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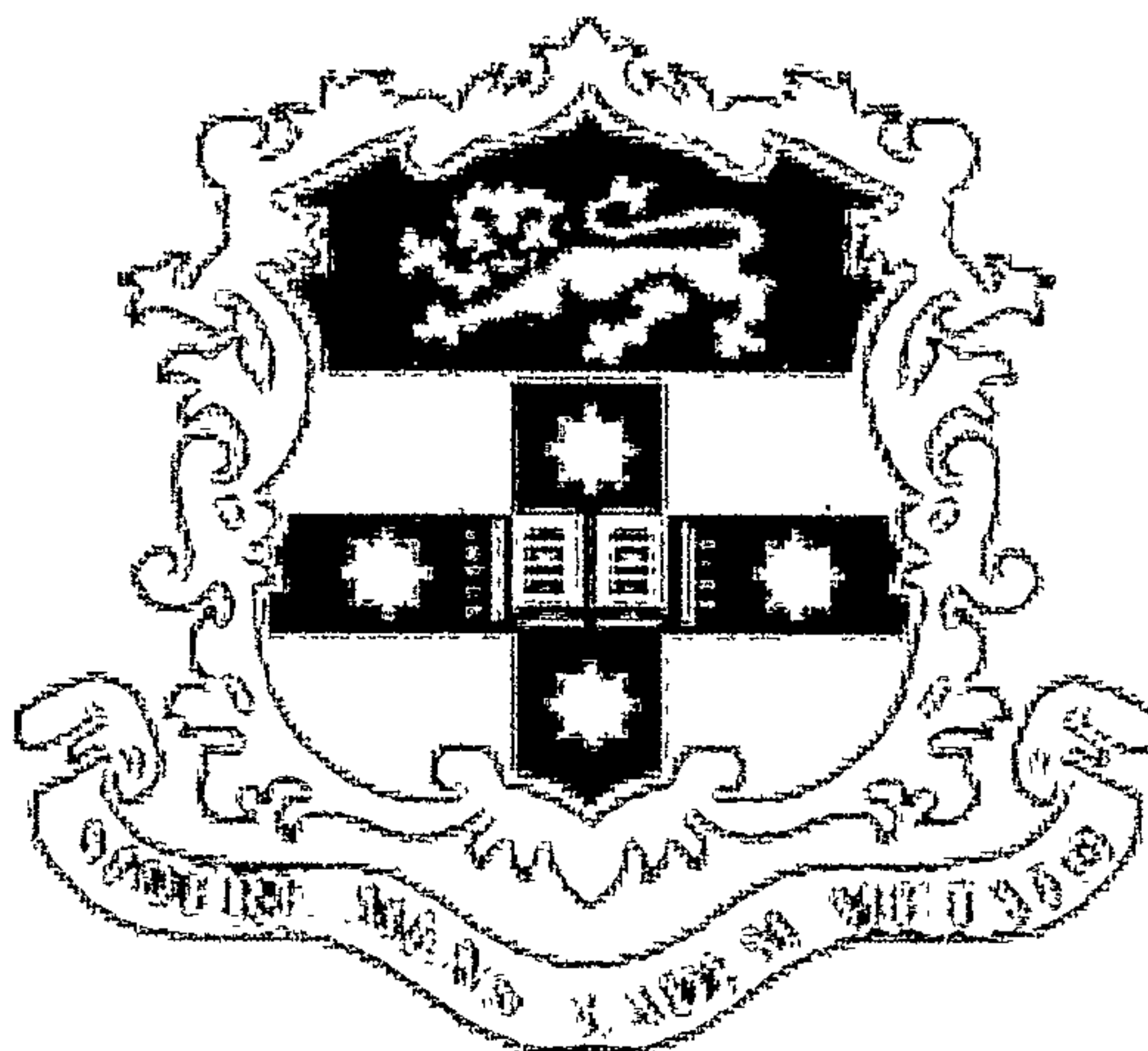
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**“CHANGES IN PHYSICAL PROPERTIES OF HUMAN  
PREMOLAR CEMENTUM AFTER THE APPLICATION OF  
CONTROLLED ORTHODONTIC FORCES”**

***Pennapa Srivicharnkul, DDS***

A Thesis submitted in partial fulfillment  
Of the requirements for the degree of  
Master of Dental Science (Orthodontics)

Discipline of Orthodontics  
Faculty of Dentistry  
University of Sydney  
Australia



## **DEDICATION**

To my parents, Pacharee and Charn Srivicharnkul, who have given me every opportunity in life. Your encouragement, support and love are always in my thought.

To all of my sisters and brothers, Pachara and Songkran Chaisatitvanich, Panida and Thongchai Srisan, Vipra and Santad Srivicharnkul, Panlapa and Paisal Tarasansombat, Suangsuda Srivicharnkul, and Santi Srivicharnkul, who have been inspirations to me. Your encouragement and motivation are endless.

To all of my beloved nieces and nephews, Yoo, Boat, Pam, Pang, Mai, Bank, Pong, Pluem and Mee, who have been the motivation and the focus of my accomplishment.



## 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.

.....



## ACKNOWLEDGMENTS

I would like to express my deep appreciation to:

Professor M Ali Darendeliler, Head of Orthodontic discipline, Faculty of Dentistry, University of Sydney, for his invaluable supervision, assistance and guidance throughout the course of this study. His enthusiastic support and encouragement over the years were essential in completing this thesis.

Professor Michael Swain, Head of Discipline of Dental Materials Science and Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, my co-supervisor, for his helpful supervision, assistance and advice with the preparation and proofreading of this work. His generosity in providing the essential knowledge and facilities for my work is very much appreciated.

Dr. Om P Kharbanda, Senior lecturer, Orthodontic discipline, Faculty of Dentistry, University of Sydney, for his advice with the preparation and proofreading of this work.

Drs. Peter Petocz, Department of Mathematical Sciences, University of Technology, Sydney, and Doungkamol Sindhusake Department of Public Health and Community Medicine, Westmead Hospital, for their advice and assistance with the statistical analysis of this work.

Drs. Lisa Rix, and Michael Chen, Oral Surgery department, United Dental Hospital for their assistance of extracting all samples.



Drs. Emma McKenzie, David Armstrong, Eugene Chan, Teriko Rex, Baljit Lalli for their help of collecting the samples. Drs. Andrew Pitsis, Roger Hammond, Stephen Moate for their help and friendship over the last three years.

All the staff of Orthodontic department, United Dental Hospital and Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, for their help and technical support on numerous occasions.

Ms. Atchana Lamsam for her assistance with the computer support.

Australian Society of Orthodontists Foundation for Research and Education for partial financial support.



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## ABBREVIATIONS

|       |                                            |
|-------|--------------------------------------------|
| 3D    | Three Dimensions                           |
| AAC   | Acellular Afibrillar Cementum              |
| BHN   | Brinell Hardness Number                    |
| BiHN  | Bierbaum Hardness Number                   |
| cAMP  | Cyclic Adenosine Mono Phosphate            |
| CEJ   | Cemento-enamel junction                    |
| cGMP  | Cyclic Guanosine Mono Phosphate            |
| CGRP  | Calcitonin Gene Related Peptide            |
| CMSC  | Cellular Mixed Stratified Cementum         |
| DS    | Drum Spring retractor                      |
| $E^*$ | Elastic Modulus                            |
| $F$   | The applied force                          |
| GPa   | Giga Pascal                                |
| H     | Hardness                                   |
| IC    | Intermediate Cementum                      |
| Kg    | Kilogram                                   |
| KHN   | Knoop Hardness Number                      |
| mm    | Millimeter                                 |
| mN    | Milli-newton                               |
| N     | Newton                                     |
| $P$   | Applied Load                               |
| PAEFC | Primary Acellular Extrinsic Fiber Cementum |
| PAIFC | Primary Acellular Intrinsic Fiber Cementum |
| PC    | Pushcoil spring                            |



|               |                                             |
|---------------|---------------------------------------------|
| PDL           | Periodontal Ligament                        |
| SCIFC         | Secondary Cellular Intrinsic Fiber Cementum |
| SCMFC         | Secondary Cellular Mixed Fiber Cementum     |
| SP            | Substance P                                 |
| TRAP          | Tartrate Resistant Acid Phosphatase         |
| UMIS          | Ultra-Micro Indentation System              |
| $\nu$         | Possion's ratio                             |
| VHN           | Vickers Hardness Number                     |
| VIP           | Vasoactive Intestinal Peptide               |
| $\delta$      | Total elastic displacement                  |
| $\mu\text{m}$ | Micron (Micrometer)                         |



## ABSTRACT

The aims of this study were divided into two parts. The first part was to evaluate hardness and elastic modulus of untreated human premolar cementum. The second part was to investigate changes of hardness and elastic modulus values of human premolar cementum after application of relatively light and heavy controlled orthodontic forces by using the Ultra-Micro Indentation System (UMIS). The sample consisted of thirty-six maxillary and/or mandibular first premolar teeth, derived from seventeen patients (nine males and eight females, mean age  $14.5 \pm 1.4$  years, range 11.7-16.4 years) who required the removal of the bilateral first premolar teeth as part of their planned orthodontic treatment. The subjects were consecutively selected and divided into two groups of nine individuals for light orthodontic force (Group I), and heavy force (Group II). For each patient, the right first premolar was moved buccally with an initial force of approximately 25 grams for Group I, and an initial force of approximately 225 grams for Group II. The left first premolars served as controls. The experiment took place over a period of four weeks. No reactivation of force was performed during this period. The experimental premolars moved  $1.33 \pm 0.56$  and  $0.89 \pm 0.60$  mm in Group I and II, respectively. After extraction, sterilized de-ionised water was used as the storage media. For the disinfection process, each sample was placed into an ultrasonic bath for a period of ten minutes and followed by 70% alcohol for a period of thirty minutes. Each tooth was then mounted with cylindrically shaped diamond bur parallel to long axis of the tooth, inserted through coronal pulp chamber. The tooth mounting with the bur was transferred to the UMIS for evaluating hardness and elastic modulus values. The root was equally marked and divided into three horizontal regions, cervical, middle and apical thirds as measured on buccal and lingual surfaces. The three horizontal regions on buccal surface were further longitudinally divided into mesial and distal segments. Two reference points on mid-



buccoenamel and mid-linguoenamel surfaces were used to allow for instrument calibration. This resulted in a total of eleven points on a tooth that were used for recording the data (6 buccal, 3 lingual and 2 enamel points). Each point traversed the preset layout of five-indentation box array. A total of 1,980 indentations were performed on enamel and cementum using a 20- $\mu$ m spherical indenter and a partial load/unload cycle, with the contact force of 5 mN and the maximum force of 500 mN, in 20 increments. The hardness values were determined as a function of penetration depth. An elastic modulus measurement was available as a by-product, in combination with Poisson's ratio. Paired *t*-test and General Linear Models (ANOVA) were used for statistical analysis. The results showed that hardness and elastic modulus of human premolar cementum gradually descend from cervical area to apical area for buccal as well as lingual surfaces, regardless of whether the application of orthodontic force or not. Apical cementum has the least hardness and elastic modulus values, and cervical cementum has the highest values. For the middle area of the root, large variation in hardness and elastic modulus values of cementum is observed. The application of orthodontic force magnitude, either relatively light or heavy force, has no effect on the hardness and elastic modulus of human premolar cementum over a period of four weeks. Gender has no effect on hardness and elastic modulus of human premolar cementum, whilst, birthplace and level of fluoride in water might be critical factors affecting the hardness and elastic modulus values.

**Keywords:** Orthodontic force, Cementum, Hardness, Elasticity, Physical properties, Ultra-Micro Indentation System (UMIS).



## 1. INTRODUCTION

Root resorption is a common idiopathic and unpredictable adverse effect of orthodontic treatment. As there is potential for severe damage and a compromised result, there is a need to improve understanding of the process and risks involved during orthodontic treatment. The mechanism behind root resorption is not yet fully understood (Brezniak and Wasserstein, 1993a and b). The resorption of the root requires the removal of both the organic and mineralised components from the cemental matrix. According to Jones and Boyde (1988), the osteoclasts played a role for both demineralization of the calcified tissue and degradation of the organic matrix after demineralization. Brudvik and Rygh (1993) reported that after the application of the orthodontic force, the pressure surface demonstrates periodontal hyalinization zone. This zone is a coagulation necrotic area of the periodontal ligament (Brudvik and Rygh, 1993; Rygh, 1977; Kvam, 1972 and Gaudet, 1970). This process of hyalinization usually precedes any form of root resorption associated with orthodontic tooth movement (Rygh, 1977). It takes approximately 10 to 35 days, after application of orthodontic forces, before resorption lacunae are noted on the tooth surfaces (Rygh, 1977).

Treatment variables play an important role in the occurrence of root resorption. The orthodontic force magnitude was shown to be a primary factor (Vardimon *et al.*, 1991; King and Fischlschweiger, 1982; Harry and Sims, 1982; Reitan, 1974 and Stenvik and Mjör, 1970). Light forces have long been recommended to reduce adverse tissue reactions (Reitan, 1964; 1974; 1985 and King and Fischlschweiger, 1982). However, Owman-Moll and co-workers (1996) in a histological study found that there was no significant difference in frequency or severity of root resorption between groups of 50-gram and 200-gram force levels.



Cementum has been described as a non-uniform mineralised connective tissue. Compared to dentine and enamel, cementum is the least mineralized. The mineral content of cementum is approximately 65%, whereas these of dentine and enamel are 70% and 92-96% on a wet weight basis, respectively (Bosshardt and Selvig, 1997).

One of the main responses of cementum is a reparative function including the integrity of the root surface. Cementum appears to play a major role in the process of root resorption. Cementum is found in several distinctly different types on human teeth. They differ with respect to structure, location, function, and rate of formation (Bosshardt and Selvig, 1997). Two types of cementum that have been classified according to presence or absence of cells are cellular and acellular cementum (Freeman, 1998). Cellular cementum is less mineralized and deposited around the apical third of cementum; while, acellular cementum covers the coronal two thirds of the root. Acellular cementum consists of only mineralized layers (Freeman, 1998 and Mjor and Pindborg, 1973).

Knowledge of physical behavior of cementum is essential for understanding how orthodontic mechanical stresses are distributed throughout the root surfaces and how physical properties of cementum are altered by application of orthodontic force. These properties of cementum such as hardness and elasticity may reveal important characteristics of root resorption previously unexplored in this regard. However, studies on hardness and elastic modulus of cementum have received little attention, possibly because of the experimental difficulties.

Malek (2000) and Clark (1997) found that there was no significant statistical difference in the hardness and elastic modulus values between maxillary and mandibular premolar teeth. Sameshima and Sinclair (2001) have recently compared



the amount of root resorption between maxillary and mandibular premolar teeth and found that there was no significant difference in the amount of root resorption between maxillary and mandibular premolar teeth. From these observations, it has been hypothesized that physical properties of cementum are correlated with root resorption process.

The Ultra Micro-Indentation System (UMIS) is intended to be used as a microprobe of material properties in the surface layer with the applications in surface engineering and in the development of surface modification processes. The UMIS is the appropriate means of measuring the hardness and elastic modulus values of the human cementum (Poolthong, 1998 and Clark, 1997). However, problems associated with the physical testing of cementum are considerable. The preparation techniques and storage media of samples have to some extent the effect on hardness measurement. Sectioning, grinding, polishing and embedding in epoxy resin raised concern that a thin film of resin remained over the cementum surface. Since cementum contains water, the conditions under which cementum has been stored may influence the water content and therefore the result of hardness study obtained (Waters, 1980).

Malek (2000) and Malek *et al.*, (2001) developed a novel method of investigation of the physical properties on unprocessed human cementum. This methodology included a new location device which was designed to allow the repetitive measurements of a given test location for different purposes. This newly designed surveyor was used to enable non-destructive testing of teeth in three-dimensions (3D). The effect of different types of storage media on human premolar cementum was assessed. Sterilized de-ionized water (Milli Q<sup>®</sup>) was found to produce least variation in hardness and elastic modulus of cementum (Malek, 2000).

The aims of this study were divided into 2 parts:



1. To evaluate hardness and elastic modulus of untreated human premolar cementum by using the Ultra-Micro Indentation System (UMIS).
2. To investigate changes of hardness and elastic modulus values on human premolar cementum after the application of relatively light and heavy controlled orthodontic forces by using the Ultra-Micro Indentation System (UMIS).



## **2. REVIEW OF LITERATURE**

### **2.1 ROOT RESORPTION**

#### **2.1.1 BACKGROUND**

Bates in 1856, was the first to discuss root resorption of permanent teeth. Ottolengui (1914) related root resorption directly to orthodontic treatment, and quoted that Schwarzkopf (1887) demonstrated resorbed roots in extracted permanent teeth. Ketcham (1927; 1929) who was the first to report on radiographic evidence of root resorption, sought to determine whether specific features of an orthodontic appliance or technique could be implicated in root resorption. He observed that root resorption occurred in every group of patients, regardless of the method used to move their teeth. Therefore, in addition to orthodontic forces, some other factors must facilitate and promote the resorptive process. Ketcham's attention was drawn to hormonal imbalance and dietary deficiencies as possible causative factors. This was followed by a wide range of histologic, clinical, and physiologic research on root resorption and orthodontic treatment.

Becks and Marshall in 1932 defined the term of resorption as the destruction of formed tooth structure. Surface root resorption may now be defined as active removal of mineralized (and a thin layer of non-mineralized) cementum and dentine (Brudvik and Rygh, 1994). The loss of dental substance apically is often unpredictable and irreversible if destruction has extended into dentine.



### 2.1.2 PREVALENCE

The prevalences of 0-100% have been reported in untreated population, depending on the source of the information (Henry and Weinman, 1951; Dermaut and De Munck, 1986; Massler and Perreault, 1954). Vlaskalic *et al.*, 1998 suggested that a certain amount of root resorption may be a normal physiological process, perhaps related to continuous bone remodeling.

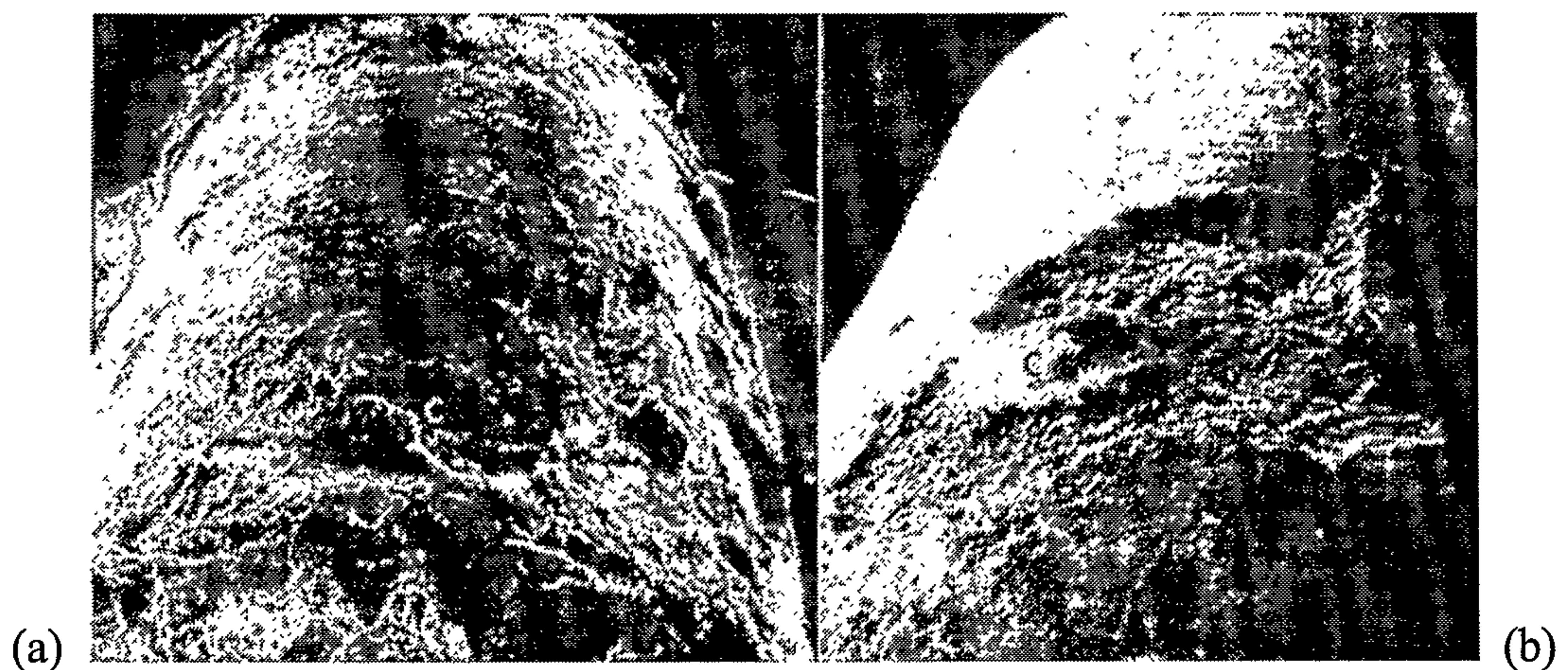


**Figure 2-1.** Electron Micrograph of resorption lacunae (a) Resorption lacunae in the middle third of a root as seen with the scanning electron microscope C, Denuded root surface. Organic tissue components cover the major portion of the lacuna. (b) The same root surface, previously covered by hyalinized tissue, after removal of organic tissue (*From Thilander B, Rygh P, Reitan K. Tissue reactions in Orthodontics. In: Graber TM, Vanarsdall RL Jr, editors. Orthodontics: Current principles and techniques. St. Louis: CV Mosby, 2000*).



Among treated subjects, root resorption has been recorded in 93 per cent of treated adolescents (Kurol *et al.*, 1996). Moderate to severe apical root resorptions ( $>2\text{mm}$  to  $<1/3$  of the root length) have been found in 12-17 per cent of orthodontically treated patients (Linge and Linge, 1991; Hollender *et al.*, 1980) and excessive root resorptions ( $>1/3$  of root length) in 1-5 per cent (Davidovitch, 1996; Levander and Malmgren, 1988).

Lupi *et al.*, 1997 used periapical radiographs of maxillary and mandibular incisors to measure apical root resorption. They reported from their sample of 88 ethnically and racially diverse adults that 15% of teeth had resorption before treatment and this increased to 73% after at least 12 months of fixed appliance treatment.

### 2.1.3 PROCESS OF ROOT RESORPTION

Root resorption of the primary dentition is a normal, essential, and physiologic process. Some deciduous teeth, even with agenesis of the permanent teeth, undergo root resorption. Scarola and Galmozzi (2001) reviewed the literatures on biology of root resorption in primary teeth. They confirmed that the involvement of the pulp and the periodontal ligament and the presence of enzymatic activity and immunologic cells had a definite role in the process of root resorption of the deciduous teeth. Root resorption of the permanent teeth is a complex biologic process of which many aspects still remain unclear (Brezniak and Wasserstein, 1993).

Root resorption has long been thought to result from the action of the odontoclasts, cells with similar cytological and functional characteristics of the osteoclasts (Ten Cate, 1998; Jones *et al.*, 1986;1988; Lindskog *et al.*, 1987; 1988; Boyde *et al.*, 1985 and Hammarstrom *et al.*, 1985). The osteoclast is a large pleomorphic multinucleated cell formed by fusion of mononuclear precursor. It is characterized by a ruffled border



pointed against the hard tissue surface (Jones *et al.*, 1988; Lindskog *et al.*, 1987; 1988; Hammarstrom *et al.*, 1985 and Marks, 1983). There is a consensus that the osteoclasts are of haematopoietic in origin that originated from the bone marrow (Takahashi *et al.*, 1989; Marks, 1983; Osdoby *et al.*, 1982 and Marks and Walker, 1981), and that the dissemination of their precursors is through the vascular system (Kahn, 1988).

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

Reitan (1974) suggested when the surface cell layer was breached, the epithelial barrier may permit blood vessel access to the tooth surface and the resorptive process can begin. Resorption of the calcified dental tissues occurs when osteoclasts have access to the mineralized tissue through a breach in the formative cell layer covering the tissue (Tronstad, 1988; Jones and Boyde, 1988 and Lindskog and Pierce, 1988). It can also occur if the precementum is mechanically damaged or scraped off (Tronstad, 1988; Wesserlink and Beertsen, 1988) or when the mineral and matrix surfaces coincide (Jones and Boyde, 1988). The mineralized or denuded root areas attract hard tissue resorbing cells to colonize the damaged areas of the root (Brudvik and Rygh,



1993; Lindskog *et al.*, 1987). Alteration in levels of cytokines and growth factors may have modified cellular metabolism, which modulate the activity of both osteoblasts and osteoclasts (Centrella *et al.*, 1992).

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

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

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

The type of root resorption that occurs during orthodontic treatment is frequently preceded by hyalinization of the PDL (Rygh, 1977). During the remodeling 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 (Rygh, 1974; Kvam, 1972; 1973). As a side effect of the cellular activity during the removal of the necrotic PDL tissue, the cementoid layer of the root and the bone are left with raw unprotected surfaces in certain areas that can readily be attacked by resorptive cells. Root resorption then occurs around this cell-free tissue, starting at the border of the hyalinized zone (Rygh, 1977). Brudvik and Rygh (1995b) implicated mononucleated non-clast cells in the initial removal of pre-cementum and mineralised acellular cementum in the periphery of the hyalinized zone. They further suggested that multi-nucleated giant cells (MNGC) without a ruffled border surface, as well as mononucleated macrophage-like cells are responsible for removal of the necrotic tissue and also for resorption of the surface parts of root cementum. In the periphery zone, fibroblast-like and cementoblast-like cells perform phagocytosis of cellular remnants and adjacent fibrous components and remove unmineralized pre-cemental structures on the root surface by collagenolytic activity (Brudvik and Rygh, 1993).

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



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

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

Brudvik and Rygh (1993) reported that after the application of the orthodontic force, the pressure surface demonstrates periodontal hyalinization, which is a sterile



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

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

1. The first sign of root resorption (initial phase) was defined as a penetration of cells from the periphery of the necrotic tissue where mononucleated fibroblast-like cells, stained negatively by tartrate resistant acid phosphatase (TRAP), started removing the precementum/cementum surface.
2. Root resorption beneath the main hyalinized zone occurred in a later phase during which multinucleated TRAP-positive cells were involved in both removing the main mass of necrotic PDL tissue and resorbing the outer layer of the root cementum. Further studies indicated that after the multinucleated TRAP-positive cells reached the subjacent contaminated and damaged root surface and removed the necrotic periodontal tissue, they continued to remove the cementum surface (Brudvik and Rygh, 1994).



When pressure is below optimal force (20-26g/cm<sup>2</sup>-Schwarz, 1932 or 83 g/cm<sup>2</sup> Miura, 1975) or is removed, root resorption ceases.

#### 2.1.4 APICAL ROOT RESORPTION

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

Henry and Weinmann (1951) found that a number of resorption defects approximately 75%, were confined to the apical third of the root. In the cervical third of the root such resorption defects are rare. In the mid-root and apical regions of mesial and buccal root surfaces, resorption defects are more numerous when compared to distal and lingual surfaces. Resorption defects are approximately 1 mm in diameter and about 100 µm in depth with mesial and buccal defects larger than distal and lingual defects. Most defects are limited to cementum, but about 30% penetrate into dentine (Henry and Weinmann, 1951; Schroeder, 1986). In histological sections, the vast majority of resorption defects are demarcated by retained reversal lines and near completed anatomical repair. Thus the frequency of root resorption episodes may well approach 100% of the erupted permanent teeth but traumatic injuries and orthodontic treatment increase the number and extent of resorption defects. This is particularly so in axially



intrusive and horizontal movements and forces beyond physiological limits (Kronfeld, 1938a; De Shields, 1969; Kvam, 1972; Reitan, 1974; Rygh, 1977; Andreasen, 1981; Harry and Sims, 1982).

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

Lindskog and Hammarstrom (1980) demonstrated that, like cartilage, dental cementum or periodontal ligament contained an anti-invasion factor, which acted as an inhibitor of proteases such as trypsin and collagenase. Whether or not this factor prevents the root surface from being attacked under certain conditions is unknown.

An assessment of the radiographic outline of the apex provides useful information regarding the risk of apical root resorption during orthodontic tooth movement (Levander and Malmgren, 1988). A root resorption index permits quantitative assessment of root conditions before treatment and can be used for evaluation of further resorption (Goldson and Henriksson, 1975).

0: No visible resorption

I: resorption less than 2 mm

II: resorption from 2 mm to 1/3 of the root length

III: resorption exceeding 1/3 of the root length



Reitan (1974) found that the anatomic environment, duration, and direction of movement constitute the determining factors in apical root resorption.

### **2.1.5 ORTHODONTIC TOOTH MOVEMENT AND ROOT RESORPTION**

Orthodontic treatment requires resorption and apposition of bone adjacent to the root. Orthodontic forces applied to the biologic system act similarly on bone and cementum, which are separated by the periodontal membrane. If there were no differences in the biologic behavior of these two organs, both would resorb equally, however, cementum is more resistant to resorption. For many years, it was thought that the root structure of the teeth was not remodelled in the same way as bone. 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 is also observed (Brezniak and Wasserstein, 1993a and b).

Gibilaro and Proffit (1996) distinguished three types of root resorption

- (1) Limited but generalized resorption, which occurs in the majority of orthodontic patients and is of little clinical significance.
- (2) Severe generalized resorption that occurs quite rarely during orthodontic treatment and may occur in its absence.
- (3) Severe resorption of only a few teeth, which occurs infrequently and is likely to be iatrogenic.

It is generally accepted that iatrogenic root resorption is a common idiopathic and unpredictable adverse effect of orthodontic treatment as stated by Ketcham (1929), Dougherty (1968), De Shields (1969), Kvam (1972), Reitan (1974), and Rygh (1977).



However, most root loss due to orthodontics does not decrease the longevity or the functional capacity of the involved teeth (Brezniak and Wasserstein, 1993).

De Shields (1969), Linge and Linge (1983) and Ronnerman and Larson (1981) studied root resorption with radiography of the anterior maxillary teeth after orthodontic movement. The variables of tooth movement, such as the amount of movement, the direction of movement and tooth "jiggling", all contributed to root resorption.

Brudvik and Rygh (1995) have shown that cementum adjacent to hyalinized (necrotic) areas of the PDL is "marked " by this contact and that clast cells attack this marked cementum when the PDL area is repaired.

#### 2.1.6 CLASSIFICATION

**Andreasen (1988)** defined three external root resorption types:

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

**Tronstad (1988)** summarized that external root resorption can be categorized into 2 types:

1. *Inflammatory resorption* occurs when the preentin or precementum becomes mineralized or, in case of the precementum, is mechanically damaged or scraped off.



- 1.1 Transient resorption -when stimulation to the damage is minimal and for a short period. Usually undetected radiographically and repaired by a cementum-like tissue.
- 1.2 Progressive resorption – when stimulation is for a long period. Tissue-pressure related ,thus if forces removed, resorption should stop.  
Usually seen as apical resorption and shortening of roots.
2. *Replacement resorption*, which 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 remodeling of bone are not able to distinguish between root cementum, dentin and bone. The osteoclasts will resorb the dental tissues just as readily as they resorb the bone, and the osteoblasts, which are not capable of forming dentin, or cementum subsequently will replace the resorbed areas of the root with bone.

**Ghafari (1994)** classified types of post-orthodontic external root resorption as the following:

1. *Inflammatory resorption*: Inflammatory mediators and phagocytic cells colonize mineralized or denuded cemental surface and later dentinal tubules or pulpal tissues. All resorptions result from an inflammatory response to stimuli.
2. *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 etiology is not removed, root resorption may progress further.
3. *Progressive resorption with bone substitution* presented 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.

4. *Progressive resorption without bone substitution.* This described the progressive inflammation without substitution of the resorbed tooth substance by bone. It may be cervical or peripheral. Not reported as a common outcome.

According to Brezniak and Wasserstein (1993a and b), root resorption after orthodontic treatment is surface resorption or transient inflammatory resorption. Replacement resorption is rarely, if ever seen after orthodontic treatment. However, Tronstad (1988) considers transient resorption as clinically insignificant as does Ghafari (1994).

### **2.1.7 AETIOLOGY**

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

#### **2.1.7.1 Biological factors**

##### **2.1.7.1.1 Individual susceptibility**

**Becks (1936)** stated that orthodontically induced root resorptions were not produced by mechanical force alone, but were the result of individual predisposition due to endogenous factors. Degrees of root resorption vary among different people and on different teeth (Vlaskalic *et al.*, 1998; Rygh, 1977; Massler and Malone, 1952; 1954).



#### 2.1.7.1.2 Genetics

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

#### 2.1.7.1.3 Hormonal Imbalance

The association between root resorption and endocrine problems such as hypothyroidism, hypopituitarism, hyperpituitarism and other diseases had been studied (Becks, 1939; Hemley, 1941). Hyperparathyroidism (Goultschin *et al.*, 1982), hypophosphatemia (Tangney, 1973), Paget's disease (Smith, 1978) have also been linked to root resorption. Pouprouk *et al.*, (1994) tested the effect of thyroxine on force-induced root resorption and found that in thyroxin-fed rat, fewer root resorption lesions were shown than in the control group.

On the contrary side, Linge and Linge (1983) suggested that hormonal imbalance does not cause but influences the phenomenon.

#### 2.1.7.1.4 Asthma/Allergy

Davidovitch *et al.* (1996) induced *allergic asthma* in guinea pigs and applied an orthodontic force against the maxillary molars. Although root resorption was not observed on these cementum-free and continuously erupting teeth, the number of alveolar bone osteoclasts in areas of compressed PDL increased over the controls, suggesting that *chemical mediators produced in the asthmatic state may influence cell populations and subsequently the resorption process.*



**McNab et al., 1999** in a study of panoramic films, concluded a statistically significant *increase in root resorption postorthodontics in asthmatics when compared to nonasthmatics*. However, this increase was *only associated with grade 1* (root blunting).

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

#### 2.1.7.1.5 Nutrition

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

#### 2.1.7.1.6 Drug

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

#### 2.1.7.1.7 Chronological age

**Thilander et al. (2000)** suggested that *adult patients experienced more root resorption* after treatment than younger patients. **Reitan (1954)** observed that the *adult alveolar bone* surface was predominantly *aplastic* before the orthodontic treatment, indicating that the periodontal structures were in a state of rest. This was substantiated



by the moderate number of cells and the fact that the fibrous tissue reacted more slowly. The turnover rate of collagen molecules is in general slower in adults than in growing children, a difference that is also reflected in the delayed onset of tissue changes in adults during tooth movement.

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

Baumrind *et al.* (1996) analyzed the relationship in orthodontically treated adults between upper central incisor displacement measured on lateral cephalograms and apical root resorption measured on anterior periapical x-ray films and found that an average of  $0.99 \pm 0.34$  mm of resorption was implied in the absence of root displacement and an average of  $0.49 \pm 0.14$  mm of resorption was implied per millimeter of retraction. Thus, a small portion of observed apical resorption could be accounted for by tooth displacement alone. Significant apical root resorption that was greater than 2.5 mm increases with age for all treatment variables. These included using of rectangular arch wires, class II elastics and open activators. **Linge and Linge (1983)** also found that *patients who started treatment before the age of eleven had less root resorption than those treated later*. The age factor also carries information about root length development (Linge and Linge, 1991)

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



patients experienced more resorption than children did in the mandibular anterior segment only.

#### **2.1.7.1.8 Dental age**

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

#### **2.1.7.1.9 Gender**

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



**2.1.7.1.10 The presence of root resorption before orthodontic treatment**

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

**2.1.7.1.11 Habits**

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

**2.1.7.1.12 Tooth form and anomalies**

Sameshima and Sinclair (2001) have found that abnormal root shape was a significant factor of root resorption. In general, dilacerated teeth had the most resorption, followed by bottle-shaped and pointed teeth. This finding is in agreement with previous studies (Kjaer, 1995; Mirabella and Artun, 1995; Newman, 1975; Oppenheim, 1942). No direct proof exists as to the reason that an abnormal root shape would resorb more easily; however, the deviant process that caused the abnormal shape in the first place is a strong possibility. A genetic component to shape inheritance is also likely but unproved; disruption of the path of eruption is another plausible cause (Sameshima and Sinclair, 2001).

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



shaped root was shown to be the most susceptible root form to root resorption (Levander and Malmgren, 1988).

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

**Lee *et al.*, (1999)** investigated the possible significance of dental anomalies as risk factors. Pre-treatment and post-treatment periapical radiographs of 84 patients with presence of at least one dental anomaly and of 84 patients without such anomalies were compared. They found that *anomaly did not appear to be at increased risk of root resorption.*

#### **2.1.7.1.13 Previous trauma**

A history of trauma to the maxillary incisors frequently has been implicated as a contributing factor to the root resorption seen in orthodontic treatment. Brin *et al.*, 1991 reported that incisors with a history of trauma that also had been subjected to a course of orthodontic treatment had more extensive resorption than either incisors that had been traumatized without orthodontic treatment, or incisors that had orthodontic treatment without a history of trauma. Linge and Linge (1991) also agreed that trauma to be a factor in root resorption. Traumatized teeth without signs of resorption, however, are not resorbed more than nontraumatized teeth (Malmgren *et al.*, 1982). Although traumatized teeth may show root resorption, orthodontic treatment can initiate the process in teeth with a previous history of root resorption (Andreasen, 1988). Treatment for traumatized teeth should be started with light, preferably



intermittent, forces to avoid prolonged tipping; the clinician should aim at a limited goal and in this way achieve a shorter treatment procedure.

#### **2.1.7.1.14 Endodontic treatment**

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

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

#### **2.1.7.1.15 Alveolar bone density**

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

#### **2.1.7.1.16 Malocclusion**

Although VonderAhe (1973) did not find a correlation between root resorption and malocclusion classification, some investigators (Hendrix *et al.*, 1994; Harris and Butler, 1992; Linge and Linge, 1991) noted that both increased overjet and the amount



of root movement correlate positively with the extent of root resorption. Kaley, 1991 showed that there were significantly more Class III patients among the severe resorption cases than would have been expected. Risk indicators for resorption that were related to treatment procedures included approximation of the maxillary incisor roots against the lingual cortical plate, maxillary surgery, and root torque. It appeared that root resorption of the mandibular anterior teeth have been reported after surgical correction of mandibular prognathism by horizontal osteotomy of the rami. (Ridell and Astrand, 1977). Ghafari (1994) proposed that orthognathic surgery influenced root resorption by affecting the blood supply to the periodontal ligament, bone and/or cementum. This precipitates the aging changes associated with adults. Harris *et al.* (1997) demonstrated greater ANB values and low angle cases were associated with greater external root resorption.

#### **2.1.7.1.17 Specific tooth**

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

However, Sameshima and Sinclair 2001 found some interesting patterns emerged: First, maxillary teeth were more severely affected than mandibular teeth. Second, the most severely resorbed teeth were maxillary lateral incisors, followed by maxillary central incisors, maxillary canines, mandibular canines, mandibular central incisors, and mandibular lateral incisors. They also explained that there were several reasons that maxillary lateral incisors were the most severely affected teeth. Maxillary lateral incisors demonstrated the highest percentages of abnormal root shapes. They also are the third most commonly missing tooth after third molars and lower second premolars.



Developmental anomalies include dens invaginatus. Brin *et al.*, 1993 found that the erupting canine often resorbed the lateral root from the palatal direction; this resorption was not visible on conventional radiographic examination.

#### **2.1.7.1.18 Loss of root length**

Loss of marginal attachment is more detrimental than loss of an equivalent amount of root length by apical root resorption. 3mm of apical root resorption is approximately equivalent to 1mm of crestal bone loss. Also, an incisor with 5mm of apical root resorption will still have 75% of its periodontal attachment remaining (Kalkwarf *et al.*, 1986).

#### **2.1.7.2 Mechanical factors**

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

##### **2.1.7.2.1 Appliances**

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

- (i) **Standard edgewise and straight-wire edgewise techniques:** Mavragani *et al.*, 2000 found that apical root resorption was decreased in the straight-wire group compared to the standard edgewise group. This may be due to the more efficient force control that this technique can offer.
- (ii) **Fixed and Removable appliances:** Linge and Linge (1983) compared root resorption resulting from fixed and removable appliances and concluded that fixed appliances are more detrimental to the roots. Stuteville (1937) on



the other hand, suggested that the jiggling forces caused by removable appliances are more harmful to the roots.

- (iii) **Begg and Edgewise techniques:** It is often stated that the light wire Begg technique causes less root resorption than Edgewise (Kinsella, 1971). Malmgren *et al.*, (1982) suggested that there is no difference between these techniques, but found that the frequency of root resorption was significantly higher (48%) in traumatized maxillary incisors when intruded by the Begg technique compared with edgewise technique (43%). Beck and Harris (1994) examined the degrees of in-treatment root resorption and found no difference between the Begg and Tweed techniques. Parker and Harris (1998) also found no statistical difference in average external apical root resorption between Tweed standard edgewise technique, Begg lightwire technique, and Roth-prescription straightwire technique.
- (iv) **Speed and Edgewise techniques:** no statistical difference in the amount of root resorption reported (Blake *et al.*, 1995).
- (v) **Sectional and Continuous mechanics:** Alexander (1996) found no significant difference between continuous and sectional archwire mechanics.
- (vi) **Intermaxillary elastics:** Linge and Linge (1983) found significantly more root resorption on the side where elastics were used and suggested that jiggling forces which resulted from function combined with elastics were responsible for the incisors' root resorption. Linge and Linge (1991) concluded that treatment with fixed appliances, rectangular arch wires, and the use of Class II elastics, showed risk factors for root resorption. It was



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

- (vii) **Maxillary expansion:** Thilander *et al.*, 2000 found that using rapid palatal expansion, premolars and molars are pressed in a buccal direction against the thin cortical plate with risk of root resorption. These finding supported the studies by Odenrick *et al.*, 1991; Vardimon *et al.*, 1991 and Hill, 1987. Handelman *et al.*, 2000, on the other hand, found the minimal amount of root resorption from rapid maxillary expansion in the adult. Sameshima and Sinclair, (2001) proposed that there was no significant difference for transverse treatments: rapid/slow expansion /none
- (viii) **Slot size and archwire type:** there was no significant difference between 0.018" and 0.022" slot or steel and titanium for all anterior teeth (Sameshima and Sinclair, 2001).
- (ix) **Edgewise and activator:** In comparing edgewise with activator-only patients, Linge and Linge (1991) found no resorption in the activator group. They also concluded that open activators, plates with clasps and vertical elastics had a very low correlation with single-root resorption.

