative correlation between root resorption and classification of malocclusion.

Open bite cases possess significantly greater degrees of resorption. Consequently, the oral forces themselves merit early recognition and interception.¹²⁹ Harris and Butler¹²⁹ stated that a tissue was indifferent to the source of the force acting on it. Tongue thrusting exerts the orthopaedic forces to anterior teeth generating the same physiologic responses as mechanotherapy intended to torque or intrude a tooth.¹²⁹

Increased overjet, but not overbite, was significantly correlated with greater root resorption.³² Linge and Linge³³ speculated that increased overjet was a risk factor for root resorption. They further discussed that increased overjet may indirectly promote root resorption because it increased chance of incisor trauma, often required active torque with rectangular arch wires, and the use of Class II elastics which all these were risk factors of root resorption.³³ In addition, the treatment of Class III malocclusions was reported by Kaley and Phillips¹⁴⁵ as a risk factor for OIIRR.

2.2.6.1.15 Specific tooth vulnerability to root resorption

In a large study of 868 patients from six orthodontic practices by Sameshima and Sinclair, no significant differences were found between right and left sides. This finding was supported by a study on the hardness and elastic modulus of the cementum of the left and right maxillary teeth. There was no significant side-to-side difference in cementum hardness or elastic modulus.¹⁴⁶ The former radiographic investigation³² further compared maxillary and mandibular dentition. The tendency for the OIIRR was found greater in the maxillary anterior teeth than their mandibular counterparts. In contrast, the maxillary buccal segment was less prone to OIIRR than the mandibular buccal segment, but it was not statistically significant. The most severely resorbed teeth in reducing order were the maxillary lateral incisor followed by the maxillary central incisor, maxillary canine, lower canine, lower lateral and lower central incisors.³² Because the deviated root forms are quite common in maxillary lateral incisors, the common finding that maxillary lateral incisors are resorbed more than other teeth during orthodontic treatment is not unexpected.^{32,33,134}

2.2.6.2 Mechanical factors

2.2.6.2.1 Various appliances and different treatment modalities

Blake *et al.*¹⁴⁷ found no statistically significant difference in root resorption after orthodontic treatment between the edgewise and Speed appliances.

Linge and Linge^{33,118} compared root resorption resulting from fixed and removeable appliances and concluded that fixed appliances are more detrimental to the roots. They also found more resorption on the side where intermaxillary elastics were used.^{26,33}

The use of class II elastics was documented as a significant risk factor of OIIRR.^{33,111,132} Mirabella and Artun¹³² found that the increased chance of OIIRR was only on the tooth that supported the elastics. One likely explanation may be the elastic force resulting in jiggling movement of the anchor teeth.

Time of treatment with rectangular archwires was found to be associated with greater root resorption³³ but was refuted by Mirabella and Artun.²⁶

When the standard edgewise and straight-wire techniques were compared, no significant correlation was observed between EARR and treatment technique.¹²⁶

Ten Hoeve and Mulie¹⁴⁸ state that the classical Begg treatment is responsible for root resorption through tipping movement in the third stage. This is in agreement with the findings of Goldson and Henrikson.¹⁴⁹

In a large retrospective study, an attempt to identify the association between OIIRR and different slot size, arch wire type, use of elastics and type of expansion was not successful.¹⁵⁰

2.2.6.2.2 Orthodontic movement type

Numerous studies have mentioned that the type of tooth movement is one of the contributing factors of OIIRR. The types of tooth movement including bodily, tipping, torque, rotation, intrusion and extrusion movement have been compared.

Various types of orthodontic tooth movement were studied with FEMs analysis.¹⁵¹ The results suggested that purely intrusive, extrusive and rotational forces produced stresses concentrated at the root apex. Tipping movement concentrated stress at the alveolar crest. Bodily movement distributed stress throughout the PDL.

Han *et al.*¹⁵² compared root resorption after orthodontic intrusion and extrusion and concluded that intrusion of teeth causes about four times more root resorption than extrusion. However, Deshields¹⁵³ and McFedden *et al.*⁹² failed to

linked root resorption and intrusive force. *Faltin et al.*¹⁵⁴ investigated the localization of root resorption after application of continuous intrusive forces. They found that the distribution of root resorption gradually descended from the apical third to the cervical third.

Reports on root resorption during bodily movement are controversial. According to Reitan(1985,1964), the stress distribution along the roots during bodily movement is less than the stress concentration at the apex resulting from tipping. Therefore risk of root resorption that is due to bodily movement should be less than that of tipping.

2.2.6.2.3 Orthodontic force magnitude

Root resorption is believed to be related initially to force magnitude.¹⁵⁵

The contradictory results were obtained from an animal study. The results suggested that force magnitude did not have a statistically significant influence on the severity of OIRR.¹⁵⁶

Harry and Sims¹⁵⁷ found that the distribution of resorbed lacunae was related directly to the amount of stress on the root surface, and the rate of lacunae development was more rapid with increasingly applied forces. In another scanning electron microscopy (SEM) study,¹⁵⁴ the two different levels of continuous intrusive forces were applied on the maxillary first premolars to

observe the amount of root resorption. The authors found that the severity of OIIRR induced by intrusion depending on the magnitude of force applied.

2.2.6.2.4 Duration of the force application (Intermittent vs Continuous forces)

The duration of the force application was reported as a significant factor for the severity of OIIRR. A dog study suggested that intermittent forces caused 40-70% less OIIRR than continuous forces.¹⁵⁶ This finding was in agreement with a rat study by Kameyama *et al.*¹⁵⁸ The theory behind this phenomenon was described that intermittent forces probably prevent the formation of hyalinization or they allow reorganization of the hyalinized periodontal tissues and restoration of the blood flow during the inactive period.^{113,159} Continuous forces, however, leave no time for repair of damaged blood vessels and other periodontal tissues, which might lead to more extensive resorption.¹⁵⁶

On the other hand, intermittent forces have been associated with OIIRR due to jiggling forces.¹⁶⁰ Early in 1964, Reitan advocated tooth movement with light and continuous forces.¹⁶¹ A confocal laser scanning microscopy study was conducted to compare “constant versus dissipating forces” on human premolar teeth.¹⁶² Eighty-four premolars were collected from 27 patients, and the treatment period was 12 weeks. The set-up was a split mouth design, where the premolar on one side was activated with a stainless-steel 0.016” wire with a

buccal offset of 1 mm. which was reactivated every 4 weeks. The contralateral premolar was moved with a super-elastic 0.016" wire with an initial activation of 4.5 mm. and was not reactivated during the 12-week period. Their results showed that the teeth receiving the super-elastic force moved significantly more, and had greater perimeter, area and volume of OIIRR (140% greater) than the teeth with the stainless-steel wire. The amount of root resorption was significantly larger in the super-elastic group.

2.2.6.2.5 Extent of tooth movement

A study in 24 beagle dogs showed a strong correlation between the amount of tooth movement and the severity of OIIRR. From the results, it was concluded that the more teeth displaced, the more root resorption would occur.¹⁵⁶

In general, the maxillary incisors are moved in longest distance, consequently are at the greatest risk of root resorption.¹⁵⁰ Sameshima and Sinclair¹⁵⁰ reported a mean amount of 1 mm more root resorption than the control when the root apices of the maxillary incisors were displaced palatally.

2.2.6.2.6 Extraction and non-extraction

Extraction patterns can influence the degree of external apical root resorption because of the positive association between the distance a tooth is moved and its

likelihood of experiencing external apical root resorption and the modal degree of resorption.^{163,164}

In cases requiring tooth extraction, the remaining teeth are usually moved relatively greater distances, particularly when maxillary incisors are retracted to reduce a large overjet.

In cases of maxillary first premolar extraction, Mohandesan *et al.*¹²⁶ reported statistically significant EARR higher than the non-extraction group.

2.2.6.2.7 Treatment duration

The significant correlation between the degree of OIIRR and the treatment duration has been shown by several studies^{116,134,150,165,166} while it has not been supported by a few studies.^{29,132,164}

Kurol, Owman-Moll and Lundgren¹⁶⁶ applied 50cN controlled continuous orthodontic force on 56 premolars. The experimental period was varied from 1 to 7 weeks with eight children in each group. They found that the amount of root resorption increased relative to the longer period of the force application. After 7 weeks, the tested teeth showed on average more than 20 times larger mean resorbed root contour than control teeth.

In a radiographic study, the amount of EARR for the maxillary incisors was calculated from standard periapical radiographs. The root length reduction of the maxillary central incisors was 0.77 and 1.67 mm (4.5 and 9.8% of the initial root length), respectively, during 6- and 12-month active treatment. Likewise, the degree of root loss of lateral incisors was on average 0.88 and 1.79 mm. (5.6 and 11.5% of the initial root length) respectively.¹²⁶

After bracket placement for six and 12 months, Årtun *et al.*¹⁶⁷ found that patients at risk of severe resorption may be identified early in treatment and it was more likely that the patients who exhibited OIIRR during the first six months of active treatment would experience OIIRR in the following six-month period than those without.

In an animal study, Maltha *et al.*¹⁵⁶ reported that the amount of OIIRR increased according to the period of force application. After 7 days of force application, root resorption was already present in some surfaces and progressing with time. After 14-17 weeks of tooth movement, the root resorption was extended up to 94% of the observed root surfaces.

On the other hand, a study of OIIRR in adult orthodontic patients supported the opposite opinion. The samples included 343 patients from four orthodontic practices. With the aid of periapical radiographs of maxillary anterior teeth and

cephalograms, the authors concluded that the treatment time did not associate with OIRR.¹³²

2.2.7 Diagnosis

The conventional method for assessment of root resorption is via radiographic means. The two-dimensional nature of radiography limits its accuracy. Quantitative analysis can be accomplished by using radiographs, however the two-dimensional shape of the root on radiographic film could not represent the actual morphology of the root material loss. The radiograph is not an adequate tool to accurately diagnose resorption in the early stage and especially not in buccal tooth movements, where the resorption is found mostly on buccal and lingual surfaces. Even large and medium-sized cavities on the buccal and lingual surfaces, regardless of vertical location on the root, are difficult to detect on radiographs.¹⁶⁶

In addition, Kurol *et al.*¹⁶⁶ showed that resorption lacunae can extend halfway into the pulp canal without being detected on periapical radiographs. However, magnification errors might lead to underestimation or overestimation of the amounts of root resorption.¹⁶⁸

The SEM studies allow researchers to explore the third dimension of the resorption craters by creating the graphic simulation. A 3-D mapping is generated from the image pair and the average pixel values taken to encode the crater depth information; consequently, shading correction is needed to correct uneven illumination due to the curvature of the microscopy field.¹⁶⁹

Digital reconstruction using computer software may increase the precision of the analysis of root resorption.^{170,171} CT scanning offers a significant advantage over conventional radiography in the detection and quantification of root resorption; however its high cost and high radiation exposure to the patient limit its use to mainly *in vitro* research.

2.2.8 Clinical consequence of OIRR

After the orthodontic treatment, some tooth mobility may occur, but only when 9 mm or more of the root has been resorbed.¹⁷²

A long-term study by Remington *et al.*³¹ examined 100 patients on average of 14 years after treatment and found no tooth loss, with hypermobility reported in

only two cases. Baumrind *et al.*¹⁷³ noted that no adverse physiologic or pathologic effects have been documented when root loss is 20% or less.

2.2.9 Prevention and Management of root resorption

A number of approaches have been suggested in the literature to minimize OIIRR and were summarized by Vlaskalic *et al.*²⁸ The recommendations included short treatment duration,^{45,174} the use of light intermittent forces,^{42-45,175} habit control^{176,177} and a thorough assessment of familial tendency and medical history.^{176,178,179}

Vlaskalic *et al.*²⁸ also suggest that the treatment of moderate to severe malocclusions be commenced when most of the incisors have open apices, which is before the age of 9 years. They recommend this strategy as incomplete root formation has been found to be significantly associated with a lower severity of OIIRR.^{175,180,181}

The avoidance of intermaxillary elastics which thus reduces jiggling forces has been suggested by Linge and Linge.³³ The limitation of tooth movements that are associated with a high risk of OIIRR (especially intrusion and torque) has been proposed by Parker and Harris.¹⁸²

It is strongly suggested that after 6 months of active orthodontic treatment, periapical radiographs be taken and when OIIRR is diagnosed, a two to three

month pause in treatment with passive arch wires is implemented.¹⁸³⁻¹⁸⁵ It has also been recommended that where OIIRR is detected, an additional radiograph be taken 3 months later.⁸⁷ Three-monthly radiographic reviews of blunt and pipette-shaped apices have been proposed by Levander *et al.*¹⁶⁵

Where severe resorption is found, the treatment goals should be revised with the patient and a compromised treatment plan may need to be agreed upon.¹⁸⁶

It is mandatory to take final radiographs at the time of removal of fixed appliances.¹⁸⁶ In the case of teeth with severe OIIRR, follow-up radiographs are recommended until additional root loss is no longer detected.¹⁸⁴

It has been recommended that retention with fixed attachments be applied with caution as occlusal trauma to the fixed teeth may lead to extreme resorption.¹⁸⁷

2.3 MICRO-CT SCAN

2.3.1 History and development

The phenomenon known as X-rays was first created and described by Wilhelm Conrad Roentgen. He reported his finding to the Wurzburg Physical-Medical Society on 28 December 1895. The name X-rays was used by Roentgen due to the unknown nature of his discovery.¹⁸⁸

Irradiation makes it possible to non-invasively see inside objects, both living and non-living. The limitation of conventional radiography is that it produces a two-dimensional projection of the three-dimensional subject. Attempts have been made to reproduce three-dimensional structures from a two-dimensional film, namely laminography or focal plane tomography.¹⁸⁹ This involves the translation of the object/subject together with the detection medium in such a way that only one narrow slice parallel to the translation plane is in focus. The contrast from features outside the slice of interest is blurred, reducing its appearance from the image. The attainment of sharp images of the slices is challenging due to the thickness of each slice and the superimposed smearing of the images outside the region of interest.¹⁸⁹

Digital computers have made possible an approach superior to laminography; computed tomography. Cormack (1963) was the first to demonstrate the ability

of X-rays to produce a projection of a cross-section of an object.¹⁹⁰ In 1973, Hounsfield developed a commercially available computed tomography system for medical imaging.¹⁹¹ This brought a further significant step forward in diagnostic medicine since it allowed images of internal features to be made based directly on their X-ray attenuation coefficients.^{192,193}

Tomography produces a two-dimensional map of X-ray absorption in a slice of the subject, thus there is no compression of the three-dimensional data into a two-dimensional plane. A series of X-ray projections is made through the slice at various angles around an axis perpendicular to the slice. Digital computing allows the series of projections or two-dimensional absorption maps to be combined into the three-dimensional map.¹⁹⁴

There are limitations to the use of this technology for patient applications; the doses of X-rays must be kept to a minimum and the duration must be reduced as involuntary movement by the subject will cause image distortion.¹⁹⁵ These constraints are not applicable to the study of inanimate objects, thus longer data collection times and greater X-ray intensities may be used to improve image quality.

There are four generations of computed tomography scanners. The first generation is known as the pencil beam system. It has the simplest arrangement

consisting of the X-ray source, a pin-hole collimator and a single detector, as designed by Hounsfield.¹⁹¹ The second generation scanner uses a parallel beam of X-rays and the third generation uses a flat fan distribution of X-rays. The fourth generation of computed tomography scanners uses a cone beam geometry of X-rays, which is a three-dimensional analogue of the two-dimensional fan beam geometry.¹⁹⁶ This design is ideal for volumetric computed tomography.

195

Advances in computed tomography have made possible the analysis of small structures at high resolution; that is computed X-ray micro-tomography (XMT). The demand for improving area detectors for consumer electronics in the 1980s prompted this innovation.¹⁹⁵

In 1982, Elliot and Dover developed the first XMT machine and produced an image of hard tissue specimens with a resolution of 12 micrometres.

Medical computed tomography scanners are able to achieve a resolution of a fraction of a millimeter. However, even with technological advances in detector design, it is unlikely the resolution can be improved due to X-ray dosage limitations. To improve the resolution by a factor of two, the exposure must be

increased by a factor of 16. A ten thousand-fold increase in exposure is required for only a ten-fold improvement in resolution.¹⁹⁴

The resolution of XMT images is in the order of micrometres (ums), approaching that of optical microscopy.

Two-dimensional digital image dimensions are measured in units of pixels. A pixel is a two-dimensional representation of the smallest unit of colour value within an image. This colour value may also be a shade of grey. Imaging software for computed tomography usually assigns the dimensions of a pixel to the x and y axis, and it is able to represent a given area. The number of pixels per surface area may be used to describe the resolution of the image. The increasing number of pixels per unit area improves image quality and increases resolution.¹⁹⁵

In three-dimensional imaging the unit voxel is used. A voxel is a three-dimensional modification of a pixel with the added dimension of depth. Thus a voxel has a volume and its dimensions have an x, y and z axis.¹⁹⁵

In addition to the smaller scale, XMT systems have another significant characteristic that is different from medical computed tomography scanners;

instead of the X-ray source moving around the subject, the specimen rotates whilst the X-ray source and detector are stationary.