#### 2.1.7.2.2 Direction of movement

Of the several modes of tooth movement, pressure from intrusive forces seems the most likely to cause external apical root resorption (Thilander *et al.*, 2000; Beck and Harris, 1994; Reitan, 1974). Parker and Harris (1998) also showed that incisor intrusions with increase in lingual root torque together were the strongest predictors of external apical root resorption. In contrast, distal bodily retraction, extrusion, or lingual crown tipping had no discernible effect. According to Thilander *et al.*(2000),



the stress distribution along the roots during bodily movement is less than that during tipping. Therefore the risk of root resorption during bodily movement should be less than tipping. DeShields (1969) and McFadden and colleagues (1989), however, found no significant associations between vertical movement of the root apex and root resorption.

#### **2.1.7.2.3 Force magnitude**

Harry and Sims (1982) found the distribution of resorbed lacunae was directly related to the amount of stress on the root surface and the rate of lacunae development was more rapid with increasingly applied forces. They concluded that higher stress causes more root resorption. Exceeding the optimal force can cause periodontal ischaemia leading to root resorption (Brezniak and Wasserstein, 1993). According to Schwarz (1932), applied force exceeding the optimal level of 20 to 26 gm/cm<sup>2</sup> causes periodontal ischemia, which can lead to root resorption. Levander and Malmgren (1994) evaluated the effect of a treatment pause on teeth in which apical root resorption was discovered. The amount of root resorption was significantly less in patients treated with a pause than in those treated without interruption. On the other hand, Hall (1978) found that intermittent forces had been linked in detrimental effects to the jiggling forces generated.

#### **2.1.7.3 Combined biological and mechanical factors**

##### **2.1.7.3.1 Treatment duration**

Several previous studies reported that the severity of root resorption was directly related to duration of treatment (Valskalic *et al.*, 1998; Baumrind *et al.*, 1996; Brezniak and Wasserstein, 1993; Linge and Linge, 1991; Goldin, 1989; Levander and Malmgren 1988; Sharpe *et al.*, 1987; Goldson and Henriksson, 1975; Reitan, 1974). The total duration of treatment is considered to be more crucial factor than magnitude



of the force (Thilander *et al.*, 2000). Linge and Linge 1991 showed that time of treatment with rectangular arch wires significantly contribute to apical root resorption. An apical root loss of 0.9mm per year during labial root torque had been reported by Goldin (1989). Levander and Malmgren (1988) found that 34% of examined teeth showed apical root resorption after 6-9 months of treatment with fixed appliances.

#### **2.1.7.3.2 Relapse**

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

#### **2.1.7.4 Causal factors**

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

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

Fuhrmann (1996) included risk factors of root resorption:

- Small alveolar process
- Thin buccal or lingual bone plates



- Eccentric position of teeth
- Basally extended maxillary sinus
- Progressive alveolar bone loss

### 2.1.8 DIAGNOSIS

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

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

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



- Limit movement associated with increased risks – intrusion and torque (Parker and Harris, 1999).

## 2.2 ORTHODONTIC FORCES

Application of orthodontic forces to the teeth produces tooth movement. An interaction of systemic (metabolic), mechanical (stress, strain), bioelectrical and local (cytokines) factors within the periodontium and supporting bone has been implicated to tooth movement. All of these factors are probably involved either directly or indirectly. The characteristics of a force system that have been associated with orthodontic tooth movement and root resorption are magnitude, type, and duration of forces.

Tooth movement has been characterised by three phases - initial, lag and post-lag phase (Storey, 1973; King and Fischlschweiger, 1982; Burstone, 1985; King *et al.*, 1991). The initial phase is a reflection of stretch and compression of the periodontal ligament and lasts only for a short period of time. The lag phase is characterised by only little or no tooth movement at all, and areas of hyalinization are a common finding in histological sections. During the post-lag phase, tooth movement is continued, and resolution of hyalinized tissue combined with frontal or undermining bone resorption is seen histologically.

### 2.2.1 MAGNITUDE OF FORCE

Force magnitude has received considerable attention in orthodontics. Smith and Storey (1952), introduced the "optimal force" and explained that there was a range of force or



"pressure" that produced the maximum rate of tooth movement. Below this range there was little movement and above it, at least in the short term, movement was slowed.

Even the concept of light forces is widely acclaimed. However, several investigators described that distribution of stress (force magnitude per area) was the direct mechanical parameter in tooth movement (Quinn and Yoshikawa, 1985; Roberts *et al.*, 1981). Magnitude of force is important as it relates to the other characteristics of the force system and the surface area of the periodontal ligament over which it is dissipated. Force distribution is critically important because the biologic system that allows teeth to move is activated by, and responds to, local changes in stress (force per unit area) and the associated local strain (unit deformation) delivered to the system. For example, 75 grams of force may be excessive for tipping tooth because of very high concentrations of stress at the alveolar crest and apex, but this may be inadequate for effective translation when accompanied by an appropriate moment. The major difference is the area over which the force is distributed, which is consideredly greater for translation than for tipping. The remodeling response is directly related to stress levels within the periodontium.

Boester and Johnston (1974), also found that there was a direct relationship between the magnitude of the applied stress and the rate of tooth movement. However, they observed that once a certain stress level was reached, further increases in stress failed to produce continued increases in the rate of movement. A similar opinion of that beyond a certain stress level increasing stress no longer alters the rate of tooth movement has been presented by Pilon *et al.*, 1996; Owman-Moll *et al.*, 1996; Hixon *et al.*, 1969; Burstone and Groves, 1961; Reitan, 1960; Andreasen and Johnson, 1967; Andreasen and Zwanziger, 1980.



Owman-Moll *et al.*, 1996, with an intra-individual study, investigated the effect on tooth movements and adverse tissue reactions (root resorption) when a fixed orthodontic appliance was activated with a controlled, continuous force of 50 grams or with a four-fold larger force 200 grams. The first premolar on both sides of the maxilla in eight individuals, six boys and two girls (mean age 13.0 years), was moved buccally during 7 weeks with 50 grams and 200 grams alternately on the right or left side. The magnitude of the mean horizontal crown movement increased 50 per cent when a force of 200 grams was applied compared with a 50 gram force (3.4-5.1 mm on average) and the difference was significant. Root resorptions were registered in histological sections of the extracted test teeth with no significant difference in frequency or severity between the two forces used. Individual variations were large regarding both tooth movement and root resorption.

External root resorption is a well-known side effect after orthodontic tooth movement. Reitan (1964,1967,1974) has always advocated the use of light orthodontic forces in order to increase the cell activity in the surrounding tissues and reduce the risk of root resorptions. King and Fischlschweiger (1982), in an investigation in rats, also supported that light forces produced insignificant root resorptions, whereas intermediate or heavy forces resulted in substantial cratering. Harry and Sims (1982), in a human study, found that the distribution of resorbed lacunae was directly related to the amount of stress on the root surface, and the rate of lacuna development was more rapid with increasingly applied forces.

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



### 2.2.2 TYPE OF FORCE

Type of applied force has another aspect, related to how force magnitude changes as the tooth responds by moving. Proffit and Fields (2000) classified orthodontic force type according to the rate of decay as

- Continuous: force maintained at some appreciable fraction of the original from one visit to the next
- Interrupted: force levels decline to zero between activations
- Intermittent: force levels decline abruptly to zero intermittently, when the orthodontic appliance is removed by the patient or perhaps when a fixed appliance is temporarily deactivated, and then return to the original level some time later.

Modern fixed appliance systems are based upon light continuous forces from the arch wire, and its influence on the efficiency of tooth movement and related root resorptions should be elucidated. A continuous force, however, may be interrupted after a limited period (Thilander *et al.*, 2000).

A controversy over the favorable effect of an interrupted force, compared to a continuous force had been demonstrated. It has been suggested that an interrupted continuous force with periods of rest may favorably affect cell proliferation in the supporting tissues, which in turn might promote further tooth movement (Thilander *et al.*, 2000). Because of the increase in number of cells, osteoid tissue is deposited in open marrow spaces on the pressure side and in other areas not undergoing direct resorption. On the tension side a gradual calcification and reorganization of newly formed tissue occurs during the rest period. Tissues; therefore, are given enough time for reorganization and the cell proliferation is favorable for further tissue changes when the appliance is again activated. (Thilander *et al.*, 2000).



Reitan (1951) showed that, during the first 24 hours of tooth movement, an interrupted type of force caused less reduction in cellular activity in areas of compression than did a continuous force. The rate of tooth movement showed that the lag phase, which is so characteristic of continuous forces was almost missing. These findings indicate that interrupted continuous forces seem to compromise the nutrient supply of the periodontal ligament to a lesser degree than do continuous forces.

Darendeliler and coworkers in 1997 supported that an ideal orthodontic force should be constant throughout the entire range of its activation. They demonstrated the drum spring (DS) retractor, which applied a constant and continuous force without the need for reactivation. The clinical sample consisted of 15 patients with upper first premolar extractions. For each patient, the upper right canine was retracted by using a DS retractor applying a constant and continuous force of 50 g; the upper left canine was fitted with a conventional pushcoil (PC) applying an initial force of 50 g, diminishing proportionally with the distal movement of the canine. During this period no archwire was used, the PC retractor was reactivated every 3 weeks whereas the DS retractor was left untouched over the entire experimental period. The DS retractor was found to be successful for space closure without any reactivation, and the continuous and constant force provided a more rapid canine movement than the continuous but diminishing force.

Levander *et al.*, (1994) evaluate the effect of a treatment pause on initially resorbed teeth. Forty patients with initial apical root resorption in 62 upper incisors were studied. In 20 patients treatment continued according to the original plan and in 20 patients active treatment was interrupted during a pause of 2-3 months. After the pause active treatment was resumed. Assessment of apical root resorption was performed on



standardized radiographs. The amount of root resorption was significantly less in patients treated with a pause than in those treated without interruption.

An intermittent force acts during a short period and is produced by all activated appliances such as removable plates, headgear, and elastics. Roberts *et al.*, 1992 reviewed that the orthodontic response in PDL is a special case of coordinated modelling (change in shape or form of bone) and remodelling (turnover of previously existing bone). He suggested that the continuous loads are most efficient in moving teeth. Intermittent loads can result in some tooth movement. The biochemical activation of the periodontium is lost when the appliance was removed for other activities. This could be thought of as a phenomenon of biological momentum: each period of recovery requires a new initiation phase to activate the PDL.

Proffit and Sellers (1986) studied the effect of intermittent forces on eruption of the rabbit incisor. Forces of 1-3 grams were applied under time conditions of one second on, nine seconds off (1:9); one second on, three seconds off (1:3); and one second on, one second off (1:1). The data indicate that with force present for 10% of the time (1:9), there was little or no effect on eruption rate. In contrast, 50% time (1:1) produced essentially the same intrusive effect as continuous force, and 25% time (1:3) gave an intermediate response. They concluded that force duration is more important than force magnitude for the vertical equilibrium, as is the case for facio-lingual equilibrium.

Oates *et al.* (1978) presented a case report on one dog, indicating that a pulsating force of 60g with a frequency of 3 pulses per minute and duration of 3 seconds and a continuous force of the same magnitude were equally effective in producing tooth movement. These findings agree well into those of Reitan (1951), who showed histological similarities between continuously and interrupted continuously moved



teeth in dogs. The interrupted continuous forces of 180g to 200g were of 10 minutes or 2 hours duration with intervals of 20 seconds and 2 minutes, respectively.

Darendeliler *et al.*, 1995 evaluated the effect of a magnetic field on bony physiology and metabolism and to monitor for possible systemic side effects. Fifteen grams of laterally directed orthodontic force were applied to move the maxillary central incisors of a sample of 18 young male Hartley guinea pigs divided into three groups: group 1, an orthodontic coil spring was used to move the incisors; group 2, a pair of samarium-cobalt magnets provided the tooth moving force; and group 3, a coil spring was used in combination with a pulsed electromagnetic field. The results showed that both the static magnetic field produced by the samarium-cobalt magnets and the pulsed electromagnetic field used in combination with the coil spring were successful in increasing the rate of tooth movement over that produced by the coil springs alone. The mechanism producing this effect appears to have involved a reduction in the "lag" phase often seen in orthodontic tooth movement. Both magnetically stimulated groups also showed increases in both the organization and amount of new bone deposited in the area of tension between the orthodontically moved maxillary incisors.

### 2.2.3 DURATION OF FORCE

The association between the increased amount and severity of root resorption and the duration of the applied force has been verified by some investigators (Kurol *et al.*, 1996; Linge and Linge, 1991; Goldin, 1989; Levander and Malmgren, 1988; Sharpe *et al.*, 1987; Kvam, 1972; Reitan, 1974; Goldson and Henriksson, 1975; Stenvik and MjÖr, 1970; Harry and Sims, 1982). However, it has also been reported that treatment time had no significant effect on the severity of root resorptions (Dermault and De Munck, 1986; Lilja and Odenrick, 1982; Linge and Linge, 1983; VonderAhe, 1973). Kurol *et al.* (1996) investigated root resorption after application of a weekly controlled



continuous orthodontic force of 50 grams. Fifty-six maxillary premolars in 18 boys and 38 girls (mean age 13.8 years) were moved buccally. The contralateral premolars served as controls. Histologically, the number of root resorptions of each tooth was more than six times higher in the test group than in the control group after one week of force application. After seven weeks, the experimental teeth showed on an average more than twenty times larger mean resorbed root contour than the control teeth. Similar observation of root resorption has been reported by Kvam (1972). In Kvam's study, twenty-three teeth from untreated patients aged 10-12 years were moved by a laterally directed spring of fifty-gram force. Seventeen teeth were used as control. All specimens were studied by scanning electron microscope. The results showed that at the end of an experimental period of ten days, resorption of cementum was initiated. After 25 days the resorption had reached the dentine and showed a characteristic honeycomb appearance. Exposed cementum and resorbed surfaces generally became more markedly influenced with increasing observation time.

This positive association between duration of force and root resorption has also been confirmed in rat study by Williams, (1984) as well as in human study by DeShields (1969) and McFadden *et al.* (1989).

Continuous heavy forces cause resorption, whereas the pause in treatment with intermittent forces allows the resorbed cementum to heal and prevents further resorption (Reitan, 1947; 1957).

#### **2.2.4 CRITICAL ANALYSIS**

Since there are several investigations into effects of orthodontic forces on tooth movement and root resorption, and various results are proposed, an importance of



experimental designs should be emphasized when the comparisons of these effects were performed. For example,

- Direction of tooth movement: Storey and Smith (1952), Hixon *et al.* (1970), moved teeth mesiodistally. Reitan (1974) investigated the effect of root tipping, intrusion and extrusion.
- Magnitudes of force: Owman-Moll *et al.* (1996) with a series of studies used 50, 100 and 200 gram force levels. Lundgren *et al.* (1996) used 50 gram force to study early tooth movement pattern after application of a controlled continuous orthodontic force.
- Types of orthodontic appliances were utilized, e.g. frictionless sectional arch (Smith and Storey, 1952; Boester and Johnston, 1974), Kloeht-type headgear (Andreasen and Johnson, 1967), full fixed appliance (Andreasen and Zwanziger, 1980), latex elastics (Mitchell *et al.* 1973), sliding mechanics (Hixon *et al.* 1970; Maltha *et al.* 1993)
- Whether there is control of force level, and how often the force was reactivated during the experimental period also plays a crucial role in interpreting effect of continuous orthodontic forces on tooth movement and root resorption. Owman-Moll *et al.* 1996 compared the effect of 50 and 200 grams on tooth movement and root resorption during a period of seven weeks. Force level was controlled every week. Whereas Kvam, (1972), measured force magnitude only at the start although the experimental periods were 5-76 days.



**Table II-a** Summary of clinical study designs of previous studies of effect of orthodontic force on tooth movement and/or root resorption

| <i>Authors</i>                   | <i>Sample</i>                                | <i>Clinical Study Design</i>                                                                                                                                                                                                                | <i>Magnitude of force (gram)</i> | <i>Duration</i>              | <i>Force Control</i> |
|----------------------------------|----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|------------------------------|----------------------|
| Storey and Smith<br>1952         | N=10<br>human<br>canines<br>(12-15y)         | <i>Distal movement of canine</i><br>Light spring on one side<br>Heavy spring on another side                                                                                                                                                | 175-300<br>400-600               | 1-9 wks                      | weekly               |
| Andreasen and<br>Johnson 1967    | N=32<br>human<br>first<br>molars<br>(8-10 y) | <i>Buccal movement of #16 and 26</i><br>Molar band on maxillary molar and<br>incisor bands<br>Kloehn-type headgear with the 200 gm<br>one side and 400 gm another side                                                                      | 200 and 400                      | 12 wks                       | weekly               |
| Kvam 1972                        | N=40<br>human<br>premolars<br>(10-12y)       | <i>Lateral movement of premolar</i><br>Fixed appliance -0.016" spring<br>from molar band on first molar, ligated to<br>a bonded bracket on premolar                                                                                         | 50                               | 5-76 days                    | -                    |
| Reitan 1974                      | N=72<br>human<br>premolars<br>(9-16y)        | Intrusion/Extrusion/Tipping<br>Fixed appliance -Sectional arch varied<br>from 0.014 to 0.018"<br>from molar band on first molar, ligated to<br>a bonded bracket on first premolar                                                           | 25 to 240                        | Varied<br>from 10-47<br>days | weekly               |
| Harry and Sims<br>1982           | N=36<br>human<br>premolars<br>(11-18 y)      | Intrusion<br>Fixed appliance -round archwire<br>.016,.018,.020" from first molars to<br>central incisors, ligated to the<br>experimental premolar with stainless steel                                                                      | 50,100,200                       | 14,35,70<br>days             | -                    |
| Owman-Moll <i>et al.</i><br>1996 | N= 32<br>human<br>premolars<br>(13.1y)       | Buccal movement of #14<br>Fixed appliance -Sectional arch<br>0.018" sentalloy heavy for 50 gm force<br>0.016"australian for force of 100 gm.<br>from molar band on 16, ligated to a<br>bonded bracket on 14 -TPA and Anterior<br>bite block | 50 and 100                       | 4-7 wks                      | weekly               |
| Owman-Moll <i>et al.</i><br>1996 | N=16<br>human<br>premolars<br>(13.0y)        | Buccal movement of #14 and 24<br>Fixed appliance -Sectional arch<br>0.018" sentalloy heavy for 50 gm force<br>0.018"australian for force of 200 gm.                                                                                         | 50 and 200                       | 7 wks                        | weekly               |



|                             |                                                  |                                                                                                                                                                                                                |                                                               |                           |        |
|-----------------------------|--------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------|--------|
|                             |                                                  | from molar band on 16, ligated to a bonded bracket on 14 and 24<br>- TPA and Anterior bite block                                                                                                               |                                                               |                           |        |
| Lundgren <i>et al.</i> 1996 | N=112<br>human<br>premolars<br>(13.8y)           | Buccal movement of #14 or 15<br>Fixed appliance -Sectional arch<br>.018" sentalloy heavy for force of 50 gm<br>from molar band on 16, ligated to a bonded bracket on 14 or 15<br>-TPA and Anterior bite block  | 50                                                            | Varied<br>from 1-7<br>wks | weekly |
| Kurol <i>et al.</i> 1996    | N=112<br>human<br>premolars<br>(13.8y)           | Buccal movement of #14 or 15<br>Fixed appliance -Sectional arch<br>.018" sentalloy heavy for force of 50 gm<br>from molar band on 16, ligated to a bonded bracket on 14 or 15<br>- TPA and Anterior bite block | 50                                                            | Varied<br>from 1-7<br>wks | weekly |
| Acar <i>et al.</i> 1999     | N= 22<br>human<br>first<br>premolars<br>(15-23y) | Tipping of premolar<br>Fixed appliance-.017*.025" SS utility<br>arches -Button is bonded to buccal<br>surface of premolar<br>-Elastic is applied from button to utility<br>arch                                | 100 gm<br>(Continuous<br>force and<br>discontinuous<br>force) | 9 wks                     | weekly |

2.3 ROOT CEMENTUM

2.3.1 CHARACTERISTICS

Cementum (from the Latin *caementum*, “quarried stone” i.e. chips of stone used in making mortar) is a specialized mineralized tissue covering the root surface and has many features in common with bone tissue (Ten Cate 1998; Thilander *et al.*, 2000). It covers the roots of the teeth and is firmly “cemented ” to the dentine of the root.

Historically, cementum on the roots of human teeth was first examined in detail by Frankel 1835 and Rachkow 1835 and by the classic histologist Anders Adolf Retzius in 1837 (Schroeder, 1986).



Cementum has been described as a non-uniform mineralised connective tissue. Several distinctly different cementum varieties are found on human teeth. They differ with respect to structure, location, function, rate of formation, clinical composition and degree of mineralization. Cementum is the least understood of all the hard tissues. In fully formed and functioning teeth, cementum is firmly attached to the radicular dentin and covers the entire surface of the root. In addition, small-localized areas of enamel close to the cemento-enamel junction are frequently covered with a particular type of cementum. Cementum increases in thickness towards the apex and may extend partially into the apical foramen.

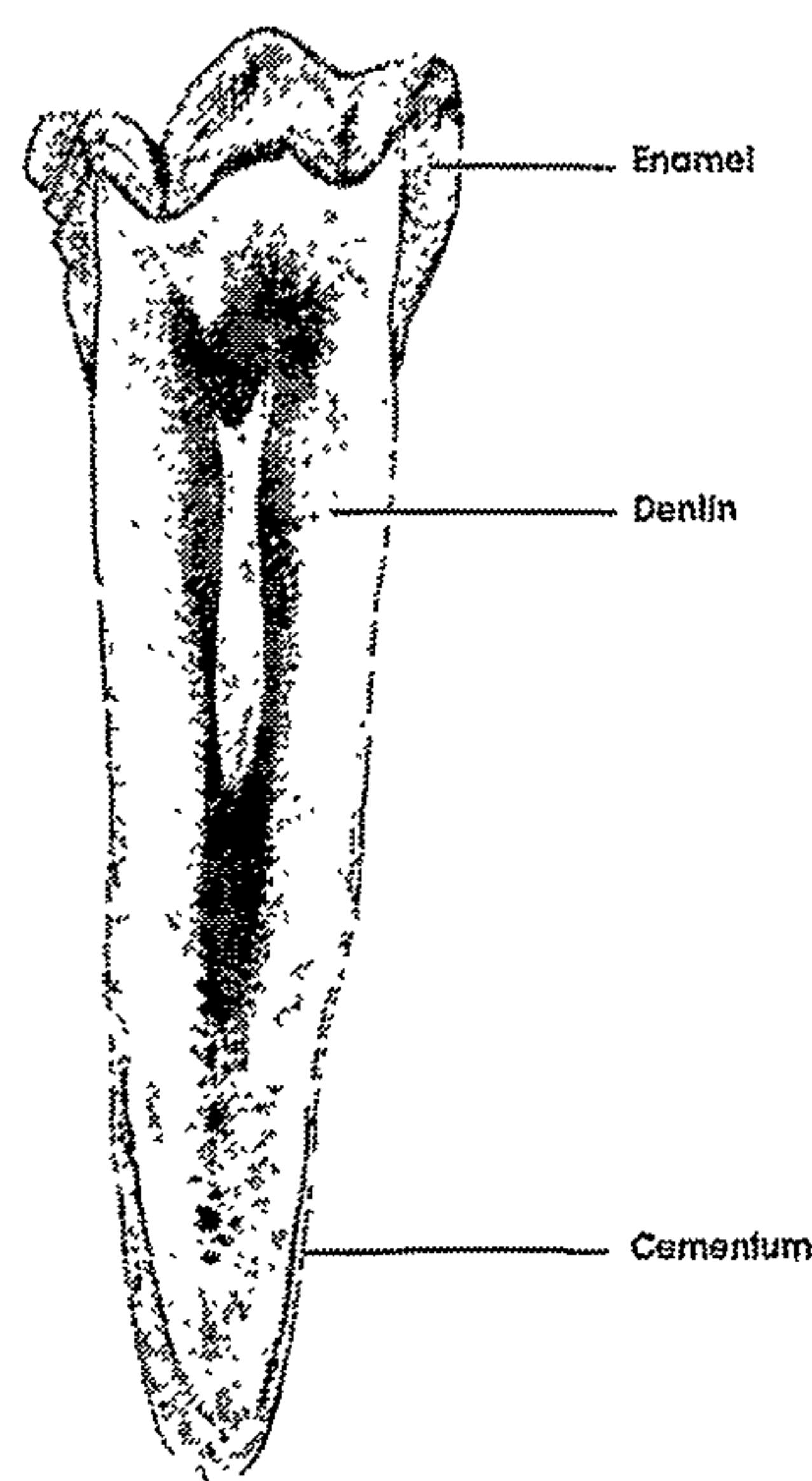


**Figure 2-2.** Ground section of a premolar showing the distribution of cementum around the root. Increasing amounts of cementum occur around the apex (*From Ten Cate AR: Oral Histology; Development, Structure, and Function, 5th edition; 1998*).



Cementum is a component of the tooth itself, but belongs functionally to the dental attachment apparatus, that is, the periodontium (Bosshardt and Selvig, 1997). One of the main functions of cementum is to provide means of functional tooth support. Cementum anchors the principal collagen fibers of the periodontal ligament to the root surface. Besides its indispensable role in tooth attachment to the surrounding alveolar bone, root cementum has important adaptive and reparative functions. The highly responsive features of cementum are crucial for maintaining occlusal relationship and for the integrity of the root surface and its function in tooth support.

Cementum attaches the PDL fibers to the root and contributes to the process of repair after damage to the root surface (i.e., orthodontic tooth movement). Cementum that is formed during the development and eruptive adjustment of the tooth is "Primary Cementum" (Thoma and Goldman, 1939). Primary cementum is essentially hyaline and the course of Sharpey's fibers can be seen distinctly. It does not have cellular elements and is in immediate contact with the dentine, covering almost its entire surface (Held, 1951).

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

Excess apposition of secondary cementum is referred to as hypercementosis. Ten Cate (1998) reported that secondary cementum overlaid primary cementum and may be either cellular or acellular.



Cementum has been described as “bonelike” structure (Ten Cate, 1998). However, unlike bone, cementum contains no blood vessels, has no innervation, does not undergo physiologic remodeling, but continues to grow in thickness throughout life. The cementum is considerably more pronounced in the apical portion of the root than in the cervical portion (Figure 2-2).

### 2.3.2 FORMATION OF CEMENTUM

Cementum formation on the roots of human teeth continues throughout life unless disturbed by periapical or periodontal pathology (Bosshardt and Selvig, 1997). A straight-line relationship between the thickness of cementum and the age of the tooth has been reported, with an average thickness of 0.1 mm at age 20 years to 0.2 mm at age 55 years (Zander and Hurzeler, 1958).

More cementum is formed apically than cervically. In addition, cementum thickness shows characteristic variations among tooth groups and tooth surface (Bosshardt, 1993; Solheim, 1990). There is a tendency for cementum to reduce root surface concavities. Thus, thicker layers of cementum may form in root surface grooves and in the furcations of multirrooted teeth. Also, great variations in width of incremental layers indicate that the rate of cementum formation may vary from time to time.

Azaz *et al.*, 1974 reported that nonfunctioning, impacted teeth generally appear to have thicker cementum than functioning teeth, and the structural architecture is different. This indicated that occlusal forces were not necessary to stimulate cementum deposition. In posterior teeth in the human, cementum is markedly thicker on the distal than on the mesial root surface, indicating a relationship to mesial drift (Dastmalchi *et al.*, 1990). Cementum is thicker in areas exposed to tensional forces compared with the pressure side of the root surface of teeth undergoing orthodontic



tooth movement in rhesus monkeys (Polson *et al.*, 1984). This finding indicated that cementum had the potential to be dynamically responsive and that its growth may be stimulated by tensional forces (Dastmalchi *et al.*, 1990).

2.3.3    **STRUCTURE AND CLASSIFICATION OF CEMENTUM**

Cementum has been classified into several types depending on the factors, which were taken into consideration (Table II-b). However, it has been widely accepted that there were two types of cementum, acellular and cellular. This classification is simple, and useful but it ignores the most important variation in the structure of cementum, which is the composition of matrix.

**Table II-b**   Classification of cementum

| Factors                             | Types                                                                                                                                                                                                                                                                                               |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Time of formation                   | <ul style="list-style-type: none"><li>• <i>Primary</i></li><li>• <i>Secondary</i></li></ul>                                                                                                                                                                                                         |
| Presence of cells within its matrix | <ul style="list-style-type: none"><li>• <i>Acellular</i></li><li>• <i>Cellular</i></li></ul>                                                                                                                                                                                                        |
| Fibrillar component of cementum     | <ul style="list-style-type: none"><li>• <i>Afibrillar</i></li><li>• <i>Intrinsic</i> fibers resulting from cementoblast activity</li><li>• <i>Extrinsic</i> fibers resulting from the incorporation of periodontal ligament fibers</li><li>• <i>Mixed fiber (Extrinsic and intrinsic)</i></li></ul> |



Secondary cementum differs from primary cementum in several points.

1. Structural differences in that the cells are incorporated into the matrix of secondary cementum.
2. Phenotypes of cells are different. This is shown by a monoclonal antibody (E11), which stained the cementoblasts and cementocytes of cellular cementum. Cells lining the surface of primary cementum do not stain for this antibody.
3. Developmental origin: The origin of primary cementoblasts is from dental follicle whereas the cells associated with the development of cellular or secondary cementum are derived from nonfollicular sources.

Ten Cate (1998) described the following types of cementum:

- 2.3.4.1 Primary Acellular Intrinsic Fiber Cementum
- 2.3.4.2 Primary Acellular Extrinsic Fiber Cementum
- 2.3.4.3 Secondary Cellular Intrinsic Fiber Cementum
- 2.3.4.4 Secondary Cellular Mixed Fiber Cementum
- 2.3.4.5 Acellular Afibrillar Cementum

Two other types of cementum have been named, depending on location and patterning, namely, intermediate and cellular mixed stratified cementum.

#### 2.3.3.1 *Primary Acellular Intrinsic Fiber Cementum (PAIFC)*

This type of cementum has not been previously classified and was documents as primary extrinsic fiber cementum, which is improper definition as the collagenous matrix of the first-formed cementum is the result of cementoblast activity and is elaborated before the periodontal ligament (PDL) forms. From this reason, the



collagen must be considered as intrinsic. Its fibrous fringe becomes connected to the PDL fiber bundles. This type of cementum has thickness of 15-20  $\mu\text{m}$ .

#### 2.3.3.2 *Primary Acellular Extrinsic Fiber Cementum (PAEFC)*

Once the PDL fiber bundles are connected to the fibrous fringe bundles of the PAIFC, further deposition of mineral in bundles results in the formation of acellular extrinsic fiber cementum.

PAEFC is composed almost entirely of densely packed bundles of Sharpey's fibers (30,000/ $\text{mm}^2$ ) and lacks any cells (Schroeder, 1986). This type of cementum functions as the principal tissue of attachment, which extends from the cervical margin of the tooth and covers at least two third of the root. Its thickness ranges between about 30  $\mu\text{m}$  and 230  $\mu\text{m}$ . Under the light microscope, PAEFC seems to be relatively structureless. Two sets of faint striations can be seen; one running parallel to the root surface indicates incremental deposition, and the other at right angles to it indicates the inserted mineralized PDL collagen fibers (Ten Cate, 1998).



**Figure 2-3.** Electron Micrograph depicting the tissues involved in tooth attachment.

Beginning at the right is mantle dentine (D), the dentin-cementum junction (DCJ) in the form of the hyaline layer, acellular intrinsic fiber cementum (AIFC), and



finally acellular extrinsic fiber cementum (AEFC) into which the fibers of PDL insert (*From Bosshardt and Schroeder, Cell Tissue Res, 1991*).

#### 2.3.3.3 *Secondary Cellular Intrinsic Fiber Cementum (SCIFC)*

This type of cementum is similar to PAIFC in that they both consist of intrinsic fibers. SCIFC contains cementocytes, intrinsic collagen fibers, and a layer of cementoid. It is confined to the apical and interradicular regions of the tooth. SCIFC is involved in repair process of root resorption. It only functions as tooth attachment in a minor way because this form of cementum is usually absent from incisor and canine teeth.

#### 2.3.3.4 *Secondary Cellular Mixed Fiber Cementum (SCMFC)*

This type of cementum was developed after further deposition of cellular cementum incorporates ligament fiber bundles of the PDL. Its extent and distribution are extremely variable, which reflects its function as an adaptive tissue.

SCMFC consists of cementocytes housed in lacunae, their laminated structure, and the presence of cementoid on its surface. Cementocytes are often widely dispersed. The fine-fibered, densely packed intrinsic fibers running parallel to the root surface and the larger, incorporated extrinsic fibers of the PDL running at right angles to the root surface. The intrinsic fibers are uniformly mineralized, whereas the extrinsic fiber bundles are variably mineralized, with many having a central unmineralized core.

#### 2.3.3.5 *Acellular Afibrillar Cementum (AAC)*

This type consists only of a mineralized ground substance. It contains neither cells nor ex- or intrinsic collagen fibers. It is found as coronal cementum covering the enamel surface and as part of AEFC and believed to be a product of cementoblasts. It plays no role in tooth attachment and should be regarded as a developmental anomaly formed



as the result of local disruptions in the reduced dental epithelium that allow follicular cells to come into contact with the enamel surface.

#### 2.3.3.6 *Intermediate Cementum (IC)*

Intermediate cementum is a form of SCIFC, which was first introduced by Bencze in 1927 (Schroeder, 1986). It is designated as a peripheral, narrow layer including cellular remains, which is found between dentine and cellular root cementum in the apical half of the root. Blackwood (1957) concluded that IC was the result of an incomplete differentiation of the first layer of cementocytes. On the other hand, Osborn (1965) suggested that some odontoblasts which became entrapped in the developing dentine or remain on the outer surface of the growing root may later become incorporated in the primary cementum or grow abnormally in conjunction with cementoblasts form the intermediate cementum. IC is not involved in tooth attachment and has no functional significance (Ten Cate, 1998).

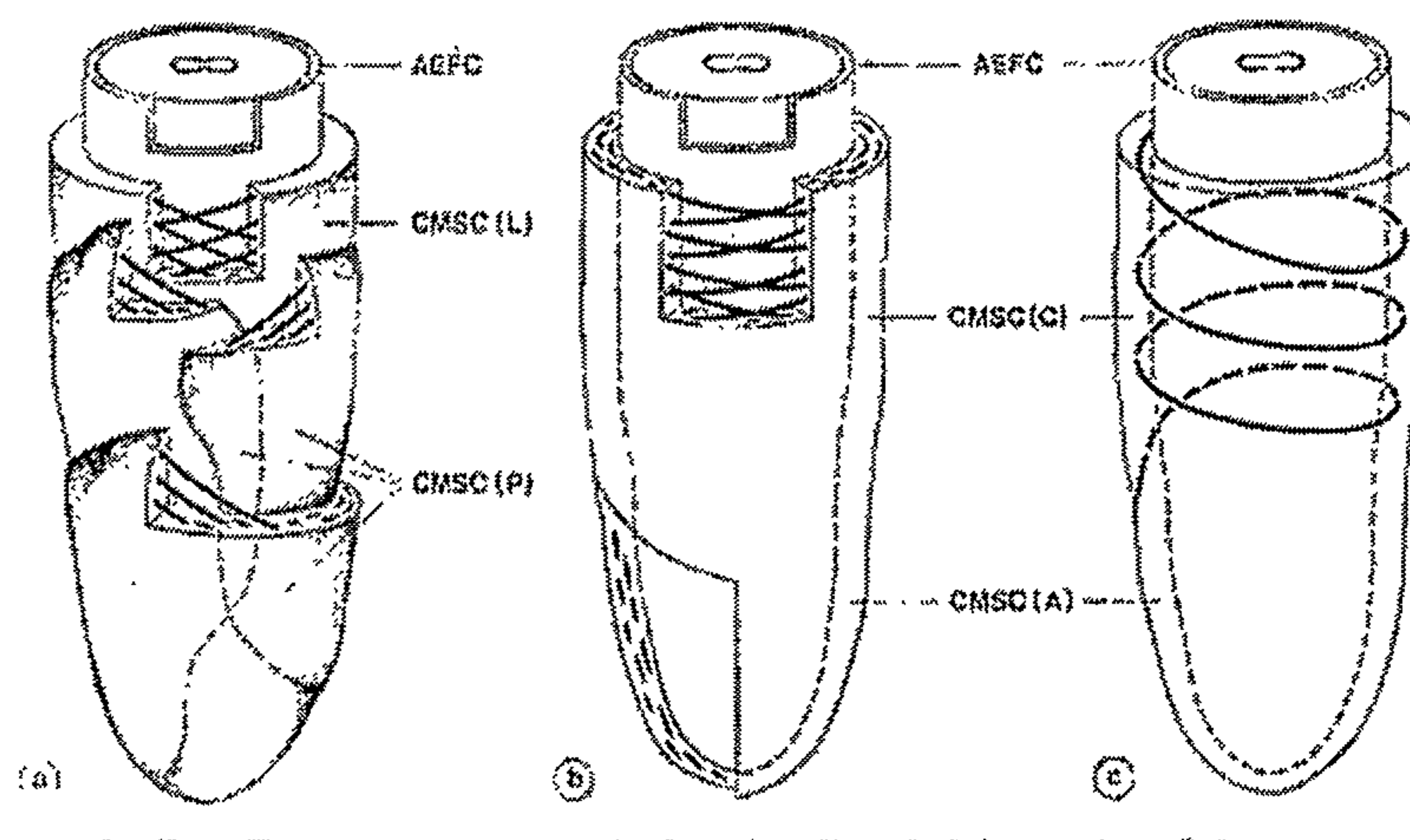


**Figure 2-4.** The orientation and course taken by intrinsic fibers of cellular, mixed stratified cementum (CMSC) in human permanent teeth, either erupted (a) or



retained and impacted (b,c). In the cervical region of erupted teeth (a), one to three layers of acellular extrinsic fiber cementum (AEFC) covering dentine reveal an exclusively radial fiber orientation. In middle-root and apical regions, erupted teeth show overlapping of CMSC, first with a lattice-like (L), later with parallel-fibered (P) structure, with the fiber bundles winding in counter-spirals around the root (a). In retained teeth, the middle root CMSC consists of circular fibers (C), winding in flat counter-spirals, while apically CMSC shows mostly axially (A) running fibers, originating as superficial terminations of fiber spirals (b,c) (*From Ten Cate AR: Oral Histology; Development, Structure, and Function, 5th edition; 1998*).

#### 2.3.3.7 Cellular Mixed Stratified Cementum (CMSC)

Cellular mixed stratified cementum consists of alternate layers of acellular extrinsic and cellular intrinsic fiber cementum. It is a coproduct of cementoblasts and fibroblasts. Its layers are very irregular and patchy. It is confined to the apical root portions and to the furcations. Its thickness varies between 100 and 1000  $\mu\text{m}$ . Given the possibility that acellular extrinsic cementum represents mineralization of ligament, this layered pattern may simply represent alternating mineralization occurring upon successive waves of cellular intrinsic fiber cementum deposited in response to adaptive needs.

### 2.3.4 BIOCHEMISTRY

Cementum is the least mineralized of the three dental hard tissue components (Cohen *et al.*, 1992; Neiders *et al.*, 1972; Selvig and Selvig, 1962). Difference in the proportional composition of the chemical constituents exist between the various cementum varieties. To about equal parts per volume, cementum is composed of water, organic matrix and mineral. On a **wet weight basis**, human cementum contains



65% inorganic material, 23% organic material and 12% water. By **volume**, the inorganic material comprises approximately 45% inorganic material, 33% organic and 22% water (Berkovitz *et al.*, 1992).

#### **2.3.4.1 Organic matrix**

**2.3.4.1.1 Collagens.** The organic matrix of cementum consists primarily of collagens. Like in bone and PDL, the two typical fibril-forming collagens type I and III are found in cementum. Biochemistry analyses of bovine (Birkedal-Hansen *et al.*, 1974; 1977) and human (Christner *et al.*, 1977) cementum have revealed that approximately 90% of the organic matrix is type I collagen, 5% type III collagen.

**2.3.4.1.2 Non-Collagenous proteins.** Cementum is rich in glycoconjugates, which represent either glycolipids, glycoprotein or proteoglycans, and harbors a variety of other proteins. Like in bone, the predominant noncollagenous proteins are bone sialoprotein and osteopontin. Bosshardt and Nanci, 1997 revealed, by using immunocytochemistry, that acellular afibrillar cementum and acellular extrinsic fiber cementum appear to contain much more of these two glycoproteins than cellular intrinsic fiber cementum.

Osteonectin is another glycosylated protein found in the extracellular matrix of mineralized tissues. An immunohistochemical study of human cementum showed that osteonectin is synthesized by acellular extrinsic fiber cementum- and cellular intrinsic fiber cementum- producing cementoblasts, cementocytes and fibroblasts (Reichert *et al.*, 1992). The other noncollagenous proteins, which are found in cementum, are fibronectin, tenascin, enamel-related proteins and osteocalcin.



#### 2.3.4.2 *Mineral component*

The *mineral component* in human cementum is hydroxyapatite  $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ , with small amounts of calcium phosphates. Transmission electron microscopy and electron diffraction analyses have shown that the mineral crystals are arranged with their crystallographic *c*-axis parallel to the long axis of the collagen fibril (Selvig and Selvig, 1962).

Acellular extrinsic fiber cementum appears more highly mineralized than cellular intrinsic fiber cementum and mixed stratified cementum.

Techniques employed to determine the extent of mineralisation and mineral composition of human cementum have included:

- Measurements of specific gravity
- X-ray densitometry
- Microhardness
- Chemical analysis
- Historadiography
- Electron probe microanalysis
- Scanning electron microscopy
- Energy dispersive x-ray analysis



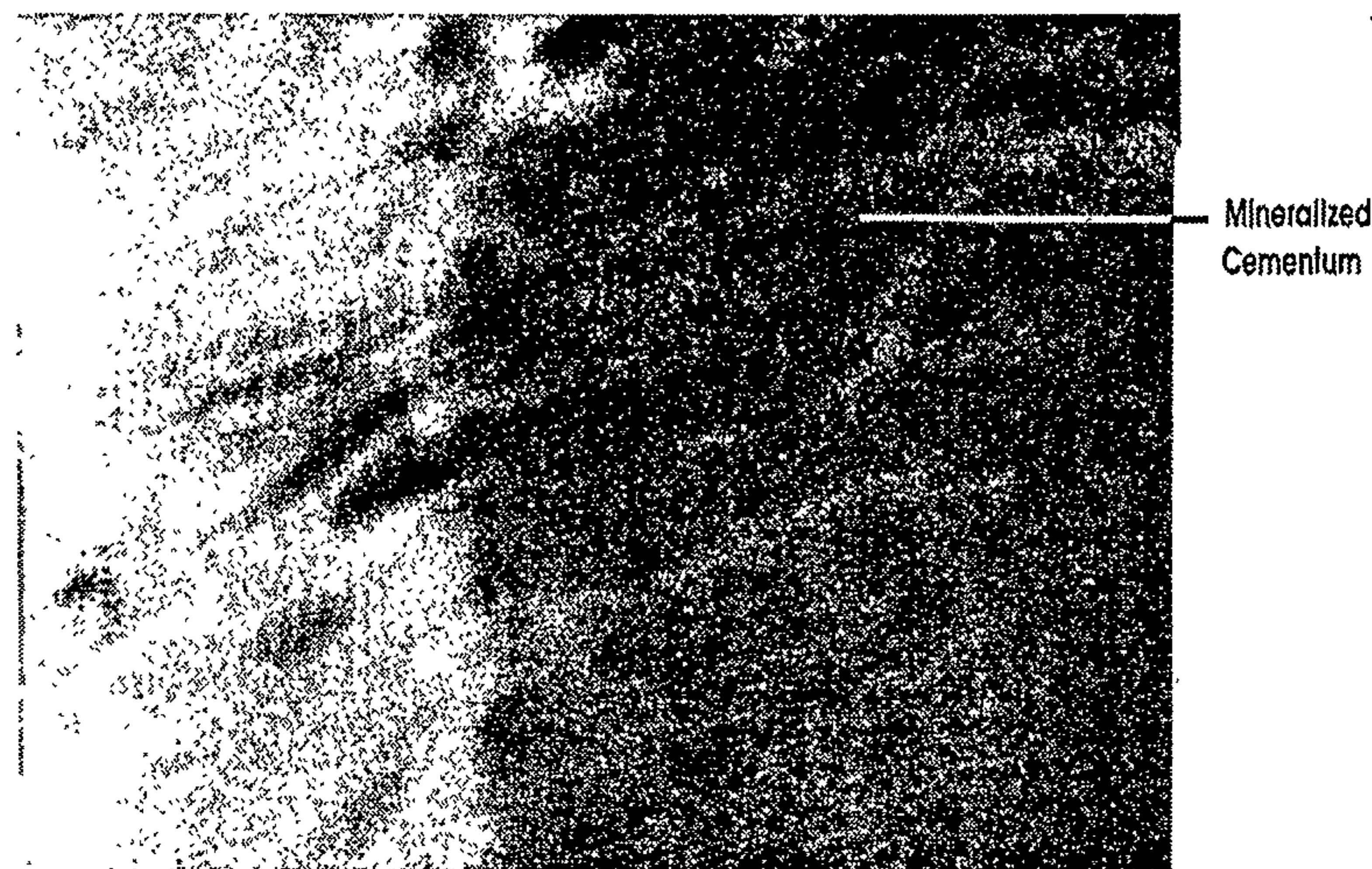


**Figure 2-5.** Electron Micrograph of the continued mineralization of cementum. Crystals are forming in collagen fibrils of the cementum matrix (*From Ten Cate AR: Oral Histology; Development, Structure, and Function. 5th edition; 1998*).

#### **2.3.4.3 Cellular Types**

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

##### **2.3.4.3.1 Cementoblasts**

Cementoblasts are cuboid in shape, about 8-12  $\mu\text{m}$  in diameter, similar to osteoblasts. They are found exclusively at the cementum-periodontal ligament interface. Their structure resembles cells actively synthesising proteins and polysaccharide-complexes (Bevelander and Nakahara, 1968; Jande and Belanger, 1970; Furseth and MjÖr, 1939). Their nucleus is euchromatin-rich, their cytoplasm strongly basophilic. They may



project a variable number of cytoplasmic processes and their actual shape depends on their position between collagen fibers (Schroeder 1986).

#### **2.3.4.3.2 Cementocytes**

Cementocytes are derived from cementoblasts and are enclosed in the product they secrete (Figures 2-6 and 2-7). Structurally and functionally, they resemble osteocytes. They vary in distribution and density in CMSC and CIFC. Young and mature cementocytes can be differentiated (Bevelander and Nakahara, 1968). The structure of young cementocytes is similar to that of cementoblasts. With increasing maturation, cementocytes decrease in size, but their lysosomal bodies and autophagic vacuoles increase in number. Cementocytes located deep in the cementum often show signs of disintegration and shrinkage. They also exhibit the structural signs of vital cells of variable metabolic activity (Furseth, 1969; 1970). Cementocytes are about 15  $\mu\text{m}$  in diameter and possess many long cytoplasmic processes up to 15  $\mu\text{m}$  in length. These processes project in all directions, but those approaching the cementum surface are longer and more numerous. Analogous to osteocytes, cementocytes can engage in "cementolytic" activity, which is parathyroid-hormone dependent and can respond to nutritional secondary hyperparathyroidism and may contribute to regulating calcium phosphate metabolism (Henrickson, 1968; Jande and Belanger, 1970).

#### **2.3.4.3.3 Fibroblasts and Cells of the Periodontal Ligament**

Berkovitz and Shore (1995) summarized that there are at least four major types of cells present i.e. connective tissue cells, epithelial cells, defense cells, and cells associated with neurovascular elements.



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

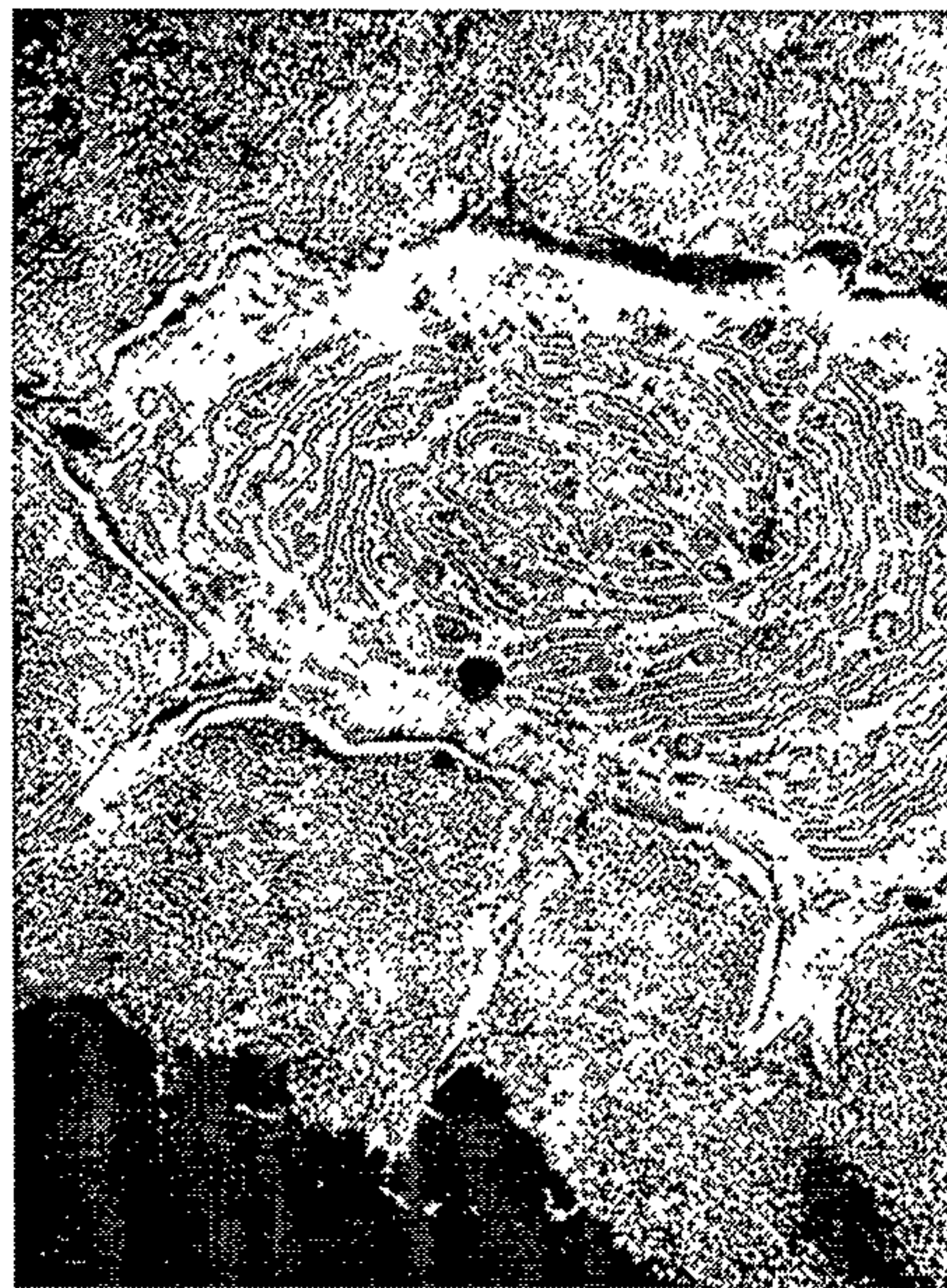


**Figure 2-6.** Cellular cementum formation. The cementoblast has embedded itself in the cementum matrix and thus become a cementocyte occupying a lacuna. The mineralization front is at bottom left (*From Furseth R: The fine structure of the cellular cementum of young human teeth. Arch Oral Biol 14:1147;1969*).



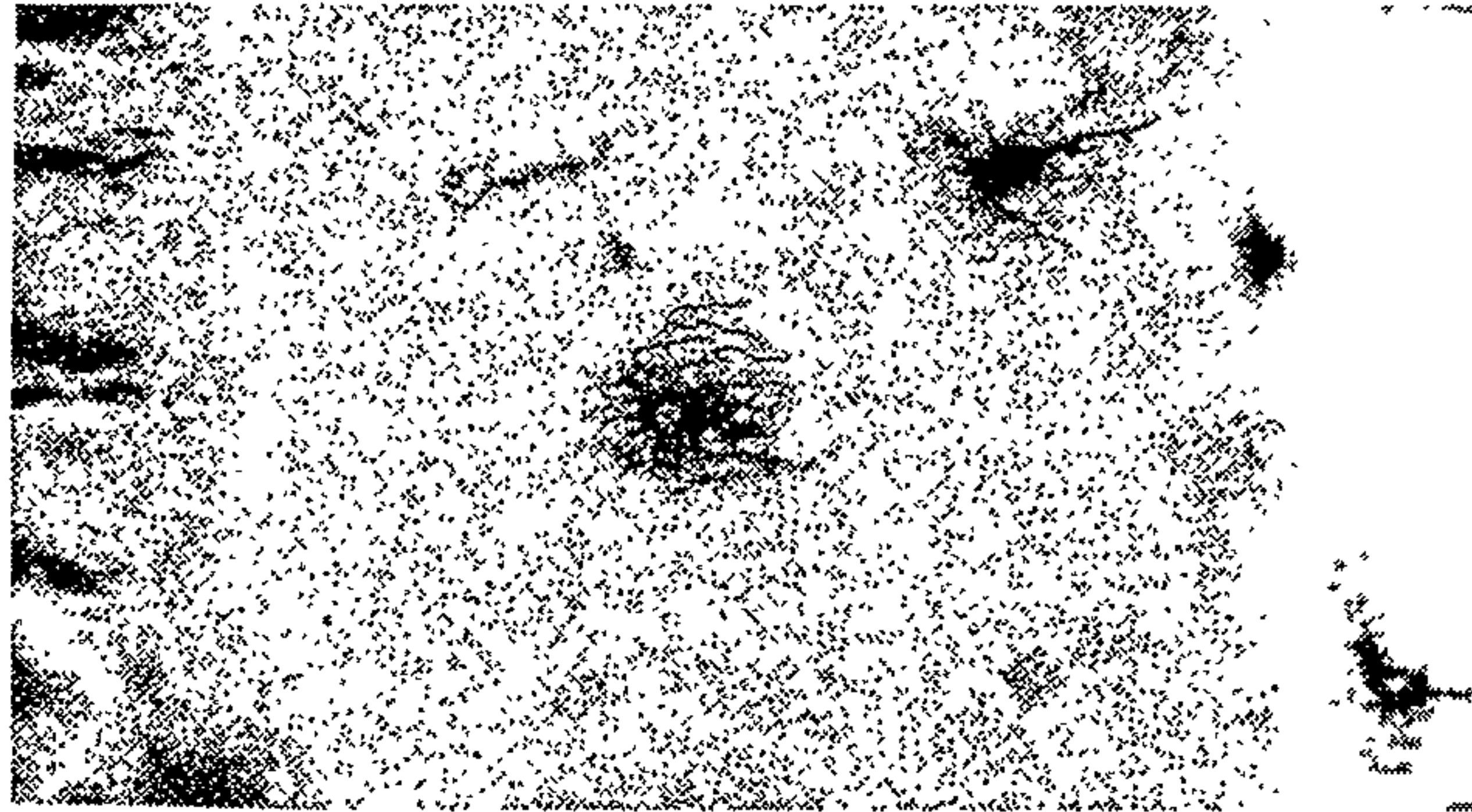


**Figure 2-7.** Cementocyte lacunae in ground section (*From Ten Cate AR: Oral Histology; Development, Structure, and Function. 5th edition; 1998*).

Fibroblasts are the primary cell type of PDL which functions as the maintenance of the collagen fibers and other components of connective tissues. Due to the dense fibrous nature of the PDL, fibroblasts appear as long, slender cells lying between and parallel to the collagen fibers (Mjor and Pindborg, 1973). In rat incisor ligament, fibroblasts occupy approximately 50% of the volume of the densely collagenous portions within the periodontal ligament (Shore and Berkovitz, 1979).

The cytoplasmic structure and composition of the fibroblasts demonstrate that their function is heavily orientated toward protein synthesis. These cells maintain the rapid turnover of extracellular ligament proteins (Rippin, 1976; 1978; Sodek, 1977).

Most of the dividing ligament cells are found in the paravascular location of the periodontal ligament. Under physiological conditions and during wound healing, fibroblasts in the periodontal ligament of mouse molars are replaced continuously by progenitor cells residing there (Gould *et al.*, 1980). From this site they migrate to the surfaces of bone and cementum (McCulloch and Melcher, 1983). Basdra *et al.*, 1996 also noted that human periodontal ligament fibroblasts exhibit in-vitro, phenotypic



characteristics, consistent with osteoblast-like cells. This suggests that such cells have the potential to differentiate into osteoblasts.

## 2.4 REPARATIVE POTENTIAL

Most external root resorption, once activated, is self-limiting. For this reason approximately 70% of all defects seen in old teeth are anatomically repaired (Henry and Weinmann, 1951 and Andreasen, 1988).

It has been hypothesized that all resorptions will be repaired once the cause of root resorption has ceased (Rygh, 1977 and Reitan, 1985). According to Brudvik *et al.*, (1994), if active force ends but passive stress of periodontal ligament remains through retention, resorption continues as long as necrotic tissue is close to the site of resorption. If force is reactivated while necrotic tissue persists near site, resorption is likely to continue (Reitan, 1972).

The duration of time of rest needed for repair of lacunae before reactivation of force is still unknown. Owman-Moll *et al.*, (1995) recorded the reparative process as early as during the first week of retention. Harry and Sims, 1982; Stenvik and Mjor, 1970 proposed that the process of repair occurred 35-70 days after force application was removed or was below optimal level. Brudvik and Rygh, (1995) showed that new mineralised cementum was observed on the resorbed root surface by 21 days. The healing process seemed to increase over time (Barber and Sims, 1981; Langford and Sims, 1982). Owman-Moll *et al.*, (1998) found that reparative cementum in the resorption cavities was seen significantly more often after 6-7 weeks of retention (82 percent) compared to 2 and 3 weeks (35 and 44 percent, respectively).



Vardimon *et al.* (1991) claimed that all resorptions would heal provided that the resorbed surface area did not exceed the unresorbed one. In fact, it has been noted that root resorption and repair with secondary cementum may occur simultaneously (Stenvik and Mjör, 1970; Barber and Sims, 1981; Harry and Sims, 1982).

Bosshardt (1994) and Bosshardt and Schroeder, (1994) have shown that two different repair matrices become attached to the resorbed root surface. Following the detachment of odontoclasts from the root surface, cementogenic cells repopulate the Howship's lacunae and attach the initial repair matrix to a thin decalcified layer of residual and exposed collagen fibrils. Two main cementum varieties are cellular intrinsic fibrillar cementum (CIFC) and acellular extrinsic fiber cementum (AEFC) (Bosshardt and Selvig, 1997; Schroeder, 1986; Henry and Weinman, 1951). The similarity of the initial formation of the two repair matrices with the initiation of AEFC and CIFC on the forming root indicated that repair cementogenesis recapitulates the events occurring during root development (Bosshardt and Selvig, 1997).

Owman-Moll and Kurol (1998) found that the repair process of root resorption was achieved by deposition of mainly CIFC. However, in the initial phase of healing, the AEFC was recorded. They observed that cellular cementum was formed when the repair process was fast and cells were captured in the repair tissue. Acellular cementum would then be associated with slow repair. Vardimon *et al.*, (1993) and Bosshardt (1994) confirmed that the initial reparative cementum was often of acellular type, but that the continued repair process of the resorption cavity occurred with rapidly formed cellular cementum.

The repair pattern of root resorption have been reported, proceeding either from the periphery of the resorption cavity (Brudvik and Rygh, 1995; Vardimon *et al.*, 1993) or



from the center of the patches outward (Barber and Sims, 1981). With the animal studies, Brudvik and Rygh, 1995; Vardimon *et al.*, 1993 claimed that fibroblast cells from the surrounding PDL played role of early repair of resorption lacunae. Owman-Moll and Kurol (1998) supported the latter concept. They reported that early repair started initially on the bottom of the resorption cavity, frequently covered by a thin layer of acellular cementum. Sometimes the reparative cementum had extended to one of the lateral walls, but never occurred on the lateral walls alone.

The repair process did not vary with the location or type of tissue, neither on the buccal or lingual side of the tooth nor in the cervical or apical parts of the root. However, the individual variations were great regarding the occurrence of repair of root resorption after elimination of the applied force (Owman-Moll and Kurol 1998).

## **2.5 PHYSICAL PROPERTIES OF HARD TISSUES**

### **2.5.1 BACKGROUND**

Base line physical properties of teeth are crucial for the knowledge of root resorption process. The data available has mostly been generated by conventional compressive and tensile tests. There are additional studies using other techniques such as bending tests and the results seemed consistent with the existing data. Data is available on a broad range of properties but tends to exhibit a large variation within each parameter.

Hardness testing is widely used to determine mechanical properties of materials. It is the non-destructive, simple process. It has been widely used to measure the surface properties of enamel and dentine in particular as the test is both easy to perform and



rapid to conduct. Specimen preparation is not time consuming (Waters 1980; Boyer 1987). Multiple tests on a small specimen are also possible. The test evaluates the resistance to deformation of a material subjected to a point force. This test can also be applied with a more instrumented testing system capable of obtaining a force-displacement relationship, and from such data a range of physical properties can be estimated (Poolthong, 1998).

There is also a correlation between the hardness and other material properties i.e. the yield strength and ultimate tensile strength (Van Noort, 1994; Ashby and Jones, 1996). It was found that the deeper into the material the indenter sinks, the softer is the material and the lower its yield strength. Moreover there is additional useful information that may be determined from the indentation tests, such as the elastic modulus.

### **2.5.2 ELASTICITY (ELASTIC MODULUS)**

Measurement of elasticity of materials is described by the term of elastic modulus or Young's modulus. This elastic modulus as designated by the letter  $E$  measures the resistance of a material to elastic deformation. The elastic modulus is related to the interatomic bonding forces within the materials and usually is the same when the material is subjected to tension or compression (Craig, 1993).

As the elastic modulus represents the ratio of the elastic stress to the elastic strain, it follows that the lower the strain for a given stress, the greater the value of the modulus. Elastic modulus is calculated from the equation:



$$E^* = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\epsilon}$$

Low modulus materials are floppy and will get larger deflections if loaded; whilst the rigid materials have higher modulus. In the case of two bodies in contact, the effective elastic modulus ( $E^*$ ) is determined by the properties of both materials. It is measured in GPa and represented by the equation:

$$1/E^* = 1 - \nu_m^2 / E_m + 1 - \nu_i^2 / E_i$$

where  $\nu_m$  and  $E_m$  are Poisson's ratio and elastic modulus of the material and  $\nu_i$  and  $E_i$  are Poisson's ratio and elastic modulus for the indenter.

Elastic modulus is given in unit of force per unit area, typically, Gigapascals (GPa). This property is indirectly related to other mechanical properties (Phillips, 1996).

### 2.5.3 HARDNESS

Hardness can be described as the ability of a material to resist permanent surface indentation or scratching. It therefore, indicates resistance to abrasion or wear (Craig, 1993; Van Noort, 1994 and Askeland, 1996). Hardness is not a fundamental property of a material, so its values vary depending upon the test method (Hodge, 1936). Hardness values are arbitrary and there is no absolute standard of hardness. Hardness has no quantitative value except in terms of a given load applied in relation to the



contact area generated in a specified manner for a specific duration and a specified penetration shape (Boyer, 1987).

Hodge and McKay (1933) defined that hardness was a measure of the resistance a material offers to:

1. Scratching
2. Indentation or Penetration
3. Elastic impact
4. Cutting
5. Permanent deformation.

There is also a correlation between hardness and other material properties, i.e. the yield strength and ultimate tensile strength (Eisenstadt, 1971; Van Noort, 1994 and Ashby and Jones, 1996). It was found that the deeper into the material the indenter sinks, the softer is the material and the lower its yield strength.

Hardness is a cheap and relatively simple means of acquiring information on the mechanical properties of materials (Boyer, 1987), such as cementum. The unit of hardness is pressure: GPa.

#### *2.5.3.1 Scratch Testing*

Hodge and McKay (1933) reported that Pickerili, using a scratch method, showed a 25% difference in the hardness of native Maori, sclerotic and malacotic teeth.

The scratch methods are gross allowing only qualitative assessment and permit only a few determinations on one sample when compared to more modern test methodologies (Richardson and Warner, 1945). It is generally agreed that "scratch" techniques are



not as simple as indentation tests and the results are of no greater value than those given by the indentation tests (Richardson and Warner, 1945).

Before one body can scratch another it must first penetrate the surface, and therefore the resistance of the surface to indentation is a factor in abrasion. Abrasion resistance is not necessarily proportional to resistance to indentation. Other factors such as ductility and the degree of elasticity of the material may be important (Richardson and Warner, 1945).

#### *2.5.3.2 Indentation Testing*

The indentation test is usually known as a method for hardness determination, which is widely used in quality control or for comparison of materials (Askeland, 1996). It is commonly measured by placing an indenter, which is much harder than the specimen, in contact with the smooth surface of the material being tested. A known load is placed upon the indenter. The hardness is then determined as the ratio of the load and the surface area or the depth of the permanent imprint, depended upon the type of the test and the geometry of the indentation used (Eisenstadt, 1971 and Mencik, 1996).

Indentation methods are often non-destructive to the component tested because they cause only small and negligible surface damage. Unlike the tensile and flexural tests, the indentation tests do not need special samples (Askeland, 1996). There is additional useful information that may be determined from indentation tests such as Elastic modulus of the material.

In static indentation tests, a load is applied to a conical or pyramidal indenter and the relationship is adopted with the applied load and the relationship of load to the area or the depth of indentation is then calculated and reported. The indentation tests



commonly used are Brinell, Knoop, Rockwell and Vickers and they are employed in different circumstances depending on the test materials.

Indentation testing can be classified into two categories. The first is macro-indentation where loads greater than 1 kg are applied. The second are micro-indentation tests that use loads less than 1kg (Boyer, 1987).

Micro-indentation hardness testing is mainly used to measure the surface properties of the material. To measure the physical properties of smaller particle specimens without macro-indentation “damage” to the sample requires the use of micro-indentation techniques (Willems *et al.*, 1993). These systems allow very small loads to be applied to samples with less than 1  $\mu\text{m}$  of penetration produced. It has been recognized as simple, reproducible and relatively non-destructive in relation to other mechanical testing (Boyer, 1987). Therefore, various standardized procedures for testing have been developed. The general procedure for hardness testing is to apply a standardized force or weight at the penetrating point through an indenter. The symmetrically shaped residual indentation is measured by microscopy for its depth, area or width depending on which testing method is being used. Depending upon the test, the area may be the surface area created under load or in other tests it may be the projected area. For a standardized load, the indentation dimensions are then related to hardness values, which may be calculated or read directly from tabulations in instruction manuals provided with the instrument.

Micro-indentation tests are commonly used in testing dental materials (Willems *et al.*, 1993). Weaver (1966) suggests no firm definition of microhardness exists but it is generally agreed that impressions of less than thirty microns in diameter, made with a load of less than 200 g, should be included in the testing range of microhardness. The



two most common micro-indentation tests for teeth are the Knoop and Vickers micro-indentation tests (Ryge *et al.*, 1961).

Comparison of different materials should be carried out by the same hardness system under similar conditions of size and shape of an indenter, duration of indentation and applied force. This stipulation arises because hardness depends on the stress distribution of the indenter, the elastic modulus of the material, the strain hardening capacity, the friction between indenter and specimen, and the work hardening produced by the indentation process itself (Tabor 1986; Vitovec 1986). Hardness also exhibits load dependence and can be affected by strain rate (Doerner and Nix, 1986). The structure of the test material may influence the hardness. Few materials are completely homogeneous. They usually contain grain boundaries and particles of different composition. Defects such as microcracks and voids often exist (CSIRO, 2000). The size (radius) of the indenter is then crucial and may give different result from the same tested specimen. That is, small indenters would measure the various individual regions whereas large indenters tend to average over many different areas. As a result, it is virtually impossible to convert from one hardness scale to another (Poolthong, 1998). Therefore, two different materials may be of the same measured hardness on one scale but of vastly different measured hardness when a different weight and/or indenter are employed. In general, hardness can be an index of mechanical strength (i.e. harder materials are usually stronger unless they are very brittle). In the clinical situation a hard material can scratch, abrade and wear away opposed softer material.

#### **2.5.3.2.1 Brinell Hardness Test**

Of the static indentation tests the best known and most widely used is that devised by Swedish scientist, Brinell (Figure 2-8). The Brinell system uses a steel or tungsten



carbide ball typically 1.6 mm in diameter (Figure 2-9a). It is commonly used in dentistry for metallic materials but not for teeth. The area of indentation is determined and the result is reported as Brinell Hardness Number (BHN). The BHN is a ratio of the load applied to the surface area of the indentation obtained. The formula for BHN is as follows:

$$\text{BHN} = \frac{P}{\pi D \left( \frac{D - \sqrt{D^2 - d^2}}{2} \right)}$$

where  $P$  is the load applied in kg,  $D$  is the diameter of the ball in mm and  $d$  is the diameter of the indentation in mm. The unit for BHN is  $\text{kg/mm}^2$  (Boyer, 1987; Askeland, 1996). The size of the ball indenter is unsuitable for a small area characterization.

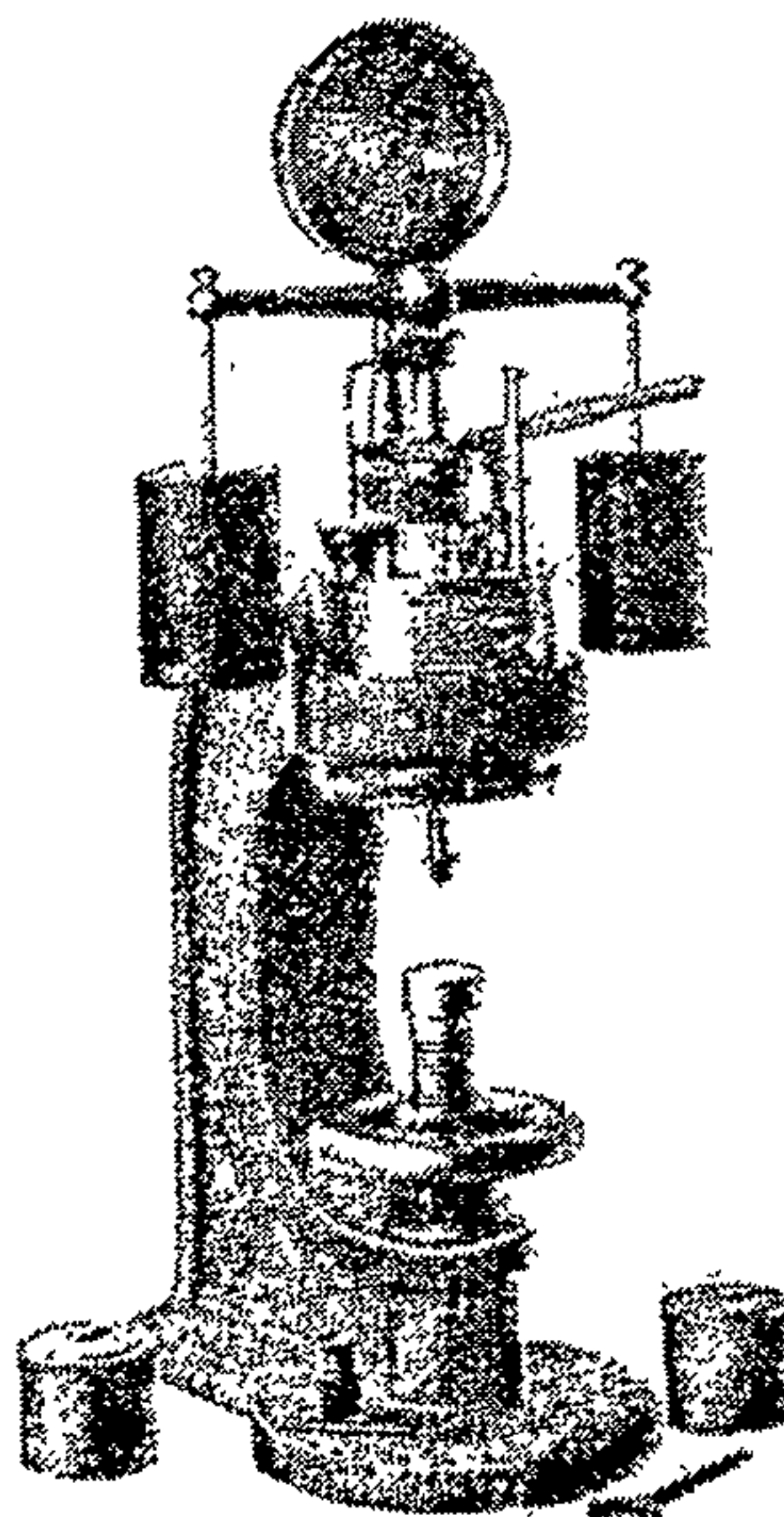


**Figure 2-8. Brinell Hardness Tester**

*(From Hodge HC. Hardness Tests on Teeth. J Dent Res. 1936;15:271-9)*



### 2.5.3.2.2 Vickers Hardness Test

The Vickers test uses a 136-degree diamond pyramid indenter, which produces a square residual indentation impression. The 136-degree angle diamond was chosen to approximate the effective contact angles of a Brinell hardness test with a spherical tipped indenter (Figure 2-9b). The resultant diagonals are measured and a Vickers Hardness Number (VHN) is then reported. The Vickers indenter appears to penetrate deeper than the Knoop indenter for the same load and thus it is less sensitive to the surface conditions. However, the Vickers indenter has small diagonal length and is prone to error from optical measurement (Boyer, 1987).

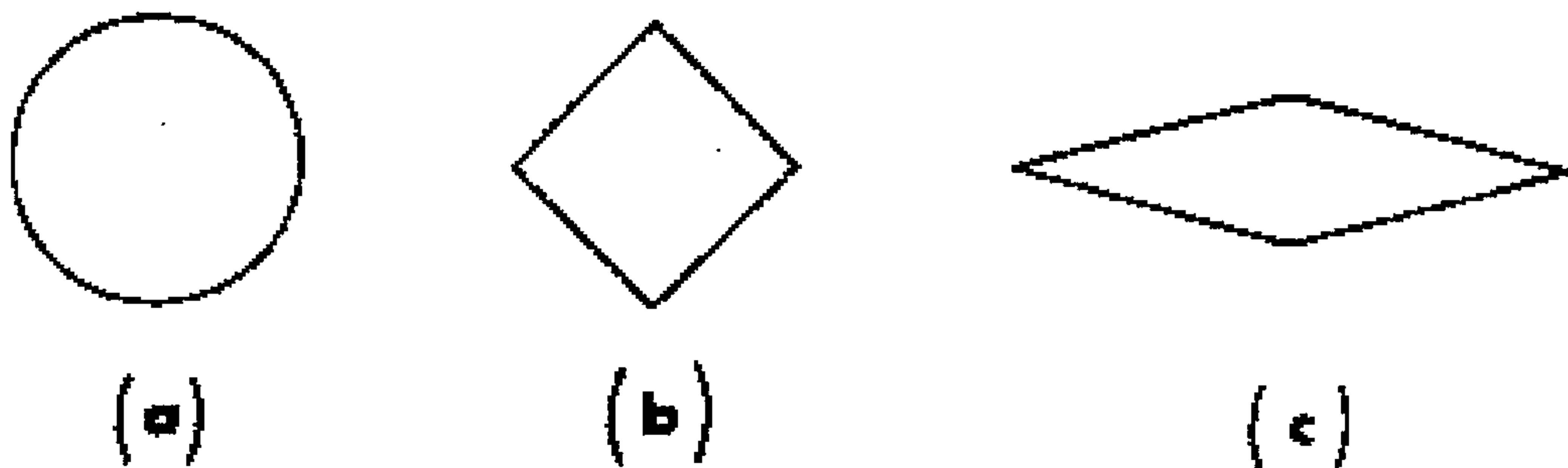


**Figure 2-9.** Shape of indentations produced by hardness testers.

(a) Brinell (b) Vickers (c) Knoop

The VHN is the ratio of the load applied to the surface area of the indentation calculated from the following formula:

$$\text{VHN} = \frac{2P \sin(\theta/2)}{d^2}$$



where  $P$  is the load applied,  $d$  is the average length of the two diagonals and  $\theta$  is 136. The unit for VHN is  $\text{kg/mm}^2$  (Boyer, 1987; Askeland, 1996).

The Vickers hardness test is useful where a small area and a hard material are being tested. The VHN is calculated from the indentation surface area under load determined from the known indenter geometry and assuming the diagonal of contact does not change upon unloading.

#### **2.5.3.2.3 Knoop Test**

In 1938, Frederick Knoop and associates at the National Bureau of Standards, U.S.A., developed a new form of pyramidal diamond indenter, which has overcome many of the objections raised against the Vickers type indenter for micro-hardness testing (Richardson and Warner, 1945). The indenter is a regular pyramid standing on a rhombic base (Richardson and Warner, 1945). It produced an indentation with one diagonal approximately seven times the length of the other. Knoop hardness test uses a diamond pyramidal indenter. The indenter produces a rhomboid shape residual indentation and the dimension of the major axis is measured (Figure 2-9c). The lengths of the major axis diagonals are measured and reported as the Knoop Hardness Numbers (KHN). The KHN is the ratio of the load applied to the area of the indentation calculated from the following formula.

$$\text{KHN} = P/C l^2$$

where  $P$  is the load applied,  $C$  is a constant relating  $l$  to the projecting area of the indentation.  $l$  is the length of the long diagonal of the indentation. The unit for KHN



is  $\text{kg/mm}^2$  (Boyer, 1987; Askeland, 1996). The loads used in micro-hardness tests are generally within the range 0.1 to 1.0 kg.

The depth of the standard Knoop indentation is only one-thirtieth the length of the longer diagonal, which means that in the average test the depth of penetration is extremely small. This makes this method particularly valuable for studying thin sections, films or platings. It certainly gives a more accurate indication of the surface hardness of a material than either the Brinell or Vickers test (Richardson and Warner, 1945).

It has been found that the Knoop-type indenter can be used to measure the hardness of brittle materials like glass. Provided caution is taken during the application and removal of the load, very little, if any, cracking or shattering takes place (Richardson and Warner, 1945).

#### *The Firth Hardometer Test* (Figure 2-10)

It is a similar instrument to the Brinell Hardness Tester but includes a microscope for measuring the impression (Hodge, 1936).



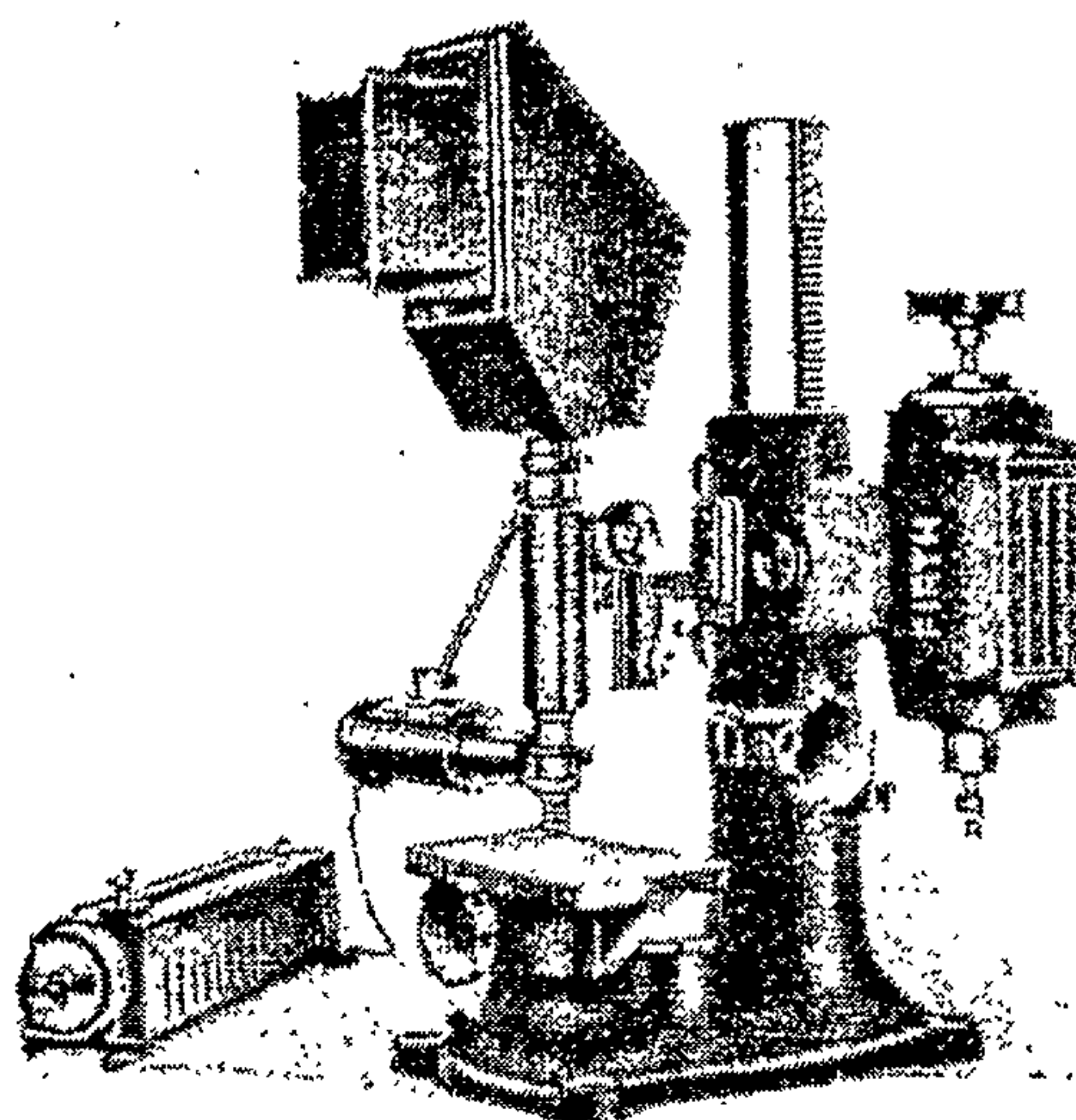


**Figure 2-10.** Firth Hardometer

*(From Hodge HC. Hardness Tests on Teeth. J Dent Res. 1936;15:271-9)*

*The Rockwell Hardness Tester* (Figure 2-11) embodies the principle of the Brinell Tester, but uses smaller loads and offers an alternative between a conical diamond and a steel ball for the impression. A load, through a lever system, of 100 kgs is used with the steel ball or 150 kg with the conical diamond-head (Hodge, 1936).