2.3.2 The SkyScan 1172 desktop X-ray micro-tomograph

The SkyScan 1172 (SkyScan, Aartselaar, Belgium)¹⁹⁷ is a compact desktop system for microscopy and micro-tomography. It consists of an X-ray shadow microscopic system and a computer with tomographic reconstruction software. The system allows the researcher to make a non-destructive three-dimensional reconstruction of the object's inner structure from two-dimensional X-ray shadow projections. A spatial resolution of 5micron corresponding to near 1×10^{-7} cubic mm. voxel size can be produced.

The system obtains multiple X-ray shadow transmission images of the object from different angular views, as the object rotates on a high-precision stage. From these shadow images, cross section images of the object are reconstructed by a modified Feldkamp cone-beam algorithm, creating a complete 3D representation of internal microstructure and density over a selected range of heights in the transmission image.

After the serial construction, cross sections can be displayed as well as a realistic 3D-image with possibilities to "rotate" and "cut" the object model. From this model, calculation of the internal morphological parameters will be possible. The recommended sample size has a diameter of up to 68 mm (for standard scan) and a height of around 70 mm. The sample is positioned on a rotating platform, which is programmed to revolve over 180 or 360 degrees with a fixed rotational

step. The distance of the platform from the X-ray source determines the magnification. The X-ray detectors consist of two camera options: the high-performance ten Megapixel (Mp) option, and the economy 1.3 Megapixel option. The images received are stored as 16 bit Tagged Image File Format (TIFF) picture files with a resolution of 1024 x 1024 pixels. After image acquisition is completed, software for axial slice-by-slice reconstruction uses the Feldkamp cone-beam algorithm (Cone beam reconstruction 2.13, SkyScan-1072, Belgium).¹⁹⁶ The resultant axial two-dimensional images are generated as 1024 x 1024 pixel bitmap (BMP) images having an 8 bit gray-scale dynamic range. The software package, VG StudioMax version 1.2 (Volume Graphics, GmbH, Heidelberg, Germany) is used to collate the axial two-dimensional slices to form a three-dimensional reconstruction of the images.

Nevertheless, current technology limits the use of micro-computed tomography to small, inanimate specimens, such as bone and extracted tooth samples, the non-destructive nature of the technique allows a variety of experiments to be conducted to investigate structural and compositional characteristics of calcified tissues.

2.3.3 X-ray micro-tomography of calcified tissues

The applications of XMT systems are numerous and include fatigue analysis, performance prediction of materials, mineral analysis, and the study of calcified tissues including bone and teeth.¹⁹⁸ Contemporary technology has mostly limited the use of XMT to inanimate and *in vitro* specimens. However, one *in vivo* study has been conducted to assess the changes in bone associated with ovariectomy in rats¹⁹⁹ and another *in vivo* study was performed on living snails.²⁰⁰

There have been various XMT studies of the mineral concentration of enamel and dentine. One study quantitatively determined the amount of mineral loss from human enamel rods after acid demineralization and how much mineral was regained after remineralisation.²⁰¹ The deciduous incisors of low birth weight children were scanned by XMT to seek abnormalities in the mineral concentration which may be related to developmental defects.²⁰² The enamel mineral concentration distribution of deciduous human molars has also been studied.²⁰³ An XMT study of the mineral concentration of carious human dentine was of high enough resolution to detect calcified and enlarged tubuli spaces in the lesion. The remineralised regions had a very high mineral content suggesting a loss of organic matter.²⁰⁴ A study of rat lower incisors was performed with sequential XMT slices to measure differences in enamel mineral

concentrations progressing from the apex to the incisal edge.²⁰⁵ A 500-year old human tooth has also been studied with XMT, investigating features including attrition, cervical root caries, sclerotic dentine and calculus²⁰⁶.

XMT has been utilized to study the anatomy of root canals.²⁰⁷ Some of the studies have involved extracted human teeth which were scanned before and after endodontic treatment and have determined the area and volume changes related to instrumentation and obturation.^{208,209} The resultant canal anatomy has also been compared following the use of different instrumentation techniques.^{210,211}

The effect of lasers on enamel has been studied with XMT technology. One study assessed the effect of the continuous wave carbon-dioxide laser. The changes in mineral density and cracking induced in enamel when lasers are used to cut enamel were investigated.¹⁹⁸ The use of a laser and phosphoric acid to etch enamel was compared with laser-only and acid-only etching. The depth of etch and amount of enamel subsurface damage were evaluated for the different etch methods. It was found that laser and acid conditioning resulted in an increased etching depth, but did not induce significant damage in the enamel subsurface.²¹² The XMT has also been used to quantify the progression of growth of enamel and dentine craters that form after sequential application of the Er:YAG laser.²¹³

There are a number of recent XMT studies involving bone. Comparisons have been made of biopsies from normal and synostosed human coronal sutures.²¹⁴ Assessments have also been made of normal and osteoarthritic bone structures in knee specimens from human cadavers.²¹⁵ One study has involved finite element analyses of human trabecular bone architecture based on XMT images to obtain information about bone mechanical characteristics.²¹⁶ A comparison has been made of different bone graft approaches in rabbit mandibles. It was found that intramembranous bone grafts integrate better than endochondral bone grafts in three-dimensions when they are grafted into membranous bony defects in the mandibles.²¹⁷ One group of authors have described the advantages of synchrotron radiation microtomography in quantifying the degree of mineralization of bone in three dimensions involving human iliac crest bone biopsy samples.²¹⁸ The process of tissue engineered bone growth into polymer scaffolds has been studied with XMT technology at a resolution of 2 micrometres.²¹⁹ Bone structural changes caused by periapical pulpal infections in rats have been analysed.²²⁰ A study involving rats during a postnatal acceleratory growth period was used to evaluate changes in the calcified tissue of the mandibular condyle from altered function. A maxillary occlusal splint was designed to shift the mandible laterally during closure. The authors found that compared to controls, the experimental animals' mandible and the condyle had a modified shape and size, including alterations in the trabecular bone of the

condyle.²²¹ The process of bone regeneration following amputation of the forelimbs of newts has been assessed via XMT.²²²

The micro-structure of bone around retrieved titanium micro-implants from humans has been investigated.²²³ Another study to assess the osseointegration of a dental implant in a rabbit tibia has compared the quality of XMT, synchrotron radiation X-ray micro-imaging and conventional dental radiography.²²⁴ Sea urchin teeth have been studied with XMT^{225,226} and so have sea urchin ossicles.²²⁷

There are a limited number of studies in the dental literature investigating root resorption using XMT technology. One study utilized X-ray microfocus-tomographical scanning to assess a case of cervical external root resorption in human teeth.²²⁸ Two studies have been conducted involving the assessment of OIIRR via XMT. A comparison was made of no force (control), light and heavy forces for the intrusion of human premolars that were treatment planned for extraction. It was found that the volume of resorption craters in the light and heavy force groups were two and four times greater than the control group respectively.¹⁶⁸ Another study which involved rats was undertaken to investigate if fluoride has a beneficial effect in reducing the incidence of OIIRR. It was concluded that fluoride on average does reduce the size of resorption craters, but the effect was variable and found not to be statistically significant.²²⁹

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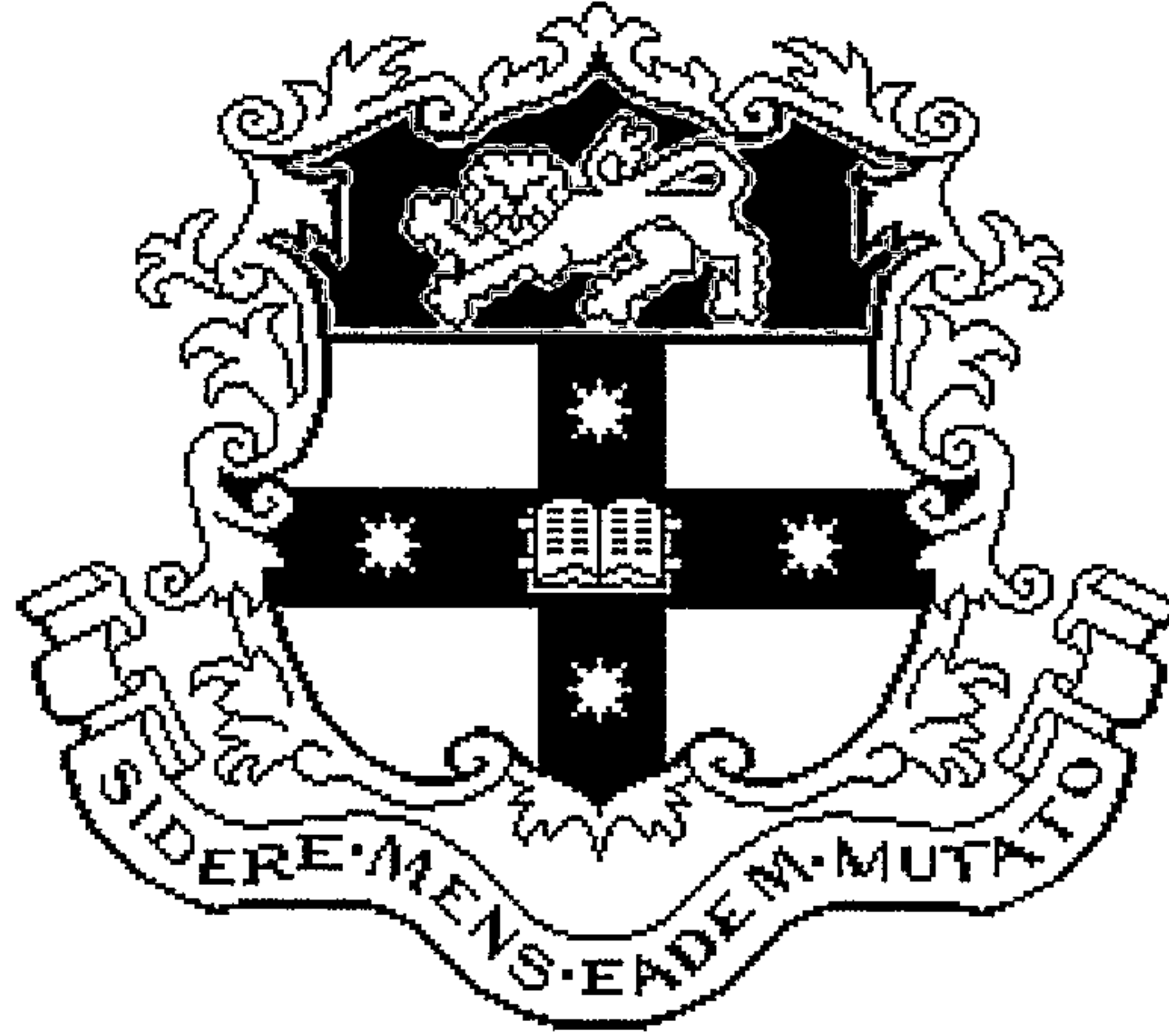
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4. MANUSCRIPT



**The extent of root resorption after the application of
continuous and controlled orthodontic forces for 12
weeks: A micro-CT scan study**

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**The extent of root resorption after the application of continuous and
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4.1 ABSTRACT

Introduction: The association between orthodontic force magnitudes was shown to be a primary factor of root resorption. The quantitative studies of the root resorption after the force application of four and eight weeks have been conducted previously. This prospective randomized clinical trial aimed to investigate the root surface topography and the volumetric amount of root resorption after the application of controlled light and heavy forces in buccal direction for 12 weeks. In addition, the present study also compared the amount of root resorption between maxillary and mandibular first premolars.

Method: Forty maxillary and mandibular first premolar teeth were collected from ten orthodontic patients (age range 12.7-18.2 years, mean 14.3 years). The right or left first premolars were randomly selected to receive two levels of forces. A light buccally directed orthodontic force of 25 grams was applied to the experimental tooth on one side while a heavy orthodontic force of 225 grams was applied on the contralateral premolar. At the end of 12 weeks of force application, the experimental teeth were extracted and were scanned with the microcomputed tomography scan X-ray system (micro-CT scan). Resorption crater analysis was performed with specially designed software for direct volumetric measurements. The extent of tooth movement producing by light and heavy forces was also measured. **Results:** Individual variation was presented in all comparisons. The light force produced significantly less root resorption than the heavy force. The results showed that the maxillary first premolar teeth were more likely to suffer from orthodontically induced inflammatory root resorption

(OIIRR) than the mandibular first premolars ($p=0.036$). There was a significant difference between buccal and lingual surfaces ($p=0.003$) with greater amount of root resorption on the buccal surface. The distribution pattern of the resorption cavities was greatest in the buccal-cervical, buccal-middle, lingual-middle and lingual-apical areas in both light and heavy force groups, corresponding with the pressure zones of tipping and translatory movement. The mean amount of tooth movement in heavy force group was almost twice as much as in light force group.

Conclusion: The volume of root resorption crater induced by the buccal force was found to be directly proportional to the magnitude of the application force. Maxillary premolars seemed to be more susceptible to root resorption than mandibular premolars.

Key words: Root resorption, light orthodontic forces, heavy orthodontic forces, X-ray microtomography, volumetric measurement

4.2 INTRODUCTION

It has long been known that orthodontic tooth movement leads to the external root resorption, since Ketcham^{1,2} reported the evidence of radiographic root resorption; however, the precise aetiology remains unclear.

Becks and Marshall³ defined the term of resorption as the destruction of formed tooth structure. Resorption of calcified dental tissue occurs when odontoclasts obtain access to the mineralised tissues by a breach in the formation cell layer covering the tissues.^{4,5} Root resorption is an undesirable effect during orthodontic movement and it is believed to take place when local areas of the periodontal ligament are overcompressed.^{6,7} Therefore, root resorption is a concern for the orthodontic specialty since it lessens the perceived value of successful orthodontic treatment.

Many previous investigations linked root resorption to various factors which may act as a single or multi-factorial cause including type of orthodontic appliance,⁸⁻¹⁰ magnitude of applied force¹¹⁻¹⁵ duration of force application,^{9,16-20} type of tooth movement,^{9-11,21} amount of tooth movement,²² systemic factors,²³ age of patient,^{24,25} gender,^{23,26} nutrition,^{26,27} previous trauma^{9,10} and ethnicity.²⁰

The association between the orthodontic force magnitude was shown to be a primary factor.^{11,12,28-31} Light forces have long been recommended to reduce adverse tissue reaction.^{11,28,29,31} However, Owman Moll and co-workers in a

histology study found that there was no significant difference in frequency or severity of root resorption between group of 50-gram and 200-gram force levels.¹³

Several authors found a greater amount of root resorption in the maxillary incisors than in the mandibular incisors.^{10,20,32} There was a limited number of studies that investigated the differences in the amount of root resorption between maxilla and mandible associated with the posterior teeth. The radiographic study by Sameshima and Sinclair³³ discovered that the prevalence and severity of root resorption in buccal segments were greater in the mandibular teeth than in the maxillary teeth. On the other hand, McNab²³ showed that among posterior teeth the maxillary first molars were the most susceptible to the external root resorption in asthmatic patients.

Previous studies at the University of Sydney have investigated the root resorption after continuous and controlled force application of four and eight weeks.³⁴⁻³⁷ This prospective randomized clinical trial aimed to investigate the root surface topography and the volumetric amount of root resorption after the application of controlled light and heavy forces in buccal direction for 12 weeks. In addition, the present study also compared the amount of root resorption between maxillary and mandibular first premolars.

4.3 MATERIAL AND METHODS

Forty maxillary and mandibular first premolar teeth were collected from ten patients (6 females, 4 males; mean age 14.3; range 12.7-18.2 years) who required extraction for orthodontic purposes at the Ondokuzmayis University, Turkey. Ethics approval was obtained from the University of Ondokuz Mayis Medical Faculty Ethic Committee and from the Human Research Ethics Committee, The University of Sydney (reference numbers are 348 and 8782 respectively). The subject selection criteria were described previously.³⁸ All subjects completed written informed consents and information of birthplaces was obtained.

The subjects were bonded with 0.022" SPEED brackets (Strite Industries, Ontario, Canada) on the first permanent molar and the experimental premolar tooth. The right or left first premolars were randomly selected to receive one of the two different levels of force. A light buccally directed orthodontic force of 25 gram was applied on the right or left first premolar using a 0.016" Titanium-Molybdenum Alloy (TMA[®], Rematitan[®], Dentaureum, Ispringen, Germany) cantilever spring while a heavy force of 225 gram was applied on the contralateral first premolar by using 0.017" x 0.025" TMA[®] cantilever spring (Beta III Titanium, 3M Unitek[™], Monrovia) (**Figure 1a,b,c**). The force magnitude was measured to the desired force levels with a strain gauge (Dentaureum, Ispringen, Germany). To avoid occlusal interference of the experimental premolars and to prevent spring deformation, light cure cement (Transbond[™] Plus light cure band adhesive, 3M Unitek[™], Monrovia) was

bonded onto the occlusal surfaces of the mandibular first permanent molar teeth (**Figure 1d**). Hence, the force system designed for this study did not have impact on the further orthodontic treatment for these subjects. Patients were seen every four weeks to ensure that the experimental appliances were in good condition.