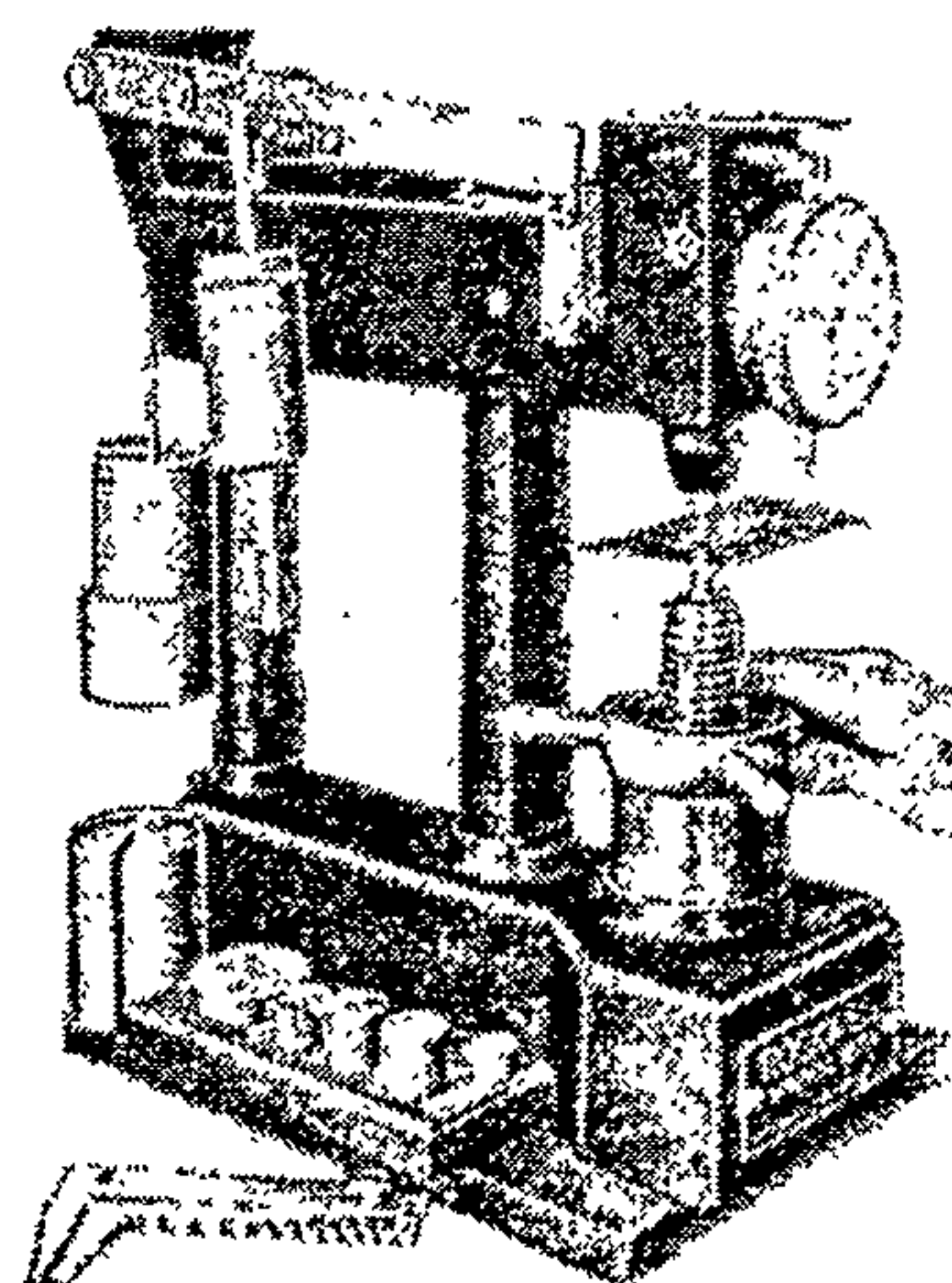


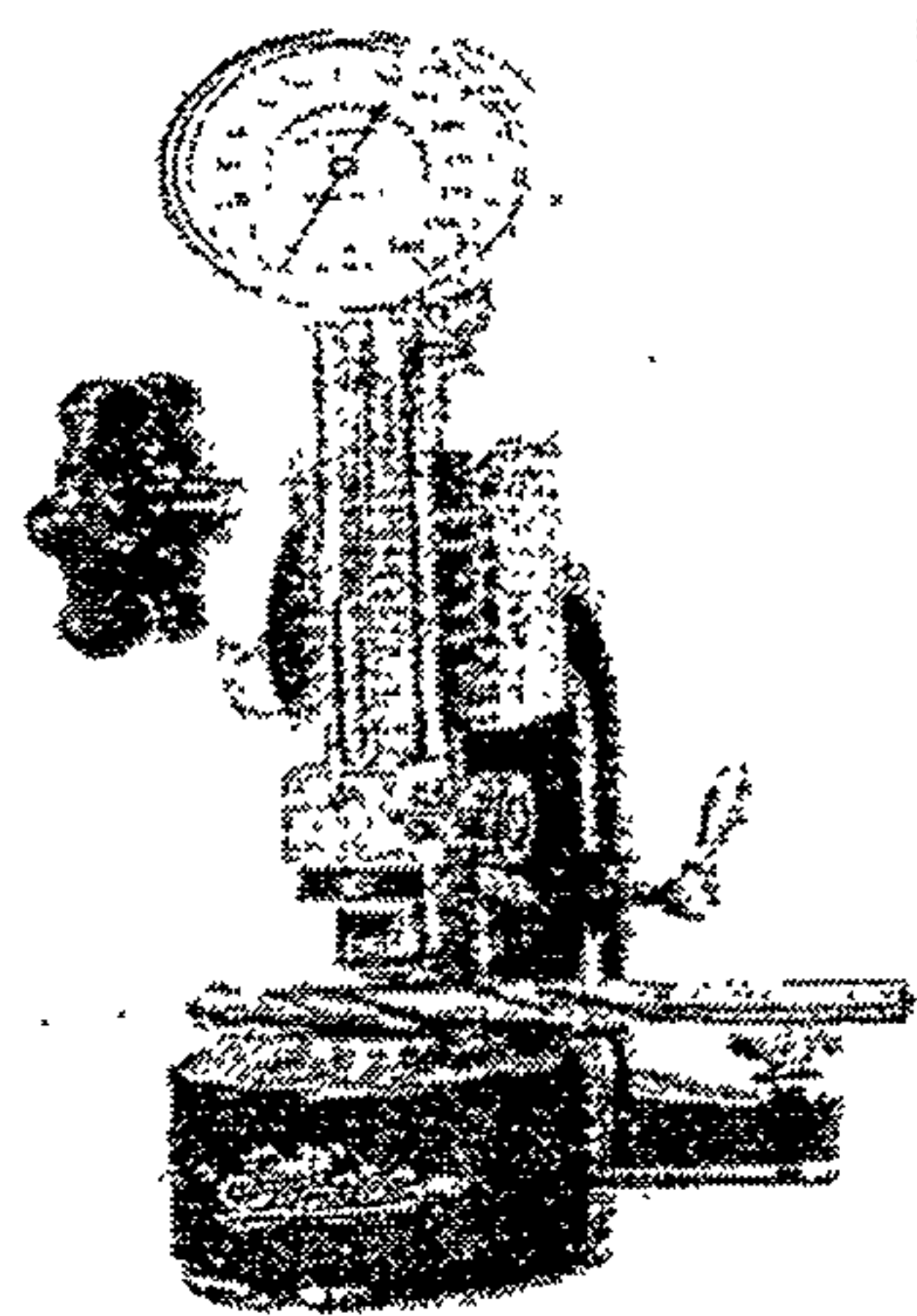
FIG. 4



**Figure 2-11. Rockwell Hardness Tester**

*(From Hodge HC. Hardness Tests on Teeth. J Dent Res. 1936;15:271-9)*

The *Shore Scleroscope Hardness Tester* (Figure 2-12) operates by dropping a tiny hammer on the surface to be tested, and measuring the height of its rebound (Hodge, 1936).

**Figure 2-12. Shore Scleroscope**

*(From Hodge HC. Hardness Tests on Teeth. J Dent Res. 1936;15:271-9)*

The *Monotron Hardness Tester* has a dial which indicates the load necessary to push a steel ball a given, constant distance into the material being tested. The hardness is taken as the load in kilograms necessary to push the steel ball of diameter 0.0018 inch (0.045 mm) into the test piece (Hodge, 1936).



The *Herbert Pendulum Hardness Tester* makes use of the speed of a swinging pendulum weight. Essentially it consists of a weighted, inverted pendulum supported on a ball of steel or on a diamond or ruby cone. The time in seconds required for ten complete swings through a small arc is recorded as the time-hardness number (Hodge, 1936).

## **2.6 ULTRA MICRO-INDENTATION SYSTEM (UMIS)**

### **2.6.1 DEVELOPMENT OF AN ULTRA MICRO-INDENTATION HARDNESS TEST**

Surface coating technology has become very important in terms of enhancing the surface properties of materials such as wear and corrosion resistance. With the use of advance technology, coatings may be only submicrometre thick, and hence the determination of their properties is impossible with the micro-indentation hardness test. When the smallest force of 1 N is applied, especially with a soft substrate material, it is impossible to limit the depth of penetration to within a micrometre when using Vickers or Knoop indenters. Moreover, a small force makes it very difficult to visualise the impression with optical measurement, and hence operator error is certainly inevitable and inaccurate results are possibly obtained (Doerner and Nix, 1986; Oliver and Pharr, 1992; Willems *et al.*, 1993). To cope with the very small scale of the investigated area of such a thin film, a new generation of Ultra Micro-Indentation System (UMIS) or nano-indentation instruments was developed (Doerner and Nix, 1986; Bell *et al.*, 1991;1992; Bell *et al.*, 1992; Oliver and Pharr, 1992; Field and Swain, 1993).



### 2.6.2 ULTRA MICRO-INDENTATION SYSTEM (UMIS 2000)

The Ultra Micro Indentation System is the instrument for the investigation of the physical properties of materials in the range of hundreds of microns down to the sub-micron range - with sub-nanometre resolution. The UMIS is used in the analysis of very hard thin films and coatings, and, of very soft materials such as polymers, rubbers and biological materials. Materials such as diamond like carbon (DLC), titanium nitrides (TiN), cartilage and teeth have been successfully analysed with the UMIS.

The UMIS instrument was developed in the mid 1980's at the National Measurement Laboratory (NML) of the Commonwealth Scientific and Industrial Research Organisation (**CSIRO**) in Australia. UMIS is the only 'sub-micrometre to micrometre' scale hardness testing instrument which uses both pyramidal and spherical diamond indenters with automatic analysis of both types of experimental data.

The UMIS 2000 is a force-driven, static measuring, ultra micro-indentation instrument used for investigating the mechanical properties of near surface regions of materials (Figure 2-13). The instrument is intended to be used as a microprobe of material properties in the surface layer with applications in surface engineering and in the development of surface modification processes.

The indenter is driven into the surface until a resistance equal to a set force is met and hence is defined as 'force-driven'. Penetration is measured under conditions of force equilibrium in a series of force steps and is therefore defined as 'static measuring'. Information is derived from the penetration on loading and also from the elastic recovery of the indentation on unloading.



The mechanical and thermal stability is also critical and the machine must be well constructed and isolated to reduce both vibration and thermal variation (Vitovec 1986; Oliver and Pharr, 1992).

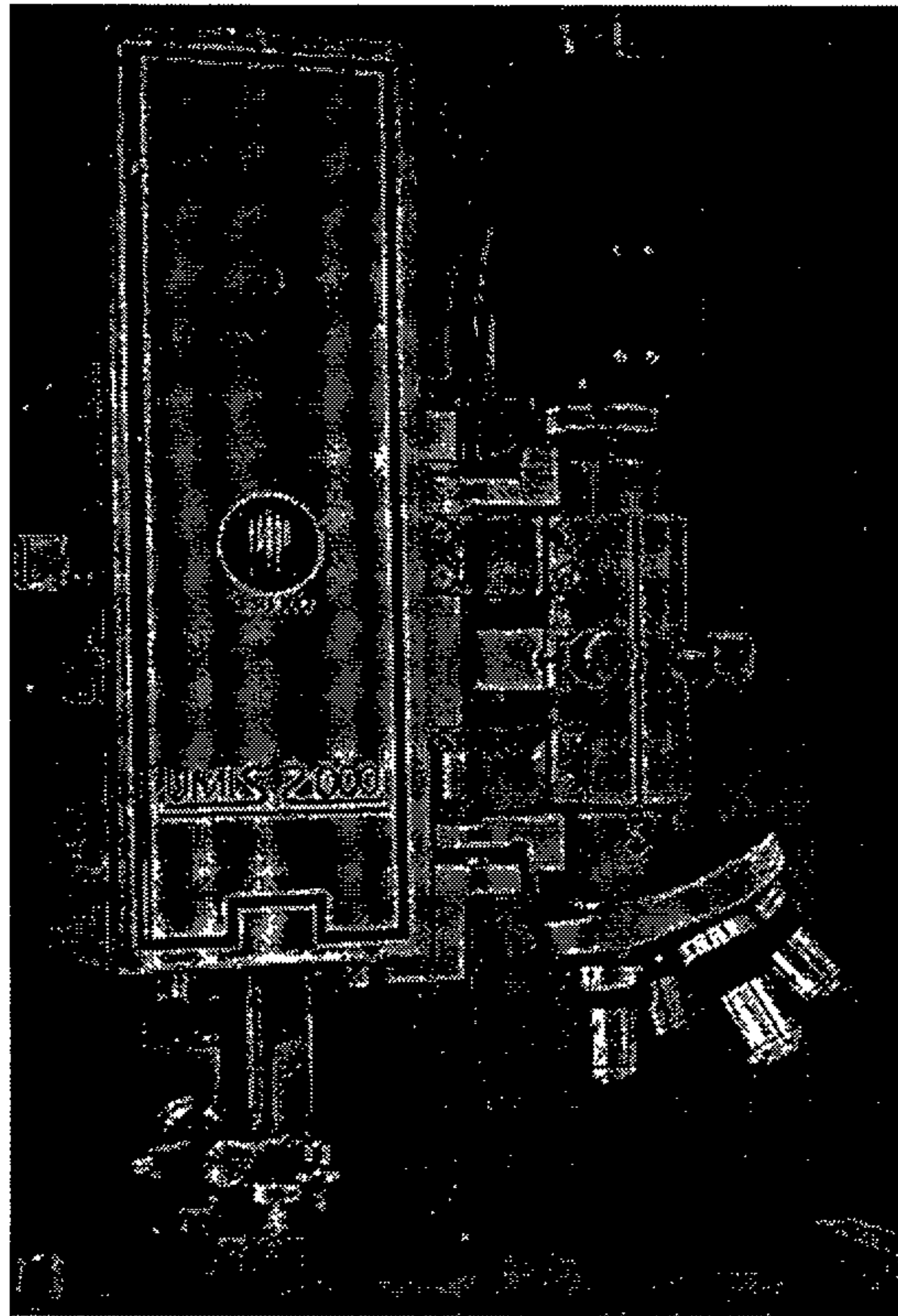


**Figure 2-13.** The UMIS machine

Precise knowledge of the imperfect indenter tip is crucial in order to know the correct projected area in the calculation. Tip calibration process is required individually for each indenter tip and should be performed regularly to ensure continued accuracy of results (Doerner and Nix, 1986; Oliver and Pharr, 1992). A method of correcting instrument compliance is also needed to allow the elastic properties of samples to be determined free of influence by the elastic behaviour of the instrument (Doerner and Nix 1986; Oliver and Pharr, 1992).



### 2.6.3 PRINCIPLES OF OPERATION OF THE ULTRA MICRO-INDENTATION SYSTEM

The operation of the instrument is controlled by a personal computer. Force-driven static measurement is used. The indenter is driven into the surface of a testing material until the resistance balances the pre-set force. The penetration of the indenter as the force remains momentarily static is determined under conditions of force equilibrium at each of a series of force steps. Data are obtained from the penetration on loading and also the elastic recovery of the indentation on the unloading procedure.

An indenter is attached to a shaft supported by spring elements (Figure 2-14).

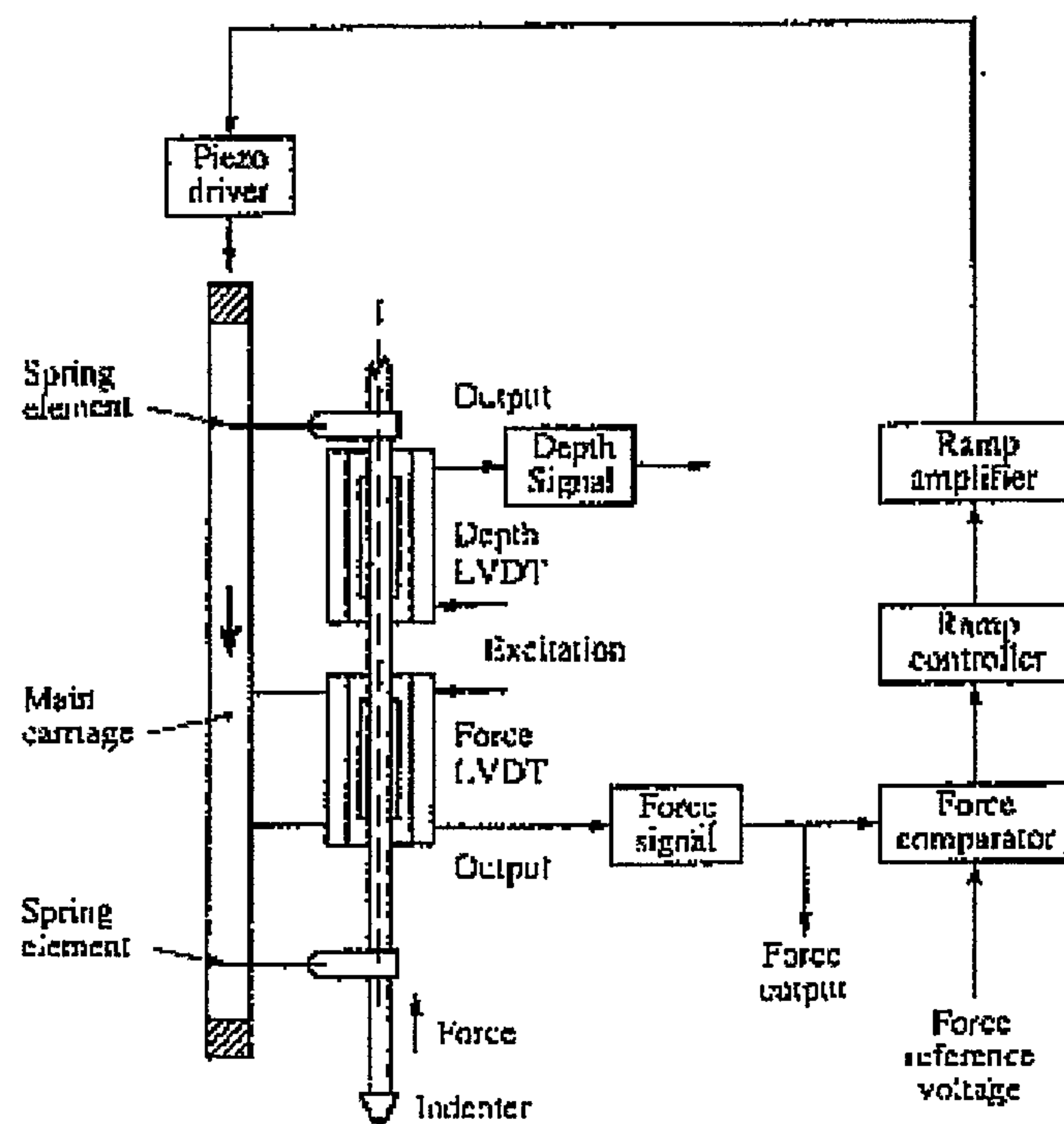


Figure 2-14. A diagram shows the force and depth measuring system



A main carriage with the spring elements is driven downwards by a long-range piezo driver. A depth LVDT (Linear Variable Differential Transformer) secured to the frame of the instrument records the position of the shaft.

When the indenter contacts the surface, the spring element is deflected relative to the main carriage carrying the spring element and this deflection is monitored by a second LVDT (force LVDT). The deflection of the spring element generates the indenting force. The depth LVDT output is zeroed when the indenter contacts the surface then establishing, a datum for the measurement of the indentation depth. A measurement cycle of loading and unloading is then followed under computer control and most commonly produces the type of load/unload sequence illustrated in Figure 2-15.

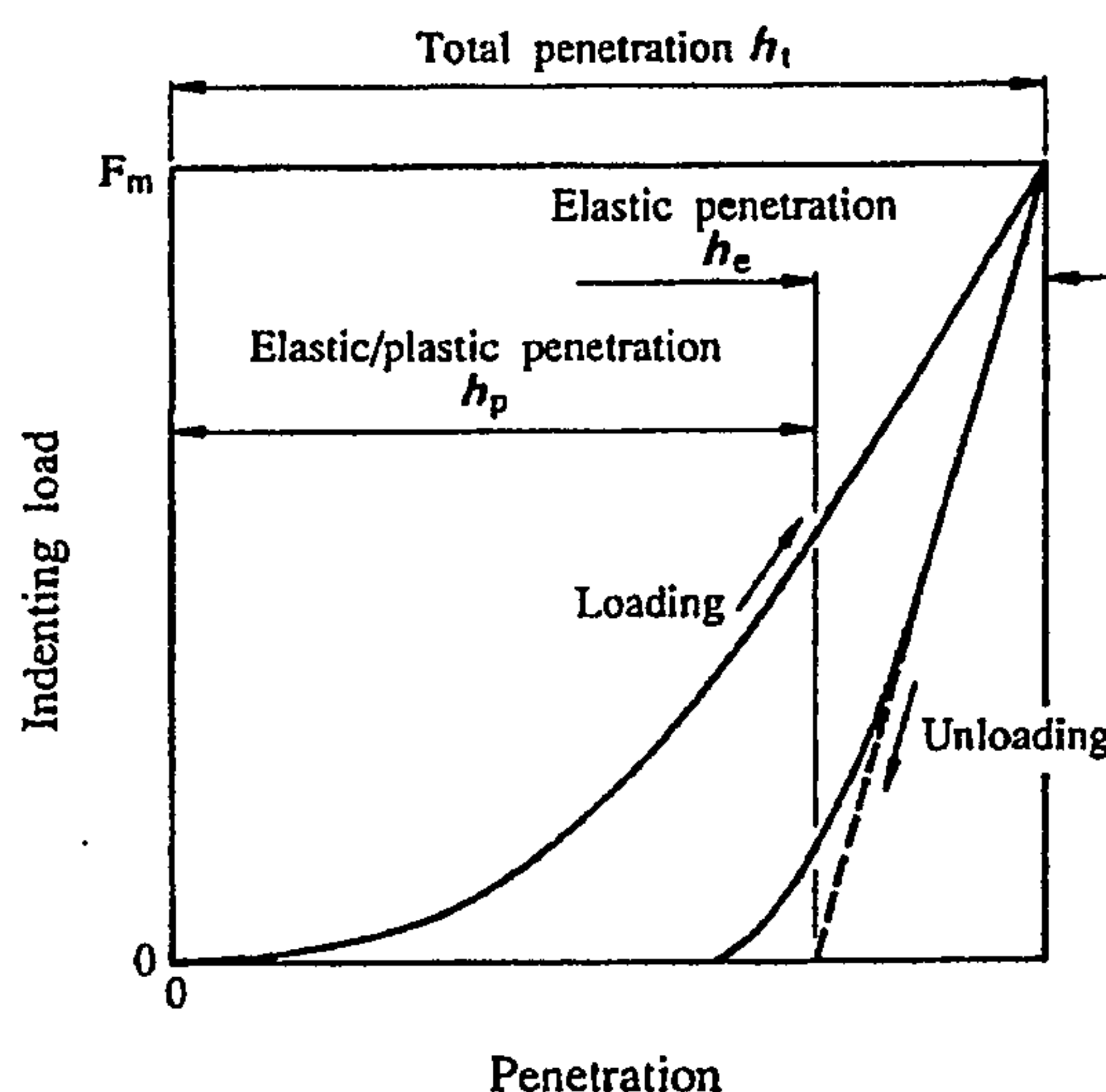


**Figure 2-15.** Typical form of the load/unload curve

(From Bell *et al.*, *The determination of surface plastic and elastic properties by Ultra Micro-indentation. Metrologia*. 1991/1992;28:463-69).

The components, which apply the force, form a feedback loop controlled by a computer-generated reference voltage. The output force signal is compared with the



reference voltage and the difference is used to control a voltage ramp. The highly amplified voltage ramp causes a piezo-electric driver to expand or contract and through the elastic spring elements apply a variable load to the indenter. This system produces the stepped force applied to the indenter controls. The rate of loading between force levels during both the loading and unloading parts of the cycle maintains the force constant during depth measurement. The use of a feedback loop to control the applied force nullifies any effect of hysteresis and non-linearity in the piezo drive.

In order to calibrate the force generation and measuring system, the instruments own control system is used to apply loads to a microbalance, which has a resolution of 1 mN. The effect of signal noise induced by vibration and other causes is also minimized by averaging the analogue signals from the measuring system "in the brief time that force equilibrium is maintained". Systematic errors due to thermal drift or mechanical instability have lead to the use of the anti-vibration cushion and also thermally isolating the instrument from the environmental effects of short-term temperature drifts.

The recovery of an indentation during the initial part of the unload circle is controlled by the total compliance of the system. Total compliance includes such effects as:

1. The elastic depression of material directly surrounding the indentation
2. The elastic deformation of the indenting mechanism including the indenter
3. The elastic distortion of the instrument structure
4. The elastic deformation of the specimen substrate and its mount
5. The elastic compression of any material at the specimen-mount interface or mount-work table interface.



Determination of the elastic modulus of the material following an indentation necessitates the separation of the first one of the above from the others. A technique has been included in the indenter evaluation module to separate the elastic contribution of the first variable from that of the others. This method gives satisfactory results providing that the product of the recovery rate and the plastic indentation depth is constant. This is usually the case for bulk materials but is true only for limited penetrations into coated materials. A compliance correction is then determined and stored in the default parameters table of the instrument. It is applied automatically to the data. The magnitude of the total compliance is determined from the initial slope of the unload cycle data (Bell *et al.*, 1991/1992).

#### 2.6.4 MODES OF INDENTING PROCEDURE

Currently two modes of operation are available. These are:

1. Continuous load/unload cycle
2. Multiple partial unload cycle.

Both methods can produce data with either a ball (spherical), pyramid diamond or other indenter but the analysis packages are currently limited to a Berkovich diamond pyramid for the continuous load/unload cycle data and a spherical indenter for the multiple partial unload cycle.

Numerical output from both analysis modes includes:

- a) Hardness at maximum depth,  $H$ , measured in GPa, and
- b) Composite elastic modulus,  $E^*$ , measured in GPa, in the form

$$1/E^* = 1-\nu_m^2 / E_m + 1-\nu_i^2 / E_i$$



where  $V_m$  and  $E_m$  are Poisson's ratio and elastic modulus of the material and  $V_i$  and  $E_i$  are Poisson's ratio and elastic modulus for the indenter

The hardness is calculated from force and projected area. Unlike a conventional Micro-Indentation Hardness test, the force displacement response is also measurable and the elastic modulus is determined from the relationship between force and depth of penetration upon loading.

### 2.6.5 CONTINUOUS LOAD/UNLOAD CYCLE

The indenting force is increased in steps to a predetermined maximum and then decreased in the same steps back to the contact value (Figure 2-16).

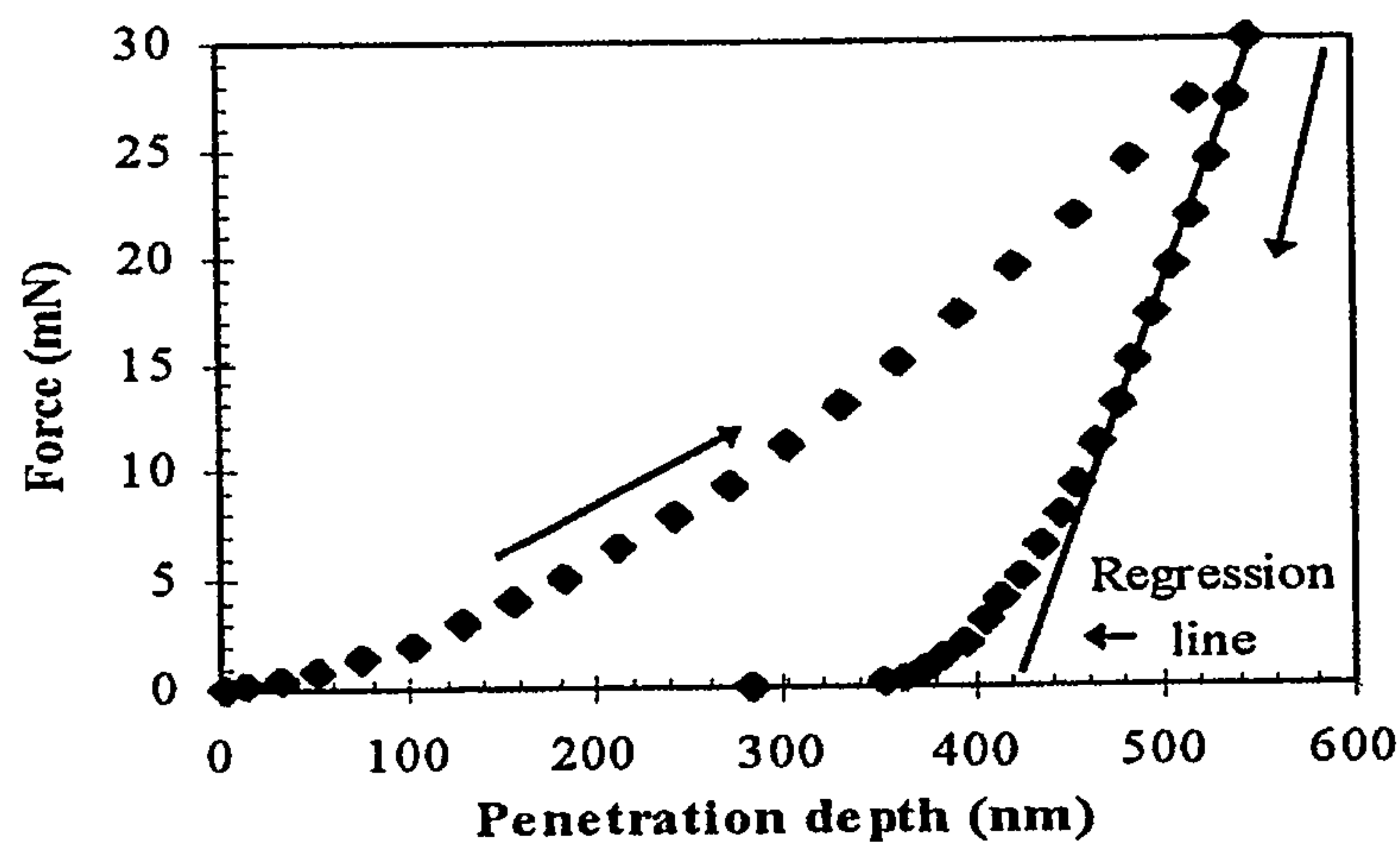


Figure 2-16. A load/unload cycle



Output from this method are:

1. Hardness at every force step (presented graphically as a function of depth of penetration for each individual penetration step)
2. Elastic modulus of the material in terms of  $E/(1-\nu)^2$  where  $\nu$  is Poisson's ratio at the maximum force.
3. A toughness index
4. The returned energy ratio  $W_e / W_t$

#### 2.6.6 MULTIPLE PARTIAL-UNLOAD CYCLE

The indenting force is increased in steps to a predetermined maximum but is partially unloaded at each force step by a preset fraction of the preceding loading step. The indentation is not unloaded stepwise from the final force (Figure 2-17).

Outputs from this method are

1. Hardness (mean contact pressure) at every force step (presented graphically as a function of depth of elastic/plastic penetration)
2. Composite elastic modulus at every force step (presented graphically as a function of depth of elastic/plastic penetration)
3. The strain index as  $x=m-2$  where  $m$  is Meyer's index, which is related to the work hardening response of a metal.

This method has advantages for determining the variation or changes of elastic modulus with depth.



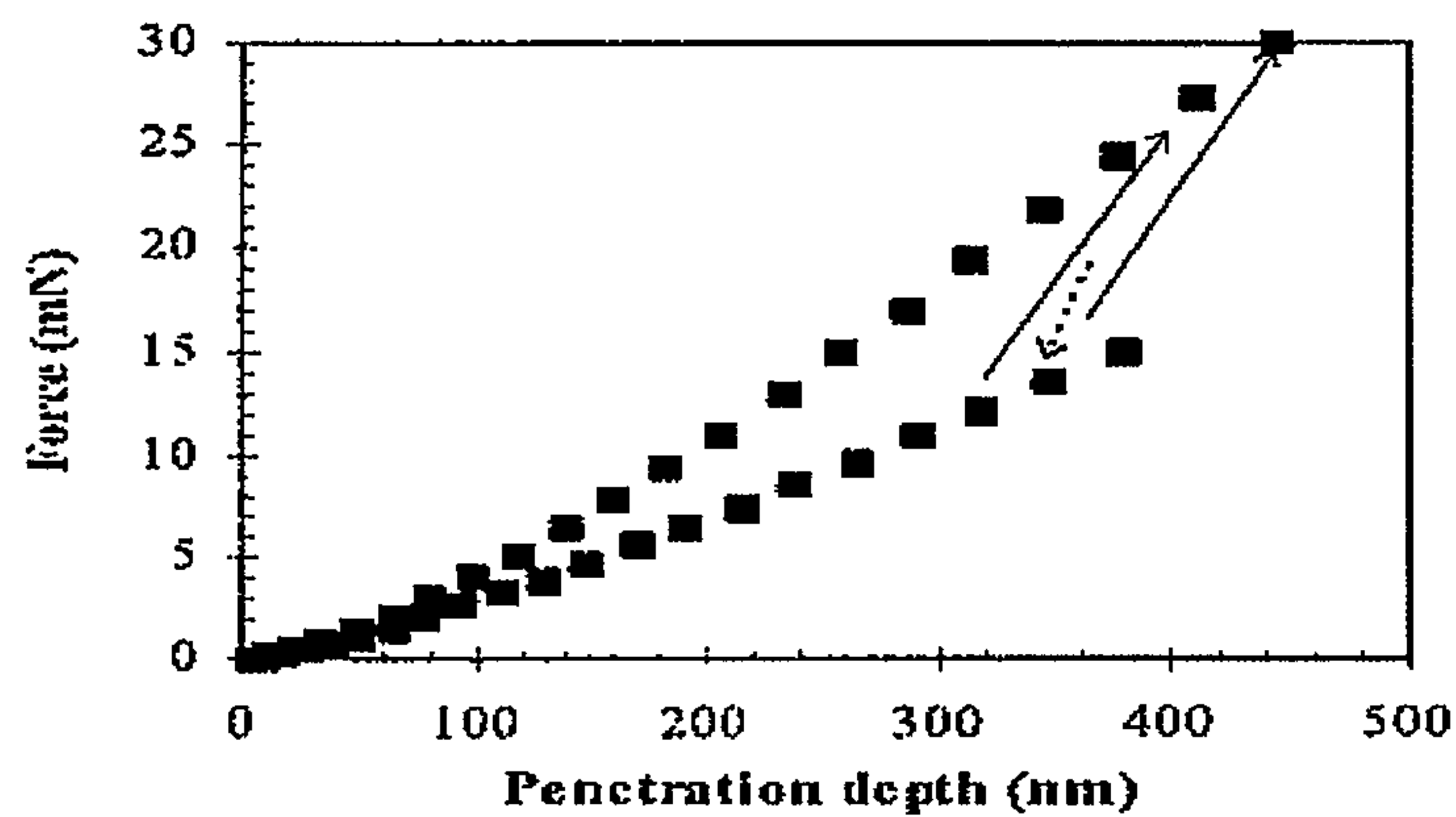


Figure 2-17. A multiple load/partial-unload cycle

#### 2.6.7 RATIONALE FOR SELECTION OF SPHERICAL INDENTER AND MULTIPLE PARTIAL-UNLOAD CYCLE

Malek (2000) examined the effect of different indenters on unpolished cementum. The results showed that the force/penetration data generated by the use of Berkovich indenter were highly variable. This is due to the Berkovich indenter required an extremely flat surface to allow a stable contact for testing procedures. This could only be obtained through resin embedding of the sample. It was assumed that the heterogenous nature of the unaltered surface of the cementum caused the sliding of the indenter as was indicated by the plots obtained. The use of the spherical indenter, therefore, appeared to eliminate problems attributed to surface asperities. Greater loads were utilized to enable the compression of the asperities and therefore compensate for the minimally prepared surface.

Another limitation with the Berkovich indenter is that the software of the Berkovich analysis only measured the elastic modulus in the "Load/Unload" cycle at only the last



point in the cycle. This reduced the accuracy of the test to a one point. However, with the "Load/Partial unload" cycle amenable to the spherical indenter, a relatively more accurate measurement of elasticity was obtained. This is due to the fact that multiple assessment of the elasticity was derived with "Load/Partial unload" analysis.

However, the Berkovich indenter has the advantage of unlimited depth of penetration. The spherical indenter is limited in depth by virtue of its construction constraints. To obtain a flawless diamond sphere is impossible. The tip is machined to a particular radius then a cone shape results. The software and physical limitations allowed calculation of up to only one third of the indenter radius. Therefore, depths greater than one third of 20- $\mu\text{m}$  radiuses could not be investigated. The depth of penetration in our study was therefore limited to 7000 nm. The first 2000 nm of data was disregarded due to the surface irregularities. The hardness was reported to a depth of 7000 nm due to limitations of the spherical indenter geometry.

From these reasons, a 20- $\mu\text{m}$  diameter spherical indenter was used in our study. The maximum force of 500 milli-Newtons allowed assessment on all area of the root, both soft and hard, as well as to enable enamel testing using the same protocol and therefore enabled comparison of the results more readily (Boyer, 1987). The UMIS 2000 has the ability to accept surface discrepancies if up to 25  $\mu\text{m}$  in a traverse without interfering with its operation (CSIRO, 2000). Weaver (1966) pointed out that in selecting the proper test load, every attempt should be made to produce the largest impression within the structure under study. This is aimed to reduce technical error. Weaver (1966) also recommended that imprints should be kept at a distance of at least twice their diagonals, therefore the 100  $\mu\text{m}^2$  array was chosen.



### 2.6.8 MULTIPLE LOAD/PARTIAL-UNLOAD CYCLE ANALYSIS

The Multiple load/partial-unload cycle analysis packages in the UMIS are appropriate only for the Spherical diamond indenter. This package converts the load/partial-unload data into composite elastic modulus as a function of contact depth together with some other outputs.

The use of spherical tipped indenter has some advantages; a smooth regular finish can be obtained, the radius is known to sufficient accuracy the initial penetration at contact is more reliably estimated and the degree of penetration of soft materials can be controlled by the choice of indenter radius.

A multiple partial-unload procedure throughout the force/displacement curve enables a near continuous assessment of contact pressure and modulus of the specimen throughout the test, whereas the major limitation of continuous plots of force-displacement data is that only one value of contact pressure and elastic modulus is determined. As shown by Field and Swain (1993) knowing two points during unloading enables the residual impression depth to be estimated from which the contact radius and therefore the contact pressure and the modulus can be determined. A modification of this procedure enables the calibration of the effective radius versus contact depth of an indenter to be determined (Swain, 1999).

Swain, 1999 in his consideration of plastic deformation of brittle materials, concluded that small spherical tipped indenters coupled with precision force-displacement systems, are able to measure the elastic-plastic or hardness of properties of materials reliably.



A modified analysis system has recently been developed to investigate spherical indentations based on a Hertzian analysis for the contact of spherical surfaces. For a sphere on a plane surface, the distance of approach is given by

$$\delta = a^2/R = (9/8)^{1/3} (1/E^*)^{2/3} (1/D)^{1/3} F^{2/3}$$

where  $\delta$  is total elastic displacement,  $E^*$  is the composite elastic modulus,  $D$  is the diameter of the spherical indenter,  $a$  is the radius of contact, and  $F$  is the applied force (Bell *et al.*, 1992). The elastic modulus of the test material ( $E_m$ ) is then calculated from the following equation

$$1/E^* = 1 - \nu_m^2 / E_m + 1 - \nu_i^2 / E_i$$

where  $\nu_m$  and  $E_m$  are Poisson's ratio and elastic modulus of the material and  $\nu_i$  and  $E_i$  are Poisson's ratio and elastic modulus for the indenter, respectively. The mean contact pressure ( $P_m$ ), over the elastic footprint enclosed by the circle of contact is calculated by where  $F$  is the force,  $a$  is the radius of the circle of contact and related by  $\delta = a^2/R$  for  $\delta \ll R$  (Bell *et al.*, 1992).

$$P_m = F / \pi a^2$$



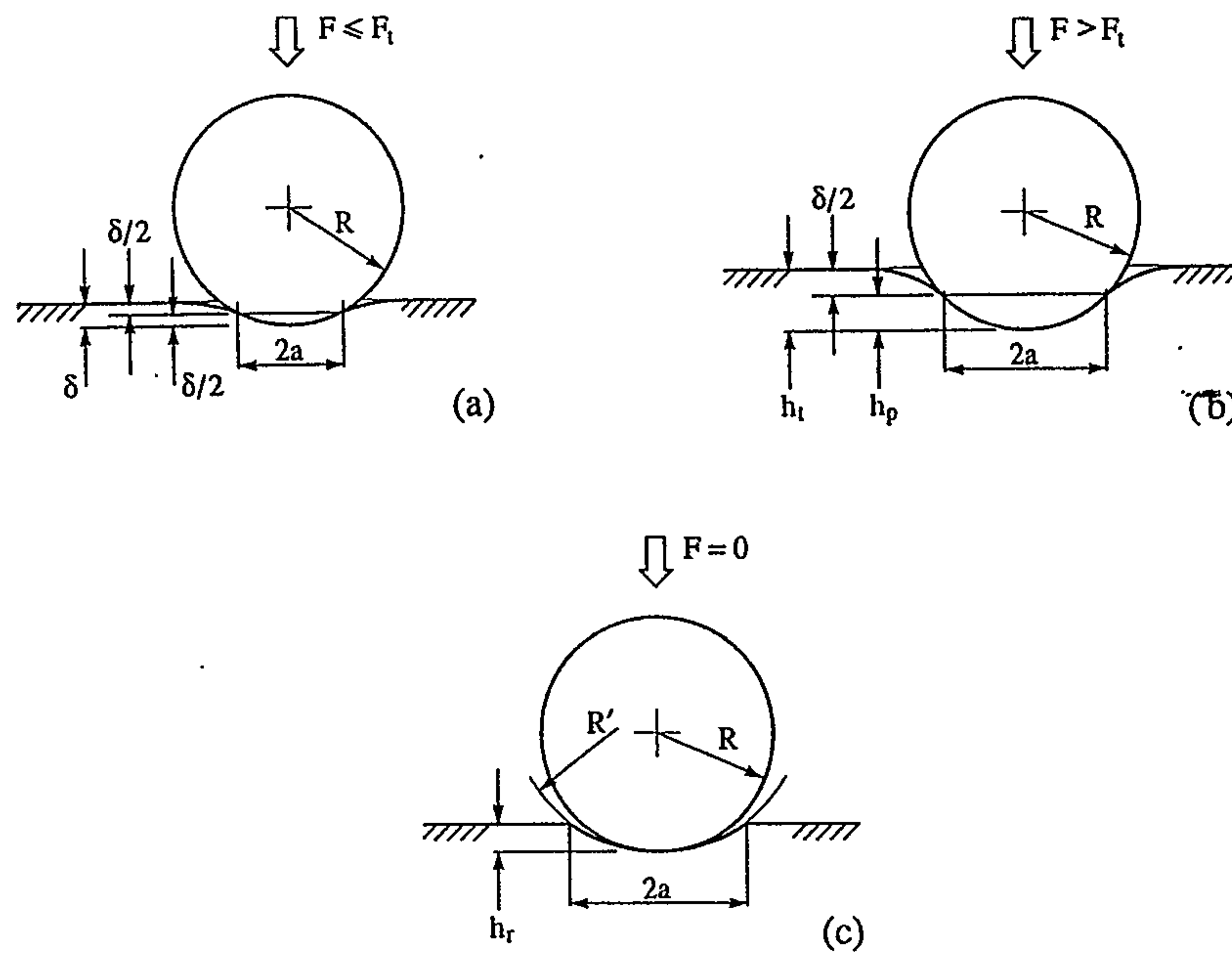


**Figure 2-18.** The geometry of the spherical indentation: (a) Loaded to the elastic/plastic transition (b) loaded beyond the transition zone and (c) unloaded (*From: Field and Swain, A simple prediction model for spherical indentation. J Mater Res 1993;8:297-306*)

In this condition, where mean pressure over the footprint does not exceed the yield stress ( $P_m < 1.1 \sigma_y$ ), the stress is insufficient to initiate plastic flow. Deformation is wholly elastic and the surface undergoes complete recovery (Bell *et al.*, 1991/1992; Field and Swain, 1993).