Specimen collection

At the end of the 12 weeks of experimentation, extraction was performed with care to avoid surgical trauma to the root cementum. Upon removal, each tooth was immediately stored in an individual container of sterilized de-ionized water (Milli Q[®], Millipore, Bedford, Massachusetts, USA) which had been earlier tested as an appropriate storage media.³⁹ The tooth was then placed in an ultrasonic bath for a period of ten minutes to remove all traces of residual periodontal ligament (PDL) and soft tissue fragments. Following the ultrasonic bath, PDL was removed by a damp gauze swab with a rubbing motion, until all visible signs of the PDL were removed. The tooth was then disinfected in 70% alcohol for 30 minutes and then bench dried at ambient room temperature ($23\pm1^{\circ}\text{C}$).

Micro-CT Scan

In this study, the SkyScan 1172 desktop X-ray micro-tomograph (SkyScan, Aartselaar, Belgium)⁴⁰ was used to scan the samples. The SkyScan 1172 is a compact desktop system for microscopy and micro-tomography (**Figure 2**). It consists of an X-ray shadow microscopic system and a computer with tomographic reconstruction software. The system allows the researcher to make a non-destructive three-dimensional (3D) reconstruction of the object's inner structure from two-dimensional X-ray shadow projections. A spatial resolution of 5 micron corresponding to near 1×10^{-7} cubic mm voxel size can be produced.

Each tooth was scanned separately 2 to 3 mm coronal to the cementoenamel junction. The aluminium filter was used with the resolution ranging from 14.3 to 16.0 μm pixel size. During the cone-beam acquisition, the teeth were rotated over 360° and 0.2 rotational step. A total of 1800 shadow images per tooth was acquired and saved as 16-bit tagged image file format (TIFF) files. From these shadow images, cross section images of the tooth were reconstructed by a modified Feldkamp cone-beam algorithm (NRecon version 1.4.2, Aartselaar, Belgium). The individual axial slices were generated as 1024x1024 pixel bitmap images having an 8-bit greyscale dynamic range.

After the serial construction, cross sections were displayed as well as a realistic 3D-image with possibilities to "rotate" and "cut" the object model using a software called VG Studio Max (version 1.2, Volume Graphics, Gmbh,

Heidelberg, Germany). The resorption craters in each cross-section were located individually, rendered and exported to be ready for the volumetric measurement in convex hull software (Chull 2D). The root surfaces on buccal and lingual aspects were divided into three levels: cervical, middle and apical. Therefore, there were six individual regions of resorption craters on both buccal and lingual aspects to be measured: buccal-cervical (BC), buccal-middle (BM), buccal-apical (BA), lingual-cervical (LA), lingual-middle (LM), and lingual-apical (LA) (**Figure 3**).

The volumetric measurement for each crater was obtained using convex hull software (Chull2D) (**Figure 4**) that was developed specifically for this purpose at the Electron Microscope Unit at the University of Sydney. After the three-dimensional reconstruction of the craters, the images were stored as cross sections of the total sample. The sum for the root resorption volume for each surface and for each tooth was calculated (Unit in voxels was transformed to mm^3). This analysis followed the same methodology as that described in a previous study.³⁴

The Amount of tooth movement

The initial and final impressions were taken with Polyvinylsilosane impression material (Imprint II Regular Body, 3MTM, MN) prior placement of the orthodontic appliance and at the end of 12 weeks respectively. Impressions were poured with die stone (Vel-mix, Kerr, Orange, Calif). The stone casts were

measured with a digital vernier caliper (Masel, Bristol, PA) for the amount of buccal displacement of the first premolars.

Statistical Analysis

Univariate analysis of variance (one-way ANOVA) was performed using the Statistic Package for Social Sciences (SPSS for Windows, version 14, SPSS Inc, Chicago, Illinois, USA). The factors used in the model were subject (random factor), force (fixed factor), surface, jaw, individual regions. Pairwise comparisons (with Bonferroni correction for multiple comparisons) were also used to compare the difference between six individual regions and between two jaws that received similar force level (i.e. maxillary-light and mandibular-light, maxillary-heavy and mandibular-heavy). Paired t-test was performed to determine the significance of intra-individual difference between light and heavy forces. Student's t-test was used to compare the amount of tooth movement between light and heavy forces and in maxilla and mandible. The significant level of each test was chosen at five per cent. During statistical evaluation, the raw data were transformed for the residual plots to conform to normality. The cube root of the volumetric reading was used to create a model for statistical analysis which replaces each volume by the radius of an equivalent hemispherical. This approach was also used in previous studies.^{15,34}

4.4 RESULTS

The 3D images of the teeth revealed the root surface topography in both light and heavy force groups (**Figure 5A,B**). After 12 weeks of force application varying diameter resorption cavities appeared in all experimental teeth. On the buccal surface, root resorption cavities tended to widen in the cervical and middle thirds of the root surface compared with the apical portion. In apical one-third, resorption craters were characterized by small cavities. In the middle and cervical regions, resorption lacunae exhibited irregular shapes. On the lingual surface the resorption craters tended to concentrate more in the apical and middle parts than in the cervical areas.

Effects of subjects on resorption crater volume

It was found that the effects of subjects on volume of root resorption craters were significant in all analyses with the p-value 0.001 when compared by tooth (**Table I**) and $p < 0.001$ for any other analyses (**Table V, VII**).

Comparison of light and heavy forces (Figure 6)

The mean cube root resorption volumes between light and heavy forces were found highly significantly different when analysed by tooth, surface, level, individual regions ($p < 0.001$) (**Table I, V, VII**). When the cube root volume of light and heavy forces was compared intra-individually, there was a significant

difference between light and heavy forces in both maxillary and mandibular teeth with the p-value 0.003 and 0.012 respectively (**Table XIII**).

Maxilla and mandible

Despite a marginally significant difference of the amount of root resorption in the maxillary and mandibular teeth ($p=0.036$) (**Table I, Figure 7**), there was no statistical difference between that of maxillary-light and mandibular-light, and between maxillary-heavy and mandibular-heavy groups (**Table II**). This implicated that the greatest difference lay between light and heavy forces.

Comparison by tooth

Considering all teeth, light forces produced significantly less volume of root resorption than heavy forces; with the mean of 1.974 mm and 2.587 mm respectively on the cube root scale (**Table III**). The maxillary premolars exhibited higher mean cube root resorption volume (mean of 2.427 mm) than the mandibular premolars (mean of 2.134 mm) (**Table IV**).

Comparison of the buccal and lingual surfaces (Table V)

When the cube root volume was compared surface-by-surface, there was a significant difference between the buccal and lingual surfaces ($p=0.003$); with a mean cube root volume of 1.229 mm on buccal and 1.052mm on lingual surfaces (**Table VI**).

The results also showed that there was marginally significant difference between the maxillary and mandibular teeth ($p= 0.015$) when the same surface was compared (**Table V**).

Comparison of six individual regions (Table VII)

A highly significant difference among six regions was presented ($p<0.001$). The distribution pattern of the resorption lacunae was highest in BC then gradually declined to BM, LM, LA, LC and BA respectively (**Table VIII**). On the buccal side, the resorption was more concentrated in the BC and BM regions. On the lingual side, the craters were higher at LM and LA regions. There was no statistical difference between BC and BM, LM and LA (**Table IX**). The pattern corresponded to regions of compression generated by tipping and translatory forces.

The lowest mean cube root volume of the resorption craters was in BA. There were also significant differences between the BA position and all other positions except LC. These lowest two positions were the locations where were expected to experience tension.

The amount of tooth movement

Heavy force produced significantly grater amount of tooth movement than light force (**Table X**). The mean amount of tooth movement in heavy force group was

almost twice as much as in light force group (**Table XI**). There was no statistically significant difference for the extent of tooth movement in maxilla and mandible (**Table XII**).

4.5 DISCUSSION

The magnitude of force has been documented to be directly correlated with the severity of orthodontically induced inflammatory root resorption (OIIRR).^{12,34,41-}

⁴³ The ideal force for tooth movement would be one that mimics a physiological balance between tooth movement and bony adaptation. Schwarz⁴⁴ advocated the optimal force level for tooth movement should be between seven and 26 gram per square centimeter. He also stated that, when force exceeded this threshold, root resorption would occur. When pressure decreases below this limit, root resorption ceases.¹³ This was later confirmed by King and Fischlschweiger.⁴⁵ In a rat study they found that light forces produced insignificant root resorption, whereas intermediate or heavy forces resulted in substantial crater formation. Histologically, Thilander *et al.* found that the greater force, the greater the hyalinization. Consequently, the removal of the thicker hyalinized zone resulted in greater root resorption.⁴⁶ The finding of the recent study that the volume of the root resorption crater was higher in the heavy force group than in the lower force group, corroborated the previous observations.^{34,36}

After 12 weeks of force application, varying diameter resorption cavities appeared in all experimental teeth. The wide resorption bays seemed to occur by the union of smaller lesions. A similar resorption characteristic was also observed by Acar *et al.*⁴⁷

The 25-gram force (light force) and a nine-fold greater force of 225-gram (heavy force) were selected as described previously.^{15,34} This facilitates comparison of results between the previous root resorption studies^{34,36} that have been conducted at the University of Sydney.

The degree of OIRR showed individual variation. Even though patients underwent a similar treatment schemes, corresponding experimental premolars of different patients exhibited varying degrees of root resorption. According to Owman-Moll *et al.*,^{13,14} individual reactions may even be more important than the increase in amount of force or length of the experimental period on both the tooth movement achieved and occurrence of root resorption. Some people appear to be intrinsically endowed with resistance to apical resorption under the stress of mechanotherapy and some, at the other extreme, are prone to experiencing severe resorption under the same regime. The results of the recent study showed that even accounting for the individual variation, there was a significant difference between light and heavy forces.

The radiographic study by Sameshima and Sinclair³³ discovered that the prevalence and severity of root resorption in buccal segments were greater in the mandibular teeth than the maxillary teeth due to the higher density of the alveolar bone. Although their results suggested that the maxillary buccal segment had less resorption than the mandibular buccal segment, there was no significant difference between maxillary and mandibular posterior teeth.³³ The results of the present study showed that the maxillary first premolar teeth were more likely to suffer from OIIRR than the mandibular first premolar teeth contrary to their radiographic findings. This may be due to the anatomical structure of the maxillary alveolar bone e.g. sinus in proximity²³ and bone density. In general, the maxillary alveolar process consists of spongy bone. This could be due to a bony structure that allows better vascularization which may transport more inflammatory cells into the resorption areas causing more root resorption.

Clustering of the resorption lacunae was highest in BC, BM then LM, LA. No statistical difference was found between BC and BM on the buccal side and LM and LA on the lingual side. The pattern corresponded to regions of compression generated by tipping movement,^{15,34,36} however, in larger area possibly because the longer period of force application resulted in greater hyalinised zone. Another possible explanation could be that the initial tipping movement of the premolars was accompanied by later translation causing the extension of the resorption area.

The distance of tooth movement was found directly related to root resorption.^{22,48}

In the present study, the mean extent of tooth movement in the heavy force group was almost two times greater than in the light force group. The trend corresponded with the greater amount of root resorption in the heavy force group than in the light force group. The result may be implicated that the more the root was displaced, the more root resorption occurred.

Quantitative analysis can be accomplished by using radiographs, however, the two-dimensional shape of the root on radiographic film could not represent the actual morphology of the root material loss. In addition, Kurol *et al.*⁴⁹ showed that resorption lacunae can extend halfway into the pulp canal without being detected on periapical radiographs. In addition, magnification errors might lead to underestimation or overestimation of the amounts of root resorption.³⁴ The SEM studies allow researchers to explore the third dimension of the resorption craters by creating the graphic simulation. A 3-D mapping is generated from the image pair and the average pixel values to encode the crater depth information; consequently, shading correction is needed to correct uneven illumination due to the curvature of the microscopy field.⁵⁰ The crater images acquired in this study were not graphic simulations. They were the exact tooth images that were simply magnified. The microtomography images allowed observation of the morphology and particular aspects of tooth anatomy as well as their volumetric evaluation.

The major limitation of the volume-estimation software used in this study related to how the craters are closed by the convex hull algorithm. The CHULL 2D software is more likely to underestimate the crater volume when the root surface curvature is high especially toward the apex of the root. This may be an explanation of the slightly less root resorption volume in LA than in LM; however, the difference was not statistically significant. This small error is omitted because this method of crater volume measurement is based on direct imaging of the tooth as a fully 3D object.

4.6 CONCLUSION

When controlled light and heavy forces were applied in a buccal direction to maxillary and mandibular first premolars for 12 weeks, the following conclusion were drawn:

1. The severity of root resorption shows individual variation.
2. The volume of resorption craters is directly proportional to the magnitude of the force applied. The light force produces significantly less root resorption than the heavy force in both maxillary and mandibular premolar teeth.
3. Maxillary premolars seem to be more susceptible to root resorption than mandibular premolars.
4. Root resorption is significantly greater on buccal surfaces than lingual surfaces on the maxillary and the mandibular premolars.
5. Root resorption is significantly greater towards cervical region on the buccal surface and apical region on the lingual surface.
6. Heavy force produces almost twice as much tooth movement as light force.

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4.8 LIST OF TABLES

Table I:	Univariate analysis of variance on the effect of jaw, force and subject on the total volume of root resorption craters
Table II:	Pairwise comparisons of upper-light with lower-light and upper-heavy with lower-heavy
Table III:	The mean total cube root resorption volume for light and heavy forces
Table IV:	The mean total cube root resorption volume for the upper and lower premolars
Table V:	Univariate of variance on the effect of jaw, force, surface and subject on the volume of root resorption craters in each surface
Table VI:	The mean total cube root resorption volume divided into surfaces
Table VII:	Univariate analysis of variance on the effect of jaw, force, position and subject on the volume of root resorption craters in each individual six regions
Table VIII:	The mean cube root resorption volume divided into six regions on the root surfaces
Table IX:	Pairwise comparisons of root resorption values between the six regions for all of the teeth
Table X:	Student's t-test to compare the amount of tooth movement producing by light and heavy forces

- Table XI:** Comparison of mean amount of tooth movement for light and heavy forces
- Table XII:** Student's t-test to compare the amount of tooth movement between maxilla and mandible
- Table XIII:** Paired t-test to compare the intra-individual difference between light and heavy forces

Table I: Univariate analysis of variance on the effect of jaw, force and subject on the total volume of root resorption craters

Tests of Between-Subjects Effects						
Dependent Variable: Cuberoot vol tooth						
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	208.038	1	208.038	255.764	.000
	Error	7.321	9	.813 ^a		
uplo	Hypothesis	.854	1	.854	4.834	.036
	Error	4.948	28	.177 ^b		
force	Hypothesis	3.763	1	3.763	21.294	.000
	Error	4.948	28	.177 ^b		
subj	Hypothesis	7.321	9	.813	4.603	.001
	Error	4.948	28	.177 ^b		

a. MS(subj)

b. MS(Error)

Table II: Pairwise comparisons of upper-light with lower-light and upper-heavy with lower-heavy

Pairwise Comparisons						
Dependent Variable: Cuberoot vol tooth						
(I) ulf	(J) ulf	Mean Difference (I-J)	Std. Error	Sig. ^a	95% Confidence Interval for Difference ^a	
					Lower Bound	Upper Bound
upper, light	upper, heavy	-.630*	.191	.017	-1.175	-.085
	lower, light	.275	.191	.969	-.269	.820
	lower, heavy	-.321	.191	.629	-.866	.224
upper, heavy	upper, light	.630*	.191	.017	.085	1.175
	lower, light	.906*	.191	.000	.361	1.451
	lower, heavy	.309	.191	.708	-.236	.854
lower, light	upper, light	-.275	.191	.969	-.820	.269
	upper, heavy	-.906*	.191	.000	-1.451	-.361
	lower, heavy	-.597*	.191	.026	-1.141	-.052
lower, heavy	upper, light	.321	.191	.629	-.224	.866
	upper, heavy	-.309	.191	.708	-.854	.236
	lower, light	.597*	.191	.026	.052	1.141

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Table III: The mean total cube root resorption volume for light and heavy forces

Dependent Variable: Cuberoot vol tooth

force	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
light	1.974	.094	1.781	2.166
heavy	2.587	.094	2.395	2.780

Table IV: The mean total cube root resorption volume for the upper and lower premolars

Dependent Variable: Cuberoot vol tooth

uplo	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
upper	2.427	.094	2.234	2.619
lower	2.134	.094	1.942	2.327

Table V: Univariate of variance on the effect of jaw, force, surface and subject on the volume of root resorption craters in each surface

Tests of Between-Subjects Effects						
Dependent Variable: Cuberoot vol surface						
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	104.019	1	104.019	255.764	.000
	Error	3.660	9	.407 ^a		
uplo	Hypothesis	.427	1	.427	6.248	.015
	Error	4.580	67	.068 ^b		
force	Hypothesis	1.881	1	1.881	27.522	.000
	Error	4.580	67	.068 ^b		
surf	Hypothesis	.630	1	.630	9.219	.003
	Error	4.580	67	.068 ^b		
subj	Hypothesis	3.660	9	.407	5.949	.000
	Error	4.580	67	.068 ^b		

a. MS(subj)

b. MS(Error)

Table VI: The mean total cube root resorption volume divided into surfaces

Estimates				
Dependent Variable: Cuberoot vol surface				
surf	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
buccal	1.229	.041	1.147	1.312
lingual	1.052	.041	.969	1.134

Table VII: Univariate analysis of variance on the effect of jaw, force, position and subject on the volume of root resorption craters in each individual six regions

Tests of Between-Subjects Effects						
Dependent Variable: Cuberoot vol						
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	34.673	1	34.673	255.764	.000
	Error	1.220	9	.136 ^a		
uplo	Hypothesis	.142	1	.142	6.073	.014
	Error	5.228	223	.023 ^b		
force	Hypothesis	.627	1	.627	26.749	.000
	Error	5.228	223	.023 ^b		
posn	Hypothesis	2.287	5	.457	19.507	.000
	Error	5.228	223	.023 ^b		
subj	Hypothesis	1.220	9	.136	5.782	.000
	Error	5.228	223	.023 ^b		

a. MS(subj)

b. MS(Error)

Table VIII: The mean cube root resorption volume divided into six regions on the root surfaces

Estimates				
Dependent Variable: Cuberoot vol				
posn	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
BC	.511	.024	.464	.559
BM	.467	.024	.420	.515
BA	.250	.024	.202	.298
LC	.267	.024	.219	.315
LM	.426	.024	.378	.474
LA	.359	.024	.311	.407

Table IX: Pairwise comparisons of root resorption values between the six egions
for all of the teeth

Pairwise Comparisons						
Dependent Variable: Cuberoot vol						
(I) posn	(J) posn	Mean Difference (I-J)	Std. Error	Sig. ^a	95% Confidence Interval for Difference ^a	
					Lower Bound	Upper Bound
BC	BM	.044	.034	1.000	-.058	.146
	BA	.261*	.034	.000	.160	.363
	LC	.245*	.034	.000	.143	.346
	LM	.086	.034	.197	-.016	.187
	LA	.153*	.034	.000	.051	.254
BM	BC	-.044	.034	1.000	-.146	.058
	BA	.217*	.034	.000	.116	.319
	LC	.201*	.034	.000	.099	.302
	LM	.042	.034	1.000	-.060	.143
	LA	.109*	.034	.026	.007	.210
BA	BC	-.261*	.034	.000	-.363	-.160
	BM	-.217*	.034	.000	-.319	-.116
	LC	-.017	.034	1.000	-.118	.085
	LM	-.176*	.034	.000	-.277	-.074
	LA	-.109*	.034	.026	-.210	-.007
LC	BC	-.245*	.034	.000	-.346	-.143
	BM	-.201*	.034	.000	-.302	-.099
	BA	.017	.034	1.000	-.085	.118
	LM	-.159*	.034	.000	-.261	-.057
	LA	-.092	.034	.116	-.194	.010
LM	BC	-.086	.034	.197	-.187	.016
	BM	-.042	.034	1.000	-.143	.060
	BA	.176*	.034	.000	.074	.277
	LC	.159*	.034	.000	.057	.261
	LA	.067	.034	.774	-.035	.169
LA	BC	-.153*	.034	.000	-.254	-.051
	BM	-.109*	.034	.026	-.210	-.007
	BA	.109*	.034	.026	.007	.210
	LC	.092	.034	.116	-.010	.194
	LM	-.067	.034	.774	-.169	.035

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Table X: Student’s t-test to compare the amount of tooth movement producing by light and heavy forces

Independent Samples Test									
		Levene's Test for Equality of Variances		t-test for Equality of Means					
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference LowerUpper
ToothMovement	Equal variances assumed	.819	.371	-4.927	38	.000	-1.94758	.39525	-2.74772-1.14743
	Equal variances not assumed			-4.927	36.189	.000	-1.94758	.39525	-2.74903-1.14612

Table XI: Comparison of mean amount of tooth movement for light and heavy forces

Group Statistics				
Force		N	Mean	Std. Error Mean
ToothMovement	Light	20	2.4498	.24625
	Heavy	20	4.3973	.30917

Table XII: Student’s t-test to compare the amount of tooth movement between maxilla and mandible

Independent Samples Test

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ToothMovement	.765	.387	.842	38	.405	.42204	.50135	-.59289	1.43698
			.842	37.434	.405	.42204	.50135	-.59339	1.43748

Table XIII: Paired t-test to compare the intra-individual difference between light and heavy forces

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	CUL - CUH	-.1735	.13954	.04413	-.2733	-.0737	-3.932	9	.003
Pair 2	CLL - CLH	-.1951	.19808	.06264	-.3368	-.0534	-3.114	9	.012

4.9 LIST OF FIGURES

- Figure 1:** Experimental appliance. (a) frontal view, (b) side view, (c,d) occlusal views.
- Figure 2:** X-ray Microcomputed Tomography
- Figure 3:** Root surface was subdivided into six individual regions (a) buccal surface, (b) lingual surface.
- Figure 4:** The convex hull algorithm (Chull 2D) reconstructs the loss of convexity by estimating a new line of closure that effectively connects the 2 points at the edge of the break, thus creating a closed subvolume for each axial slice of the crater. The total crater volume is calculated by summing the subvolumes for these closed cross sections.
- Figure 5A:** Three-dimensional reconstructed images of a human premolar that has been subjected to 12 weeks of buccal movement with a light force (25g) (a) buccal (b) lingual (c) mesial (d) distal
- Figure 5B:** Three-dimensional reconstructed images of a human premolar that has been subjected to 12 weeks of buccal movement with a heavy force (225g) (a) buccal (b) lingual (c) mesial (d) distal
- Figure 6:** Box-plot of the cube root of the total volume of the difference force levels

Figure 7: Box-plot of the cube root volume of the resorption craters for maxillary and mandibular experimental teeth

Figure 1: Experimental appliance. (a) frontal view, (b) side view, (c,d) occlusal views.

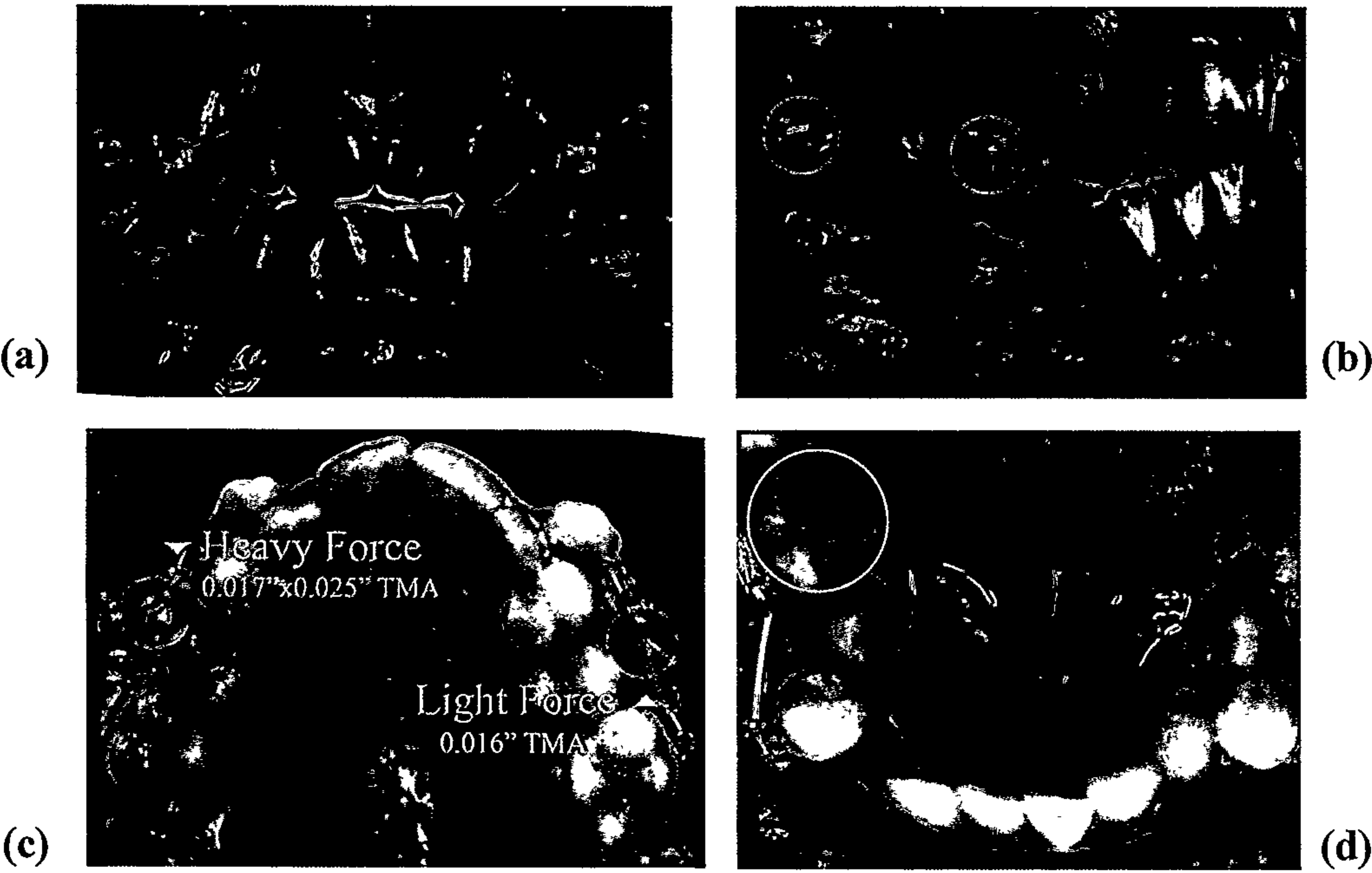


Figure 2: X-ray Microcomputed Tomography



Figure 3: Root surface was subdivided into six individual regions (a) buccal surface, (b) lingual surface

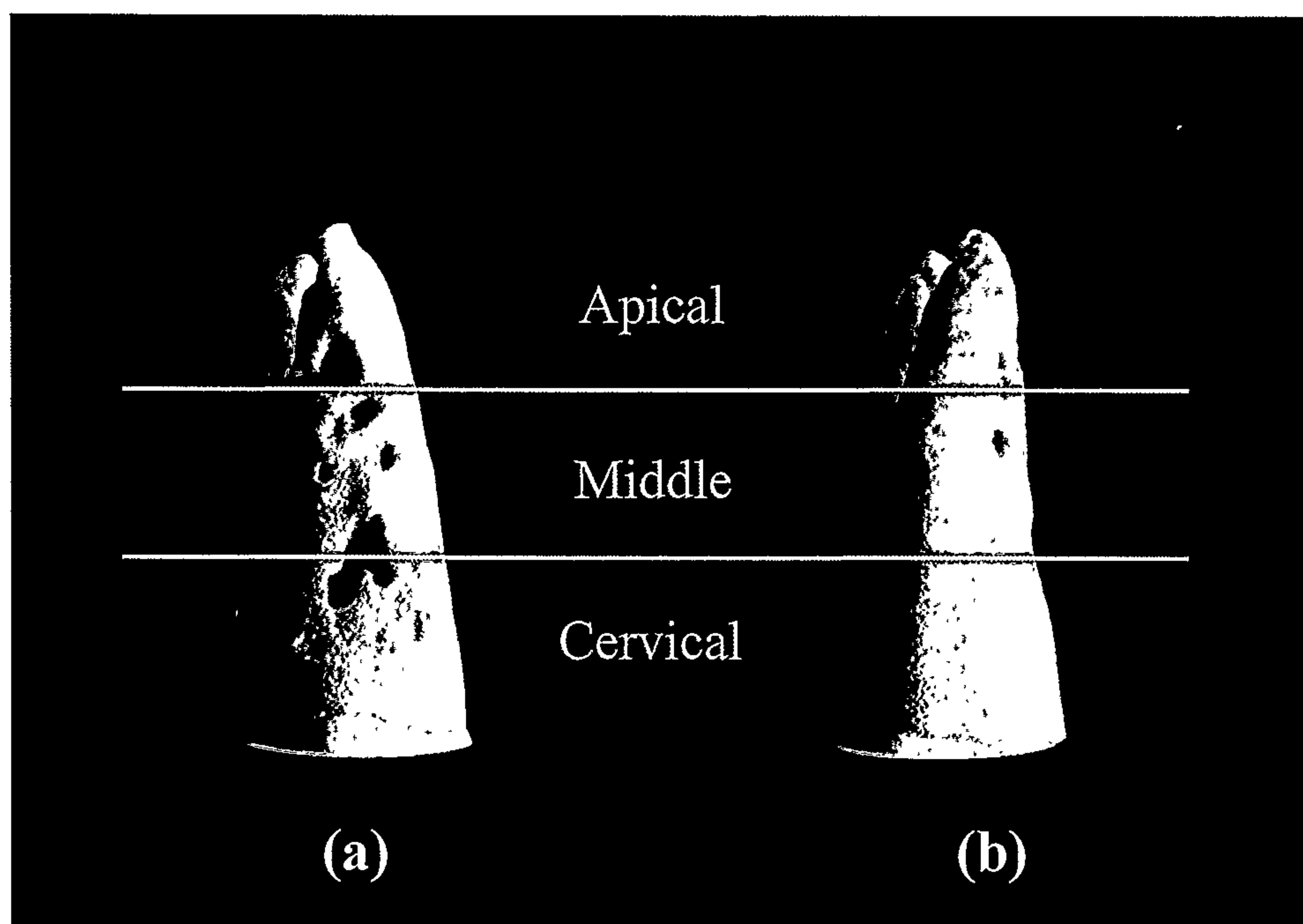


Figure 4: The convex hull algorithm (Chull 2D) reconstructs the loss of convexity by estimating a new line of closure that effectively connects the 2 points at the edge of the break, thus creating a closed subvolume for each axial slice of the crater. The total crater volume is calculated by summing the subvolumes for these closed cross sections.

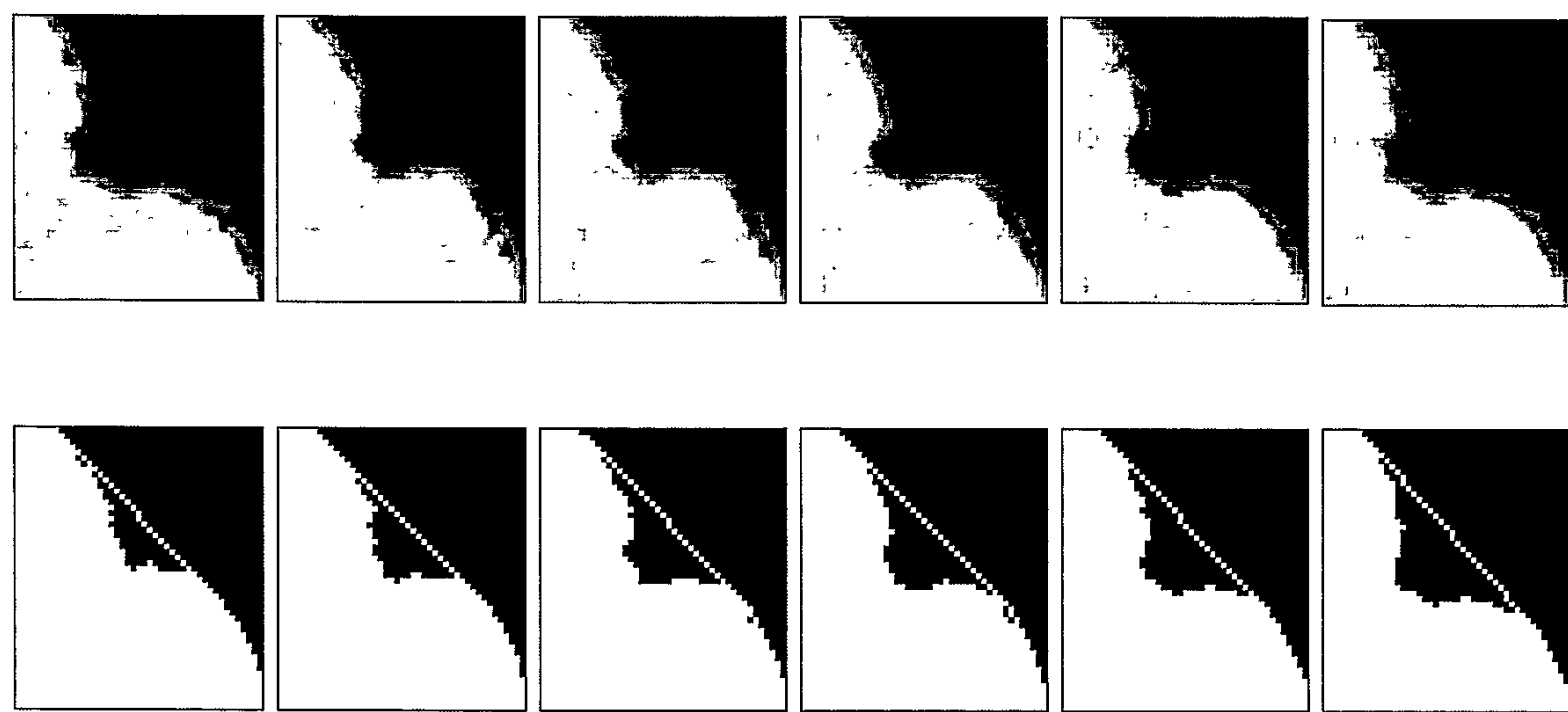


Figure 5A: Three-dimensional reconstructed images of a human premolar that has been subjected to 12 weeks of buccal movement with a light force (25g) (a) buccal (b) lingual (c) mesial (d) distal