When the mean pressure exceeds the yield stress ( $P_m > 1.1 \sigma_y$ ), plastic flow develops beneath the indenter and the interaction between a sphere and a surface material is represented by the sphere pressing against a concave material surface. The critical condition for transition from elastic to elastic/plastic behavior is assumed to exist when the mean pressure equals the hardness of the surface layer.



When the system is partially unloaded, it is possible to follow the transition from elastic to plastic behavior. For elastic only behavior, the unloading data superimposes on the loading data, whereas upon the onset of plastic deformation there is an offset between the loading and unloading data points. With knowledge of contact diameter as a function of load, and the mean pressure, determination of the change of hardness with depth of penetration or as a function of indentation strain ( $a/R$ ) is possible. By plotting the mean contact pressure as stress against the indentation strain ( $\epsilon = a/R$ ) as strain, a representative stress-strain curve can be estimated (Bell *et al.*, 1991/1992; Bell *et al.*, 1992; Field and Swain, 1993).

## 2.7 PHYSICAL PROPERTIES OF TEETH

Knowledge of biophysical behavior of teeth is essential for a number of reasons. In restorative study, matching properties of restorative materials to the properties of teeth is considered useful to enhance the longevity of the restoration. For orthodontics, knowledge of physical behaviour of cementum is essential for understanding how orthodontic mechanical stresses are distributed throughout the root surfaces and how physical properties of cementum are altered by application of orthodontic force. These properties of cementum such as hardness and elastic modulus may reveal important characteristics of root resorption previously unexplored in this regard.

The published data, however, are very inconsistent even there have been many attempts to study on these properties. It was suggested that the physical properties of teeth were functions of microstructural orientations (such as enamel prismatic orientation), chemical composition and individual variation (Xu *et al.*, 1998). Spears



(1997) and Lees and Rollins (1972) have shown that enamel may behave anisotropically, different stiffness in different directions of enamel cap. This anisotropy is considered to be the result of the prismatic structure of enamel, with high stiffness being along the direction of prisms and low stiffness being across them. As a result, different prism orientations between test pieces may have resulted in different values of stiffness being recorded. Difference in chemical composition between test pieces is another factor affecting these physical properties. Malek *et al.*, (2001), Mahoney *et al.*, (2000), Poolthong (1998), Brear *et al.*, (1990), Hodgkinson *et al.*, (1989) and Craig *et al.*, (1961) concluded that hardness as well as elastic modulus were positively correlated with calcium mineral content. Chemical composition is known to be susceptible to oral environment such as fluoride intake (Von Der Fehr, 1967 and Weatherell *et al.*, 1972).

Hardness is not a fundamental property. It has no quantitative value except in terms of a given load applied in relation to the contact area, generated in a specified manner for a specific duration and a specified penetration shape. Therefore, taking this into consideration; different values can be expected from different testing designs.

Elastic modulus, or stiffness, of enamel varied highly considerable due to the test method. By using compression test, Stanford *et al.*, 1960 mechanically measured Young's modulus values on different sections of a human molar. The data revealed that in molar enamel, Young's modulus across the direction of prisms ( $32.4 \pm 4.1$  GPa) was greater than Young's modulus along the direction of prisms ( $9.65 \pm 3.45$  GPa).

Craig and Peyton (1960) determined the proportional limit of cusp enamel varied from 30,600 pounds/square inch (psi) to 64,800 psi, with an average of 51,200 psi. The ultimate compressive strength ranged from 33,200 psi to 74,400 psi with an average of 55,700 psi.



Craig *et al.*, (1961) carried out a similar study, and found that the values of Young's modulus of enamel along the direction of prisms was  $77.9 \pm 4.8$  GPa which was almost eight times greater than the corresponding value found by Stanford *et al.* Gilmore *et al.*, (1970) calculated a value of 73 GPa for Young's modulus for bovine enamel in the direction parallel to prisms. Spear (1997) investigated the Young's modulus of dental enamel by the use of finite element stress analysis to create a model, which simulated the mechanical properties of enamel. He found that predicted values of Young's modulus along the direction of prisms are comparable with those values obtained by Craig *et al.*, (1961) and Gilmore *et al.*, (1970), but not with those low values obtained by Stanford *et al.*, (1960). Predictions of Young's modulus values across the direction of prisms were also made, and the model was less stiff in this direction. Predicted values of Young's modulus are presented to range from 19-91 GPa perpendicular to the orientation of the crystals, to 93-113 GPa parallel to the orientation of the crystals. He concluded that human prismatic enamel was almost certainly anisotropic with respect of stiffness.

Ryge *et al.*, (1961) studied hardness of human enamel and dentine by using Knoop and Vicker diamond indenters at loads of 1,5,10,25,50,100,1000 and 10,000 grams. No type of teeth was mentioned. Each specimen were mounted in self-curing resin and polished with aloxite paper. They found that the hardness of dentine ranged from 30-82 KHN and 65-80 VHN. For dental enamel, hardness ranged from 123-355 KHN and 242-348 VHN.

Dalitz (1962) found no indication of a relationship between age and dentine hardness after testing incisors and canines removed from 18 individuals with an age range of 14-56 years. Later in 1965, Pothmann reported no difference of hardness of dentine from a range of age groups (11-70 years).



Renson and Braden (1971) observed hardness of radicular dentine of incisors, canines and premolars and the coronal dentine of molars by the use of various geometries of indenters: sphere, cylinder and cone. A total of 48 specimens were prepared from 12 incisors, 12 canines, 12 premolars and 12 molars and sectioned 1.0-2.0 mm in thickness. They concluded that there were small deviations between hardness values for different teeth.

Davidson and co-workers (1974), reported human enamel hardness in KHN. The hardness recorded with the load applied parallel to the direction of the prism axis was  $367 \pm 17$  KHN. The hardness recorded with the load applied perpendicular to the direction of the prism axis was less at  $327 \pm 34$  KHN.

Willems *et al.*, 1993 examined the hardness of human molar enamel by the use of Nano Indenter<sup>TM</sup> (Nano instruments, Inc., Knoxville, TN, USA). Extracted human molars were embedded in epoxy resin and sectioned in such a way that the enamel at the occlusal part of the tooth could be investigated. By a continuous load cycle, a pyramidal diamond indenter with a small load of 0.2  $\mu$ N was applied. The result revealed that human molar enamel had hardness values of  $3.39 \pm 0.18$  GPa and elastic modulus was  $90.59 \pm 16.13$  GPa.

Meredith *et al.*, (1996) measured hardness and Young's modulus of human enamel and dentine by a Knoop indenter. 3 human molar teeth were embedded in chemically polymerizing resin, sectioned buccolingually into 2-mm slices cut perpendicular to the mesiodistal axis of the tooth. Sections were selected from the mid-portion of each tooth. Different locations were selected. Each indentation in enamel was parallel to the outer tooth surface and in dentine to the amelodentinal junction. Loads of 0.98 N for dentine and 4.9 N for enamel were set up. It has been shown that the mean hardness



values for dentine was 60.7 KHN; whilst the mean values of Young's modulus of dentine was  $10.3 \text{ GNm}^{-2}$  calculated using a value for  $\alpha_1$  of 0.45. For enamel, there was a decrease in KHN in enamel with an increase in distance from the enamel surface at a linear rate of approximately  $-0.023 \text{ HK}\mu\text{m}^{-1}$ . Such an observation does not appear to have been reported in other literatures. Mean values of Young's modulus of enamel was  $299.5 \text{ GNm}^{-2}$  calculated using a value for  $\alpha_1$  of 0.45.

Kinney *et al.*, 1996 measured the hardness of fully hydrated peritubular and intertubular dentine at two locations within unerupted human third molars: within 1 mm of the dentine enamel junction and within 1 mm of the pulp. The hardness of fully hydrated peritubular dentine was independent of location, and ranged from 2.23 to 2.54 GPa. The hardness of fully hydrated intertubular dentine did depend upon location, and was significantly greater near the dentine enamel junction (values ranged from 0.49 to 0.52 GPa) than near the pulp (0.12-0.18 GPa). A Nanoindenter was used to estimate the Young's modulus of dehydrated peritubular and intertubular dentine from the unloading portion of the load displacement curve. The modulus values averaged 29.8 GPa for the peritubular dentine (considered to be a lower limit), and ranged from 17.7 to 21.1 GPa for the intertubular dentine, with the lower values obtained for dentine near the pulp.

Poolthong (1998) by the use of UMIS machine studied 6 human maxillary first premolars. Teeth were embedded, and cut horizontally at the cervical area to obtain crown and root sections. Hardness of buccal side enamel and cusp tip was reported as  $4.74 \pm 0.16$  and  $4.45 \pm 0.25$  GPa, respectively; whereas the elastic modulus of buccal side enamel and cusp tip was  $90.79 \pm 2.22$  and  $83.83 \pm 6.32$  GPa. He agreed that indentation location contributed to some variation of hardness and elastic modulus. It might be unreliable to compare two data of hardness from different studies that had different experimental designs.



Table II-c The previous studies of the physical properties of human enamel

| AUTHOR                 | TEST              | TOOTH                                      | ENAMEL<br>HARDNESS*                                                                                    | ENAMEL<br>ELASTICITY*   |
|------------------------|-------------------|--------------------------------------------|--------------------------------------------------------------------------------------------------------|-------------------------|
| Hodge & McKay          | 1933 Scratch      | Apical 1/3 of canine Sagittal section      | 2050 BHNs                                                                                              |                         |
| Craig <i>et al.</i>    | 1961 -            | - Along direction of prism                 |                                                                                                        | 77.9±4.8 GPa            |
| Ryge <i>et al.</i>     | 1961 Knoop        | - -                                        | 123-355 KHN                                                                                            |                         |
|                        | Vickers           | - -                                        | 242-348 VHN                                                                                            |                         |
| Stanford <i>et al.</i> | 1960 Compression  | Molar Across direction of prism -          |                                                                                                        | 32.4±4.1                |
|                        |                   |                                            | Along direction of prism -                                                                             | 9.65±3.45               |
| Davidson <i>et al.</i> | 1974 Knoop        | - Perpendicular to direction of prism axis | 327±34 KHN                                                                                             |                         |
|                        |                   |                                            | Parallel to orientation of crystal                                                                     | 367±17 KHN              |
|                        |                   |                                            |                                                                                                        |                         |
| Willems <i>et al.</i>  | 1993 Nanoindenter | Molars Occlusal surface                    | 3.39 ±0.18 GPa                                                                                         | 90.59±16.13             |
| Spear                  | 1997 FEM          | Perpendicular to orientation of crystal    |                                                                                                        | 19-91                   |
|                        |                   | Parallel to orientation of crystal         |                                                                                                        | 93-113                  |
| Meredith <i>et al.</i> | 1996 Knoop        | Molar                                      | Decrease with an increase in distance from enamel surface at a linear rate of 0.023 HKµm <sup>-1</sup> | 299.5 GNm <sup>-2</sup> |
| Poolthong              | 1998 UMIS         | Premolar Buccal side enamel                | 4.74±0.16 GPa                                                                                          | 90.79±2.22GPa           |
|                        |                   | Cusp tip                                   | 4.45±0.25 GPa                                                                                          | 83.83±6.32 GPa          |
| Xu <i>et al.</i>       | 1998 Vickers      | Third molar Occlusal section               | 3.62±0.20 GPa                                                                                          | 94±5GPa                 |
|                        |                   | Axial section                              | 3.37±0.15 GPa                                                                                          | 80±4GPa                 |
| Malek                  | 2000 UMIS         | Premolar All surfaces Apical 1/3           | 3.2-3.50GPa                                                                                            | 49.35-50.46GPa          |
| Mahoney <i>et al.</i>  | 2000 UMIS         | Primary molars                             | 4.88±0.35 GPa                                                                                          | 80.35±7.71 GPa          |

\*Mean (Standard deviation)



Xu *et al.*, 1998 examined the effect of microstructural features of teeth on physical properties of human enamel teeth, by a sharp indenter. 28 human third molars were divided into two groups: 10 for the indentation in direction parallel to the occlusal surface and 18 for the indentation in direction perpendicular to the occlusal surface. All teeth were flatten and polished by diamond paste. Vickers diamond indenter and 6 indentation loads of 2,3,5,10,20 and 50 N were used. They found that hardness of human molar enamel ranged from  $2.83 \pm 0.1$  to  $3.74 \pm 0.48$  GPa and elastic modulus ranged from  $78 \pm 1$  to  $98 \pm 4$  GPa. The physical properties of teeth were functions of microstructural orientation; hence single values of properties should not be used without information on microstructural orientation.

Mahoney *et al.*, 2000 used the UMIS to measure hardness and elastic modulus of enamel and dentine on 8 primary maxillary first molar teeth. Each tooth was embedded in cold curing epoxy resin and sectioned. 30 indentations were made in enamel and dentine using a Berkovitch indenter. Primary enamel had a mean hardness of  $4.88 \pm 0.35$  GPa whilst hardness of dentine was  $0.92 \pm 0.11$  GPa. Elastic modulus of enamel was  $80.35 \pm 7.71$  GPa and that of dentine  $19.89 \pm 1.92$  GPa. Their study showed a positive correlation between elastic modulus and hardness of both primary enamel and dentine. They suggested that hardness and elastic modulus might correlate with calcium mineral content.

Malek (2000) using the new methodology and UMIS 2000 studied the hardness and elastic modulus of human enamel with a minimally prepared method. The results showed that the hardness and elastic modulus values of human premolar enamel were 3.2-3.50GPa and 49.35-50.46GPa, respectively.



### **2.7.1 HARDNESS AND ELASTIC MODULUS OF CEMENTUM**

Hardness and elastic modulus of human cementum have been studied by several investigators. Hodge and McKay (1933) were the first ones who investigated the hardness of cementum, by sagittally sectioning of a canine in which enamel, dentine, pulp and cementum were included. The microhardness or Bierbaum hardness number was the ratio of the area of impression by the force producing the impression. The average hardness of 90 BiHNs was reported in apical cementum.

Rautiola and Craig (1961) investigated the hardness of cementum and underlying dentine of normal teeth and teeth which periodontal disease would. 18 freshly extracted teeth were obtained from patients who had no previous history to scaling. 4 teeth were embedded directly in casting plastic within 20 minutes after extraction. The remaining 14 teeth were immersed and stored in neutral formalin until embedded in plastic. The teeth were cast in plastic, sectioned, ground, and stored in water similar to the method followed by Craig and Peyton (1958; 1960). Storage in tap water, neutral formalin, or direct embedding into plastic had no apparent effect on microhardness of dentin and cementum. Either longitudinal or surface sections were prepared. An "MO" Tukon hardness tester with a Knoop diamond indenter was used. A 25-gram load with a 15 second contact time was used throughout the study. A total of 1640 indentations were made into various locations of 26 sections of the 18 different teeth. The data indicated that no difference was observed in hardness of cementum from surface sections and longitudinal sections. Also, there was no difference on hardness of exposed and unexposed cementum. For all teeth the mean KHN was 39.6 ( $\pm 6.1$ ) for unexposed cementum and 39.3 ( $\pm 5.3$ ) for exposed cementum. No measurable difference was observed in the microhardness of exposed and unexposed cementum. They also suggested that there was no difference between inner and outer cementum. They noted that normal variation in hardness found in all areas of cementum.



Waters (1980) found lower micro-hardness values of cementum as compared to dentine. He suggested that the lower stiffness or elastic modulus is to compensate for the movement of the root during functioning.

Poolthong *et al.*, (1996) was the first used the UMIS to measure the hardness and elasticity of human premolar teeth. 3 human premolars were used and cut to expose three different portions; middle third of crown, cervical third and apical third of root. Direction of indenter to microstructural orientation was not addressed. They reported that the cementum in the apical third ( $H = 0.82 \pm 0.08$  GPa,  $E = 9.3 \pm 0.23$  GPa) gave lower hardness and elastic modulus values when compared to the cervical third ( $H = 1.5 \pm 0.09$  GPa,  $E = 12.3 \pm 0.43$  GPa).

Poolthong, later in 1998 used 6 human maxillary first premolars, Teeth were embedded, and cut horizontally at the cervical area to obtain crown and root sections. 2 cuts were made in root section. The first one was made at the apical third of root to obtain cementum. Another cut was made horizontally to achieve cross-section of root at middle third. The Berkovich and 20  $\mu\text{m}$  spherical indenters were used alternately. The results revealed that hardness and elastic modulus at apical third of cementum were  $0.57 \pm 0.48$  and  $8.55 \pm 0.84$  GPa whereas cementum at middle third showed hardness of  $0.63 \pm 0.06$  and elastic modulus of  $11.95 \pm 1.24$  GPa. The cementum at the middle third showed higher hardness and elastic modulus than that of apical third. He explained by the different mineral contents in 2 cell structures of cementum, acellular and cellular. Cellular cementum is mostly found in the apical third and is less calcified, thus having a lower hardness and elastic modulus than the acellular cementum which is more highly calcified.



Clark (1997), using UMIS 2000 studied the hardness and elastic modulus values of apical cementum on thirty-two human premolar teeth. Each sample was embedded in epoxy resin, horizontally sectioned and measured the hardness and elastic modulus values by the UMIS. The mean values of hardness and elastic modulus of cementum from the apical third of premolar teeth were  $0.36 \pm 0.08$  GPa and  $12.31 \pm 2.03$  GPa,



**Table II-d**     The previous studies of the physical properties of human cementum

| AUTHOR              | TEST         | TOOTH                                       | CEMENTUM<br>HARDNESS*          | CEMENTUM<br>ELASTICITY*         |
|---------------------|--------------|---------------------------------------------|--------------------------------|---------------------------------|
| Hodge & McKay       | 1933 Scratch | Cuspid apical 1/3<br>Sagittal section       | 90BHNs                         |                                 |
| Ichiro & Nihei      | 1959 Vickers |                                             | 14-21 VHNs                     |                                 |
| Rautiola & Craig    | 1961 Knoop   | Exposed cementum<br>Unexposed cementum      | 39.3±5.3 KHN<br>39.6±6.1 KHN   |                                 |
| Schemel             | 1984 Vickers |                                             | 49.6 VHNs                      |                                 |
| Clark               | 1997 UMIS    | Premolar Apical 1/3                         | 0.36±0.08 GPa                  | 12.31±2.03 GPa                  |
| Poolthong<br>et al. | 1996 UMIS    | Premolar Cervical 1/3<br>Apical 1/3         | 1.5±0.09 GPa<br>0.82 ±0.08 GPa | 12.3±0.43 GPa<br>9.3 ± 0.23 GPa |
| Poolthong           | 1998 UMIS    | Premolar Middle 1/3<br>x-section Apical 1/3 | 0.63±0.06 GPa<br>0.57±0.48 GPa | 11.95±1.24 GPa<br>8.55±0.84 GPa |
| Malek               | 2000 UMIS    | Premolar All surfaces<br>Apical1/3          | 0.25±0.08-<br>0.35±0.08        | 4.11±1.47-<br>5.5±2.02          |
| Malek               | 2000 UMIS    | Premolar All surfaces<br>Cervical 1/3       | 0.39±0.1 -<br>0.43±0.01        | 6.32±2.28-<br>7.23±2.48         |

\*Mean (Standard deviation)



respectively. He found a statistically significant difference between the hardness of male and female cementum, with female teeth being harder. Several reasons were proposed to explain the difference but the most likely is that air storage of the female specimens allowed them to dehydrate causing an increase in the hardness value. He found no statistical differences between the hardness of cementum from maxillary teeth when compared to those of mandibular teeth nor the buccal surface when compared to the lingual surface nor when the premolar was in the first or second position. Also there was no statistical difference between the mean values of elastic modulus of cementum when all the variables were compared. Gender, arch, tooth position and tooth surface seemed not to affect the mean values of elastic modulus of the teeth measured.

Several weak points with this method of sample preparation were explained by the author. Dehydration of cementum was occurred during embedding in the epoxy resin due to the exothermic effect of resin. In addition, the amount of exposed cementum surface, which was removed during the polishing procedure, was unknown. The whole cemental layer may be removed.

Recently efforts have been made to establish standardised protocols for evaluation of hardness and elastic modulus of cementum. Malek (2000) developed a new method for investigating the hardness and elastic modulus of human cementum along the root surface on a minimally prepared tooth. With this approach, the sample can be retrieved for further investigations. This methodology included a new location device which was designed to allow the repetitive measurements of a given test location for different purposes. A total of nine teeth were collected for his study. At the apical third, the values of hardness and elastic modulus of all surfaces of human premolar cementum were 0.25(0.08)- 0.35(0.08) and 4.11(1.47)- 5.5(2.02) GPa, respectively. At the



cervical third, these were 0.39(0.1) -0.43(0.01) and 6.32(2.28)- 7.23(2.48) GPa, respectively.

## 2.8 EFFECT OF STORAGE MEDIA

To date, there have been a few published studies on the storage media and its effect on the physical properties of teeth. During storage, dissolution of mineral is possible and a change in water content of hard tissues may occur if a storage solution sets up an unfavorable osmotic gradient. Therefore, physical properties of cementum may be affected by different chemical solutions used for storage over time. Rautiola and Craig (1961) looked at storage in tap water, neutral formalin, and direct embedding into plastic, none of which were found to affect the hardness of dentine and cementum. However, they used resin embedding prior to hardness testing which can nullify the effect of storage media. Waters (1980) reported that storage in formalin could cause dehydration and also cross-linking of proteinaceous material. Also commercially available formalin was generally acidic due to the formation of formic acid, which would result in the dissolution of the mineral component.

Malek (2000) investigated the effect of time and types of five storage media: 70% alcohol, desiccation, Milli Q and both Milton 24 hr and 10 minute soak, on hardness and elastic modulus of human premolar cementum. Twenty teeth were collected and divided into five groups of four teeth. The samples were tested within 6 hours of extraction to establish baseline data. They were then stored for one month at constant ambient room temperature  $23 \pm 1^{\circ} \text{C}$  their respective media. After one month, the teeth were systematically tested and every month thereafter for the three-month period. He found that Milli Q<sup>®</sup> exhibited the most stable media in which individual tooth could be



stored for up to nine months without any significant alteration in hardness and elasticity of cementum.



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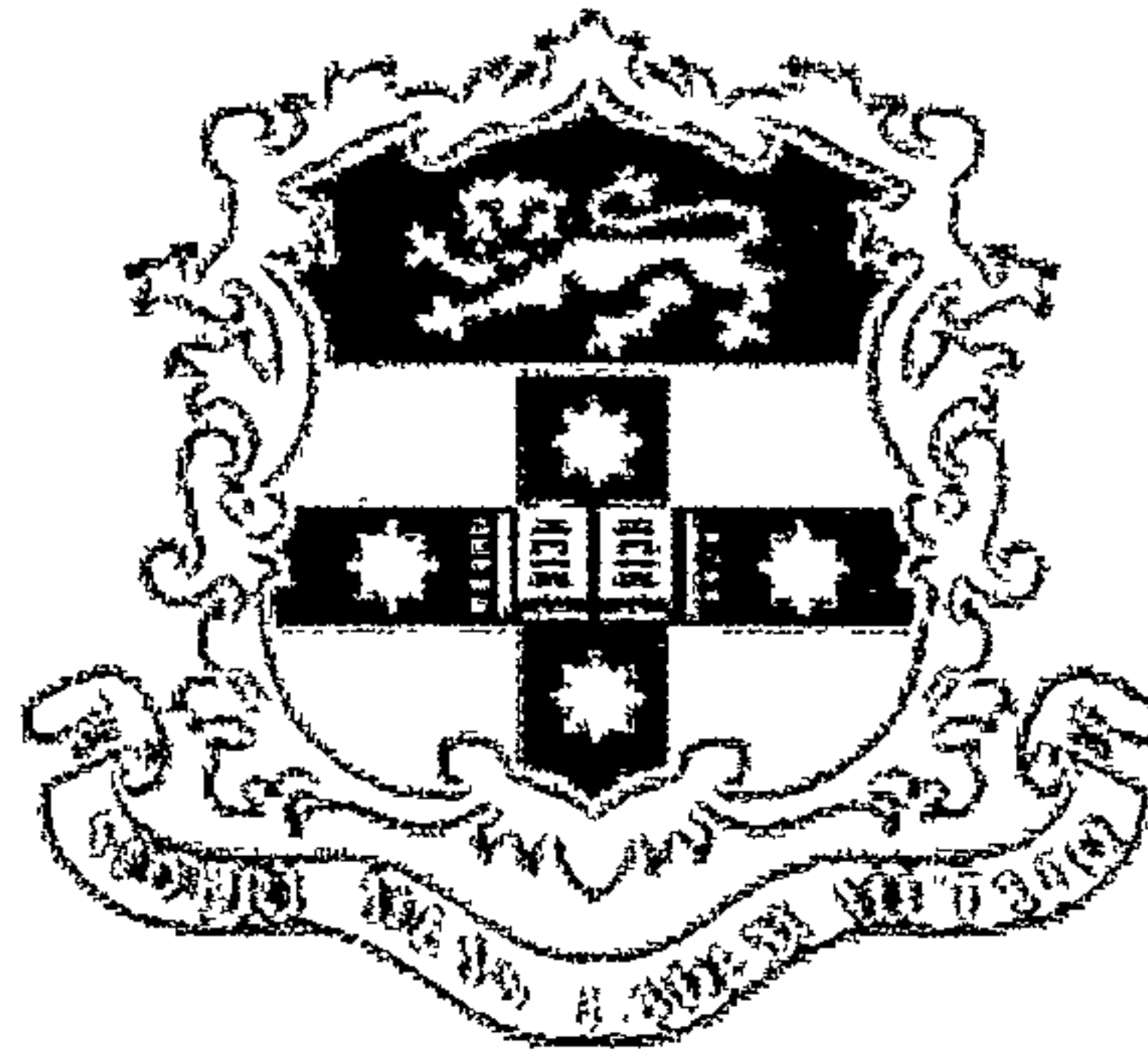
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#### **4. MANUSCRIPT**



### **CHANGES IN PHYSICAL PROPERTIES OF HUMAN PREMOLAR CEMENTUM AFTER THE APPLICATION OF CONTROLLED ORTHODONTIC FORCES**



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#### 4.1 ABSTRACT

The aims of this study were divided into two parts. The first part was to evaluate hardness and elastic modulus of untreated human premolar cementum. The second part was to investigate changes of hardness and elastic modulus values of human premolar cementum after application of relatively light and heavy controlled orthodontic forces by using the Ultra-Micro Indentation System (UMIS). The sample consisted of thirty-six maxillary and/or mandibular first premolar teeth, derived from seventeen patients (nine males and eight females, mean age  $14.5 \pm 1.4$  years, range 11.7-16.4 years) who required the removal of the bilateral first premolar teeth as part of their planned orthodontic treatment. The subjects were consecutively selected and divided into two groups of nine individuals for light orthodontic force (Group I), and heavy force (Group II). For each patient, the right first premolar was moved buccally with an initial force of approximately 25 grams for Group I, and an initial force of approximately 225 grams for Group II. The left first premolars served as controls. The experiment took place over a period of four weeks. No reactivation of force was performed during this period. The experimental premolars moved  $1.33 \pm 0.56$  and  $0.89 \pm 0.60$  mm in Group I and II, respectively. After extraction, sterilized de-ionised water was used as the storage media. For the disinfection process, each sample was placed into an ultrasonic bath for a period of ten minutes and followed by 70% alcohol for a period of thirty minutes. Each tooth was then mounted with cylindrically shaped diamond bur parallel to long axis of the tooth, inserted through coronal pulp chamber. The tooth mounting with the bur was transferred to the UMIS for evaluating hardness and elastic modulus values. The root was equally marked and divided into three horizontal regions, cervical, middle and apical thirds as measured on buccal and lingual surfaces. The three horizontal regions on buccal surface were further longitudinally divided into mesial and distal segments. Two reference points on mid-



buccoenamel and mid-linguoenamel surfaces were used to allow for instrument calibration. This resulted in a total of eleven points on a tooth that were used for recording the data (6 buccal, 3 lingual and 2 enamel points). Each point traversed the preset layout of five-indentation box array. A total of 1,980 indentations were performed on enamel and cementum using a 20- $\mu$ m spherical indenter and a partial load/unload cycle, with the contact force of 5 mN and the maximum force of 500 mN, in 20 increments. The hardness values were determined as a function of penetration depth. An elastic modulus measurement was available as a by-product, in combination with Poisson's ratio. Paired *t*-test and General Linear Models (ANOVA) were used for statistical analysis. The results showed that hardness and elastic modulus of human premolar cementum gradually descend from cervical area to apical area for buccal as well as lingual surfaces, regardless of whether the application of orthodontic force or not. Apical cementum has the least hardness and elastic modulus values, and cervical cementum has the highest values. For the middle area of the root, large variation in hardness and elastic modulus values of cementum is observed. The application of orthodontic force magnitude, either relatively light or heavy force, has no effect on the hardness and elastic modulus of human premolar cementum over a period of four weeks. Gender has no effect on hardness and elastic modulus of human premolar cementum, whilst, birthplace and level of fluoride in water might be critical factors affecting the hardness and elastic modulus values.

**Keywords:** Orthodontic force, Cementum, Hardness, Elasticity, Physical properties, Ultra-Micro Indentation System (UMIS)



## 4.2 INTRODUCTION

Root resorption as an undesirable consequence of orthodontic treatment has been related to several factors of both biological variations and treatment modalities. It is clinically important to understand mechanism behind root resorption that is still unclear.<sup>1-2</sup>

Treatment variables play an important role in the occurrence of root resorption. The orthodontic force magnitude was shown to be a primary factor.<sup>3-8</sup> Light forces have long been recommended to reduce adverse tissue reactions.<sup>3,5,7-8</sup> However, Owman-Moll and co-workers in a histological study found that there was no significant difference in frequency or severity of root resorption between groups of 50-gram and 200-gram force levels.<sup>9</sup>

The association between the increased amount of root resorption and the duration of the applied force has been evaluated by some investigations.<sup>4,10-13</sup> It has been reported that treatment time had no significant effect on the severity of root resorptions.<sup>14-16</sup> Kurol *et al.*<sup>10</sup> investigated root resorption after application of a weekly controlled continuous orthodontic force of 50 grams. Fifty-six maxillary premolars in 18 boys and 38 girls (mean age 13.8 years) were moved buccally. The contralateral premolars served as controls. Histologically, the number of root resorptions of each tooth was more than 6 times higher in the test group than in the control group after 1 week of force application. After 7 weeks, the experimental teeth showed on an average more than 20 times larger mean resorbed root contour than the control teeth. Similar observation of root resorption has been reported by Kvam.<sup>13</sup> In Kvam's study, 23 teeth from untreated patients aged 10-12 years were moved by a laterally directed spring of 50-gram force. 17 teeth were used as control. All specimens were studied by



scanning electron microscope. The results showed that at the end of an experimental period of 10 days, resorption of cementum was initiated. Exposed cementum and resorbed surfaces generally became more markedly influenced with increasing observation time.<sup>13</sup>

Cementum has been described as a non-uniform mineralized connective tissue.<sup>17</sup> Compared to dentine and enamel, cementum is the least mineralized. The mineral content of cementum is approximately 65%, whereas those of dentine and enamel are 70% and 92-96% on a wet weight basis, respectively.<sup>18</sup> Cementum is found in several distinctly different types on human teeth.<sup>17</sup> Two types of cementum that have been classified according to presence or absence of cells are cellular and acellular cementum.<sup>19</sup> Cellular cementum is less mineralized and deposited around the apical third of cementum; while, acellular cementum covers the coronal two thirds of the root. Acellular cementum consists of only mineralized layers.<sup>18-19</sup>

Knowledge of physical behaviour of cementum is essential for understanding how orthodontic force stresses are distributed throughout the root surfaces and how physical properties of cementum are altered by application of orthodontic force. These properties of cementum such as hardness and elasticity may reveal important characteristics of root resorption previously unexplored in this regard. However, studies on hardness and elastic modulus of cementum have received little attention because of the experimental difficulties.

Apical cementum exhibited the least elastic modulus and hardness values.<sup>20-21</sup> The cementum at the middle third showed higher hardness and elastic modulus than that of the apical third.<sup>20-21</sup> These observations may be due to the different mineral contents of cellular cementum which is less calcified,<sup>21</sup> thus having a lower hardness and elastic modulus than the acellular cementum, which is more highly calcified. Hodgskinson *et*



*al.*,<sup>22</sup> and Brear *et al.*,<sup>23</sup> also concluded that hardness was positively correlated to the amount of mineralization in mineralized tissues.

Root resorption will occur if osteoclastic cells obtain access to the mineralized tissue by a breach in the dental cementum.<sup>24</sup> The mineralized root areas attract the resorbing cells to colonize the damaged areas of the root.<sup>25-26</sup> Therefore, it has been hypothesized that changes of hardness and elastic modulus of the cementum might be correlated with the amount of root resorption and its extent due to the alteration of level of mineral content in cementum. Malek<sup>28</sup>, and Clark<sup>29</sup> found that there was no significant statistical difference in the hardness and elastic modulus values between maxillary and mandibular premolar teeth. Sameshima and Sinclair<sup>30</sup> recently compared the amount of root resorption between maxillary and mandibular premolar teeth and found that both of maxillary and mandibular premolar teeth showed no significant difference in the amount of root resorption.

The Ultra Micro-Indentation System (UMIS)<sup>31</sup> is a nano-indentation instrument used for investigating the mechanical properties of near surface regions of materials with applications in surface engineering and in the development of surface modification processes. The UMIS is an appropriate means of measuring the physical properties of the teeth. Clark<sup>29</sup> studied the hardness and elastic modulus values of apical cementum on 32 human premolar teeth. Each sample was embedded in epoxy resin, horizontally sectioned and measured the hardness and elastic modulus values by the UMIS. Several weak points with this method of sample preparation were explained by the author. Dehydration of cementum occurred during embedding in the epoxy resin due to the exothermic effect of resin. In addition, the amount of exposed cementum surface, which was removed during the polishing procedure, was not known. The whole cemental layer might have been removed. Recently efforts have been made to establish standardised protocols for evaluation of hardness and elastic modulus of



cementum. Malek *et al.*<sup>20</sup> developed a new method for investigating the hardness and elastic modulus of human cementum along the root surface on a minimally prepared tooth. With this approach, the sample can be tested without the necessity of sectioning and embedding in any storage media. This methodology included a new location device which was designed to allow the repetitive measurements of a given test location for different purposes.

Storage media of samples play an important role on hardness measurement.<sup>32</sup> Since cementum contains water, the conditions under which cementum has been stored may influence the water content and therefore the result obtained. Malek<sup>28,33</sup> assessed effect of 5 different types of storage media on human premolar cementum. He concluded that sterilized de-ionized water (Milli Q<sup>®</sup>) produced the least change in physical properties of cementum for a period of nine months.

The aims of this study were divided into two parts. The first part was to evaluate hardness and elastic modulus of untreated human premolar cementum. The second part was to investigate changes of hardness and elastic modulus values of human premolar cementum after application of relatively light and heavy controlled orthodontic forces by using the Ultra-Micro Indentation System (UMIS).



### 4.3 MATERIALS AND METHODS

Thirty-six maxillary and/or mandibular first premolar teeth were collected from seventeen patients (nine males and eight females, mean age 14.5 years, range 11.7-16.4 years) who were ready for orthodontic treatment in the United Dental Hospital.\*

The selection criteria were as follows:

1. Patient who required the removal of the bilateral first premolar teeth as part of his/her planned orthodontic treatment.
2. No previous reported or observed dental treatment to the teeth to be extracted
3. No previous reported or observed trauma to the teeth to be extracted
4. No previous reported orthodontic treatment involving the teeth to be extracted
5. No past and present signs and symptoms of any periodontal disease
6. No past and present signs and symptoms of bruxism
7. No significant medical history that would affect the dentition
8. No craniofacial and dentoalveolar syndromes
9. Completed apexogenesis

The periapical radiographs with the long cone parallel technique were taken prior to the movement for assessing the completion of apexogenesis; measurements of caries and periodontal pockets were performed before the experimental period. All information related to fluoride consumption, which may affect the process of dental development, and/or physical and structural properties of hard tissues, was obtained.

### METHODS

The subjects were consecutively selected and divided into two groups. Group I, light orthodontic force of 25 grams, consisted of eight individuals; all patients have either maxillary or mandibular bilateral first premolar extraction except one patient had both maxillary and mandibular bilateral first premolar extraction. Group II, heavy



orthodontic force of 225 grams, consisted of nine individuals; all patients had either maxillary or mandibular first premolar used. For each patient, the 0.022-inch slot SPEED brackets (Strite Industries Ltd., Ontario, Canada) were bonded to maxillary and/or mandibular first premolars and first molars on both right and left sides. The first molars functioned as the anchor teeth for a sectional wire. The self-ligated SPEED brackets were selected due to their self-adjusting ligatureless design, including the highly resilient spring clip. This spring clip ensured the standard ligation, as well as a reduced level of friction.<sup>34</sup> The left first premolars served as control. Each right first premolar was moved buccally by the sectional archwire (Figures 1a-1b).

In Group I that 25-gram initial force was required, round 0.016-inch Titanium-Molybdenum Alloy (TMA<sup>®</sup>,Ormco, USA) sectional archwire was bent using a millimetric template with 40-degree activation. In Group II which 225-gram initial force was required, 0.017x0.025-inch TMA<sup>®</sup> sectional archwire was also bent using the millimetric template with 90-degree activation. TMA<sup>®</sup> wire was chosen because of its unique properties of high springback, and formability, and low stiffness.<sup>35</sup> Each spring was attached between the first molar and first premolar brackets and adjusted to fit passively to avoid unwanted moments. The sectional arch was then rechecked for a level of activation to achieve a buccally directed force of 25 grams (approximately 0.25 N) and 225 grams (approximately 2.25 N) for Group I and II, respectively. The force magnitude was measured to the nearest of 1 gram with a force gauge (Dentaurum, Germany) while the archwire was inserted into the slot of the bracket (Figure 2).

Multi-Cure Glass Ionomer cement (3M Unitek<sup>™</sup>, USA) was applied over the occlusal surfaces of mandibular first molar teeth to avoid any contact on the first premolar teeth. The experimental periods were of four weeks' duration. An interpremolar width between the central pits of both experimental and control premolars was measured and



recorded at the time of spring issue and removal. During this four-week period, no reactivation of force was performed. All manipulations of patients were performed by one operator.

At the end of the fourth week, the extraction of the first premolars was performed by one of the two surgeons; great care was taken to avoid surgical trauma to the root cementum. Upon removal, each tooth was immediately placed in an individual container of sterilized de-ionized water (Milli Q<sup>®</sup>), which has been earlier tested as an appropriate storage media.<sup>33</sup> The tooth was 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, a damp gauze swab removed the PDL with a rubbing motion, until all visible signs of the PDL were removed. The tooth was then disinfected in 70% alcohol for 30 minutes. Following the disinfection process, the tooth was immediately stored in Milli Q<sup>®</sup> at ambient room temperature ( $23\pm 1^{\circ}\text{C}$ ).

#### **SPECIMEN PREPARATION FOR UMIS MEASUREMENT**

After extraction and disinfecting procedures, a cylindrically shaped diamond bur was inserted through coronal pulp chamber into the tooth parallel to the long axis of the tooth and cemented with Multi-Cure Glass Ionomer cement (3M Unitek<sup>™</sup>, USA) to support the tooth during testing (Figure 3). The tooth with the bur was mounted on the location jig which was developed by Malek *et al.*<sup>20</sup> The apical third of the tooth was supported by an extendible arm of the jig (Figures 4-5). This specially designed jig was constructed to enable non-destructive testing of teeth in three-dimensions (3D). The jig enabled the precise identification of the location and angulation of the tooth in 3D (X,Y,Z coordinates), allowing repetitive measurements for different purposes.<sup>20,28</sup>



## INDENTATION LOCATION

As the surface of the sample was irregular, the root was equally marked and divided into three horizontal regions as measured on the buccal and lingual surfaces. The buccal surface was further divided longitudinally into mesial and distal segments. Two points on the enamel of buccal and lingual surfaces were used to allow for instrument calibration. This resulted in a total of eleven points: six points on buccal surfaces, three points on lingual surfaces and two on enamel surfaces (Figure 6).

The surface to be tested needed to be carefully selected. If root resorption occurred in correspondence with the test point, the flat neighboring position would be selected. The test point was identified using x10 and x20 video magnification within the UMIS<sup>31</sup> (Video microscope, CSIRO Australia) to avoid irregularities on the surface (Figure 7). The UMIS allowed 25  $\mu\text{m}$  working surface variation. The working length was accomplished by scanning the near region until an area was found with a similar depth of focus.