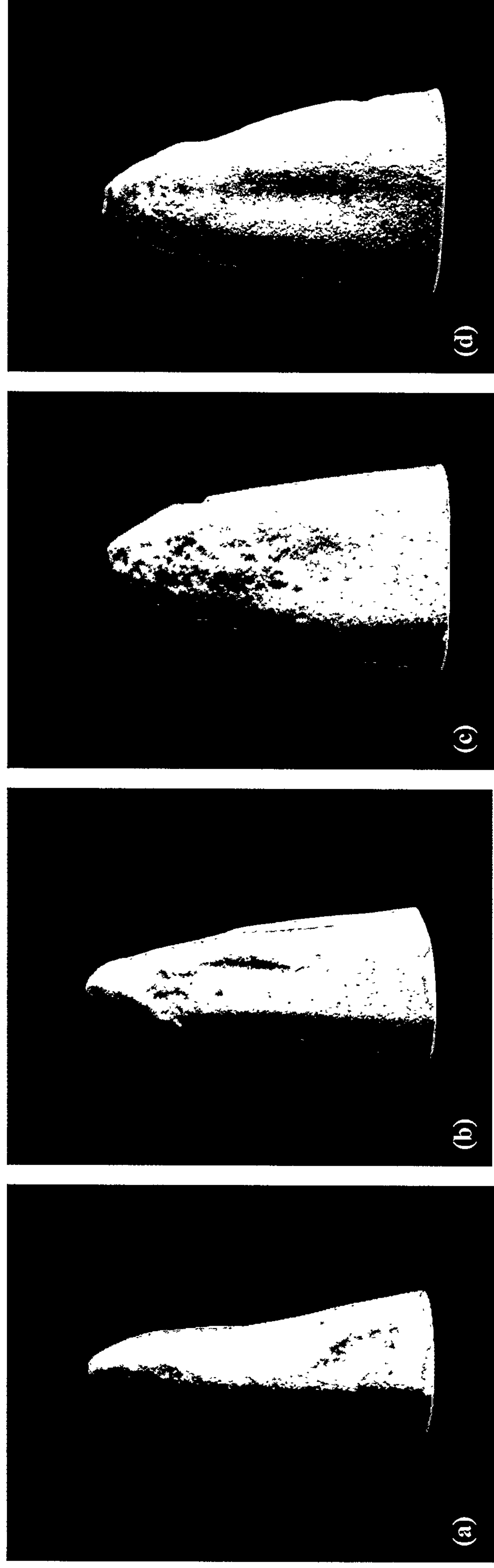


Figure 5B: Three-dimensional reconstructed images of a human premolar that has been subjected to 12 weeks of buccal movement with a heavy force (225g) (a) buccal (b) lingual (c) mesial (d) distal

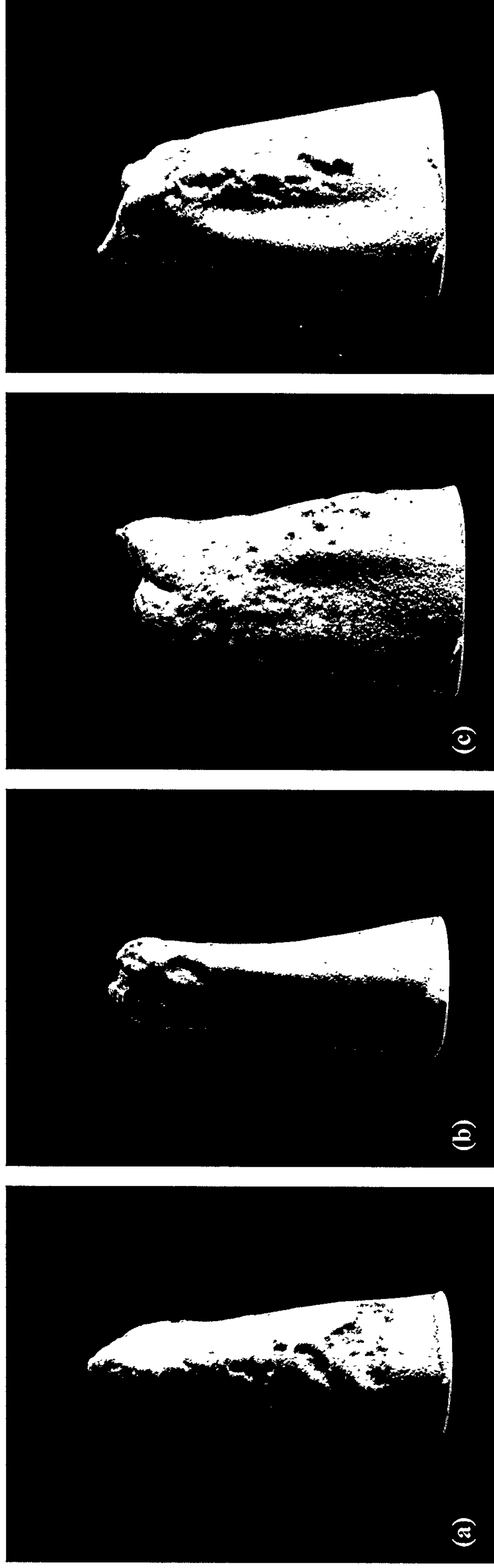


Figure 6: Box-plot of the total volume of the difference force levels

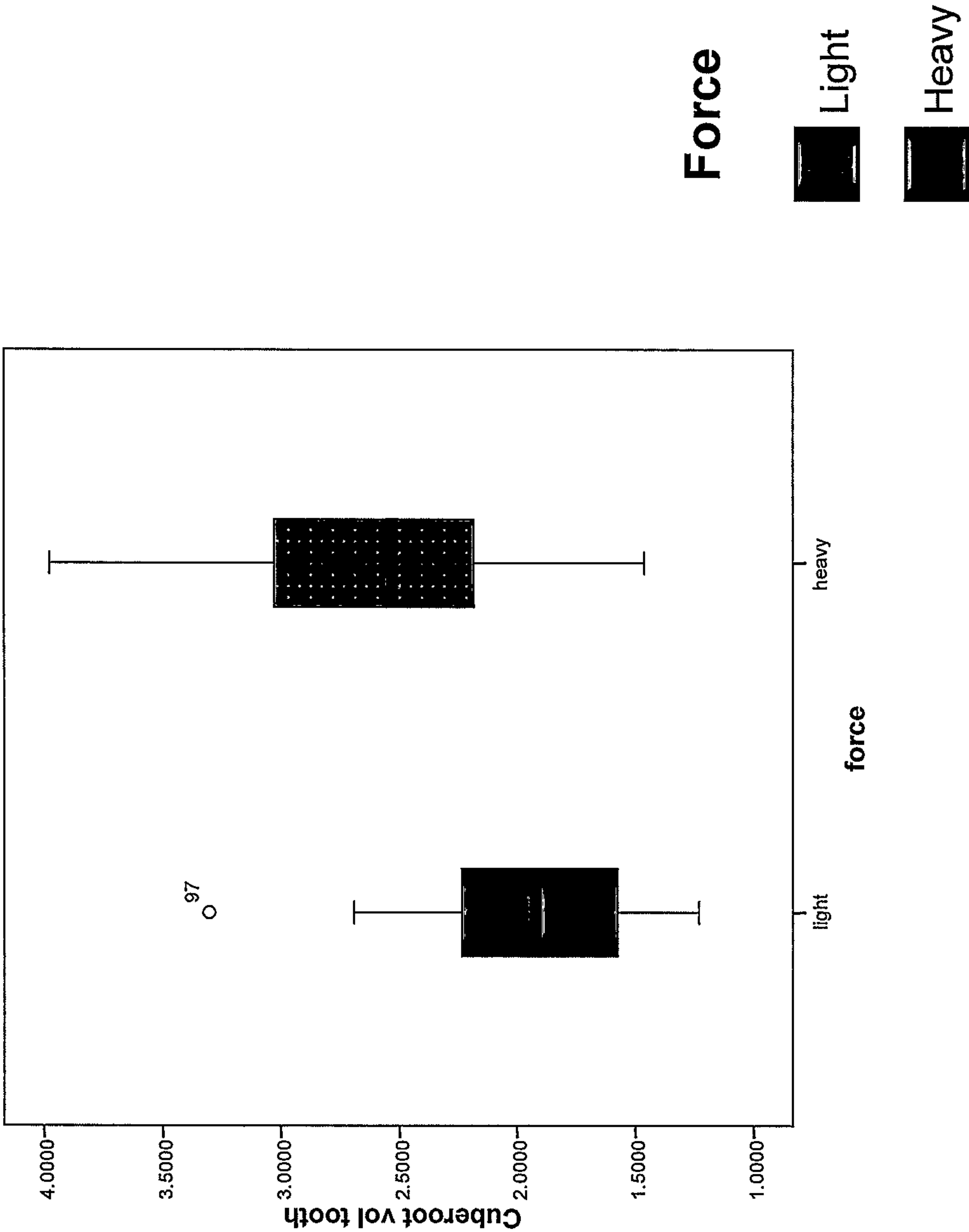
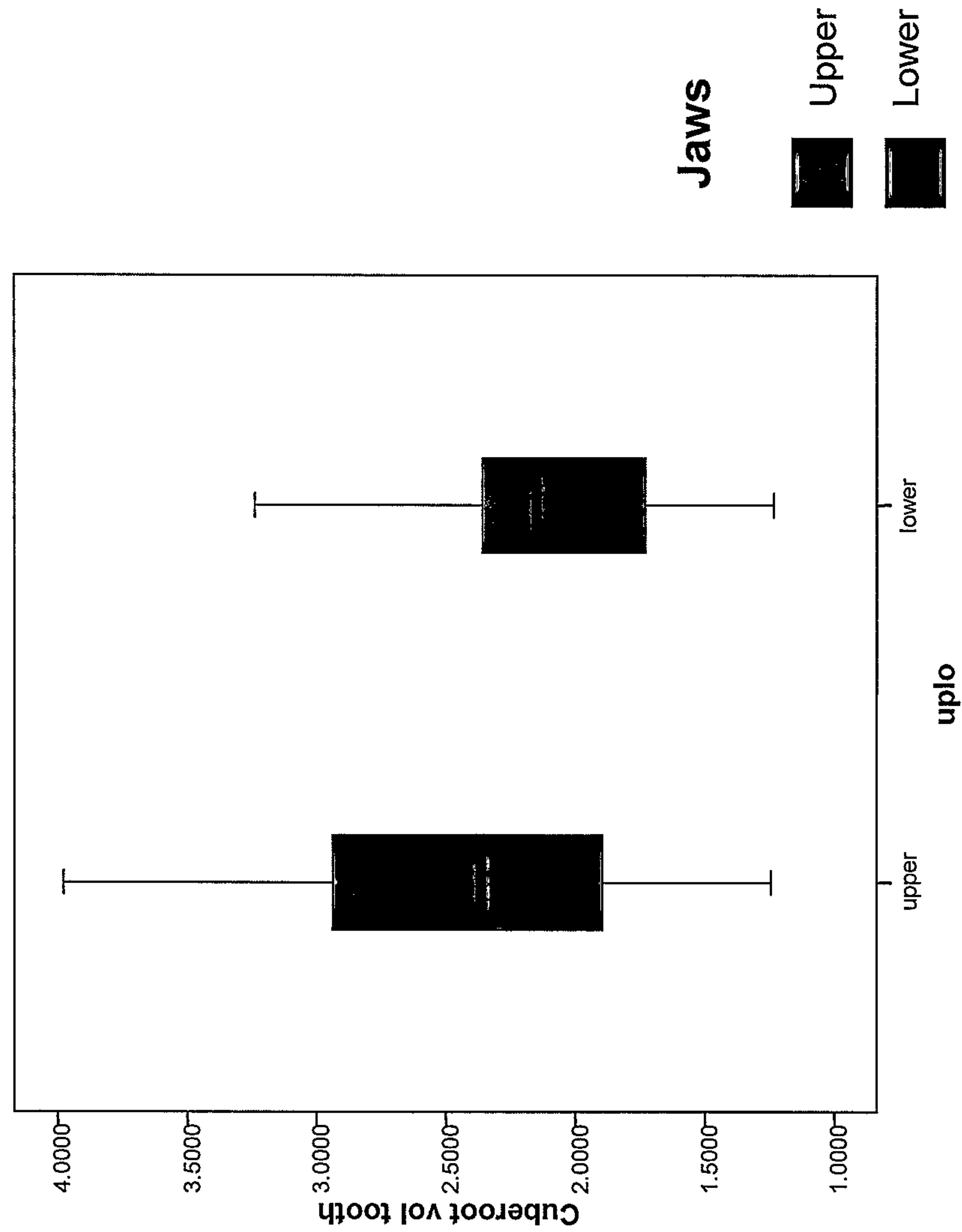


Figure 7: Box-plot of the cube root volume of the resorption craters for maxillary and mandibular experimental teeth



5. FUTURE DIRECTIONS

The results of the present study indicated that the volume of resorption craters was directly proportional to the magnitude of the buccally directed force applied. An alternative study could be to compare amount of root resorption in different directions of forces.

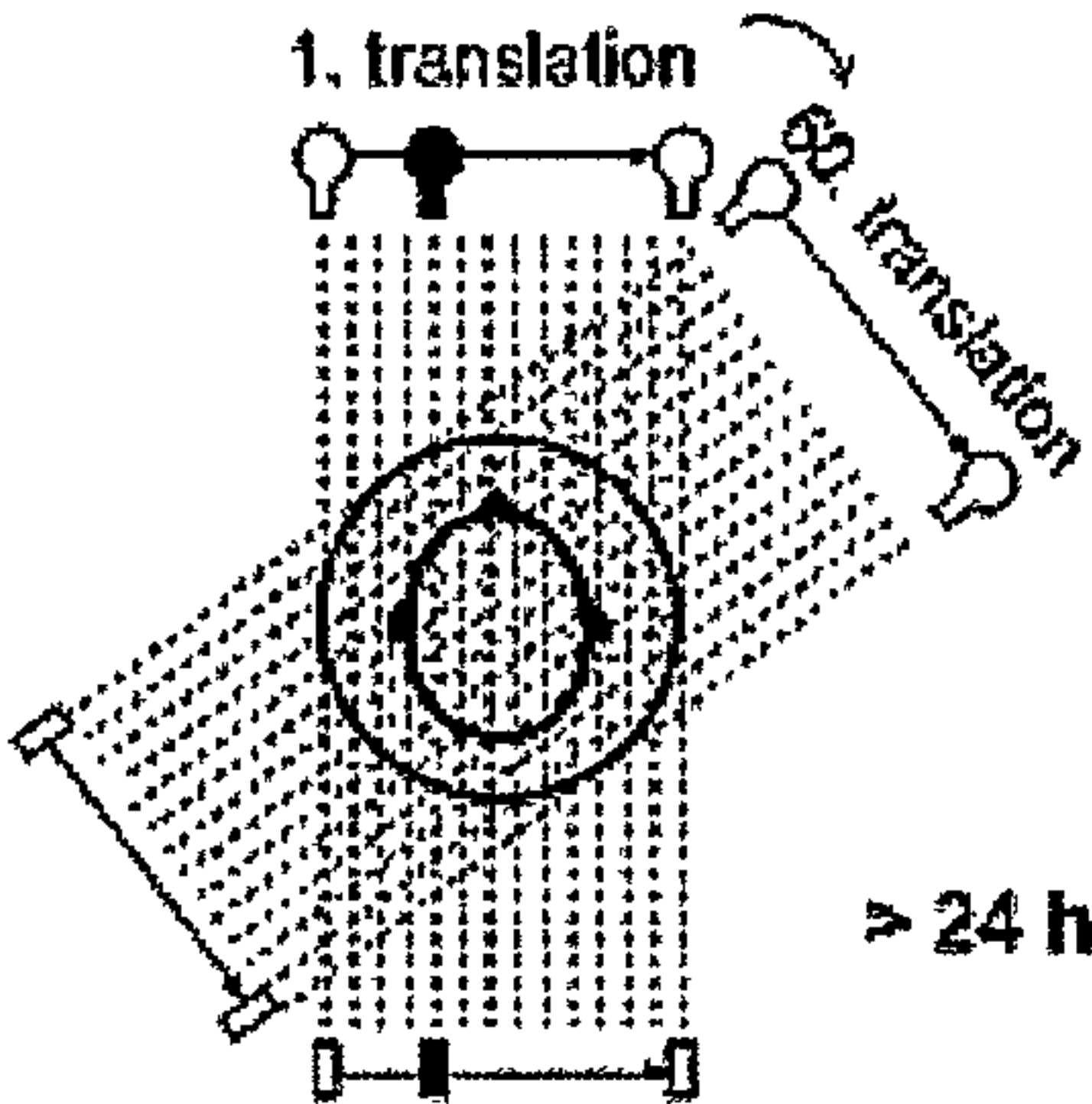
The high resolution cone-beam CT image of the subject may be taken prior to the force application. In supplement to the micro-CT scan, the initial 3D image of the experimental tooth would make possible a comparison and calculation of the volume of apical root loss.

In the current study, 12-week of force application was chosen to investigate the extent of root resorption in the prolonged activation of force. In the future, this might be compared with previous 4- and 8-week force application studies to see the effects of force duration.

6. APPENDIX

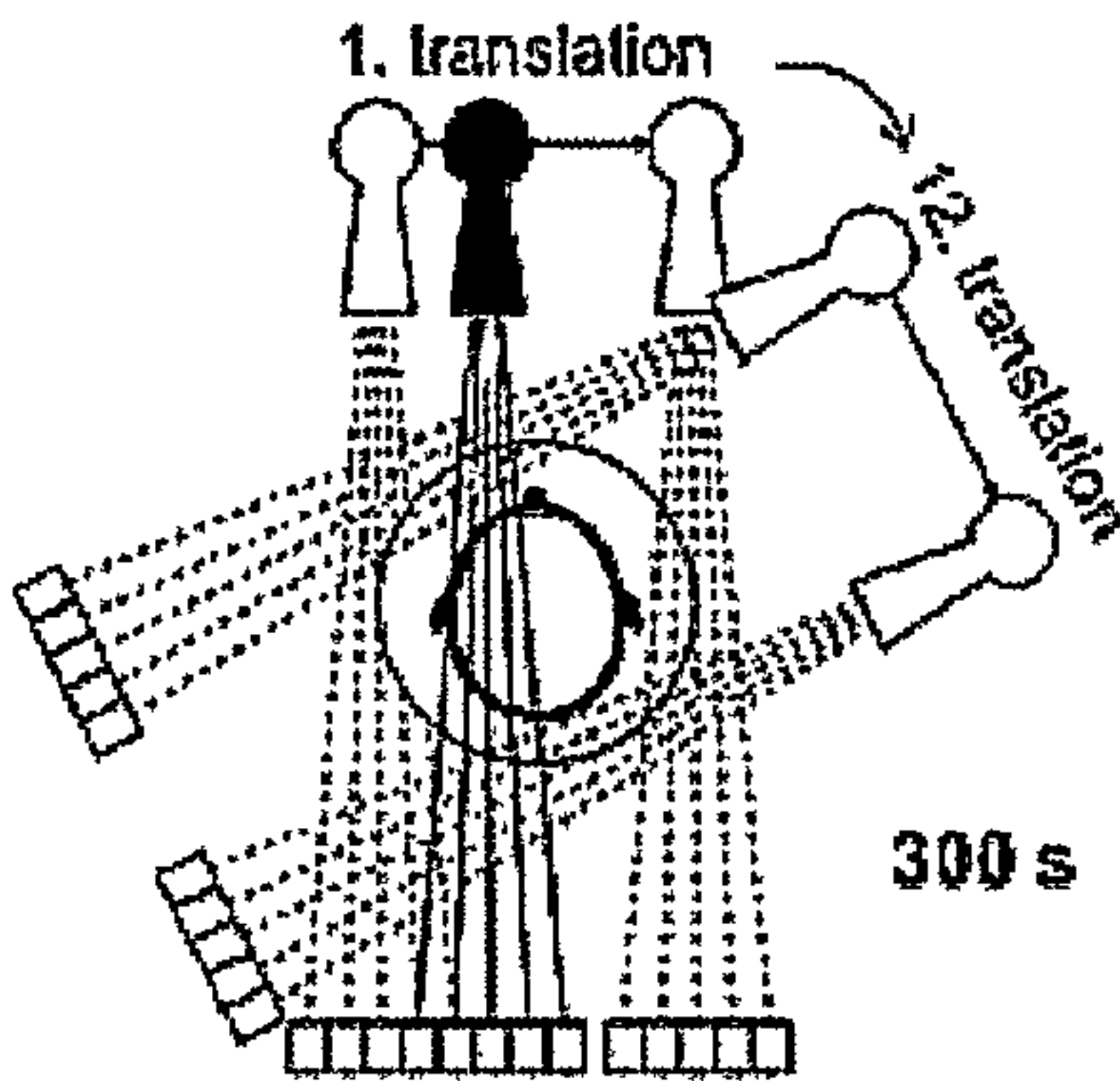
Appendix 1: Four scanner generations (from Kalender, 2006)¹⁹⁰

pencil beam (1970)



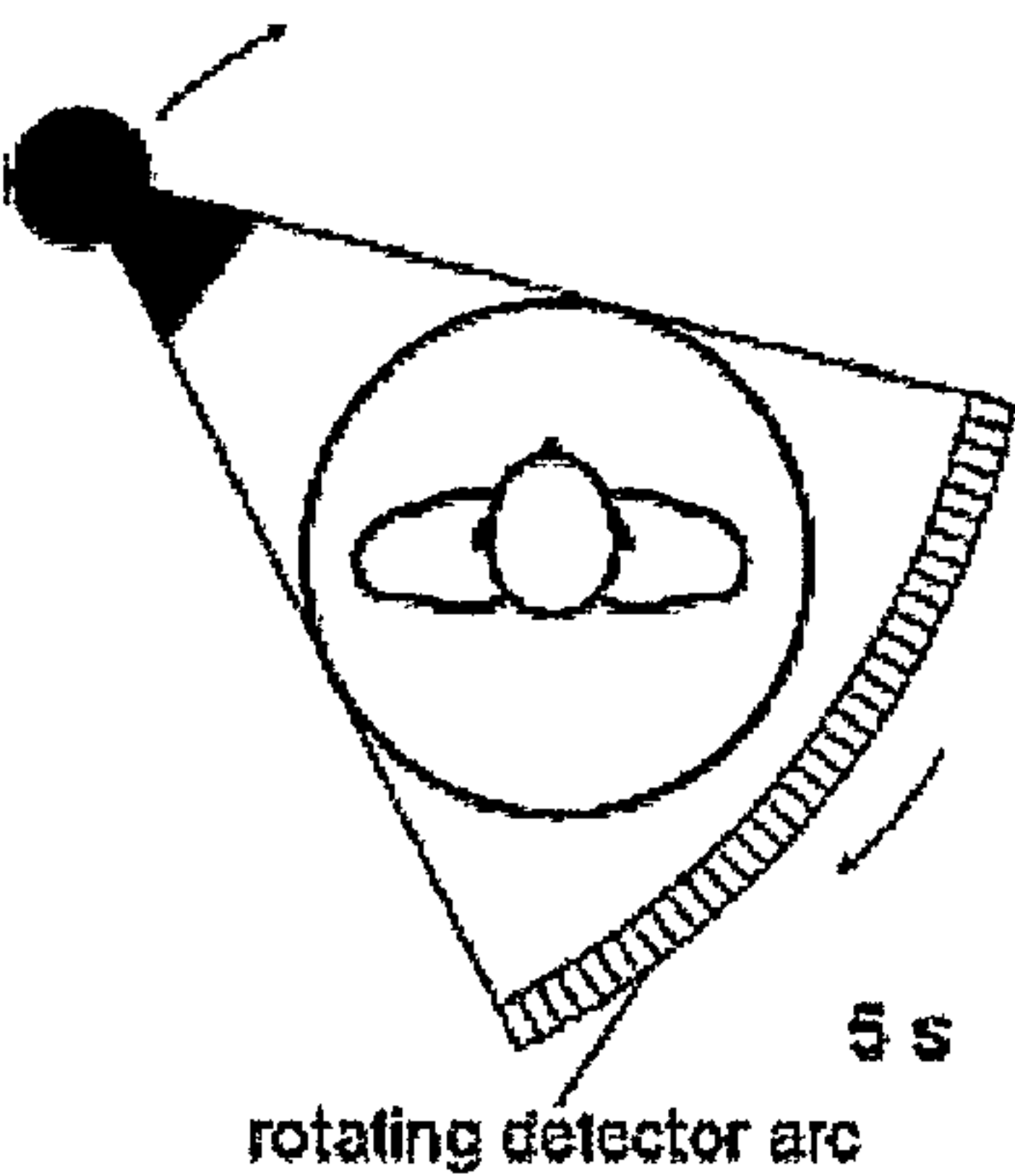
(a) 1st generation: translation/rotation

partial fan beam (1972)



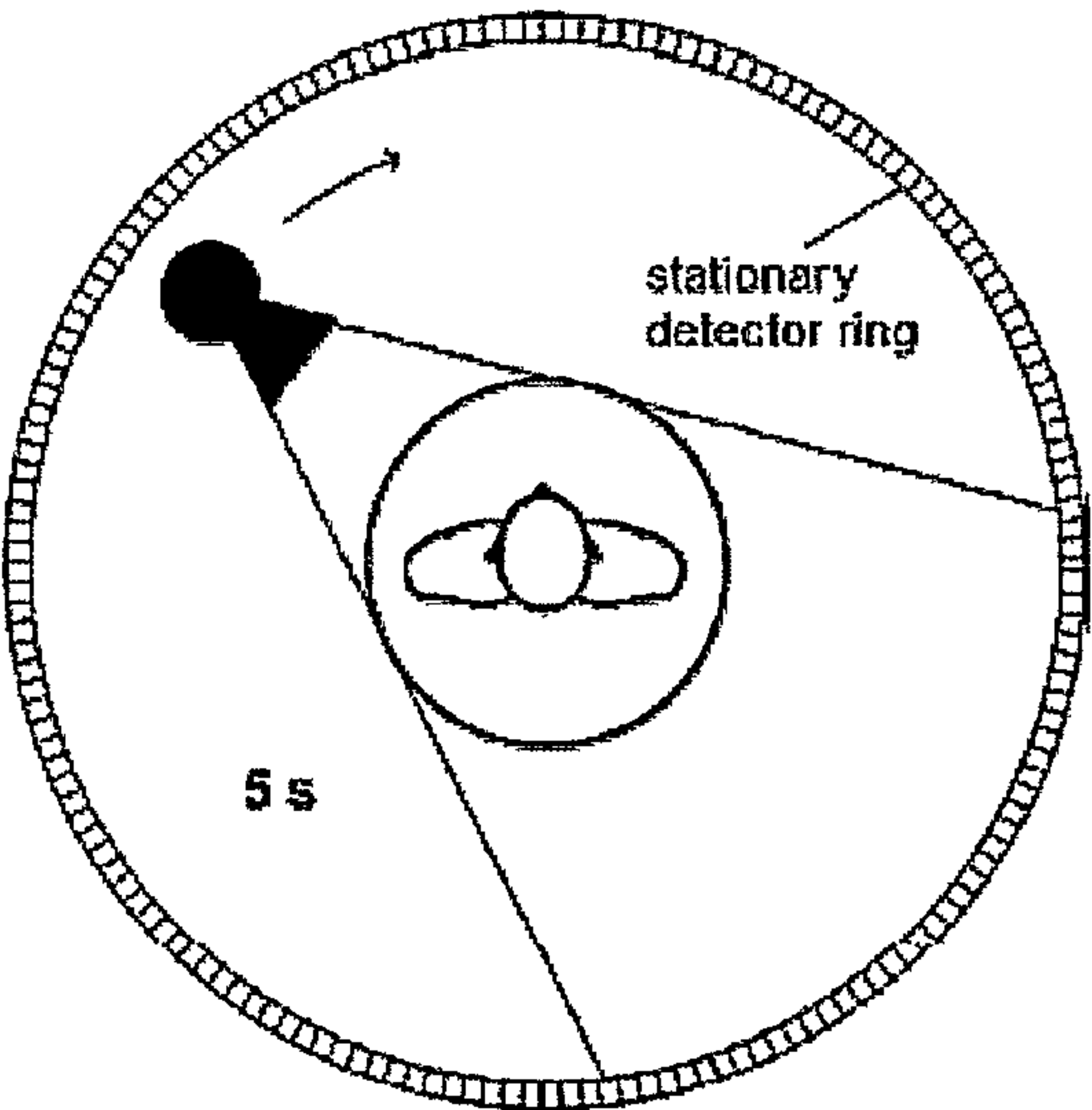
(b) 2nd generation: translation/rotation

fan beam (1976)



(c) 3rd generation: continuous rotation

fan beam (1978)



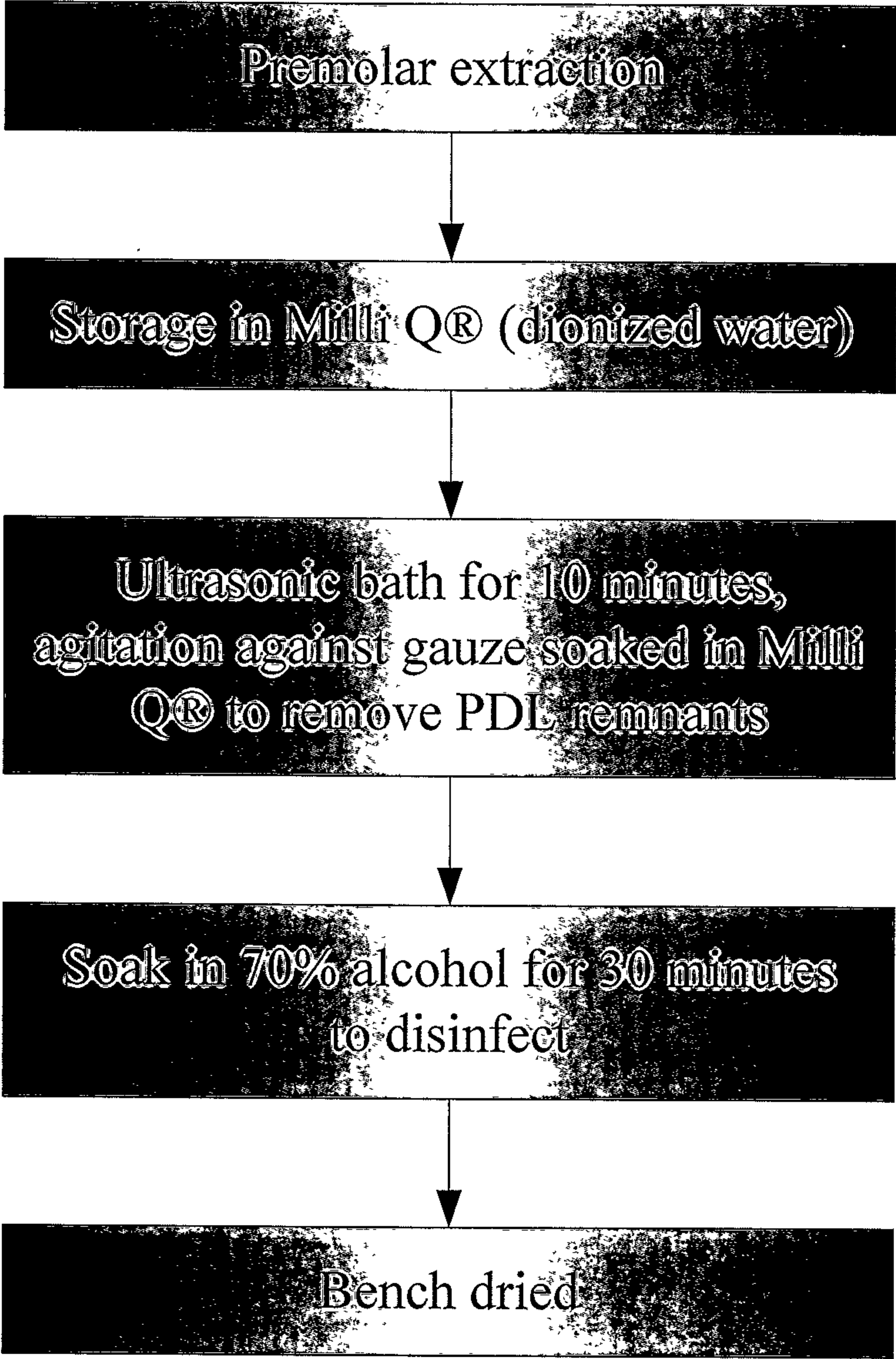
(d) 4th generation: continuous rotation

Appendix 2: Performance characteristics^a of CT in a comparison from 1972 to 2005 (from Kalender, 2006)¹⁹⁰