## BASIS OF TESTING

Each point traversed the preset layout, five-location box array (Figure 8). In operation, a 20- $\mu\text{m}$  diamond spherical indenter and a partial load/unload cycle were used in testing. The aim was to determine the hardness as a function of penetration depth. The biaxial elastic modulus  $[E/(1-\nu)^2]$  was also available from such observation which enabled Young's Modulus to be determined, if Poisson's ratio is known. The indenter was loaded from the contact force (5 mN) to the maximum accumulating force (500 mN), in 20 increments. The testing environment was temperature-controlled at room temperature ( $23\pm 1^\circ\text{C}$ ). Data generated with the UMIS was analyzed and imported into an Excel spreadsheet to enable storage and comparison of the results. The elastic modulus measurements presented were for depths between 2000-7000 nm. The first 2000 nm were eliminated due to irregularity of surfaces. The hardness results were



reported for depths of 7000 nm, which was the limit of the spherical form of the 20- $\mu$ m sphero-conical indenter used (Figures 9a-9b).

## STATISTICAL ANALYSIS OF DATA

A preliminary analysis was carried out on 6 buccal points of all samples. For each horizontal third of buccal surfaces (cervical third, middle third and apical third), the comparisons between distobuccal and mesiobuccal points were performed by using paired *t*-test.

Statistical analysis of the present study was divided into 2 parts. The first part of the study was to demonstrate hardness and elastic modulus of untreated human premolar cementum. The data of all control premolars in Group I and II were used. The second part was to investigate the effect of 25-gram and 225-gram orthodontic forces on hardness and elastic modulus of human premolar cementum. Due to the nature of the data, the differences (control-experiment) in the hardness and elastic modulus values between control and experimental premolars in each sample were used as the raw data for the second part analysis.

For Part I analysis, General Linear Models (ANOVA) were used to investigate the effect of position (6 positions: buccocervical, buccomiddle, buccoapical, linguocervical, linguomiddle, linguoapical positions), layer (cervical third, middle third and apical third), birthplace, sex (female and male) and subject (17 subjects) on hardness and elastic modulus of untreated human premolars.

For Part II analysis, General Linear Models (ANOVA) were used to investigate the effect of force magnitude (2 levels: 25 or 225 grams), position and subject on these differences. A significance level of  $P < 0.05$  was used, and all analyses were carried



out using SPSS version 8.0 software (Statistical Package for Social Sciences, Chicago, USA).

Prior to measuring all samples, the UMIS machine was calibrated by testing a standard specimen (Glassy carbon) with known properties.<sup>36</sup> During calibration, the UMIS machine was set up with the same force (500 mN) and a 20- $\mu$ m spherical indenter as the experiment design. The Poisson's ratio (0.17)<sup>22</sup> was imported into the program. The penetration depth pattern from calibration was compared to that of the reference data.<sup>36</sup> The result did not show any significant difference.

Method error for the experiment was analyzed by calculating the mean absolute percentage error of 10 randomly selecting points. The results showed that mean absolute percentage error of hardness and elastic modulus were 10% and 18%, respectively.

#### 4.4 RESULTS

During a period of four weeks, the experimental premolars of Group I and II moved  $1.33 \pm 0.56$  and  $0.89 \pm 0.60$  mm, respectively. The results of the preliminary analysis revealed that there was no statistically significant difference in the hardness and elastic modulus between mesiobuccal and distobuccal locations on each horizontal level third of all samples; therefore, the averages of both were used in the next step of analysis (Tables I a-d).

The result for the hardness and elastic modulus of enamel and cementum are presented in Table II. Since the enamel was considered for the reference purpose only, the values of hardness and elastic modulus of enamel were not included in all the analyses.



For Part I analysis, the results showed that there was statistically significant difference in hardness and elastic modulus between position, birthplace, layer and subjects. Gender did not show any significant difference. The pairwise comparisons in hardness and elastic modulus between 6 positions of untreated human premolars were presented in Tables III a-b. The findings of the present study revealed that there was no significant difference of hardness and elastic modulus between linguocervical, linguomiddle and linguoapical positions. For the buccal positions, the buccocervical position had statistically significant difference in hardness and elastic modulus from buccoapical position. There was large variation in hardness and elastic modulus at buccomiddle position. The pairwise comparisons in hardness and elastic modulus between 3 horizontal layers of untreated human premolars were presented in Tables IV a-b. There was significant difference between elastic modulus of cervical third, middle third and apical third. The hardness of cervical third was similar in evidence as the middle third, but significant difference from apical third.

For Part II analysis, the differences in hardness and elastic modulus between control and experimental teeth were referred as 'deltahardness' and 'deltaelasticity', respectively. Data was first divided into two groups: force application (including 25 and 225 gram force levels) and control groups. The effect of application of orthodontic force on hardness and elastic modulus was assessed by using the paired *t*-test. If the mean values of deltahardness and deltaelasticity were equal to zero, the null hypotheses would be accepted. The result showed that the mean values were close to zero (deltahardness = -0.556 and deltaelasticity = 0.139); therefore, the application of either 25-gram or 225-gram orthodontic force magnitudes had no statistically significant effect on the hardness and elastic modulus of cementum (Table V).



When deltahardness and deltaelasticity between 25-gram and 225-gram force groups were compared, the result showed that there were similar amounts of changes on both the hardness and elastic modulus for all the 6 root positions, and for both force magnitude groups. For the subject, there was no significant difference between subjects in deltahardness, but significant differences in deltaelasticity (Tables VI and VII and figures 10-11).

#### 4.5 DISCUSSION

The mechanism and aetiology of root resorption, despite have been investigated extensively, are not yet fully understood. Knowledge of physical behaviour of cementum is essential for understanding how orthodontic mechanical stresses are distributed throughout the root surfaces and how physical properties of cementum are altered by application of orthodontic force. These properties of cementum such as hardness and elastic modulus may reveal important characteristics of root resorption previously unexplored in this regard. However, studies on these basic properties have received little attention, possibly because of the experimental difficulties.

In consideration of the hardness data, the explanations of the differences attained in various studies<sup>21,27-29</sup> were those relating to the geometry of the indenters and experimental design. Hardness is not a fundamental property.<sup>37</sup> It has no quantitative value except in terms of a given load applied in relation to the contact area, generated in a specified manner for a specific duration and a specified penetration shape. Therefore, taking this into consideration; different values can be expected from different testing designs.

In the mineralising tissues, fluoride is incorporated within the interior of the mineral crystallites as an integral part of the crystal lattice, causing an alteration of physical



properties of mineralised tissues.<sup>38-39</sup> Von Der Fehr<sup>40</sup> and Weatherell *et al.*,<sup>41</sup> indicated that hardness and elastic modulus of tooth surface could be affected by exposure to the oral environment such as fluoride intake. In the present study, all patients were living in the same area and had no fluoride supplementation. However, 6 out of 17 subjects had been migrated from outside areas. The history related to their fluoride intake is not clear. As a result, this might have been affecting the mineral content of cementum and possibly, its hardness and elastic modulus, accordingly.

Two types of cementum that have been classified according to presence or absence of cells are cellular and acellular cementum.<sup>19</sup> Cellular cementum is less mineralized and deposited around the apical third of cementum; while, acellular cementum covers the coronal two thirds of the root. Acellular cementum consists of only mineralized layers.<sup>18-19</sup>

The force magnitude of 50 grams was recommended as the optimal force level when buccal tipping movement of premolars was desired.<sup>9,42-43</sup> Darendeliler *et al.*,<sup>44</sup> with the study of the drum spring canine retractor which applied a constant and continuous force, mentioned that 50 grams of force was probably below the optimal force level and biological potential for upper permanent canines. In our study, therefore, the 25-gram force was used as relatively light force level and a nine-folded force of 225 grams was considered as relatively heavy force level.

The use of round versus rectangular sectional wires in Group I and II raises the question in heavy force with rectangular wire introduces bodily movement or not, which might change the stress distribution on the root surface. However, the play between 0.017x0.025 rectangular wire and 0.022" slot edgewise bracket is about 10 degrees.<sup>45</sup> This implies that the full length of buccal crown movement before torquing effect take into action will be 1.8-2.2 mm, if bracket was bonded at the mid of the



crown and centre of rotation is about one third of average 22.0 mm tooth length from root apex.<sup>46</sup> Therefore, the average amount of buccal tooth movement measured in round wire in Group I and rectangular wire in Group II were in range of possible play.

The UMIS 2000 is intended to be used as a microprobe of material properties in the surface layer. By principle of the UMIS machine, which allowed only 25  $\mu\text{m}$  working surface variation, flat surface of sample was required during indenting. However, the root surface is heterogenous and human cementum is so soft that the repeated measurement at the same point impossible. As a result, mean absolute percentage error values for both hardness and elastic modulus, 10 and 18% respectively, were considered as acceptable levels.

The findings of the part I study support that untreated apical cementum has a comparably least elastic modulus and hardness in relation to cementum at the coronal two third of root which was presented by Poolthong<sup>21</sup> and Malek<sup>28</sup>. For the buccal surface, there was definitely a trend showing that the hardness and elastic modulus gradually decrease from cervical area to apical area. There was statistically significant difference of hardness and elastic modulus between buccocervical area and bucco-apical area in untreated human premolar cementum. However, in the buccomiddle area, the elastic modulus values are similar as these values of bucco-apical area, whereas the hardness values are similar as the hardness values of bucco-cervical area. This appears to be due to the structure of cementum types. Acellular extrinsic fiber cementum, which extends from the cervical margin of the tooth and covers at least two third of the root, appears more highly mineralized than cellular intrinsic fiber cementum and mixed stratified cementum, which are confined to the apical root portions and to the furcations.<sup>47</sup> Cellular Mixed Stratified Cementum which consists of alternate layers of acellular extrinsic and cellular intrinsic fiber cementum extends variable.<sup>19</sup> Difference in chemical composition between test locations is another factor



affecting the physical properties of cementum. Malek *et al.*,<sup>33</sup> Mahoney *et al.*,<sup>48</sup>, Poolthong<sup>21</sup>, Brear *et al.*,<sup>23</sup> and Hodgkinson *et al.*,<sup>22</sup> concluded that hardness as well as elastic modulus were positively correlated with calcium mineral content. Chemical composition is known to be susceptible to oral environment such as fluoride intake.<sup>40-41</sup>

For the untreated lingual cementum, the same trend of gradually decreasing in hardness and elastic modulus from the cervical third to apical third was present, however, it did not show any significant difference of hardness and elastic modulus between cervical, middle and apical thirds. This might be due to the direction and distribution of masticatory forces.

Several previous studies compared the physical properties of dentine and cementum and found that dentine appeared to have a higher elastic modulus than cementum.<sup>21,27,32</sup> The elastic modulus of cementum was relatively low possibly because the compensation for the root movement when functioning.<sup>44</sup> Rautiola and Craig<sup>27</sup> showed that the hardness of dentine was 61-82 kg/mm<sup>2</sup> whereas the hardness of cementum was 40 kg/mm<sup>2</sup>. Poolthong<sup>21</sup> found that the elastic modulus values of dentine ranged from 17.5-22.9 GPa, whereas the hardness of dentine ranged from 0.88-1.13 GPa. From the same study, the elastic modulus and hardness of cementum were presented with 8.6-12.0 GPa and 0.57-0.63 GPa, respectively. Extensive root resorption sometimes involves dentine. However, due to the operative principle of UMIS, indentation could not be performed in the resorption lacunae. Therefore, the test result of the present study may represent an underestimation of effect of orthodontic force application.

The relationship between the orthodontic force magnitude and the amount of root resorption has been studied by several researchers.<sup>3-9</sup> King and Fischlschweiger<sup>5</sup>



reported that light forces produced insignificant cemental cratering whereas intermediate or heavy forces resulted in a substantial amount of root resorption. However, Owman-Moll *et al.*<sup>9</sup> showed that the severity of root resorptions was not significantly affected by increase of the force magnitude. They speculated that heavy force application might initially be too large to express cellular reactions on the root surface. However, this higher force had influenced the root surface so that in a longer perspective when the force was reduced, due to tooth movement, extensive root resorption may take place.<sup>9</sup> From the findings of the present study, it was noted that high level of orthodontic force proved to have no influence on hardness and elastic modulus of cementum.

With both the 25-gram and 225-gram buccally directed forces, which were applied into crowns of premolar teeth, buccal crown tip would occur. When a tooth is tipped, the stress distribution in the periodontium is uneven; there is high compressive stress in the cervical and apical thirds of the ligament, and lower stress in the middle third.<sup>49</sup> On this basis, we may expect that the stress developed between the cementum and the alveolar sockets is at its maximum on the opposite side of the root apex to that of the crown (Figure 12). It has been hypothesised that the difference of stress level in different locations would influence different response of physical properties of cementum. The pairwise comparison by position of hardness in experimental teeth of both Group I and II showed that there was an alteration of hardness values in linguo-apical area, comparing to the pairwise comparison by position of hardness in control of both Group I and II (Table VIII-a). The same observation was found in elastic modulus of experiment and control premolar when pairwise comparison was performed (Table VIII-b). The findings of the present study raise in the question if the application of orthodontic force has significant effect on hardness and elastic modulus of cementum.



To evaluate the effect of relatively light and heavy orthodontic force levels on hardness and elastic modulus of human premolar cementum intraindividually, the deltahardness and deltaelasticity between 25-gram and 225-gram force groups of each position were compared, there was no statistically significant difference among all positions (Tables VI and VII). Therefore, even the application of orthodontic force appeared to affect the hardness and elastic modulus of linguo-apical area premolar because of tipping movement, the difference in elastic modulus and hardness between untreated cementum and cementum after the application of either 25 or 225 gram orthodontic force did not show a significant difference. This might be due to the duration of force application. Further study should be undertaken over effect of orthodontic force duration on changes of physical properties of human premolar cementum.

One of the main findings of the present study is that the individual variation in the hardness and elastic modulus of human premolar cementum is large. This is in agreement with the earlier studies on root resorption<sup>1,2,8-11,28</sup> that individual factors determined the relationship between applied force and root resorption. The major source of variation is probably not the magnitude of force alone, but also the variation in metabolic response.<sup>9</sup>

#### **4.6 CONCLUSIONS**

This study investigated the hardness and elastic modulus values of human cementum in thirty-six maxillary and/or mandibular first premolar teeth, derived from seventeen untreated adolescent patients (nine males, eight females, mean age 14.5 years) as evaluated by the Ultra-Micro Indentation System (UMIS) in regard to the application of relatively light and heavy levels of buccally directed orthodontic forces over a period of four weeks. The following conclusions were drawn:



1. Hardness and elastic modulus of human premolar cementum gradually descend from cervical area to apical area for buccal as well as lingual surfaces, regardless of the application of orthodontic force.
2. Apical cementum has the least hardness and elastic modulus values, and cervical cementum has the highest values. For the middle area of the root, large variation in hardness and elastic modulus values of cementum is observed.
3. The application of orthodontic force magnitude, either relatively light or heavy force, has no effect on the hardness and elastic modulus of human premolar cementum.
4. Gender has no effect on hardness and elastic modulus of human premolar cementum, whilst, birthplace and its fluoride level in water might be crucial factors affecting hardness and elastic modulus values.

#### **4.7 ACKNOWLEDGMENTS**

This research was partially sponsored by the Australian Society of Orthodontists Foundation for Research and Education. We would like to thank Drs. Om P Kharbanda and Pat Skinner, Faculty of Dentistry, University of Sydney for their advice with the preparation and proofreading of this work, Mr. Kenneth Tyler, Senior Technical Staff, Biomaterials Research Unit, Faculty of Dentistry, University of Sydney, for his technical support and Drs. Lisa Rix and Michael Chen, Oral Surgery department, United Dental Hospital for their assistance of extracting all premolar teeth.

\*The design of the study was approved by the Ethics Committee of the Central Sydney Area Health Service (Ethical approval - Project 5/98 of Human Ethics Review Committee).



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**Table I-a** Comparison of elastic modulus and hardness between distobuccal and mesiobuccal locations on each level third of control 25-gram subgroup\*

| <i>Parameters</i> | <i>Location</i>   | <i>Cervical 1/3</i> | <i>Middle 1/3</i> | <i>Apical 1/3</i> |
|-------------------|-------------------|---------------------|-------------------|-------------------|
| Elastic modulus   | Mesiobuccal       | 4.89±2.22           | 2.85±2.31         | 1.81±1.17         |
|                   | Distobuccal       | 4.90±2.77           | 3.17±2.10         | 2.44±2.01         |
|                   | Significant level | 0.992               | 0.764             | 0.425             |
|                   |                   | NS                  | NS                | NS                |
| Hardness          | Mesiobuccal       | 0.33±0.08           | 0.24±0.06         | 0.17±0.08         |
|                   | Distobuccal       | 0.31±0.10           | 0.26±0.07         | 0.20±0.06         |
|                   | Significant level | 0.732               | 0.419             | 0.367             |
|                   |                   | NS                  | NS                | NS                |

\* Mean± Standard deviation (Unit= GPa)

**Table I-b** Comparison of elastic modulus and hardness between distobuccal and mesiobuccal locations on each level third of control 225-gram subgroup\*

| <i>Parameters</i> | <i>Location</i>   | <i>Cervical 1/3</i> | <i>Middle 1/3</i> | <i>Apical 1/3</i> |
|-------------------|-------------------|---------------------|-------------------|-------------------|
| Elastic modulus   | Mesiobuccal       | 3.39±1.67           | 2.98±1.77         | 2.03±1.05         |
|                   | Distobuccal       | 3.68±1.43           | 2.52±0.99         | 2.09±1.61         |
|                   | Significant level | 0.699               | 0.506             | 0.922             |
|                   |                   | NS                  | NS                | NS                |
| Hardness          | Mesiobuccal       | 0.23±0.06           | 0.22±0.05         | 0.17±0.04         |
|                   | Distobuccal       | 0.26±0.07           | 0.23±0.08         | 0.16±0.06         |
|                   | Significant level | 0.374               | 0.754             | 0.892             |
|                   |                   | NS                  | NS                | NS                |

\* Mean± Standard deviation (Unit= GPa)



**Table I-c** Comparison of elastic modulus and hardness between distobuccal and mesiobuccal locations on each level third of experimental 25-gram subgroup\*

| <i>Parameters</i> | <i>Location</i>   | <i>Cervical 1/3</i> | <i>Middle 1/3</i> | <i>Apical 1/3</i> |
|-------------------|-------------------|---------------------|-------------------|-------------------|
| Elastic modulus   | Mesiobuccal       | 4.07±1.93           | 3.27±1.75         | 2.66±1.60         |
|                   | Distobuccal       | 4.11±2.28           | 3.69±2.10         | 3.00±2.15         |
|                   | Significant level | 0.97                | 0.65              | 0.705             |
|                   |                   | NS                  | NS                | NS                |
| Hardness          | Mesiobuccal       | 0.31±0.08           | 0.26±0.07         | 0.22±0.05         |
|                   | Distobuccal       | 0.28±0.07           | 0.27±0.08         | 0.21±0.08         |
|                   | Significant level | 0.423               | 0.766             | 0.741             |
|                   |                   | NS                  | NS                | NS                |

\* Mean± Standard deviation (Unit= GPa)

**Table I-d** Comparison of elastic modulus and hardness between distobuccal and mesiobuccal locations on each level third of experimental 225-gram subgroup\*

| <i>Parameters</i> | <i>Location</i>   | <i>Cervical 1/3</i> | <i>Middle 1/3</i> | <i>Apical 1/3</i> |
|-------------------|-------------------|---------------------|-------------------|-------------------|
| Elastic modulus   | Mesiobuccal       | 3.77±1.74           | 2.32±1.25         | 2.23±2.20         |
|                   | Distobuccal       | 4.16±2.64           | 2.37±1.56         | 1.57±0.78         |
|                   | Significant level | 0.718               | 0.937             | 0.412             |
|                   |                   | NS                  | NS                | NS                |
| Hardness          | Mesiobuccal       | 0.26±0.09           | 0.23±0.09         | 0.19±0.13         |
|                   | Distobuccal       | 0.30±0.08           | 0.22±0.06         | 0.17±0.03         |
|                   | Significant level | 0.326               | 0.837             | 0.712             |
|                   |                   | NS                  | NS                | NS                |

\* Mean± Standard deviation (Unit= GPa)



**Table II     The elastic modulus and hardness of all samples**

| <i>Location</i>     | <i>Group of force level</i> | <i>Control</i>          |                  | <i>Experimental</i>     |                  |
|---------------------|-----------------------------|-------------------------|------------------|-------------------------|------------------|
|                     |                             | <i>Elastic Modulus*</i> | <i>Hardness*</i> | <i>Elastic Modulus*</i> | <i>Hardness*</i> |
| Bucco-cervical 1/3  | 25 g                        | 4.90±2.43               | 0.32±0.09        | 4.09±2.05               | 0.30±0.07        |
|                     | 225 g                       | 3.50±1.51               | 0.25±0.07        | 3.97±2.18               | 0.28±0.08        |
|                     | Average                     | 4.22±2.11               | 0.28±0.08        | 4.03±2.08               | 0.29±0.08        |
| Bucco-middle 1/3    | 25 g                        | 3.01±2.15               | 0.25±0.07        | 3.48±1.89               | 0.27±0.07        |
|                     | 225 g                       | 2.75±1.41               | 0.23±0.07        | 2.34±1.37               | 0.23±0.07        |
|                     | Average                     | 2.88±1.80               | 0.24±0.07        | 2.91±1.72               | 0.25±0.08        |
| Bucco-apical 1/3    | 25 g                        | 2.12±1.63               | 0.19±0.07        | 2.83±1.85               | 0.22±0.06        |
|                     | 225 g                       | 2.06±1.32               | 0.17±0.05        | 1.90±1.64               | 0.19±0.09        |
|                     | Average                     | 2.09±1.46               | 0.18±0.07        | 2.37±1.78               | 0.20±0.08        |
| Linguo-cervical 1/3 | 25 g                        | 3.79±1.87               | 0.28±0.09        | 4.41±2.37               | 0.29±0.06        |
|                     | 225 g                       | 3.95±1.42               | 0.26±0.05        | 3.37±1.99               | 0.23±0.08        |
|                     | Average                     | 3.87±1.61               | 0.26±0.08        | 3.89±2.19               | 0.26±0.07        |
| Linguo-middle 1/3   | 25 g                        | 3.58±1.95               | 0.25±0.05        | 3.30±1.61               | 0.25±0.08        |
|                     | 225 g                       | 3.02±1.41               | 0.25±0.06        | 2.78±1.47               | 0.19±0.06        |
|                     | Average                     | 3.30±1.68               | 0.25±0.06        | 3.04±1.52               | 0.24±0.07        |
| Linguo-apical 1/3   | 25 g                        | 2.58±1.72               | 0.23±0.07        | 2.54±1.43               | 0.23±0.07        |
|                     | 225 g                       | 2.11±1.59               | 0.19±0.06        | 1.66±1.02               | 0.13±0.09        |
|                     | Average                     | 2.49±1.67               | 0.22±0.08        | 2.13±1.30               | 0.18±0.09        |
| Bucco-enamel        | 25 g                        | 35.65±12.03             | 5.71±2.31        | 24.85±13.96             | 4.40±2.17        |
|                     | 225 g                       | 30.11±8.35              | 4.73±1.56        | 30.69±11.24             | 3.62±1.68        |
| Linguo-enamel       | 25 g                        | 31.04±6.68              | 5.72±1.69        | 28.67±12.21             | 3.87±2.11        |
|                     | 225 g                       | 28.44±10.41             | 4.21±1.68        | 34.88±8.98              | 4.87±1.84        |
| Enamel              | Average                     | 31.31±9.56              | 5.06±1.92        | 29.77±11.81             | 4.15±1.87        |

\* Mean± Standard deviation (Unit= GPa)



**Tables III a**                      The pairwise comparisons of hardness between 6 positions of untreated human premolars.

| Pairwise Comparisons                         |                       |                       |            |                   |                                                     |             |
|----------------------------------------------|-----------------------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
| Dependent Variable: HARDC Hardness (control) |                       |                       |            |                   |                                                     |             |
| (I) Position on tooth                        | (J) Position on tooth | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|                                              |                       |                       |            |                   | Lower Bound                                         | Upper Bound |
| 11 buccal-top                                | 12 buccal-mid         | 3.559E-02             | .015       | .305              | -9.705E-03                                          | 8.088E-02   |
|                                              | 13 buccal-low         | .105*                 | .015       | .000              | 5.954E-02                                           | .150        |
|                                              | 21 lingual-top        | 2.339E-02             | .019       | 1.000             | -3.208E-02                                          | 7.887E-02   |
|                                              | 22 lingual-mid        | 3.018E-02             | .019       | 1.000             | -2.529E-02                                          | 8.565E-02   |
|                                              | 23 lingual-low        | 5.508E-02             | .019       | .053              | -3.873E-04                                          | .111        |
| 12 buccal-mid                                | 11 buccal-top         | -3.559E-02            | .015       | .305              | -8.088E-02                                          | 9.705E-03   |
|                                              | 13 buccal-low         | 6.924E-02*            | .015       | .000              | 2.395E-02                                           | .115        |
|                                              | 21 lingual-top        | -1.219E-02            | .019       | 1.000             | -6.766E-02                                          | 4.328E-02   |
|                                              | 22 lingual-mid        | -5.410E-03            | .019       | 1.000             | -6.088E-02                                          | 5.006E-02   |
|                                              | 23 lingual-low        | 1.950E-02             | .019       | 1.000             | -3.597E-02                                          | 7.497E-02   |
| 13 buccal-low                                | 11 buccal-top         | -.105*                | .015       | .000              | -.150                                               | -5.954E-02  |
|                                              | 12 buccal-mid         | -6.924E-02*           | .015       | .000              | -.115                                               | -2.395E-02  |
|                                              | 21 lingual-top        | -8.143E-02*           | .019       | .000              | -.137                                               | -2.596E-02  |
|                                              | 22 lingual-mid        | -7.465E-02*           | .019       | .001              | -.130                                               | -1.918E-02  |
|                                              | 23 lingual-low        | -4.974E-02            | .019       | .124              | -.105                                               | 5.727E-03   |
| 21 lingual-top                               | 11 buccal-top         | -2.339E-02            | .019       | 1.000             | -7.887E-02                                          | 3.208E-02   |
|                                              | 12 buccal-mid         | 1.219E-02             | .019       | 1.000             | -4.328E-02                                          | 6.766E-02   |
|                                              | 13 buccal-low         | 8.143E-02*            | .019       | .000              | 2.596E-02                                           | .137        |
|                                              | 22 lingual-mid        | 6.782E-03             | .021       | 1.000             | -5.727E-02                                          | 7.083E-02   |
|                                              | 23 lingual-low        | 3.169E-02             | .021       | 1.000             | -3.236E-02                                          | 9.574E-02   |
| 22 lingual-mid                               | 11 buccal-top         | -3.018E-02            | .019       | 1.000             | -8.565E-02                                          | 2.529E-02   |
|                                              | 12 buccal-mid         | 5.410E-03             | .019       | 1.000             | -5.006E-02                                          | 6.088E-02   |
|                                              | 13 buccal-low         | 7.465E-02*            | .019       | .001              | 1.918E-02                                           | .130        |
|                                              | 21 lingual-top        | -6.782E-03            | .021       | 1.000             | -7.083E-02                                          | 5.727E-02   |
|                                              | 23 lingual-low        | 2.491E-02             | .021       | 1.000             | -3.915E-02                                          | 8.896E-02   |
| 23 lingual-low                               | 11 buccal-top         | -5.508E-02            | .019       | .053              | -.111                                               | 3.873E-04   |
|                                              | 12 buccal-mid         | -1.950E-02            | .019       | 1.000             | -7.497E-02                                          | 3.597E-02   |
|                                              | 13 buccal-low         | 4.974E-02             | .019       | .124              | -5.727E-03                                          | .105        |
|                                              | 21 lingual-top        | -3.169E-02            | .021       | 1.000             | -9.574E-02                                          | 3.236E-02   |
|                                              | 22 lingual-mid        | -2.491E-02            | .021       | 1.000             | -8.896E-02                                          | 3.915E-02   |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



**Tables III b**                      The pairwise comparisons of elastic modulus between 6 positions of untreated human premolars.

| Pairwise Comparisons                            |                       |                       |            |                   |                                                     |             |
|-------------------------------------------------|-----------------------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
| Dependent Variable: ELASTC Elasticity (control) |                       |                       |            |                   |                                                     |             |
| (I) Position on tooth                           | (J) Position on tooth | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|                                                 |                       |                       |            |                   | Lower Bound                                         | Upper Bound |
| 11 buccal-top                                   | 12 buccal-mid         | 1.335*                | .375       | .008              | .216                                                | 2.454       |
|                                                 | 13 buccal-low         | 2.126*                | .375       | .000              | 1.007                                               | 3.246       |
|                                                 | 21 lingual-top        | .346                  | .459       | 1.000             | -1.025                                              | 1.717       |
|                                                 | 22 lingual-mid        | .915                  | .459       | .722              | -.456                                               | 2.286       |
|                                                 | 23 lingual-low        | 1.731*                | .459       | .004              | .360                                                | 3.101       |
| 12 buccal-mid                                   | 11 buccal-top         | -1.335*               | .375       | .008              | -2.454                                              | -.216       |
|                                                 | 13 buccal-low         | .792                  | .375       | .546              | -.328                                               | 1.911       |
|                                                 | 21 lingual-top        | -.989                 | .459       | .493              | -2.360                                              | .382        |
|                                                 | 22 lingual-mid        | -.420                 | .459       | 1.000             | -1.790                                              | .951        |
|                                                 | 23 lingual-low        | .396                  | .459       | 1.000             | -.975                                               | 1.767       |
| 13 buccal-low                                   | 11 buccal-top         | -2.126*               | .375       | .000              | -3.246                                              | -1.007      |
|                                                 | 12 buccal-mid         | -.792                 | .375       | .546              | -1.911                                              | .328        |
|                                                 | 21 lingual-top        | -1.781*               | .459       | .002              | -3.151                                              | -.410       |
|                                                 | 22 lingual-mid        | -1.211                | .459       | .139              | -2.582                                              | .159        |
|                                                 | 23 lingual-low        | -.396                 | .459       | 1.000             | -1.766                                              | .975        |
| 21 lingual-top                                  | 11 buccal-top         | -.346                 | .459       | 1.000             | -1.717                                              | 1.025       |
|                                                 | 12 buccal-mid         | .989                  | .459       | .493              | -.382                                               | 2.360       |
|                                                 | 13 buccal-low         | 1.781*                | .459       | .002              | .410                                                | 3.151       |
|                                                 | 22 lingual-mid        | .569                  | .530       | 1.000             | -1.014                                              | 2.152       |
|                                                 | 23 lingual-low        | 1.385                 | .530       | .149              | -.198                                               | 2.968       |
| 22 lingual-mid                                  | 11 buccal-top         | -.915                 | .459       | .722              | -2.286                                              | .456        |
|                                                 | 12 buccal-mid         | .420                  | .459       | 1.000             | -.951                                               | 1.790       |
|                                                 | 13 buccal-low         | 1.211                 | .459       | .139              | -.159                                               | 2.582       |
|                                                 | 21 lingual-top        | -.569                 | .530       | 1.000             | -2.152                                              | 1.014       |
|                                                 | 23 lingual-low        | .816                  | .530       | 1.000             | -.767                                               | 2.398       |
| 23 lingual-low                                  | 11 buccal-top         | -1.731*               | .459       | .004              | -3.101                                              | -.360       |
|                                                 | 12 buccal-mid         | -.396                 | .459       | 1.000             | -1.767                                              | .975        |
|                                                 | 13 buccal-low         | .396                  | .459       | 1.000             | -.975                                               | 1.766       |
|                                                 | 21 lingual-top        | -1.385                | .530       | .149              | -2.968                                              | .198        |
|                                                 | 22 lingual-mid        | -.816                 | .530       | 1.000             | -2.398                                              | .767        |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.



**Tables IV a-b**      The pairwise comparisons of elastic modulus and hardness between 3 layers of untreated human premolars.

**Pairwise Comparisons**

Dependent Variable: ELASTC Elasticity (control)

|                 |                 | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------|-----------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Tooth Layer | (J) Tooth Layer |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 1 top           | 2 middle        | 1.080*                      | .305       | .002              | .341                                                   | 1.819          |
|                 | 3 bottom        | 1.879*                      | .305       | .000              | 1.140                                                  | 2.618          |
| 2 middle        | 1 top           | -1.080*                     | .305       | .002              | -1.819                                                 | -.341          |
|                 | 3 bottom        | .800*                       | .305       | .029              | 6.067E-02                                              | 1.539          |
| 3 bottom        | 1 top           | -1.879*                     | .305       | .000              | -2.618                                                 | -1.140         |
|                 | 2 middle        | -.800*                      | .305       | .029              | -1.539                                                 | -6.067E-02     |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.

**Pairwise Comparisons**

Dependent Variable: HARDC Hardness (control)

|                 |                 | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------|-----------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Tooth Layer | (J) Tooth Layer |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 1 top           | 2 middle        | 2.599E-02                   | .013       | .125              | -4.622E-03                                             | 5.659E-02      |
|                 | 3 bottom        | 8.045E-02*                  | .013       | .000              | 4.984E-02                                              | .111           |
| 2 middle        | 1 top           | -2.599E-02                  | .013       | .125              | -5.659E-02                                             | 4.622E-03      |
|                 | 3 bottom        | 5.446E-02*                  | .013       | .000              | 2.385E-02                                              | 8.507E-02      |
| 3 bottom        | 1 top           | -8.045E-02*                 | .013       | .000              | -.111                                                  | -4.984E-02     |
|                 | 2 middle        | -5.446E-02*                 | .013       | .000              | -8.507E-02                                             | -2.385E-02     |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



**Table V** Comparison of deltahardness and deltaelasticity between control and experimental groups (Paired *t*-test)

|                                | <i>t</i> -test | Degrees<br>of<br>freedom | Sig<br>(2-tailed) |
|--------------------------------|----------------|--------------------------|-------------------|
| Deltahardness<br>(cont-expt)   | -0.556         | 161                      | 0.579             |
| Deltaelasticity<br>(cont-expt) | 0.139          | 160                      | 0.889             |

**Table VI** ANOVA for Deltahardness between position, force magnitude and subject (*Dependent Variable: deltahardness (control-experiment)*)

| <i>Source</i> |            | <i>Type III<br/>Sum of<br/>squares</i> | <i>Degrees of<br/>freedom</i> | <i>Mean<br/>squares</i> | <i>F ratio</i> | <i>P value</i> |
|---------------|------------|----------------------------------------|-------------------------------|-------------------------|----------------|----------------|
| Position      | Hypothesis | 0.066                                  | 5                             | 0.013                   | 1.991          | 0.083          |
|               | Error      | 0.979                                  | 147                           | 0.007                   |                |                |
| Force level   | Hypothesis | 0.010                                  | 1                             | 0.010                   | 1.495          | 0.223          |
|               | Error      | 0.979                                  | 147                           | 0.007                   |                |                |
| Subject       | Hypothesis | 0.052                                  | 8                             | 0.007                   | 0.994          | 0.443          |
|               | Error      | 0.979                                  | 147                           | 0.007                   |                |                |



**Table VII** ANOVA for Deltaelasticity between position, force magnitude and subject (*Dependent Variable: deltaelasticity (control-experiment)*)

| <i>Source</i> |            | <i>Type III<br/>Sum of<br/>squares</i> | <i>Degrees of<br/>freedom</i> | <i>Mean<br/>squares</i> | <i>F ratio</i> | <i>P value</i> |
|---------------|------------|----------------------------------------|-------------------------------|-------------------------|----------------|----------------|
| Position      | Hypothesis | 7.088                                  | 5                             | 1.418                   | 0.271          | 0.928          |
|               | Error      | 764.213                                | 146                           | 5.234                   |                |                |
| Force level   | Hypothesis | 3.854                                  | 1                             | 3.854                   | 0.736          | 0.392          |
|               | Error      | 764.213                                | 146                           | 5.234                   |                |                |
| Subject       | Hypothesis | 90.852                                 | 8                             | 11.356                  | 2.170          | 0.033*         |
|               | Error      | 764.213                                | 146                           | 5.234                   |                |                |

\*Significant difference ( $P < 0.05$ )



**Tables VIII a**                      The pairwise comparisons of hardness between 6 positions of experimental human premolars.

| Pairwise Comparisons                              |                       |                       |            |                   |                                                     |             |
|---------------------------------------------------|-----------------------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
| Dependent Variable: HARDE Hardness (experimental) |                       |                       |            |                   |                                                     |             |
| (I) Position on tooth                             | (J) Position on tooth | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|                                                   |                       |                       |            |                   | Lower Bound                                         | Upper Bound |
| 11 buccal-top                                     | 12 buccal-mid         | 4.333E-02             | .017       | .155              | -6.431E-03                                          | 9.310E-02   |
|                                                   | 13 buccal-low         | 8.777E-02*            | .017       | .000              | 3.801E-02                                           | .138        |
|                                                   | 21 lingual-top        | 3.457E-02             | .020       | 1.000             | -2.638E-02                                          | 9.551E-02   |
|                                                   | 22 lingual-mid        | 5.281E-02             | .020       | .160              | -8.141E-03                                          | .114        |
|                                                   | 23 lingual-low        | .109*                 | .020       | .000              | 4.769E-02                                           | .170        |
| 12 buccal-mid                                     | 11 buccal-top         | -4.333E-02            | .017       | .155              | -9.310E-02                                          | 6.431E-03   |
|                                                   | 13 buccal-low         | 4.444E-02             | .017       | .128              | -5.326E-03                                          | 9.420E-02   |
|                                                   | 21 lingual-top        | -8.766E-03            | .020       | 1.000             | -6.971E-02                                          | 5.218E-02   |
|                                                   | 22 lingual-mid        | 9.474E-03             | .020       | 1.000             | -5.147E-02                                          | 7.042E-02   |
|                                                   | 23 lingual-low        | 6.531E-02*            | .020       | .026              | 4.359E-03                                           | .126        |
| 13 buccal-low                                     | 11 buccal-top         | -8.777E-02*           | .017       | .000              | -.138                                               | -3.801E-02  |
|                                                   | 12 buccal-mid         | -4.444E-02            | .017       | .128              | -9.420E-02                                          | 5.326E-03   |
|                                                   | 21 lingual-top        | -5.320E-02            | .020       | .152              | -.114                                               | 7.744E-03   |
|                                                   | 22 lingual-mid        | -3.496E-02            | .020       | 1.000             | -9.591E-02                                          | 2.598E-02   |
|                                                   | 23 lingual-low        | 2.087E-02             | .020       | 1.000             | -4.008E-02                                          | 8.182E-02   |
| 21 lingual-top                                    | 11 buccal-top         | -3.457E-02            | .020       | 1.000             | -9.551E-02                                          | 2.638E-02   |
|                                                   | 12 buccal-mid         | 8.766E-03             | .020       | 1.000             | -5.218E-02                                          | 6.971E-02   |
|                                                   | 13 buccal-low         | 5.320E-02             | .020       | .152              | -7.744E-03                                          | .114        |
|                                                   | 22 lingual-mid        | 1.824E-02             | .024       | 1.000             | -5.214E-02                                          | 8.862E-02   |
|                                                   | 23 lingual-low        | 7.407E-02*            | .024       | .031              | 3.696E-03                                           | .144        |
| 22 lingual-mid                                    | 11 buccal-top         | -5.281E-02            | .020       | .160              | -.114                                               | 8.141E-03   |
|                                                   | 12 buccal-mid         | -9.474E-03            | .020       | 1.000             | -7.042E-02                                          | 5.147E-02   |
|                                                   | 13 buccal-low         | 3.496E-02             | .020       | 1.000             | -2.598E-02                                          | 9.591E-02   |
|                                                   | 21 lingual-top        | -1.824E-02            | .024       | 1.000             | -8.862E-02                                          | 5.214E-02   |
|                                                   | 23 lingual-low        | 5.583E-02             | .024       | .288              | -1.454E-02                                          | .126        |
| 23 lingual-low                                    | 11 buccal-top         | -.109*                | .020       | .000              | -.170                                               | -4.769E-02  |
|                                                   | 12 buccal-mid         | -6.531E-02*           | .020       | .026              | -.126                                               | -4.359E-03  |
|                                                   | 13 buccal-low         | -2.087E-02            | .020       | 1.000             | -8.182E-02                                          | 4.008E-02   |
|                                                   | 21 lingual-top        | -7.407E-02*           | .024       | .031              | -.144                                               | -3.696E-03  |
|                                                   | 22 lingual-mid        | -5.583E-02            | .024       | .288              | -.126                                               | 1.454E-02   |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



**Tables VIII b**            The pairwise comparisons of elastic modulus between 6 positions of experimental human premolars.