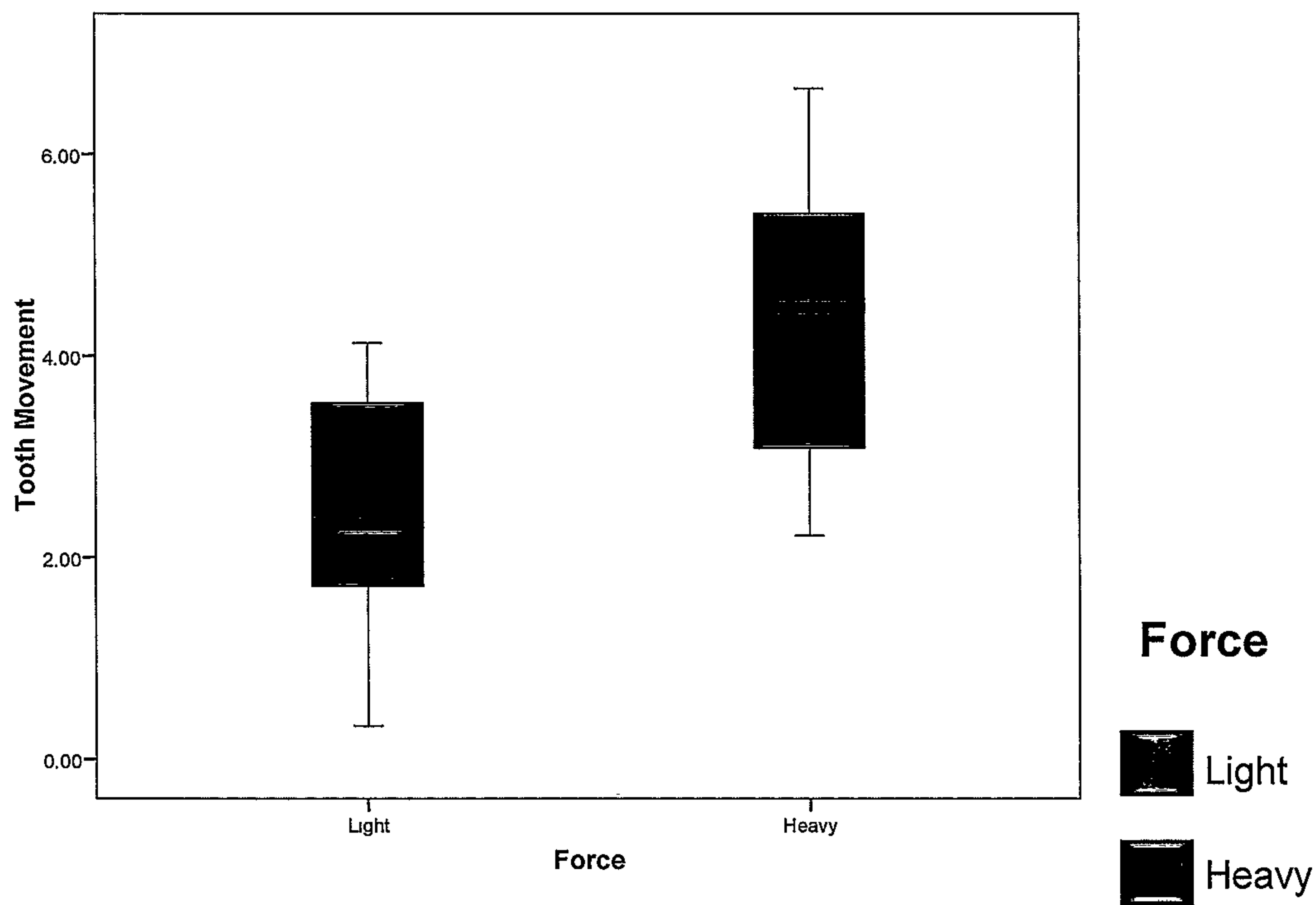
	1972	1980	1990	2004	2005 (DSCT)
Rotation time (s)	300	5–10	1–2	0.33–0.5	0.33
Data per 360° scan (MB)	0.058	1	1–2	10–100	20–200
Data per spiral scan (MB)	–	–	24–48	200–4000	200–8000
Image matrix ^b	80 × 80	256 × 256	512 × 512	512 × 512	512 × 512
Power (kW)	2	10	40	60–100	2 × 80
Slice thickness, mm	13	2–10	1–10	0.5–1	0.5–1
Spatial resolution (LP cm ^{−1})	3	8–12	10–15	12–25	12–25
Contrast resolution	5 mm/5 HU/ 50 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy

^a Typical values for high performance scanners.
^b Values refer to the calculated matrix. Monitor displays often use 1024 × 1024 matrices by means of interpolation.

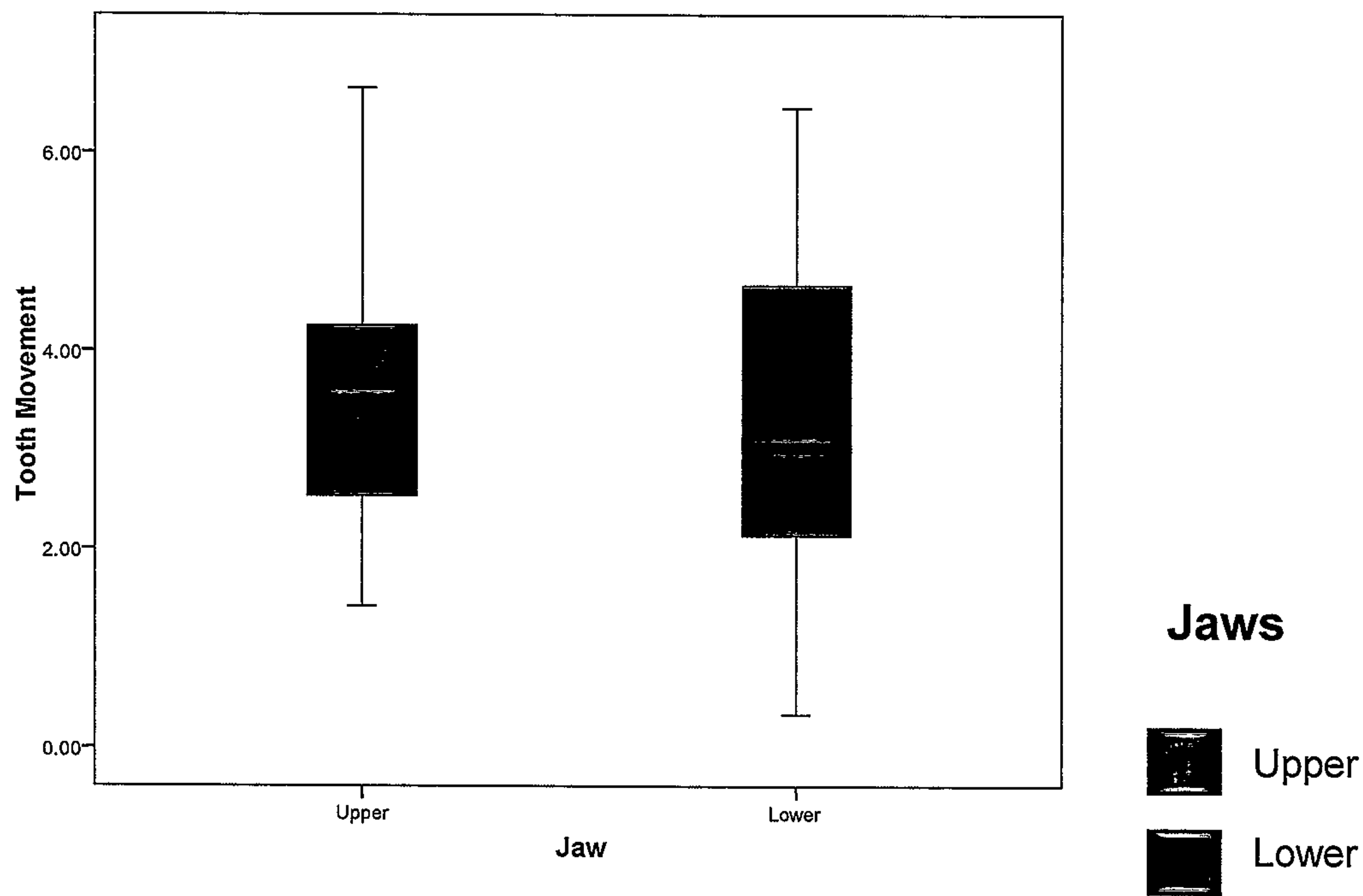
Appendix 3: Diagram for sample preparation



Appendix 4: Box-plot of the amount of tooth displacement in the light and heavy force groups



Appendix 5: Box-plot of the amount of tooth displacement for the maxilla and mandibular first premolars



Appendix 6A: Provisional Ethics Approval from the Human Research Ethics
Committee, The University of Sydney



The University of Sydney

NSW 2006 Australia

Human Research Ethics Committee

www.usyd.edu.au/ethics/human

Manager:

Gail Briody

Telephone: (02) 9351 4811

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Human Secretariat

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Email: roslyn.todd@usyd.edu.au

bdeleon@usyd.edu.au

16 November 2005

Professor M A Darendeliler
Discipline of Orthodontics
Faculty of Dentistry
Sydney Dental Hospital – C12
The University of Sydney

Dear Professor Darendeliler

I am pleased to inform you that the Human Research Ethics Committee at its meeting on 13 December 2005 gives **provisional approval** to your protocol titled ***“The Extent of Root Resorption After The Application of Continuous and Controlled Orthodontic Forces For 12 Weeks Using Micro-CT Scan”***

Details of the approval are as follows:

Ref No.:	12-2005/2/8782
Approval Period:	December 2005 – December 2006
Completion Date of Project:	31 July 2007
No. of Participants:	10
Authorised Personnel:	Professor M A Darendeliler Dr A Paetyangkul Associate Professor T Turk

To comply with the *National Statement on Ethical Conduct in Research Involving Humans*, and in line with the Human Research Ethics Committee (HREC) requirements this approval is for a 12-month period. At the end of the approval period, the HREC will approve extensions for a further 12-month, subject to a satisfactory annual report. The HREC will forward to you an Annual Progress Report form, at the end of each 12-month period. **Your report will be due on 31 December 2006.**

Conditions of Approval Applicable to this Project

- The final approval letter/s from the Ondokuz Mayıs University (OMU), Turkey and the approved local version of the Participant Information Statement/s and Consent Form/s with English translations must be provided as soon as available to the Ethics Committee.

Conditions of Approval Applicable to all Projects

- (1) Modifications to the protocol cannot proceed until such approval is obtained in writing. (Refer to the website www.usyd.edu.au/ethics/human under 'Forms and Guides' for a Modification Form).
- (2) The confidentiality and anonymity of all research subjects is maintained at all times, except as required by law.
- (3) All research subjects are provided with a Participant Information Sheet and Consent Form, unless otherwise agreed by the Committee.
- (4) The Participant Information Sheet and Consent Form are to be on University of Sydney letterhead and include the full title of the research project and telephone contacts for the researchers, unless otherwise agreed by the Committee.
- (5) The following statement must appear on the bottom of the Participant Information Sheet. ***Any person with concerns or complaints about the conduct of a research study can contact the Manager, Ethics Administration, University of Sydney, on (02) 9351 4811.***
- (6) The standard University policy concerning storage of data and tapes should be followed. While temporary storage of data or tapes at the researcher's home or an off-campus site is acceptable during the active transcription phase of the project, permanent storage should be at a secure, University controlled site for a minimum of seven years.
- (7) A report and a copy of any published material should be provided at the completion of the Project.

Yours sincerely



**Associate Professor J D Watson
Chairman
Human Research Ethics Committee**

Cc: Dr Anchalee Paetyangkul, Discipline of Orthodontics, Faculty of Dentistry, Sydney Dental Hospital – C12, The University of Sydney

Appendix 6B: Ethic Approval from the University of Ondokuz Mayıs Medical
Faculty Ethic Committee (English version)

**UNIVERSITY OF ONDOKUZ MAYIS
MEDICAL FACULTY
ETHICS COMMITTEE**

28 December 2005

Associate Professor Dr. Tamer Türk
Faculty of Dentistry
Department of Orthodontics

The evaluation of the research project entitled **“The Extend of Root Resorption After the Application of Continuous and Controlled Orthodontic Forces for 12 Weeks Using Micro-CT Scan”** presented to the Ethics Committee of Ondokuz Mayıs University (OMU) Medical Faculty has come to a conclusion. This research project has been evaluated according to your explanations concerning the aim, the rationale and the method, and has been approved unanimously on December 26th 2005 according to the fifth article of the directive of the Ethics Committee of OMU Medical Faculty.



Professor Dr. Yüksel Kesim
Chairwoman
Ethics Committee of OMU Medical Faculty

Appendix 6C: Ethic Approval from the University of Ondokuz Mayıs Medical

Faculty Ethic Committee (Turkish version)

**ONDOKUZ MAYIS ÜNİVERSİTESİ
TIP FAKÜLTESİ
ETİK KURUL BAŞKANLIĞI**

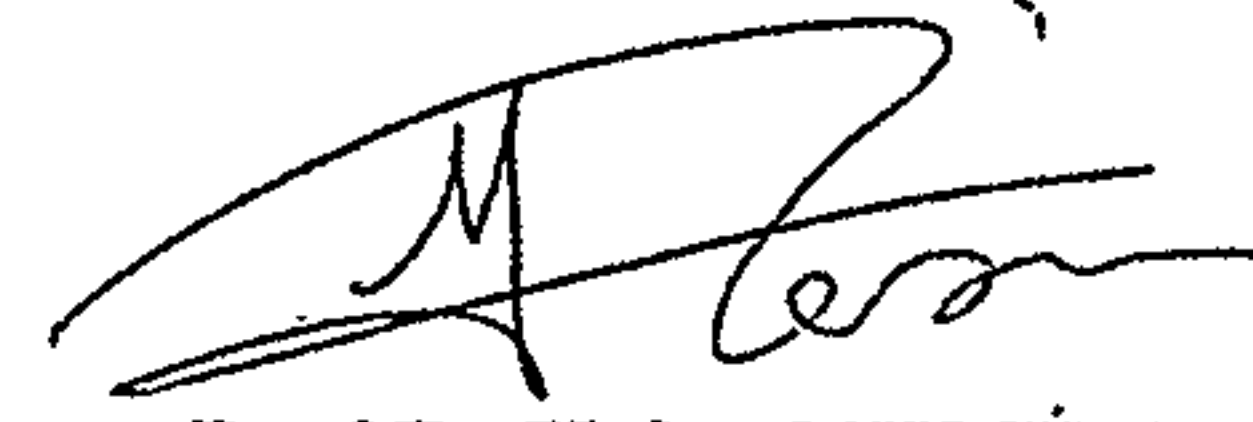
Sayı: EK: 348

28.12.2005

Sayın Doç.Dr.Tamer TÜRK

Etik kurulumuza sunmuş olduğunuz “Oniki Hafta Devamlı Kontrollü Ortodontik Kuvvet Uygulama Sonrası Kök Rezorpsiyon Derecesinin Mikro-BT Tarama İncelemesi” başlıklı ilaç dışı araştırma projeniz ile ilgili değerlendirme çalışmaları sonuçlandırılmıştır. Projeniz amaç, gerekçe, yaklaşım ve yöntemle ilgili açıklamalarınızı dikkate alarak değerlendirilmiş olup, OMÜ Tıp Fakültesi Etik Kurul yönergesinin 5. maddesi gereği sorumluluk araştırmacılara ait olmak üzere ve 6 ayda bir etik kurula bilgi verilerek etik yönden uygulanabilir olduğuna 26.12.2005 etik kurulumuzda oy birliği ile karar verilmiştir.

Bilgilerinize rica ederim.



Prof.Dr.Yüksel KESİM
Etik Kurul Başkanı

**Appendix 6D: Ethics Approval from the Human Research Ethics Committee,
The University of Sydney (2006)**



The University of Sydney

NSW 2006 Australia

Human Research Ethics Committee
www.usyd.edu.au/ethics/human

Senior Ethics Officer:

Gail Briody

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Email: roslyn.todd@usyd.edu.au

bdeleon@usyd.edu.au

14 June 2006

Professor M A Darendeliler
Discipline of Orthodontics
Faculty of Dentistry
Sydney Dental Hospital – C12
The University of Sydney

Dear Professor Darendeliler

**Title: *The Extent of Root Resorption After The Application of
Continuous and Controlled Orthodontic Forces For 12 Weeks
Using Micro-CT Scan***

Ref: 12-2005/2/8782

Thank you for providing the approval from the Ondokuz Mayis University (OMU), Turkey and the approved local versions of the Participant Information Statements & Consent Forms, fulfilling the conditions of approval for the above-mentioned protocol.

This has been filed with your original application.

Yours sincerely

**Associate Professor J D Watson
Chairman
Human Research Ethics Committee**

Cc: Dr Anchalee Paetyangkul, Discipline of Orthodontics, Faculty of Dentistry, Sydney Dental Hospital – C12, The University of Sydney

**Appendix 6E: Ethics Approval from the Human Research Ethics Committee,
The University of Sydney (2007)**



The University of Sydney

NSW 2006 Australia

Human Research Ethics Committee

www.usyd.edu.au/ethics/human

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Gail Briody

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Human Secretariat

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(02) 9036 9308

Facsimile: (02) 9036 9310

21 March 2007

Professor M A Darendeliler
Discipline of Orthodontics
Faculty of Dentistry
Sydney Dental Hospital - C12
The University of Sydney

Dear Professor Darendeliler

Title ***The Extent of Root Resorption After The Application of
Continuous and Controlled Orthodontic Forces For 12 Weeks
Using Micro-CT Scan***

Reference: 8782

Thank you for forwarding the Annual Report Form, as requested, for the above
referenced study. Your protocol has been renewed to **31 December 2007**.

NOTE:

Any changes to the authorised personnel must be advised and new staff must
complete Section 1.4 and the Declaration of Researchers on the application form.
Return both forms to the Senior Ethics Officer, Ethics Administration.