| Pairwise Comparisons                                 |                       |                       |            |                   |                                                     |             |
|------------------------------------------------------|-----------------------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
| Dependent Variable: ELASTE Elasticity (experimental) |                       |                       |            |                   |                                                     |             |
| (I) Position on tooth                                | (J) Position on tooth | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|                                                      |                       |                       |            |                   | Lower Bound                                         | Upper Bound |
| 11 buccal-top                                        | 12 buccal-mid         | 1.115                 | .383       | .063              | -2.851E-02                                          | 2.258       |
|                                                      | 13 buccal-low         | 1.661*                | .383       | .000              | .517                                                | 2.804       |
|                                                      | 21 lingual-top        | .133                  | .469       | 1.000             | -1.267                                              | 1.534       |
|                                                      | 22 lingual-mid        | .983                  | .469       | .568              | -.417                                               | 2.383       |
|                                                      | 23 lingual-low        | 1.923*                | .479       | .001              | .492                                                | 3.354       |
| 12 buccal-mid                                        | 11 buccal-top         | -1.115                | .383       | .063              | -2.258                                              | 2.851E-02   |
|                                                      | 13 buccal-low         | .546                  | .383       | 1.000             | -.598                                               | 1.689       |
|                                                      | 21 lingual-top        | -.982                 | .469       | .571              | -2.382                                              | .419        |
|                                                      | 22 lingual-mid        | -.132                 | .469       | 1.000             | -1.532                                              | 1.269       |
|                                                      | 23 lingual-low        | .808                  | .479       | 1.000             | -.623                                               | 2.239       |
| 13 buccal-low                                        | 11 buccal-top         | -1.661*               | .383       | .000              | -2.804                                              | -.517       |
|                                                      | 12 buccal-mid         | -.546                 | .383       | 1.000             | -1.689                                              | .598        |
|                                                      | 21 lingual-top        | -1.528*               | .469       | .021              | -2.928                                              | -.127       |
|                                                      | 22 lingual-mid        | -.678                 | .469       | 1.000             | -2.078                                              | .723        |
|                                                      | 23 lingual-low        | .263                  | .479       | 1.000             | -1.169                                              | 1.694       |
| 21 lingual-top                                       | 11 buccal-top         | -.133                 | .469       | 1.000             | -1.534                                              | 1.267       |
|                                                      | 12 buccal-mid         | .982                  | .469       | .571              | -.419                                               | 2.382       |
|                                                      | 13 buccal-low         | 1.528*                | .469       | .021              | .127                                                | 2.928       |
|                                                      | 22 lingual-mid        | .850                  | .541       | 1.000             | -.767                                               | 2.467       |
|                                                      | 23 lingual-low        | 1.790*                | .550       | .021              | .147                                                | 3.434       |
| 22 lingual-mid                                       | 11 buccal-top         | -.983                 | .469       | .568              | -2.383                                              | .417        |
|                                                      | 12 buccal-mid         | .132                  | .469       | 1.000             | -1.269                                              | 1.532       |
|                                                      | 13 buccal-low         | .678                  | .469       | 1.000             | -.723                                               | 2.078       |
|                                                      | 21 lingual-top        | -.850                 | .541       | 1.000             | -2.467                                              | .767        |
|                                                      | 23 lingual-low        | .940                  | .550       | 1.000             | -.703                                               | 2.584       |
| 23 lingual-low                                       | 11 buccal-top         | -1.923*               | .479       | .001              | -3.354                                              | -.492       |
|                                                      | 12 buccal-mid         | -.808                 | .479       | 1.000             | -2.239                                              | .623        |
|                                                      | 13 buccal-low         | -.263                 | .479       | 1.000             | -1.694                                              | 1.169       |
|                                                      | 21 lingual-top        | -1.790*               | .550       | .021              | -3.434                                              | -.147       |
|                                                      | 22 lingual-mid        | -.940                 | .550       | 1.000             | -2.584                                              | .703        |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



#### 4.10 LIST OF FIGURES

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- Figure 12** Tipping movement of tooth after the application of buccally directed force



**Figure 1-a**                      Diagram of force application in Group I

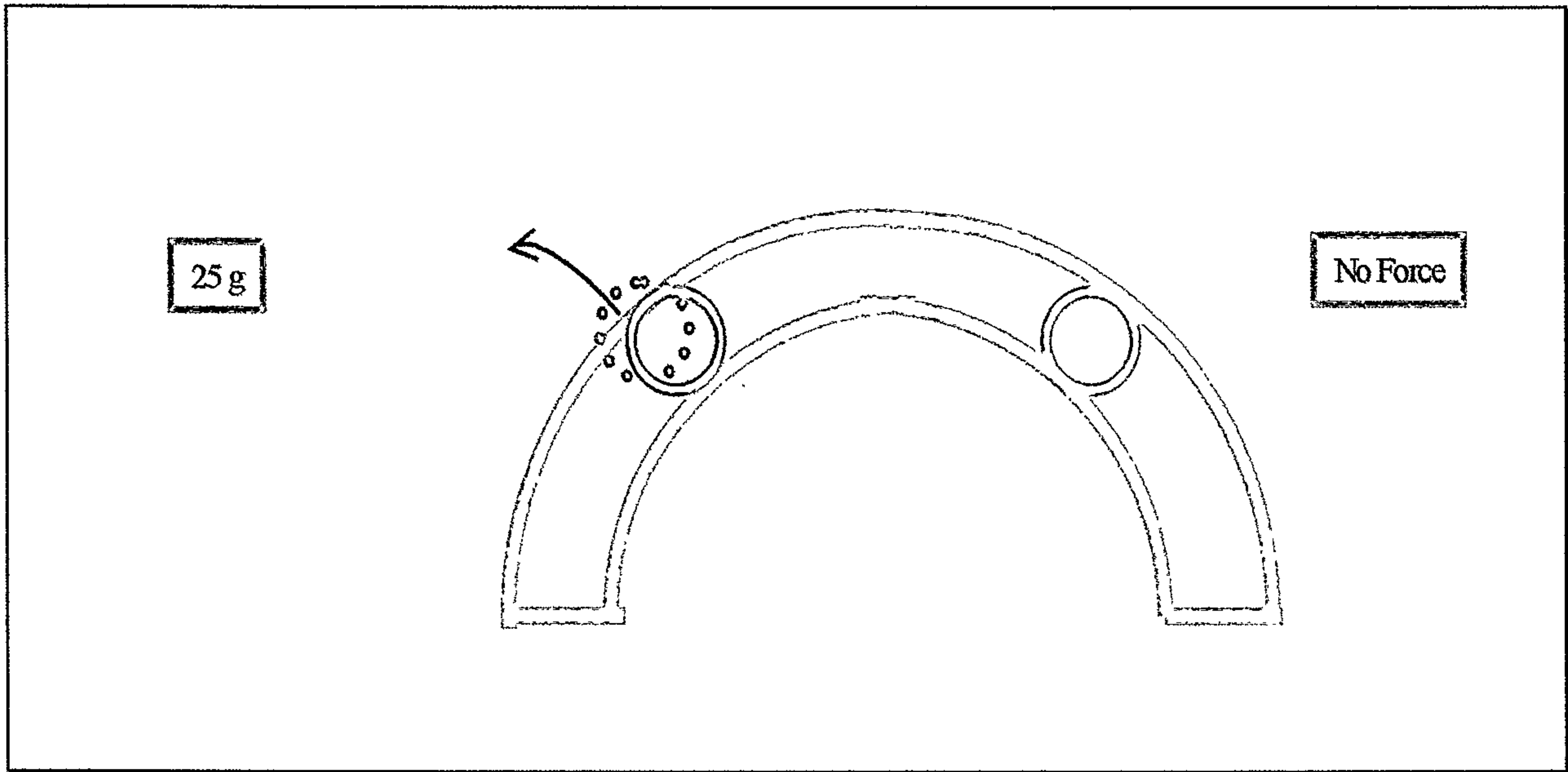


**Figure 1-b**                      Diagram of force application in Group II

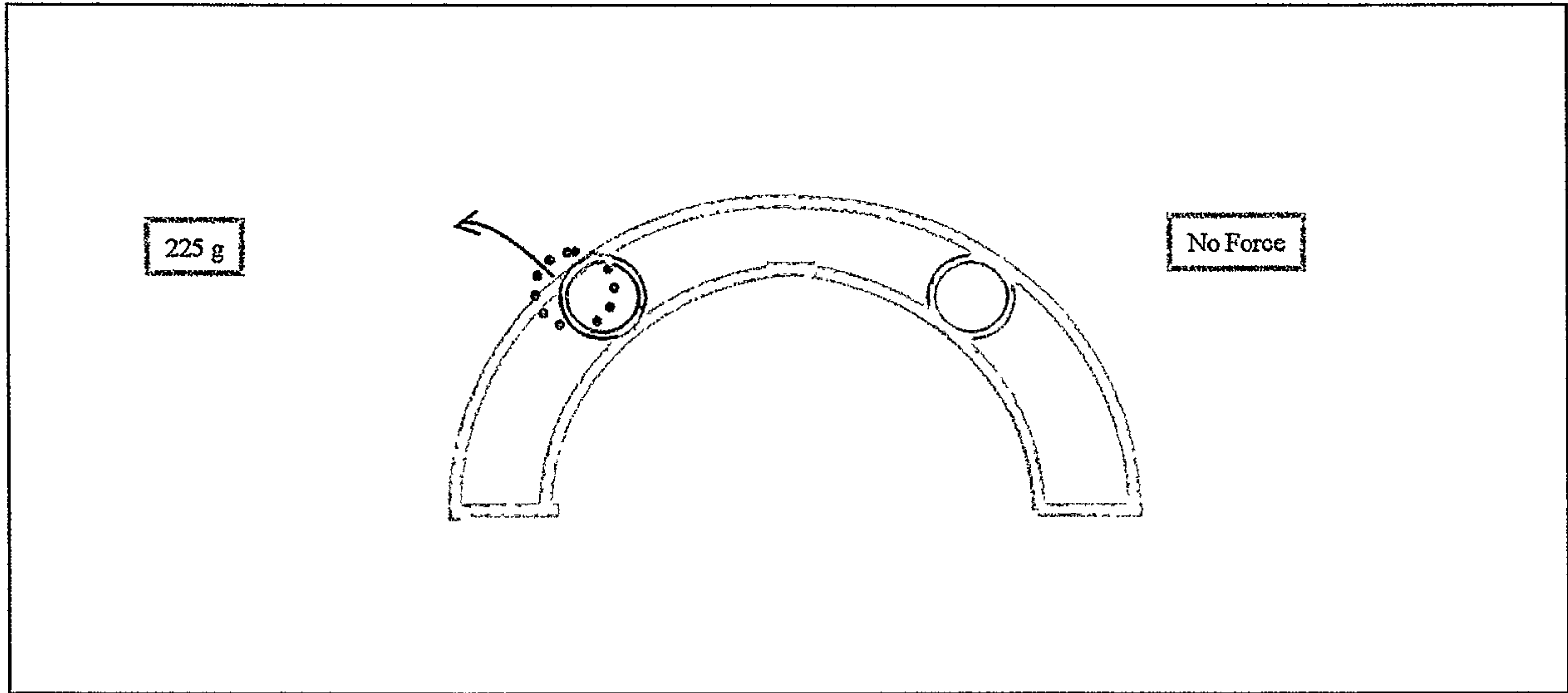




**Figure 2** Orthodontic appliance in situ: R- experimental side L control side

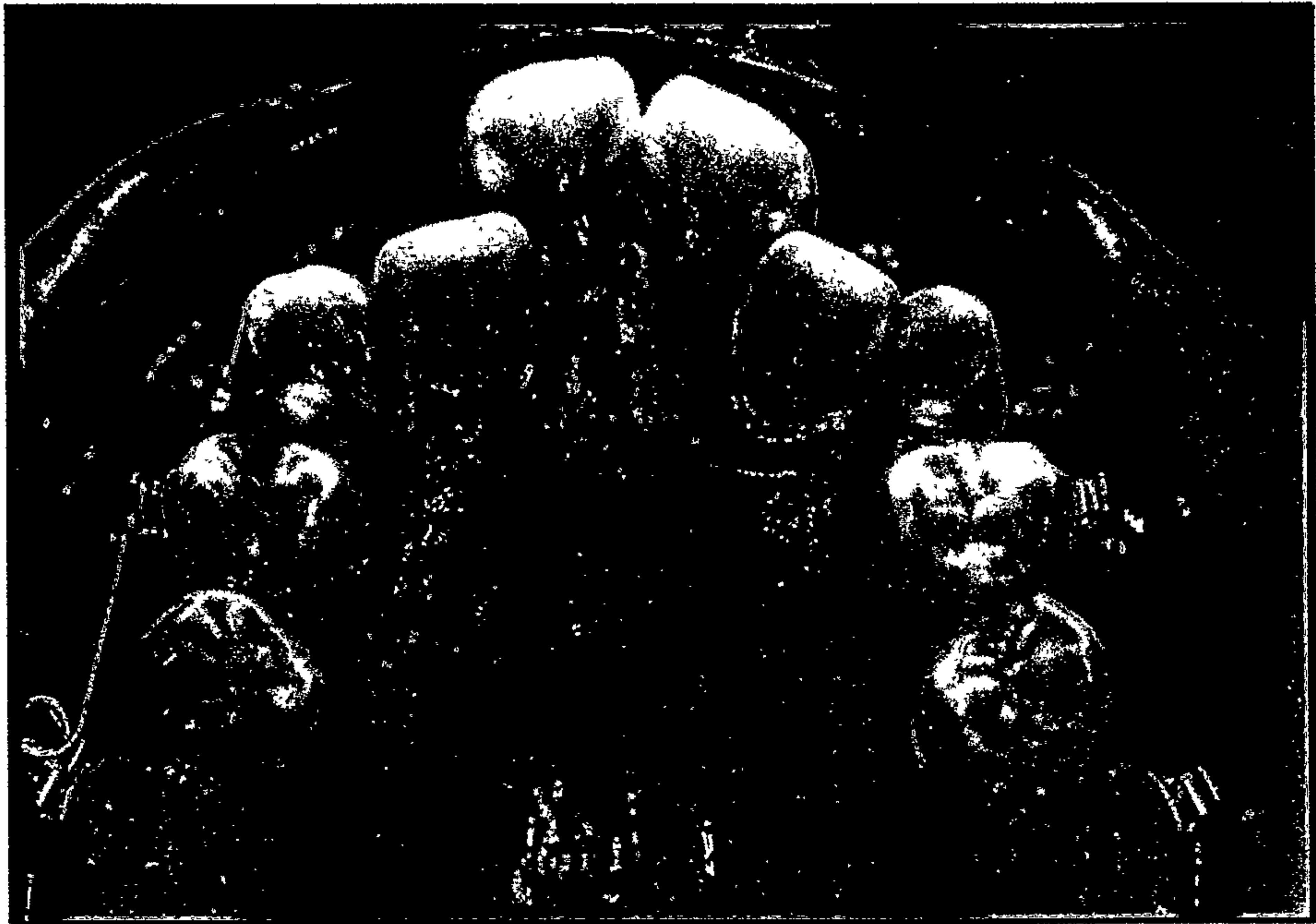
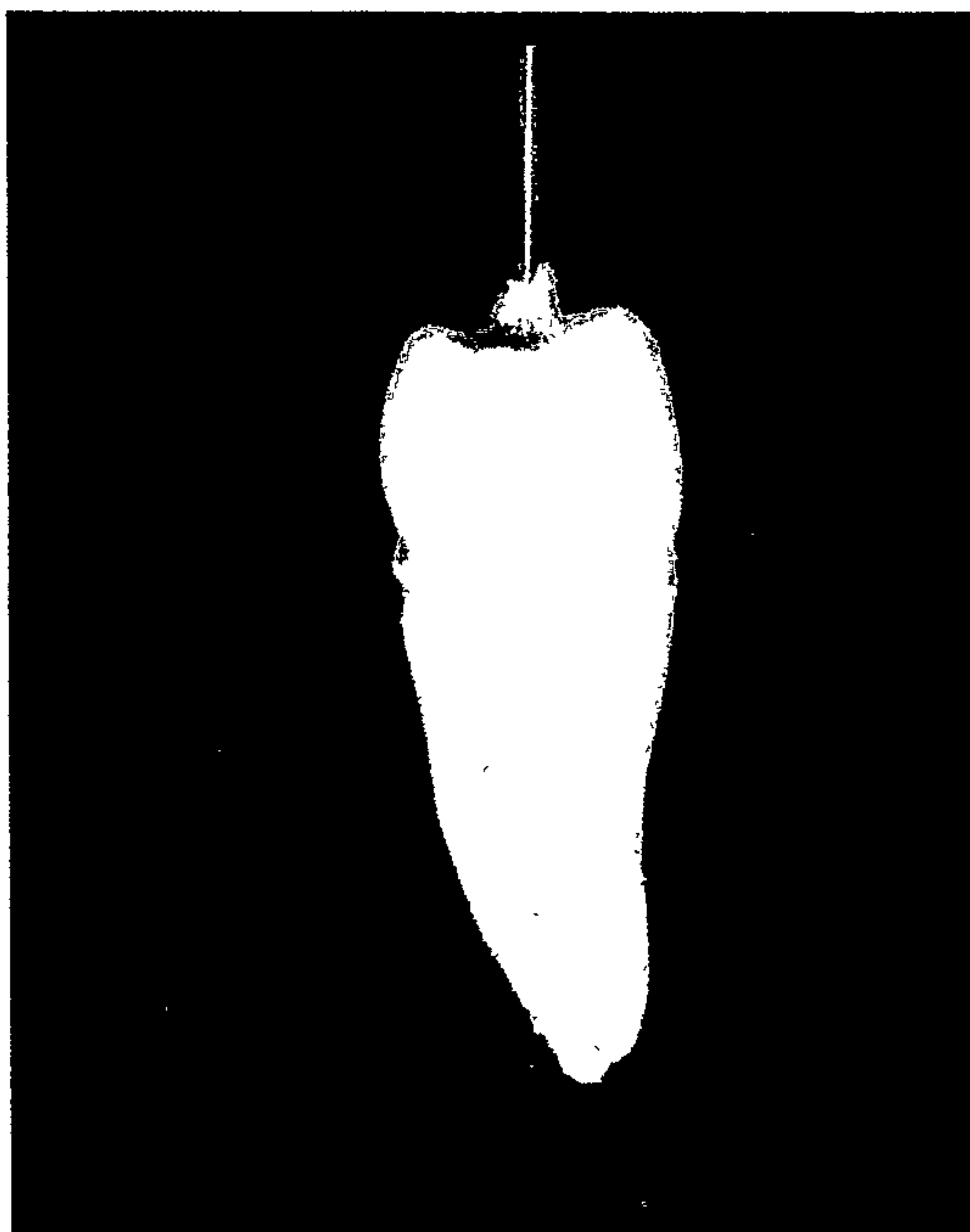




**Figure 3**

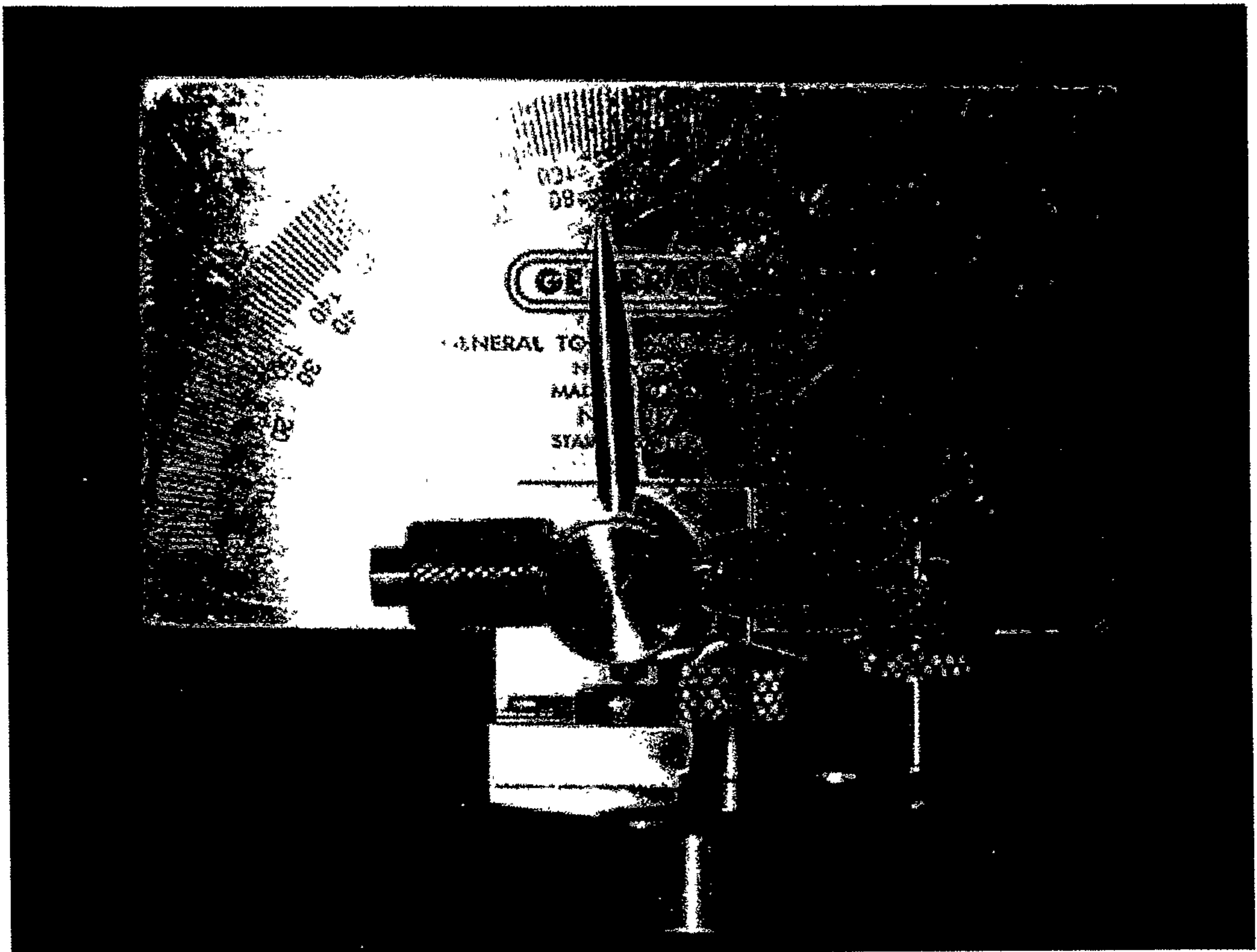
Specimen Preparation: A cylindrically shaped diamond bur was inserted into the tooth parallel to the long axis of the tooth and cemented with Multi-Cure Glass Ionomer cement.





**Figures 4**

The tooth with the bur was mounted on the location jig. The apical third of the tooth was supported by an extendible arm of the jig.





**Figures 5**

The tooth with the bur was mounted on the location jig. The apical third of the tooth was supported by an extendible arm of the jig.

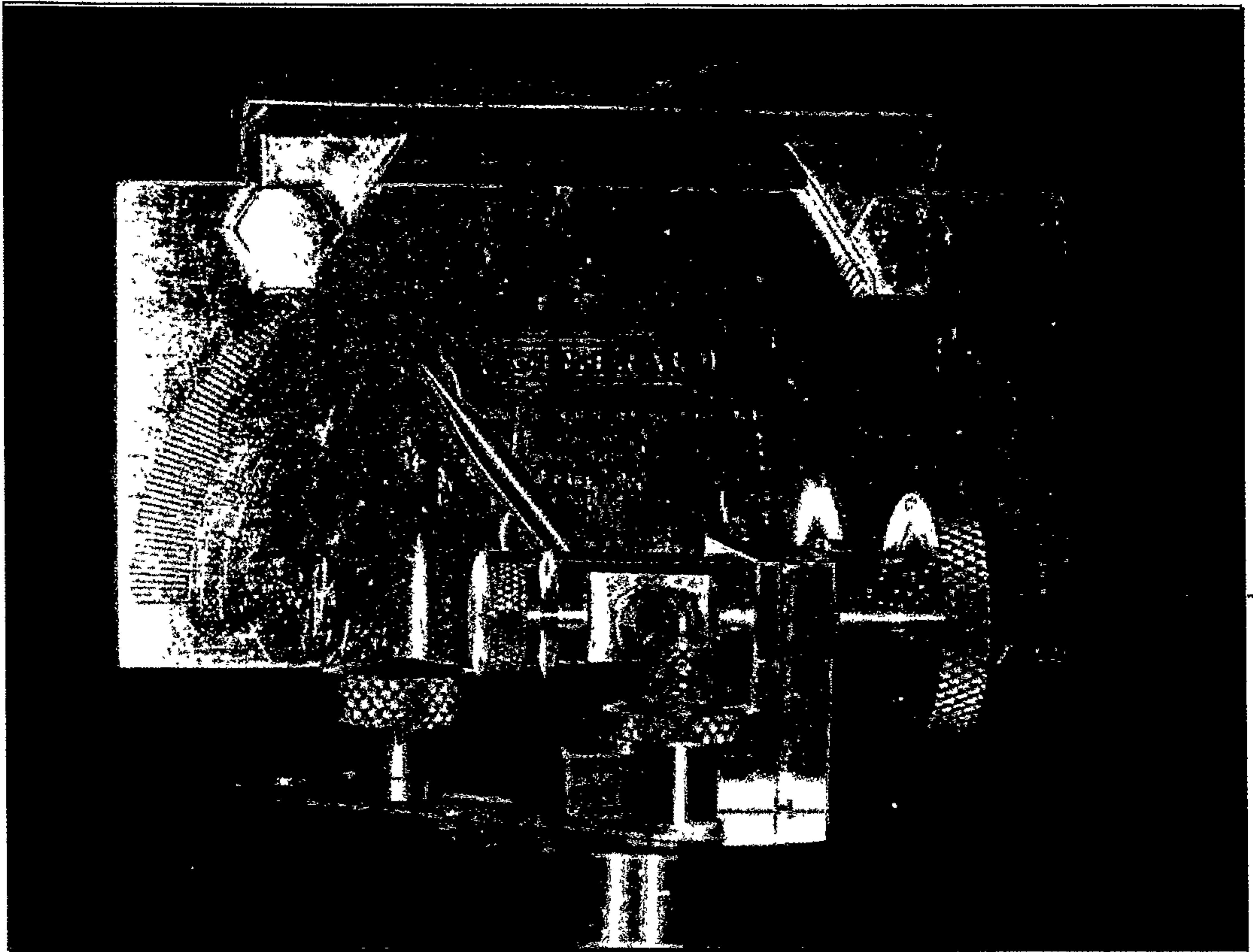




Figure 6      Locations of Indentation

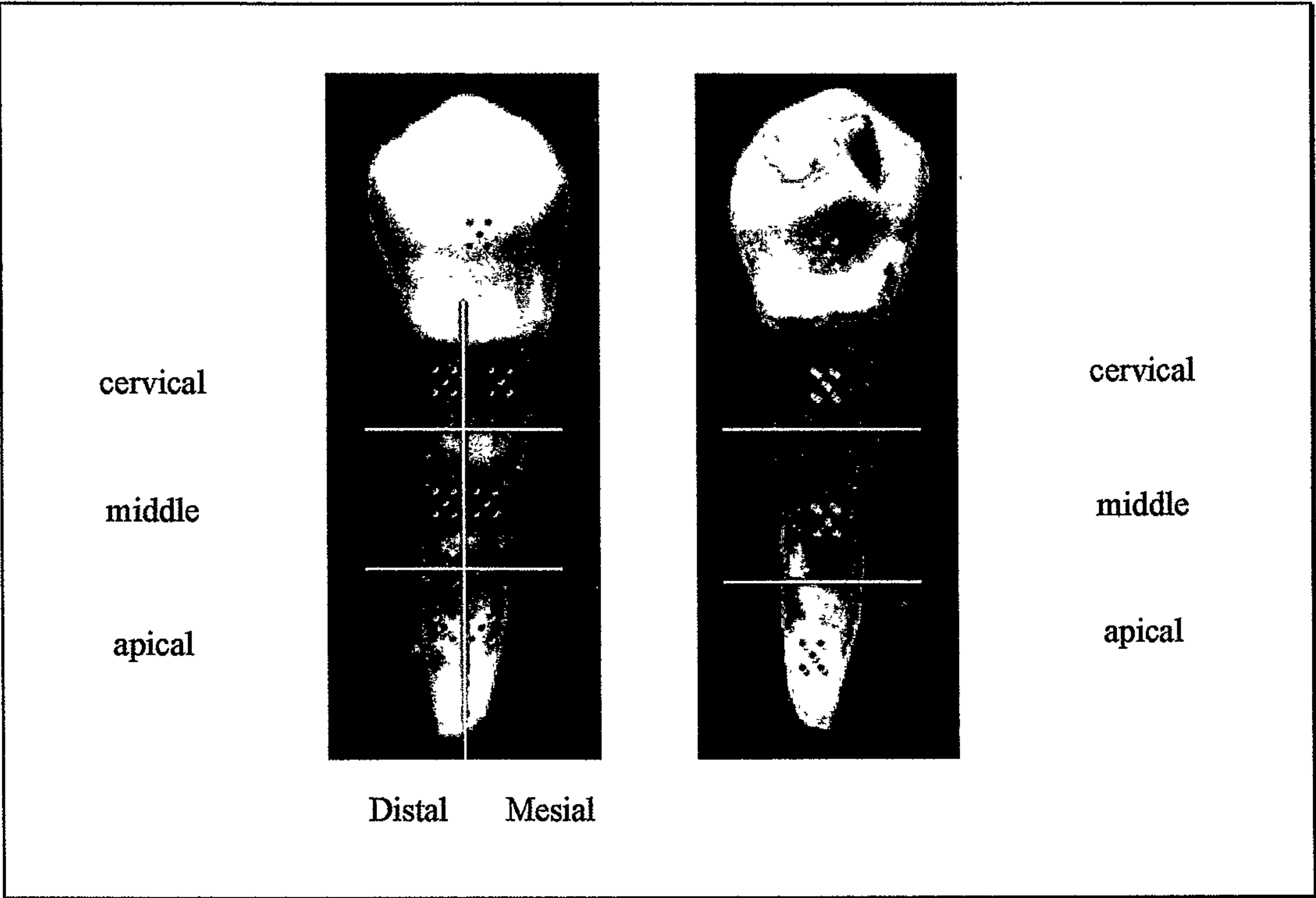




**Figure 7**      The UMIS machine and Videomicroscope

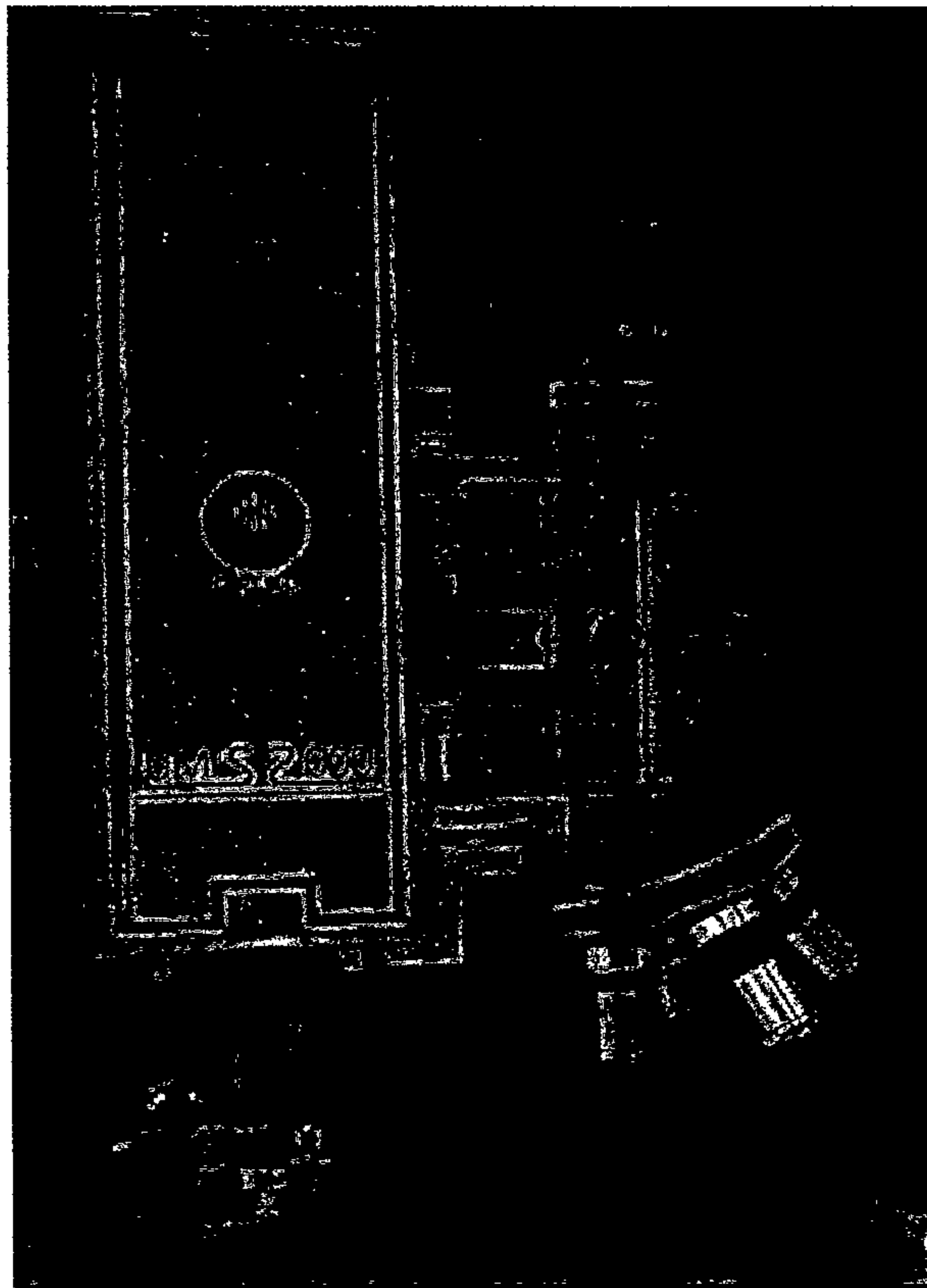




**Figure 8** The preset layout (five indentation box array) of the point.

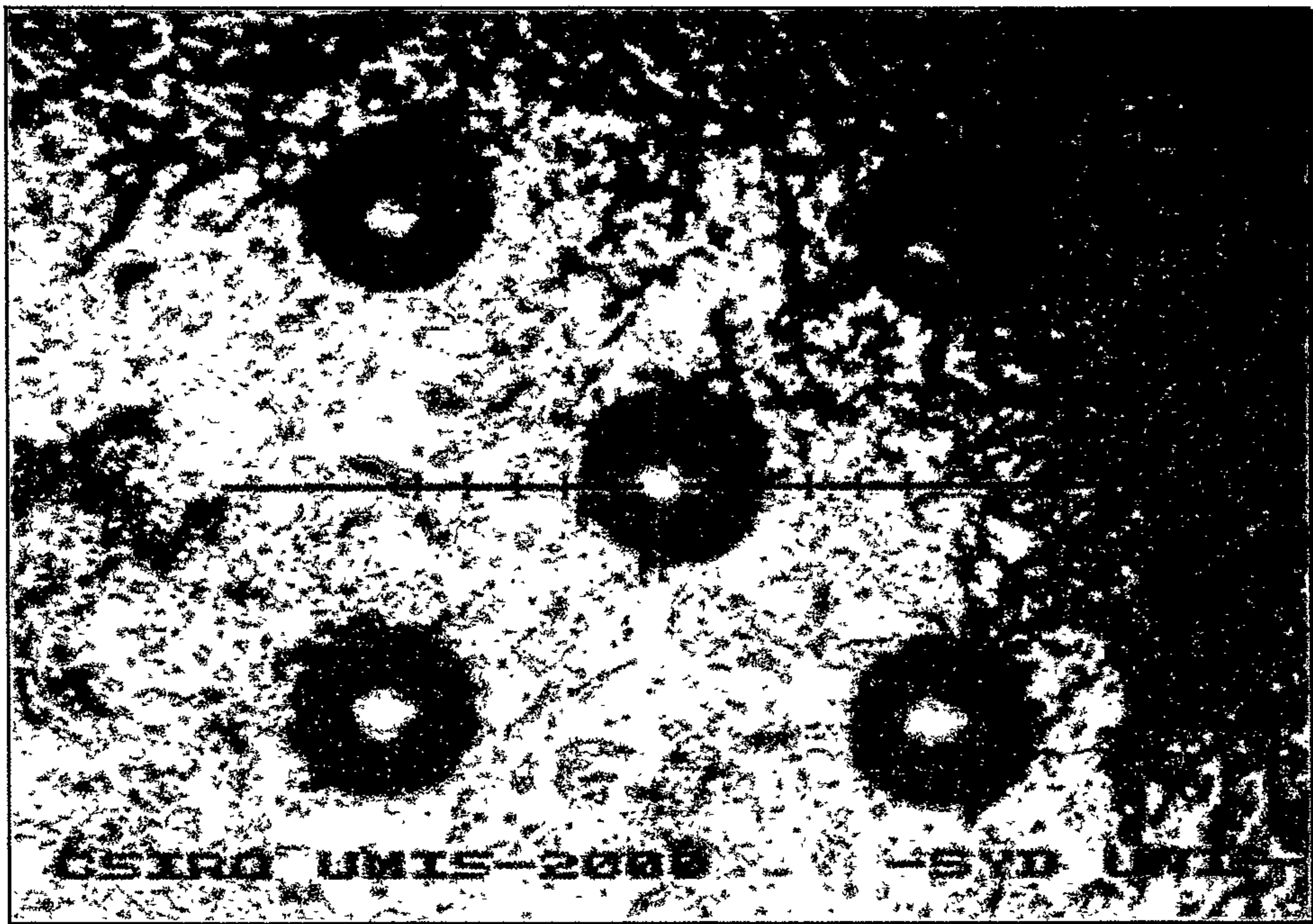




**Figure 9-a** Correlation between hardness and penetration plot in one location of one tooth (EH5-LC1)

X-axis: Penetration (nm)  
Y-axis: Hardness (GPa)

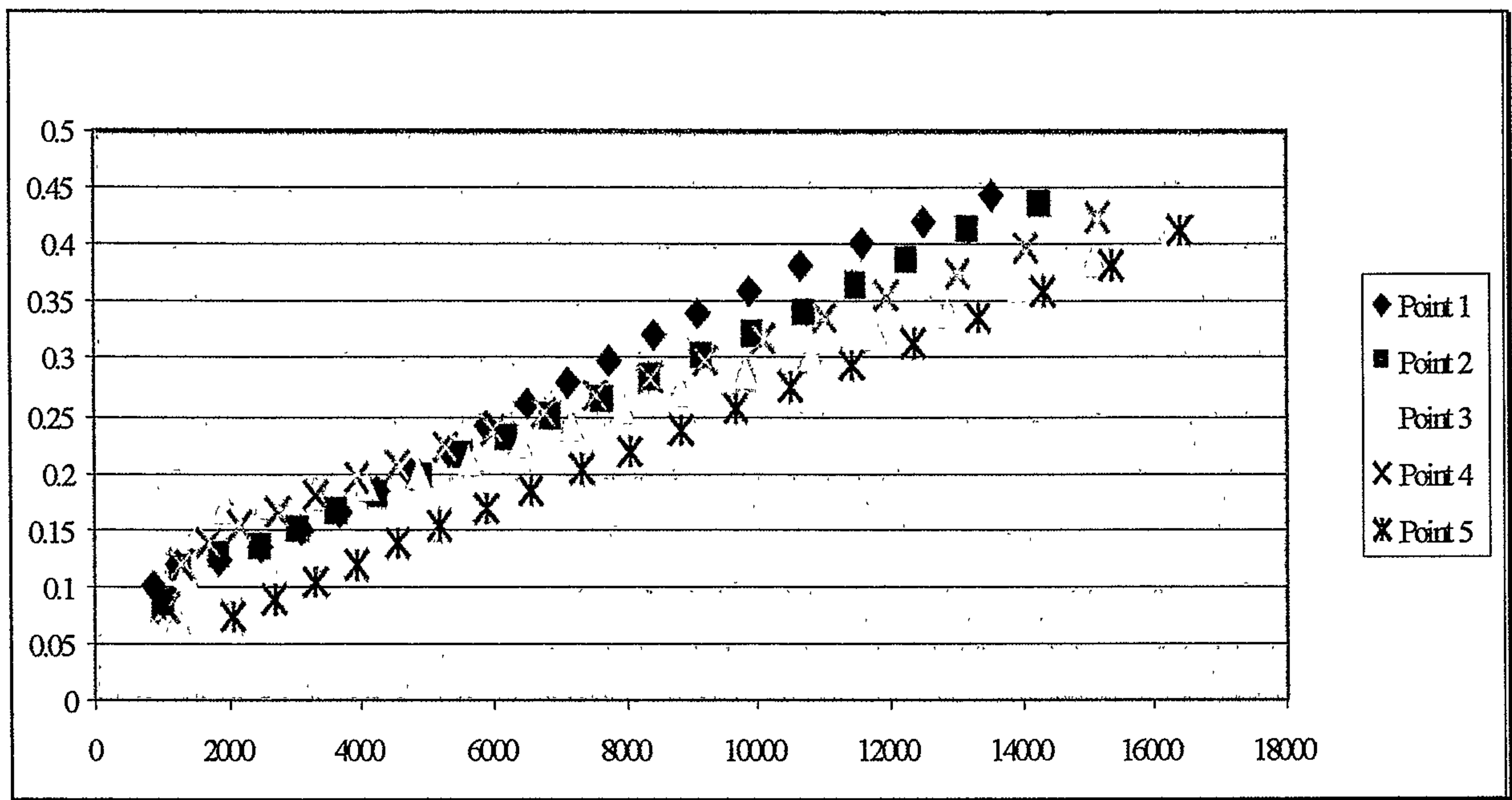




**Figure 9-b** Correlation between elastic modulus and penetration plot in one location of one tooth (EH5-LC1)

X-axis: Penetration (nm)  
Y-axis: Elastic Modulus (GPa)

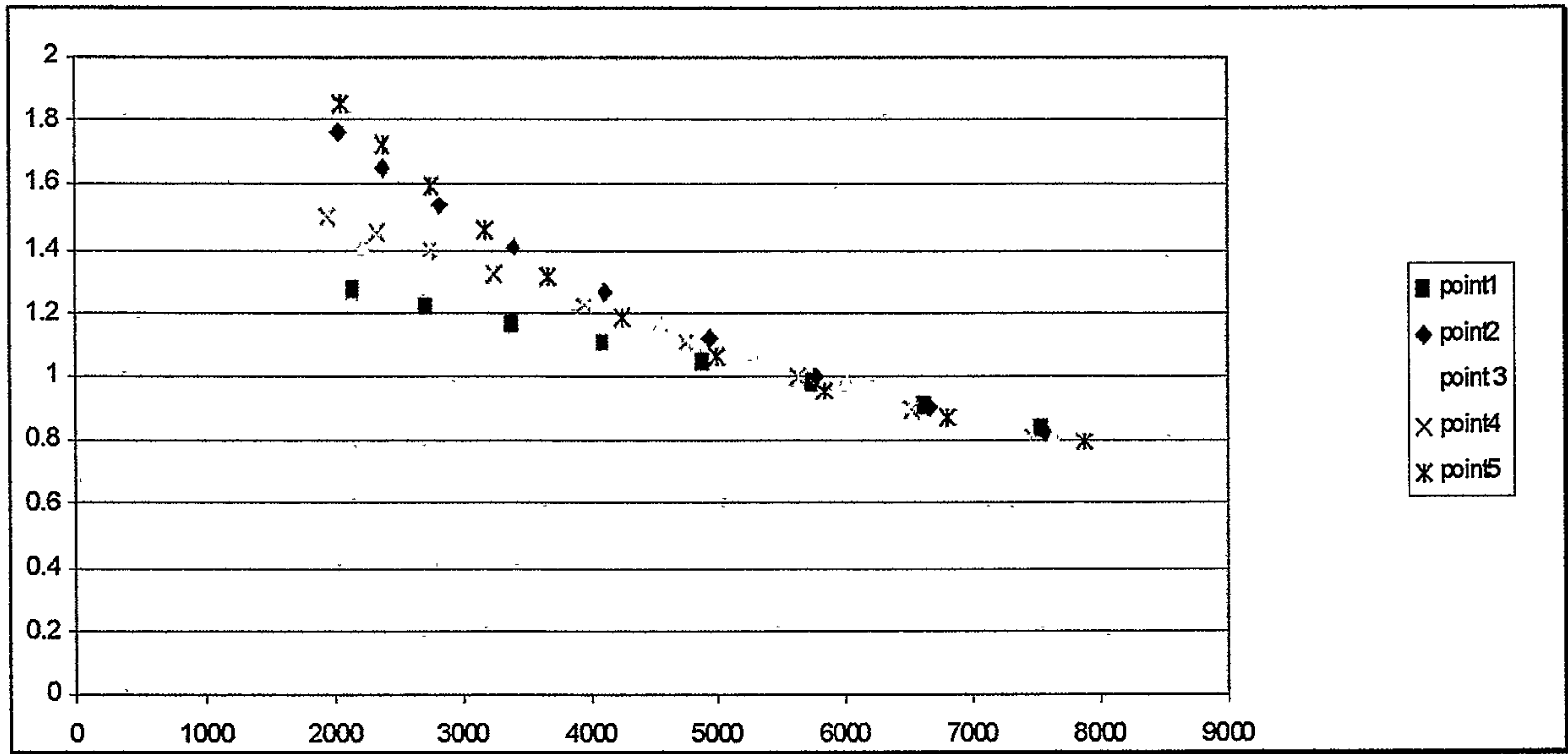




**Figure 10** Deltahardness of light and heavy force groups in buccocervical, buccomiddle, buccoapical, linguocervical, linguomiddle, linguoapical positions.