Yours sincerely

**Associate Professor J D Watson
Chairman
Human Research Ethics Committee**

Appendix 7A: Patient's Information Sheet



The University of Sydney

Dr. Anchalee Paetyangkul
MDSc Postgraduate
Discipline of Orthodontics
Telephone: (02) 9293 3388
Fax: (02) 9351 8336

Discipline of Orthodontics
Sydney Dental Hospital
Level 2, 2 Chalmers Street
Sunny Hills NSW 2010

RESEARCH STUDY INTO EVALUATION OF THE EFFECTS OF ORTHODONTIC FORCE ON HUMAN PREMOLAR CEMENTUM

INFORMATION FOR PARTICIPANTS

You are invited to take part in a research study into evaluation of the effects of orthodontic force on human premolar root surface (cementum).

The objective is to investigate the effect of orthodontic force on the root surface of the tooth, a surface we refer to as root cementum. When orthodontic braces are applied to teeth, a part of the root cementum and the tooth root beneath sometimes dissolves away. This process is called root resorption. Different forces generated by the braces will generate different degree of root resorption. This study will investigate the resorption processes for different type of forces over a period of 12 weeks of force application. To complete this study, extracted human teeth are required. You are eligible to participate in this study because it has been recommended that you have some teeth extracted as part of your routine orthodontic care.

This study is being conducted by Dr. Anchalee Paetyangkul, and Professor M. Ali Darendeliler from the University of Sydney. Associate Professor Tamer Türk from the Ondokuzmayis University will be in charge of the clinical part of this research project that will be carried out in Turkey.

If you agree to participate in this study, you will undergo the following procedures. Prior to the extraction of your teeth, on both side of your mouth, an orthodontic bracket will be applied to the upper and lower first molar and first premolar. A spring will be attached to the tooth to be extracted. A small piece of removable plastic will be bonded to the opposing bottom first molar. The braces will be in place for eighty-four (84) days or twelve (12) weeks at which time arrangement will have been made to have the premolar teeth extracted by an oral surgeon at the Dental School of the Ondokuzmayis University. The orthodontic spring, brackets and the plastic will be removed on that day.

As in any orthodontic procedure, where force is applied to a tooth, some pain or discomfort may be experienced for up to three (3) days following the placement of the spring. Any discomfort experienced may be relieved with common pain relief such as paracetamol (e.g. Panadol) or ibuprofen (e.g. Nurofen). If great discomfort is felt during the experimental period and you wish to discontinue with the study, the orthodontic spring can be removed immediately.

All aspect of the study, including results, will be strictly confidential and only the investigators named above will have access to information on participants. A report of the study may be submitted for publication but individual participants will not be identifiable in such a report.

While we intend that this research study furthers medical knowledge and may improve orthodontic techniques in a way that minimises root resorption, it will not be of direct benefit to you.

Participation in this study is entirely voluntary: you are in no way obliged to participate and if you do participate, you can withdraw at any time. Whatever your decision, please be assured that it will not affect your medical treatment or your relationship with medical staff. Of the people treating you, only the investigators named above, your dentist, and the oral surgeon extracting your teeth will be aware of your participation or non-participation.

When you have read this information, Associate Professor Tamer Türk will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact:

Associate Professor Tamer Türk

Address: University of Ondokuz Mayıs

Faculty of Dentistry

Department of Orthodontics

55139 Samsun TURKEY

Telephone: +90362 3121919/3005

Fax: +90362 4576032

This information sheet is for you to keep.

This study has been approved by Ethical Committee of the OMU (Ondokuz Mayıs University) Medical Faculty and Human Research Ethics Committee of the University of Sydney. Any person with concerns or complaints about the conduct of a research study can contact the Secretary on (02) 9515 6766.

Appendix 7B: Guardian's Information Sheet



The University of Sydney

Dr. Anchalee Paetysangkul

MDS Sc Postgraduate

Discipline of Orthodontics

Telephone: (02) 9293 3388

Fax: (02) 9351 8336

Discipline of Orthodontics

Sydney Dental Hospital

Level 2, 2 Chalmers Street

Sunny Hills NSW 2010

RESEARCH STUDY INTO EVALUATION OF THE EFFECTS OF ORTHODONTIC FORCE ON HUMAN PREMOLAR CEMENTUM

INFORMATION FOR PARENT/GUARDIAN

Your child is invited to take part in a research study into evaluation of repair of root surface material (cementum) following orthodontic force application on human premolars.

The objective is to investigate the effect of orthodontic force on the root surface of the tooth, a surface we refer to as root cementum. When orthodontic braces are applied to teeth, a part of the root cementum and the tooth root beneath sometimes dissolves away. This process is called root resorption. Different forces generated by the braces will generate different degree of root resorption. This study will investigate the resorption processes for different type of forces over a period of 12 weeks of force application. To complete this study, extracted human teeth are required. Your child is eligible to participate in this study because it has been recommended that he/she have some teeth extracted as part of his/her routine orthodontic care.

This study is being conducted by Dr. Anchalee Paetysangkul and Professor M. Ali Darandililer from the University of Sydney. Associate Professor Tamer Türk from the Ondokuzmayis University will be in charge of the clinical part of this research project that will be carried out in Turkey.

If you agree to allow your child to participate in this study, your child will undergo the following procedures. Prior to the extraction of their teeth, on both side of the mouth, an orthodontic bracket will be applied to the upper and lower first molar and first premolars. A spring will be attached to the tooth to be extracted. A small piece of removable plastic will be bonded to the opposing bottom first molar. The braces will be in place for eighty-four (84) days or twelve (12) weeks at which time arrangement will have been made to have the premolar teeth extracted by an oral surgeon at the Dental School of the Ondokuz Mayis University. The orthodontic spring, brackets and the plastic will be removed on that day.

As in any orthodontic procedure, where force is applied to a tooth, some pain or discomfort may be experienced for up to three (3) days following the placement of the spring. Any discomfort experienced may be relieved with common pain relief such as paracetamol (e.g. Panadol) or ibuprofen(e.g. Nurofen). If great discomfort is felt during the experimental period and your child wishes to discontinue with the trial, the orthodontic spring can be removed immediately.

All aspect of the study, including results, will be strictly confidential and only the investigators named above will have access to information on participants. A report of the study may be submitted for publication but individual participants will not be identifiable in such a report.

While we intend that this research study furthers medical knowledge and may improve orthodontic techniques in a way that minimises root resorption, it will not be of direct benefit to your child.

Participation in this study is entirely voluntary: your child is in no way obliged to participate and if your child does participate, your child can withdraw at any time. Whatever your decision, please be assured that it will not affect the medical treatment or you/your child's relationship with medical staff. Of the people treating the child, only the investigators named above, your child's dentist, and the oral surgeon extracting your teeth will be aware of your child's participation or non-participation.

When you have read this information, Associate Professor Tamer Türk will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact:

Associate Professor Tamer Türk

Address: University of Ondokuz Mayıs

Faculty of Dentistry

Department of Orthodontics

55139 Samsun TURKEY

Telephone: +90362 3121919/3005

Fax: +90362 4576032

This information sheet is for you to keep.

This study has been approved by Ethical Committee of the OMU (Ondokuz Mayıs University) Medical Faculty and Human Research Ethics Committee of the University of Sydney. Any person with concerns or complaints about the conduct of a research study can contact the Secretary on (02) 9515 6766.

Version 2

Date 09/10'06

Appendix 8A: Consent form for Participant



The University of Sydney

Dr. Anchalee Paatyangkul
MDSc Postgraduate
Discipline of Orthodontics
Telephone: (02) 9293 3388
Fax: (02) 9351 8336

Discipline of Orthodontics
Sydney Dental Hospital
Level 2, 2 Chalmers Street
Surry Hills NSW 2010

RESEARCH STUDY INTO EVALUATION OF THE EFFECTS OF ORTHODONTIC FORCE ON HUMAN PREMOLAR CEMENTUM

PARTICIPANT CONSENT FORM

I, _____ [name], of
_____ [parent/guardian address] have
read and understood the Information for Participant on the above named research study and have
discussed the study with Associate Professor Tamer Türk.

I have been made aware of the procedures involved in the study, including any known or expected
inconvenience, risk, discomfort or potential side effect and of their implications as far as they are
currently known by the researchers.

I understand that my participation in this study will allow the researchers to have access to their dental
record and I agree to this.

I freely choose to participate in this study and understand that I can withdraw my participation at any
time.

I also understand that the research study is strictly confidential.

I hereby agree to allow myself to participate in this research study.

Name: _____

Signature: _____

Date: _____

Name of Witness: _____

Signature of Witness: _____

Appendix 8B: Consent form for Parents/Guardian



The University of Sydney

Dr. Anchalee Paatyangkul
MDSc Postgraduate
Discipline of Orthodontics
Telephone: (02) 9293 3388
Fax: (02) 9351 8336

Discipline of Orthodontics
Sydney Dental Hospital
Level 2, 2 Chalmers Street
Sunny Hills NSW 2010

RESEARCH STUDY INTO EVALUATION OF THE EFFECTS OF ORTHODONTIC FORCE ON HUMAN PREMOLAR CEMENTUM PARENT / GUARDIAN CONSENT FORM

I, _____ [name], the parent/guardian
of _____ [child's name] of
_____ [parent/guardian address] have
read and understood the Information for Parent/Guardian on the above named research study and have
discussed the study with Associate Professor Tamer Türk.

I have been made aware of the procedures involved in the study, including any known or expected
inconvenience, risk, discomfort or potential side effect and of their implications as far as they are
currently known by the researchers.

I understand that my child's participation in this study will allow the researchers to have access to their
dental record and I agree to this.

I freely choose to allow my child to participate in this study and understand that I can withdraw their
participation at any time.

I also understand that the research study is strictly confidential.

I hereby agree to allow my child to participate in this research study.

Name: _____

Signature: _____

Date: _____

Name of Witness: _____

Signature of Witness: _____

Appendix 9: Raw data for root resorption volume

Upper Light Force						
Tooth ID	Creter volume					
	Buccal side (mm ³)			Ligual side (mm ³)		
	Cervical	Middle	Apical	Cervical	Middle	Apical
ER12L02	0.1548	0.0010	-	0.0862	-	0.0046
ER22L01	0.1186	0.0109	0.0774	0.0518	0.0349	0.0585
ER31L01	0.0820	0.0474	0.0286	0.0359	0.0644	0.0003
ER41L01	0.0834	0.0198	0.1189	0.0915	0.0139	-
ER51L01	0.1204	0.1588	0.0578	0.0437	0.1028	0.0909
ER62L01	0.0232	0.1375	0.0206	-	0.0379	0.0448
ER81L02	0.2572	0.0046	0.0009	0.0089	0.0002	0.0343
ER91L01	0.0225	0.3130	0.0509	0.1793	0.0748	0.0360
ER102L01	0.2635	0.7723	0.1431	0.0051	0.1945	0.1049
ER112L01	0.0908	0.0433	0.0665	0.0024	0.0311	0.0271
Total	1.2163	1.5086	0.5648	0.5047	0.5545	0.4013
	3.2896			1.4605		
	4.7501					

Upper Heavy Force						
Tooth ID	Creter volume					
	Buccal side (mm ³)			Lingual side (mm ³)		
	Cervical	Middle	Apical	Cervical	Middle	Apical
ER11H01	0.1914	0.1653	0.0911	0.0440	0.2602	0.0330
ER21H01	0.3956	0.4453	0.1012	0.0986	0.1902	0.1478
ER32H01	0.1320	0.0522	0.0215	0.1950	0.0808	-
ER42H02	0.1295	0.0322	0.0074	0.0888	0.2655	0.0023
ER52H01	0.2111	0.0657	0.0929	0.1297	0.2522	0.0639
ER61H01	0.1746	0.0089	0.1079	0.1126	0.1390	0.0716
ER82H01	0.0868	0.0332	0.0121	-	0.0169	0.0095
ER92H01	0.1871	0.4512	0.0042	0.0980	0.4138	0.0255
ER101H02	0.6488	0.5887	0.0128	0.2781	0.8352	0.0877
ER111H01	0.3099	0.0391	0.0241	0.1491	0.0352	0.0392
Total	2.4666	1.8818	0.4752	1.1938	2.4889	0.4804
	4.8237			4.1631		
	8.9868					

Lower Light Force						
Tooth ID	Creter volume					
	Buccal side (mm ³)			Lingual side (mm ³)		
	Cervical	Middle	Cervical	Middle	Cervical	Middle
ER13L01	0.0240	0.0280	0.0000	0.0247	0.0069	0.0123
ER23L01	0.2271	0.0380	0.0006	-	0.0147	0.0565
ER34L01	0.2353	0.0698	0.0096	0.0142	0.0148	0.0749
ER44L01	0.0461	0.1366	0.0275	0.0470	0.0325	0.0586
ER54L01	0.0607	0.1882	0.0053	0.0680	0.0570	0.0946
ER63L01	0.2017	0.0306	-	0.0001	0.1315	0.0413
ER84L01	0.0551	0.0360	-	-	0.0258	0.0113
ER94L02	0.0668	0.1221	0.0522	0.0079	0.0276	0.0522
ER103L01	0.0753	0.0844	0.0044	-	0.1929	0.0645
ER113L01	0.0351	0.1187	-	-	0.0303	0.0208
Total	1.0272	0.8525	0.0996	0.1618	0.5340	0.4870
	1.9793			1.1829		
	3.1622					

Lower Heavy Force						
Tooth ID	Creter volume					
	Buccal side (mm ³)			Lingual side (mm ³)		
	Cervical	Middle	Cervical	Middle	Cervical	Middle
ER14H01	0.0512	0.1384	0.0127	0.0161	0.1613	0.0673
ER24H01	0.3511	0.2863	-	0.1205	0.2942	0.1729
ER33H01	0.1053	0.1603	0.0071	0.0003	0.0257	0.0428
ER43H01	0.0329	0.0541	0.0035	-	0.0191	0.0761
ER53H01	0.1290	0.1145	-	-	0.2943	0.1542
ER64H01	0.0415	0.0565	0.0006	0.0331	0.2092	0.1930
ER83H01	0.4389	0.3575	0.0151	-	0.0789	0.0718
ER93H01	0.3423	0.2680	0.2462	0.0026	0.0474	0.1984
ER104H01	0.2869	0.3103	0.0257	0.0464	0.2288	0.2566
ER114H01	0.1291	0.1138	0.0335	-	0.0492	0.0783
Total	1.9081	1.8598	0.3443	0.2190	1.4080	1.3115
	4.1122			2.9385		
	7.0507					

Appendix 10: Raw data for the distance of tooth movement

Upper Light Force			
Tooth ID	T1	T2	Distance
ER12L02	19.5810	21.0026	1.4215
ER22L01	21.9727	23.7090	1.7363
ER31L01	15.8595	17.5578	1.6984
ER41L01	20.2986	22.3207	2.0221
ER51L01	20.2321	23.6354	3.4033
ER62L01	21.2942	24.9515	3.6573
ER81L02	20.5144	23.1272	2.6129
ER91L01	20.4091	23.5729	3.1638
ER102L01	19.9545	23.6280	3.6735
ER112L01	18.6160	22.4029	3.7869
Average			2.7176
Standard deviation			0.8824

Upper Heavy Force			
Tooth ID	T1	T2	Distance
ER11H01	17.5467	23.5141	5.9674
ER21H01	22.8832	27.2285	4.3453
ER32H01	16.5217	20.6787	4.1569
ER42H02	18.1832	22.1209	3.9377
ER52H01	19.4551	22.4936	3.0385
ER61H01	18.2103	22.8331	4.6228
ER82H01	18.8704	21.3235	2.4531
ER92H01	17.8939	21.8756	3.9817
ER101H02	19.1958	25.8457	6.6499
ER111H01	18.1933	24.5552	6.3620
Average			4.5515
Standard deviation			1.3147

Lower Light Force			
Tooth ID	T1	T2	Distance
ER13L01	15.3205	17.6368	2.3163
ER23L01	16.8943	19.9385	3.0442
ER34L01	20.0556	22.1131	2.0575
ER44L01	13.6943	14.0266	0.3323
ER54L01	16.5187	17.7266	1.2079
ER63L01	17.6441	21.7713	4.1272
ER84L01	15.3757	17.2713	1.8956
ER94L02	16.4545	18.8124	2.3579
ER103L01	17.8351	21.6198	3.7847
ER113L01	15.8178	16.5133	0.6955
Average			2.1819
Standard deviation			1.1757

Lower Heavy Force			
Tooth ID	T1	T2	Distance
ER14H01	15.5073	18.5166	3.0093
ER24H01	15.5741	20.1895	4.6154
ER33H01	19.3124	21.5321	2.2197
ER43H01	18.3856	20.9324	2.5467
ER53H01	17.5378	22.4731	4.9353
ER64H01	17.3357	20.4696	3.1339
ER83H01	16.6768	21.6249	4.9482
ER93H01	16.8131	22.6809	5.8678
ER104H01	15.8725	20.5774	4.7049
ER114H01	16.3362	22.7863	6.4501
Average			4.2431
Standard deviation			1.3625