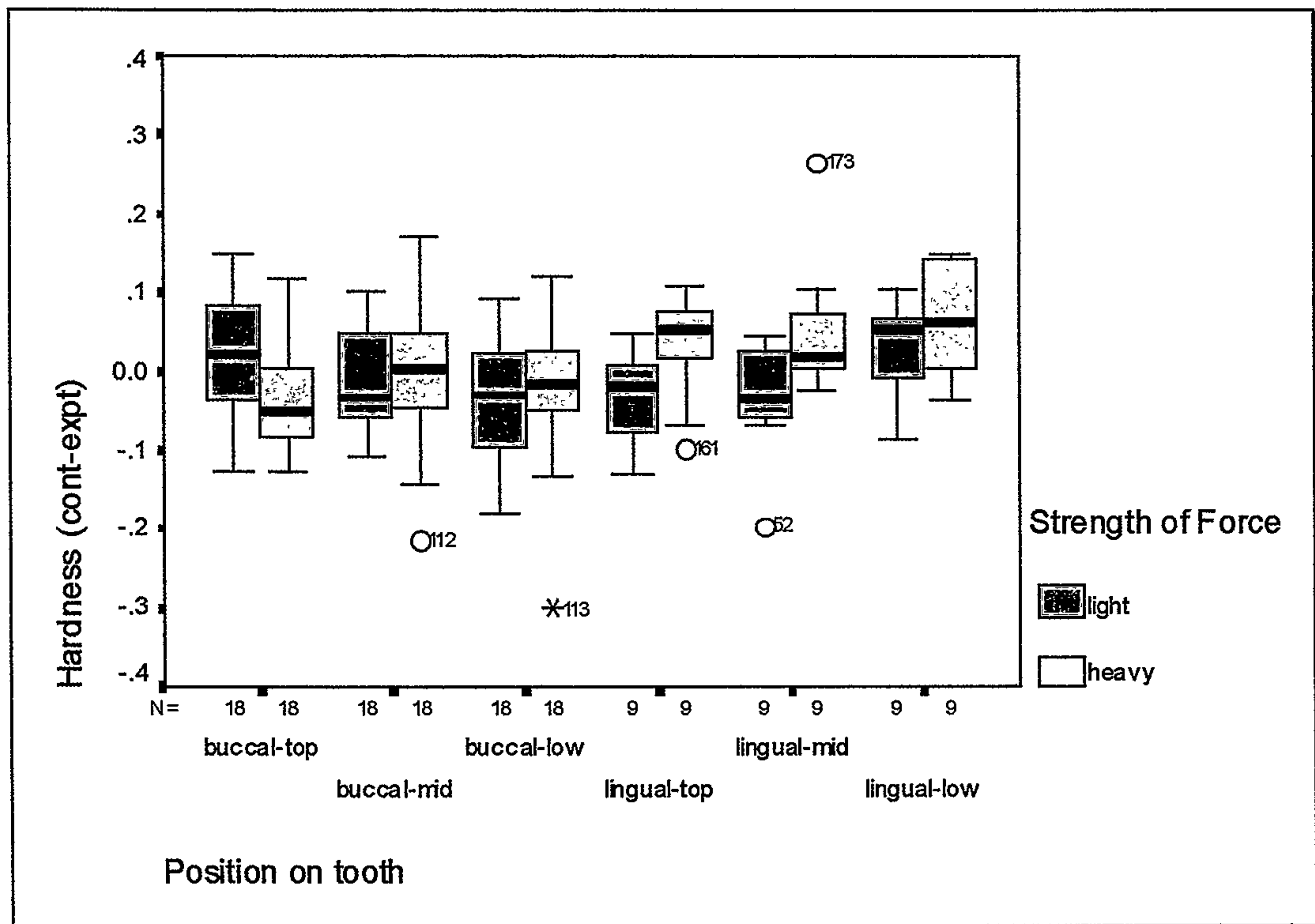




**Figure 11**                      Deltaelasticity of light and heavy force groups in buccocervical, buccomiddle, buccoapical, linguocervical, linguomiddle, linguoapical positions.

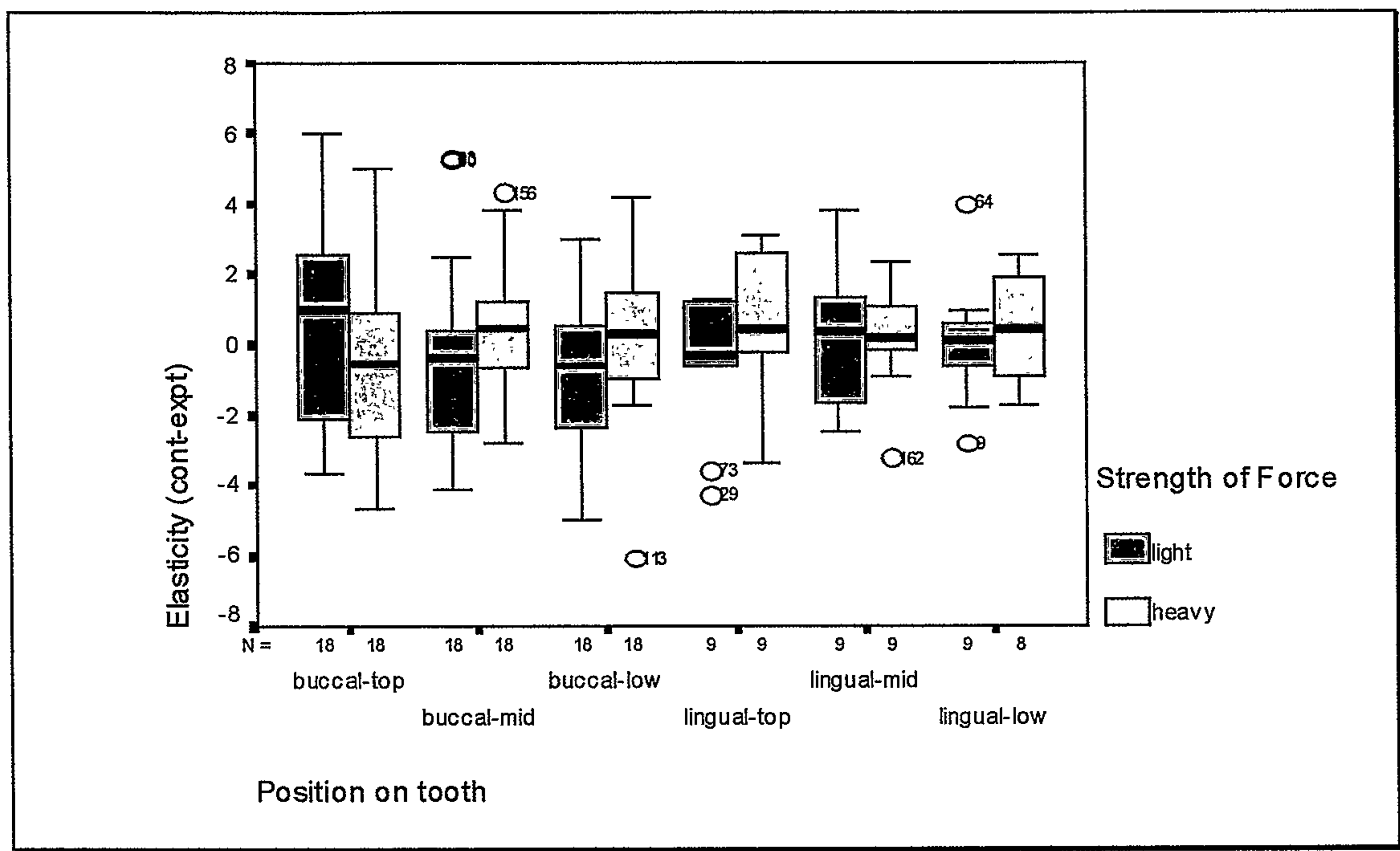
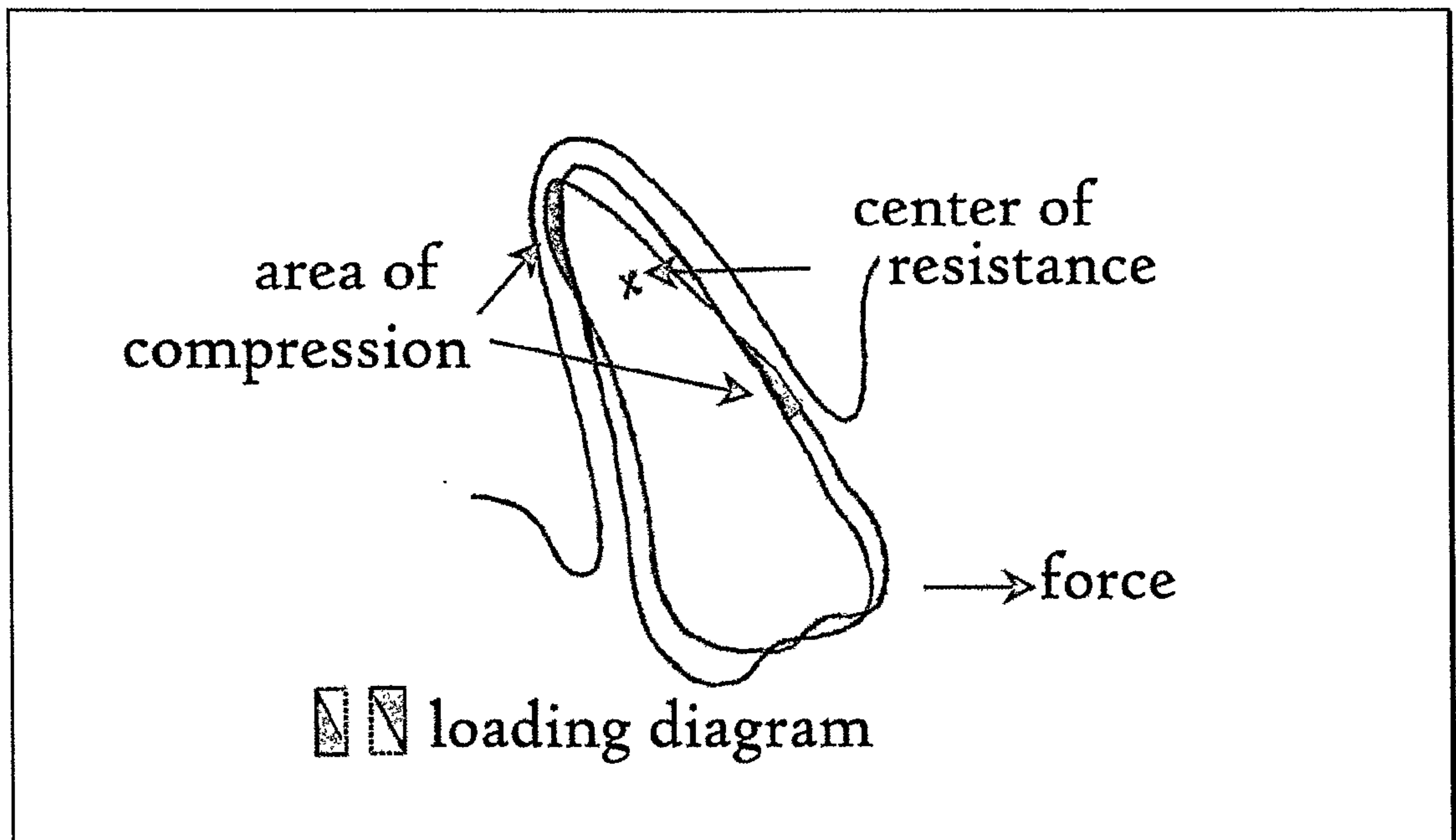




**Figure 12**                      Tipping movement of tooth after the application of buccally directed force





## 5. FUTURE APPLICATIONS

Since application of orthodontic force on the crown of the tooth leads to the stress distribution in the periodontium, compression of the periodontal membranes frequently impedes vascular circulation and cell differentiation, causing degradation of the cells and vascular structure (Thilander *et al.*, 2000). Roberts and Chase (1981) concluded that the perturbation of periodontal cells as a result of orthodontic forces might change the influx of calcium and sodium ions into the cells. As a result, changes of physical properties of human premolar cementum might be expected to occur after application of orthodontic forces. However, the results of the present study showed that there were no statistically significant changes of hardness and elastic modulus values of human premolar cementum after application of 25-gram and 225-gram orthodontic forces during a period of four weeks. This raises the question of whether orthodontic force magnitudes have a significant effect on changes of the mineral content in root cementum. Further investigation of the distribution of mineral content within cementum will provide comprehensive details on changes of physical properties of human premolar cementum after application of relatively light and heavy controlled orthodontic forces.

Duration of treatment has been considered to be main factor causing root resorption (Sameshima and Sinclair, 2001; Kurol *et al.*, 1996; Blake *et al.*, 1995; Beck and Harris, 1994; Linge and Linge, 1991; Goldin, 1989). However, no previous studies observed effect of duration of orthodontic force on physical properties of human cementum. This aspect of correlation between duration of orthodontic force application and changes of hardness and elastic modulus values of human premolar



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cementum warrants further work and may provide an insight in to the influence of orthodontic force application on the physical properties of cementum.

The effects of orthodontic tooth movement on the periodontal tissues, and the surrounding alveolar bone have been studied extensively. Histological studies have implicated necrosis as the main cause of cell death (Rygh, 1973; 1974; 1974). Kerr *et al.*, 1972 divided cell death into 2 major types: apoptosis and necrosis. Cellular necrosis, or accidental cell death, is usually the result of trauma. Apoptosis was defined as programmed cell death. Kerr *et al.*, 1972 suggested that apoptosis was an essential mechanism during development and normal tissue turnover and in response to tissue stress or tissue injury. Rana *et al.*, 2001 suggested that rate of tooth movement may be influenced by the stimulation or inhibition of apoptosis. Understand the role of apoptosis in tooth movement will further knowledge of this mechanism and possibly a control of root resorption process.



6. APPENDIX

6.1 SAMPLE INFORMATION

6.1.1 LIGHT FORCE GROUP

| #  | Name           | Sex | Age  | DOB      | Control<br># | Experi<br>ment# |
|----|----------------|-----|------|----------|--------------|-----------------|
| L1 | Molina, A      | F   | 13.4 | 12-12-86 | 14           | 24              |
| L2 | Luong, TA      | F   | 16   | 26-05-84 | 14           | 24              |
| L3 | Rajayogan, S   | M   | 14.5 | 20-11-85 | 14           | 24              |
| L4 | Adib, S        | M   | 13.5 | 22-12-86 | 14           | 24              |
| L5 | Valdivia, G    | F   | 15.8 | 31-08-84 | 14           | 24              |
| L6 | Ye, ZH         | F   | 13.6 | 10-10-86 | 44           | 34              |
| L7 | Astudillo, T   | F   | 13.8 | 17-10-86 | 14           | 24              |
| L8 | Canagasunda, R | M   | 16.1 | 25-08-84 | 44           | 34              |
| L9 | Canagasunda, R | M   | 16.1 | 25-08-84 | 14           | 24              |



6.1.2 HEAVY FORCE GROUP

| #  | Name          | Sex | Age  | DOB      | Control # | Experiment# |
|----|---------------|-----|------|----------|-----------|-------------|
| H1 | Ellem, E      | F   | 16.4 | 22-12-83 | 14        | 24          |
| H2 | Ollerenshaw,C | M   | 15.3 | 04-02-85 | 14        | 24          |
| H3 | Shen, D       | M   | 15.6 | 05-10-84 | 14        | 24          |
| H4 | Berrio, V     | F   | 12.6 | 19-11-87 | 14        | 24          |
| H5 | Johnson, N    | M   | 15.7 | 17-09-84 | 14        | 24          |
| H6 | Hamka, A      | M   | 13   | 22-08-87 | 14        | 24          |
| H7 | Guo, J        | M   | 13.2 | 23-06-87 | 44        | 34          |
| H8 | Chien, C      | M   | 11.7 | 22-02-89 | 14        | 24          |
| H9 | Adams, K      | F   | 15.1 | 11-10-85 | 14        | 24          |



## 6.2 FLUORIDE INFORMATION

### 6.2.1 LIGHT FORCE GROUP

| #  | Name         | Sex | Ethnicity  | Birthplace | Address                                                                              |
|----|--------------|-----|------------|------------|--------------------------------------------------------------------------------------|
| L1 | Molina, A    | F   | Argentina  | Sydney     | At birth-13.4 yrs: Fivedock                                                          |
| L2 | Luong, T     | F   | Vietnamese | Vietnam    | At birth-2 yrs: Vietnam<br>2-15 yrs: Canley Vale 2166<br>15-16 yrs: Home bush 2140   |
| L3 | Rajayoga, S  | M   | Sri Lanka  | England    | At birth-9 yrs: South London<br>9-15 yrs: Wentworthville 2145<br>Home bush           |
| L4 | Adib, S      | M   | *          | *          | *                                                                                    |
| L5 | Valdivia, G  | F   | Chilean    | Chile      | At birth-2 yrs: Chile<br>2-15 yrs: Harris Park                                       |
| L6 | Ye, Z        | F   | Chinese    | China      | At birth-10 yrs: Canton, China<br>10-14 yrs: Campsie 2194                            |
| L7 | Astudillo, T | F   | Chilean    | Sydney     | At birth-13 yrs: Liverpool<br>13-15 yrs: Mt. Pritchard 2170                          |
| L8 | Canagasu,R   | M   | Sri Lanka  | Sri Lanka  | At birth-14 yrs: Sri Lanka<br>14-16 yrs: Auburn 2144<br>16-17 yrs: Pendle Hills 2145 |
| L9 | Canagasu,R   | M   | Sri Lanka  | Sri Lanka  | At birth-14 yrs: Sri Lanka<br>14-16 yrs: Auburn 2144<br>16-17 yrs: Pendle Hills 2145 |



6.2.2 HEAVY FORCE GROUP

| #  | Name         | Sex | Ethnicity  | Birthplace | Address                                                                                       |
|----|--------------|-----|------------|------------|-----------------------------------------------------------------------------------------------|
| H1 | Ellem, E     | F   | Australian | Sydney     | At birth-present: Massield 2122<br>Eastwood 2122                                              |
| H2 | Ollerensh, C | M   | Australian | Sydney     | At birth-present: San Souci 2219                                                              |
| H3 | Shen, D      | M   | Chinese    | Shiang Hai | At birth-12 yrs: Shiang Hai<br>12-13 yrs: Campsie<br>13-14 yrs: Rockdell<br>14-15 yrs: Elwood |
| H4 | Berrio, V    | F   | Spanish    | Sydney     | At birth-present: Woolloomooloo<br>2011                                                       |
| H5 | Johnson, N   | M   | Australian | Sydney     | At birth-present: Wollongong                                                                  |
| H6 | Hamka, A     | M   | Lebanese   | Sydney     | At birth-7 yrs: Brigh Tonlesands<br>2216<br>7-13 yrs: Klgarah 2217                            |
| H7 | Guo, J       | M   | Chinese    | China      | At birth-6 yrs: Shutung lew<br>6-13 yrs: Belmore 2192                                         |
| H8 | Chien, C     | M   | Chinese    | Sydney     | At birth- present: Haberfiled 2045                                                            |
| H9 | Adams, K     | F   | Australian | Sydney     | At birth-present: Millers Point<br>2000 and Surry Hills                                       |



6.3 RESULT

6.3.1. HARDNESS DATA SUMMARY

| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H1   | 14    | BC1      | 0.208489 | 0.213136 | 0.180275 | 0.219059 | 0.133838 | 0.190959 |
| H1   | 14    | BC2      | 0.191985 | 0.077509 | 0.228717 | 0.116966 | 0.068628 | 0.136761 |
| H1   | 14    | BC3      | 0.077141 | 0.03626  | 0.049825 | 0.106076 | 0.090031 | 0.071867 |
| H1   | 14    | 1BC      | 0.255647 | 0.25889  | 0.30352  | 0.325069 | 0.328713 | 0.294368 |
| H1   | 14    | 2BC      | 0.301305 | 0.155359 | 0.352936 | 0.307086 | 0.268873 | 0.277112 |
| H1   | 14    | 3BC      | 0.131925 | 0.175722 | 0.165871 | 0.288098 | 0.19493  | 0.191309 |
| H1   | 14    | LC1      | 0.284709 | 0.389614 | 0.208605 | 0.326585 | 0.28653  | 0.299209 |
| H1   | 14    | LC2      | 0.266161 | 0.375597 | 0.321327 | 0.187758 | 0.374968 | 0.305162 |
| H1   | 14    | LC3      | 0.15545  | 0.188984 | 0.220253 | 0.113444 | 0.257434 | 0.187113 |
| H1   | 14    | BE1      | 1.459904 | 1.884713 | 2.484823 | 3.758849 | 3.200206 | 2.557699 |
| H1   | 14    | LE1      | 2.632696 | 1.678703 | 5.18144  | 1.00526  | 13.15437 | 4.730494 |
| H1   | 24    | BC1      | 0.182119 | 0.273969 | 0.203429 | 0.347132 | 0.30717  | 0.262764 |
| H1   | 24    | BC2      | 0.180479 | 0.213601 | 0.137646 | 0.191635 | 0.205388 | 0.18575  |
| H1   | 24    | BC3      | 0.063665 | 0.075693 | 0.163106 | 0.017871 | 0.153496 | 0.094766 |
| H1   | 24    | 1BC      | 0.129951 | 0.297501 | 0.256824 | 0.336559 | 0.345255 | 0.273218 |
| H1   | 24    | 2BC      | 0.207855 | 0.222747 | 0.248880 | 0.366166 | 0.196854 | 0.248500 |
| H1   | 24    | 3BC      | 0.26557  | 0.166694 | 0.17674  | 0.238775 | 0.234101 | 0.216376 |
| H1   | 24    | LC1      | 0.229622 | 0.315696 | 0.312562 | 0.313692 | 0.409935 | 0.316301 |
| H1   | 24    | LC2      | 0.187874 | 0.348737 | 0.30175  | 0.425661 | 0.358393 | 0.324483 |
| H1   | 24    | LC3      | 0.549886 | 0.233849 | 0.189822 | 0.35223  | 0.309652 | 0.327088 |
| H1   | 24    | BE1      | 3.667253 | 4.73007  | 3.295638 | 3.852016 | 4.286067 | 3.966209 |
| H1   | 24    | LE1      | 3.546871 | 2.766206 | 3.632180 | 3.523662 | 5.497308 | 3.793246 |
| H2   | 14    | BC1      | 0.198238 | 0.339276 | 0.359259 | 0.308697 | 0.363503 | 0.313795 |
| H2   | 14    | BC2      | 0.358108 | 0.395476 | 0.559188 | 0.446366 | 0.338067 | 0.419441 |
| H2   | 14    | BC3      | 0.367286 | 0.334677 | 0.358313 | 0.318138 | 0.999409 | 0.475564 |
| H2   | 14    | 1BC      | 0.447666 | 0.421146 | 0.305584 | 0.258332 | 0.22102  | 0.33075  |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H2   | 14    | 2BC      | 0.160457 | 0.234693 | 0.289558 | 0.223486 | 0.20031  | 0.221701 |
| H2   | 14    | 3BC      | 0.105155 | 0.096949 | 0.159463 | 0.090647 | 0.069943 | 0.104432 |
| H2   | 14    | LC1      | 0.218045 | 0.260854 | 0.184755 | 0.228392 | 0.223641 | 0.223137 |
| H2   | 14    | LC2      | 0.133987 | 0.137193 | 0.165434 | 0.165481 | 0.169881 | 0.154395 |
| H2   | 14    | LC3      | 0.0803   | 0.088521 | 0.0807   | 0.099876 | 0.0807   | 0.086019 |
| H2   | 14    | BE1      | 6.776715 | 5.854473 | 5.199063 | 6.54052  | 6.661063 | 6.206367 |
| H2   | 14    | LE1      | 5.882548 | 3.225478 | 3.508443 | 4.149469 | 6.409408 | 4.635069 |
| H2   | 24    | BC1      | 0.223478 | 0.266807 | 0.260103 | 0.247581 | 0.284392 | 0.256472 |
| H2   | 24    | BC2      | 0.153752 | 0.214084 | 0.211322 | 0.199844 | 0.241701 | 0.204141 |
| H2   | 24    | BC3      | 0.168644 | 0.196989 | 0.127023 | 0.163078 | 0.220245 | 0.175196 |
| H2   | 24    | 1BC      | 0.352796 | 0.324263 | 0.300009 | 0.338317 | 0.359671 | 0.335011 |
| H2   | 24    | 2BC      | 0.248338 | 0.278123 | 0.366336 | 0.290536 | 0.316183 | 0.299903 |
| H2   | 24    | 3BC      | 0.013747 | 0.032131 | 0.035392 | 0.034806 | 0.037198 | 0.030655 |
| H2   | 24    | LC1      | 0.266575 | 0.251113 | 0.259315 | 0.30701  | 0.296572 | 0.276117 |
| H2   | 24    | LC2      | 0.255513 | 0.208771 | 0.219252 | 0.207073 | 0.240069 | 0.226136 |
| H2   | 24    | LC3      | 0.10839  | 0.137604 | 0.112299 | 0.201495 | 0.13525  | 0.139008 |
| H2   | 24    | BE1      | 6.866229 | 7.617966 | 9.4986   | 5.721208 | 2.856978 | 6.512196 |
| H2   | 24    | LE1      | 3.622542 | 3.856448 | 6.000161 | 6.05092  | 6.240257 | 5.154066 |
| H3   | 14    | BC1      | 0.18285  | 0.190834 | 0.169235 | 0.180139 | 0.168473 | 0.178306 |
| H3   | 14    | BC2      | 0.281238 | 0.224391 | 0.067852 | 0.255786 | 0.238471 | 0.213547 |
| H3   | 14    | BC3      | 5.533477 | 0.048723 | 34.51702 | 27.22351 | 23.7676  | 18.21807 |
| H3   | 14    | 1BC      | 0.263744 | 0.2691   | 0.24141  | 0.214567 | 0.244327 | 0.24663  |
| H3   | 14    | 2BC      | 0.101681 | 0.259514 | 0.313407 | 0.29064  | 0.242741 | 0.241597 |
| H3   | 14    | 3BC      | 0.19535  | 0.204397 | 0.210796 | 0.112122 | 0.095382 | 0.163609 |
| H3   | 14    | LC1      | 0.157489 | 0.182072 | 0.130972 | 0.176363 | 0.166675 | 0.162714 |
| H3   | 14    | LC2      | 0.142444 | 0.105132 | 0.242486 | 0.199959 | 0.229533 | 0.183911 |
| H3   | 14    | LC3      | 0.154311 | 0.294841 | 0.297536 | 0.199037 | 0.235704 | 0.236286 |
| H3   | 14    | BE1      | 2.47082  | 2.362693 | 2.708293 | 3.605722 | 1.849999 | 2.599505 |
| H3   | 14    | LE1      | 1.131466 | 4.8447   | 3.143809 | 1.731645 | 1.64817  | 2.499958 |
| H3   | 24    | BC1      | 0.288453 | 0.25685  | 0.235322 | 0.278533 | 0.234794 | 0.25879  |
| H3   | 24    | BC2      | 0.123934 | 0.152916 | 0.129292 | 0.175776 | 0.20937  | 0.158257 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H3   | 24    | BC3      | 0.080455 | 0.104951 | 0.186998 | 0.193549 | 0.180625 | 0.149316 |
| H3   | 24    | 1BC      | 0.158601 | 0.147554 | 0.167617 | 0.177292 | 0.173707 | 0.164954 |
| H3   | 24    | 2BC      | 0.115678 | 0.10505  | 0.098521 | 0.113315 | 0.054767 | 0.097466 |
| H3   | 24    | 3BC      | 0.125719 | 0.144456 | 0.082585 | 0.138031 | 0.14972  | 0.128102 |
| H3   | 24    | LC1      | 0.200537 | 0.247426 | 0.223494 | 0.282406 | 0.319303 | 0.254633 |
| H3   | 24    | LC2      | 0.22769  | 0.185926 | 0.120127 | 0.178977 | 0.226664 | 0.187877 |
| H3   | 24    | LC3      | 0.147864 | 0.220229 | 0.155597 | 0.484171 | 0.188749 | 0.239322 |
| H3   | 24    | BE1      | 3.045555 | 1.768222 | 3.518994 | 3.393755 | 4.768148 | 3.298935 |
| H3   | 24    | LE1      | 1.942473 | 2.938934 | 2.507969 | 2.700218 | 5.609348 | 3.139788 |
| H4   | 14    | BC1      | 0.265192 | 0.240724 | 0.25084  | 0.295453 | 0.303696 | 0.271181 |
| H4   | 14    | BC2      | 0.208807 | 0.239956 | 0.331401 | 0.237491 | 0.264795 | 0.25649  |
| H4   | 14    | BC3      | 0.122849 | 0.13518  | 0.146175 | 0.191103 | 0.136068 | 0.146275 |
| H4   | 14    | 1BC      | 0.267729 | 0.234009 | 0.217716 | 0.231333 | 0.266504 | 0.243458 |
| H4   | 14    | 2BC      | 0.211948 | 0.166525 | 0.188592 | 0.192018 | 0.236648 | 0.199146 |
| H4   | 14    | 3BC      | 0.214762 | 0.132792 | 0.195069 | 0.151844 | 0.192894 | 0.177472 |
| H4   | 14    | LC1      | 0.327773 | 0.261126 | 0.286206 | 0.273766 | 0.239075 | 0.277589 |
| H4   | 14    | LC2      | 0.21036  | 0.168167 | 0.213115 | 0.220846 | 0.210674 | 0.204633 |
| H4   | 14    | LC3      | 0.086276 | 0.086082 | 0.090333 | 0.114893 | 0.117846 | 0.099086 |
| H4   | 14    | BE1      | 3.962011 | 5.284326 | 5.57203  | 3.665523 | 5.143278 | 4.725434 |
| H4   | 14    | LE1      | 2.722204 | 14.88225 | 4.168416 | 10.84579 | 8.738567 | 8.271446 |
| H4   | 24    | BC1      | 0.210475 | 0.200069 | 0.240268 | 0.285916 | 0.374064 | 0.262158 |
| H4   | 24    | BC2      | 0.234242 | 0.260619 | 0.25475  | 0.261846 | 0.266958 | 0.255683 |
| H4   | 24    | BC3      | 0.203129 | 0.209596 | 0.141567 | 0.138974 | 0.183002 | 0.175254 |
| H4   | 24    | 1BC      | 0.2412   | 0.237638 | 0.266341 | 0.250444 | 0.205003 | 0.240125 |
| H4   | 24    | 2BC      | 0.207935 | 0.215287 | 0.192536 | 0.226673 | 0.231944 | 0.214875 |
| H4   | 24    | 3BC      | 0.219994 | 0.175738 | 0.12841  | 0.162989 | 0.173043 | 0.172035 |
| H4   | 24    | LC1      | 0.290297 | 0.221    | 0.224196 | 0.12778  | 0.196188 | 0.211892 |
| H4   | 24    | LC2      | 0.20887  | 0.153885 | 0.203101 | 0.182736 | 0.199341 | 0.189587 |
| H4   | 24    | LC3      | 0.108541 | 0.160264 | 0.157741 | 0.166264 | 0.217026 | 0.161967 |
| H4   | 24    | BE1      | 2.003353 | 3.273019 | 2.101428 | 3.175099 | 3.699167 | 2.850413 |
| H4   | 24    | LE1      | 2.72745  | 2.165306 | 2.044121 | 1.353692 | 6.147144 | 2.887543 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H5   | 14    | BC1      | 0.37502  | 0.48078  | *        | *        | 0.23364  | 0.363147 |
| H5   | 14    | BC2      | *        | *        | *        | 0.25168  | 0.36777  | 0.309725 |
| H5   | 14    | BC3      | 0.14332  | 0.05354  | 0.17161  | 0.27726  | 0.17014  | 0.163174 |
| H5   | 14    | 1BC      | 0.309869 | 0.345932 | 0.331827 | 0.332526 | 0.354114 | 0.334854 |
| H5   | 14    | 2BC      | 0.12283  | 0.1487   | 0.16935  | 0.18146  | 0.17515  | 0.159498 |
| H5   | 14    | 3BC      | 0.23911  | 0.24086  | 0.2438   | 0.16994  | *        | 0.223428 |
| H5   | 14    | LC1      | 0.27825  | 0.2468   | 0.23938  | 0.25105  | 0.20076  | 0.243248 |
| H5   | 14    | LC2      | 0.14686  | 0.17724  | 0.14431  | 0.16696  | 0.14393  | 0.15586  |
| H5   | 14    | LC3      | 0.20157  | 0.1803   | 0.1992   | 0.16988  | 0.24211  | 0.198612 |
| H5   | 14    | BE1      | 5.119121 | 9.727455 | 3.248921 | 6.558898 | 4.934051 | 11.03681 |
| H5   | 14    | LE1      | 5.788864 | 3.459397 | 3.923293 | 4.211064 | 4.951907 | 10.25577 |
| H5   | 24    | BC1      | 0.30899  | 0.27805  | 0.23968  | 0.28354  | 0.31839  | 0.28573  |
| H5   | 24    | BC2      | 0.19955  | 0.1743   | 0.28036  | 0.23458  | 0.2115   | 0.220058 |
| H5   | 24    | BC3      | 0.21076  | 0.23504  | 0.20513  | 0.23496  | 0.2131   | 0.219798 |
| H5   | 24    | 1BC      | 0.36808  | 0.36285  | 0.36031  | 0.33242  | 0.37294  | 0.35932  |
| H5   | 24    | 2BC      | 0.27401  | 0.32877  | 0.36707  | 0.33051  | 0.36005  | 0.332082 |
| H5   | 24    | 3BC      | 0.14814  | 0.19962  | 0.158165 | 0.17203  | 0.20619  | 0.176829 |
| H5   | 24    | LC1      | 0.32814  | 0.31022  | 0.28125  | 0.32127  | 0.32171  | 0.312518 |
| H5   | 24    | LC2      | 0.36803  | 0.18078  | 0.24216  | 0.24649  | 0.12109  | 0.23171  |
| H5   | 24    | LC3      | 0.19154  | 0.0678   | 0.2152   | 0.24232  | 0.17011  | 0.177394 |
| H5   | 24    | BE1      | 5.352346 | 6.571353 | 5.547915 | 5.424474 | 8.193816 | 6.217981 |
| H5   | 24    | LE1      | 2.670612 | 7.711374 | 7.522827 | 5.072958 | 5.160204 | 5.627595 |
| H6   | 14    | BC1      | 0.326997 | 0.417483 | 0.360338 | 0.348047 | 0.345655 | 0.359704 |
| H6   | 14    | BC2      | 0.26554  | 0.282339 | 0.275483 | 0.262711 | 0.293101 | 0.275835 |
| H6   | 14    | BC3      | 0.171433 | 0.18616  | 0.133379 | 0.195314 | 0.207329 | 0.178723 |
| H6   | 14    | 1BC      | 0.363446 | 0.366379 | 0.414296 | 0.412771 | 0.447934 | 0.400965 |
| H6   | 14    | 2BC      | 0.277018 | 0.269049 | 0.326307 | 0.308509 | 0.292417 | 0.29466  |
| H6   | 14    | 3BC      | 0.185265 | 0.204724 | 0.195357 | 0.190315 | 0.214643 | 0.198061 |
| H6   | 14    | LC1      | 0.339336 | 0.392577 | 0.372963 | 0.388506 | 0.367444 | 0.372165 |
| H6   | 14    | LC2      | 0.268575 | 0.085308 | 0.302416 | 0.132475 | 0.327654 | 0.223286 |
| H6   | 14    | LC3      | 0.180522 | 0.223109 | 0.217505 | 0.20032  | 0.132708 | 0.190833 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H6   | 14    | BE1      | 2.861323 | 2.79616  | 5.193663 | 2.287252 | 5.096221 | 3.646924 |
| H6   | 14    | LE1      | 4.844984 | 3.784389 | 8.218666 | 5.184599 | 6.316406 | 5.669809 |
| H6   | 24    | BC1      | 0.277238 | 0.260462 | 0.208663 | 0.25941  | 0.275489 | 0.256252 |
| H6   | 24    | BC2      | 0.299113 | 0.356921 | 0.268364 | 0.357224 | 0.299619 | 0.316248 |
| H6   | 24    | BC3      | 0.169472 | 0.201606 | 0.198832 | 0.359473 | 0.322002 | 0.250277 |
| H6   | 24    | 1BC      | 0.283933 | 0.365968 | 0.25884  | 0.389048 | 0.353719 | 0.330302 |
| H6   | 24    | 2BC      | 0.236308 | 0.339426 | 0.354671 | 0.27752  | 0.290209 | 0.299627 |
| H6   | 24    | 3BC      | 0.10047  | 0.173366 | 0.1556   | 0.225764 | 0.127714 | 0.156583 |
| H6   | 24    | LC1      | 0.287541 | 0.286943 | 0.239405 | 0.256925 | 0.293464 | 0.272856 |
| H6   | 24    | LC2      | 0.224979 | 0.217736 | 0.22643  | 0.235108 | 0.234147 | 0.22768  |
| H6   | 24    | LC3      | 0.13912  | 0.14752  | 0.150825 | 0.165916 | 0.167242 | 0.154125 |
| H6   | 24    | BE1      | 2.969279 | 3.288033 | 4.968721 | 3.786563 | 4.521366 | 3.906793 |
| H6   | 24    | LE1      | 4.486351 | 2.19209  | 4.566562 | 4.733164 | 4.378258 | 4.071285 |
| H7   | 44    | BC1      | 0.2338   | 0.24776  | 0.23512  | 0.32059  | 0.24405  | 0.256264 |
| H7   | 44    | BC2      | 0.18092  | 0.14259  | 0.14064  | 0.14502  | 0.1176   | 0.145354 |
| H7   | 44    | BC3      | 0.12124  | 0.14344  | 0.14921  | 0.14197  | 0.1361   | 0.138392 |
| H7   | 44    | 1BC      | 0.28829  | 0.23818  | 0.28211  | 0.32392  | 0.20129  | 0.266758 |
| H7   | 44    | 2BC      | 0.17968  | 0.11961  | 0.16823  | 0.1796   | 0.17049  | 0.163522 |
| H7   | 44    | 3BC      | 0.18036  | 0.1683   | 0.2041   | 0.14781  | 0.16764  | 0.173642 |
| H7   | 44    | LC1      | 0.0935   | 0.08979  | 0.08858  | 0.09651  | 0.11083  | 0.095842 |
| H7   | 44    | LC2      | 0.13888  | 0.11324  | 0.09583  | 0.08997  | 0.0841   | 0.104404 |
| H7   | 44    | LC3      | 0.07231  | 0.05716  | 0.03792  | 0.07276  | 0.06507  | 0.061044 |
| H7   | 44    | BE1      | 1.590327 | 1.915324 | 2.138474 | 2.284156 | 2.976574 | 2.180971 |
| H7   | 44    | LE1      | 2.615074 | 0.32643  | 0.631156 | 1.695311 | 3.119791 | 1.677553 |
| H7   | 34    | BC1      | 0.14014  | 0.17176  | 0.15034  | 0.04732  | 0.1684   | 0.135592 |
| H7   | 34    | BC2      | 0.23346  | 0.27738  | 0.24539  | 0.24973  | 0.24373  | 0.249938 |
| H7   | 34    | BC3      | 0.08751  | 0.17191  | 0.14058  | 0.18326  | 0.20436  | 0.157524 |
| H7   | 34    | 1BC      | 0.20947  | 0.20451  | 0.12131  | 0.27457  | 0.28409  | 0.21879  |
| H7   | 34    | 2BC      | 0.09331  | 0.11836  | 0.05316  | 0.11098  | 0.11667  | 0.098496 |
| H7   | 34    | 3BC      | 0.20648  | 0.18113  | 0.20175  | 0.24762  | 0.27886  | 0.223168 |
| H7   | 34    | LC1      | 0.19323  | 0.14621  | 0.11014  | 0.11014  | 0.15058  | 0.14206  |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H7   | 34    | LC2      | 0.36908  | 0.35176  | 0.33262  | 0.36876  | 0.36804  | 0.358052 |
| H7   | 34    | LC3      | 0.16172  | 0.34048  | 0.22646  | 0        | *        | 0.182165 |
| H7   | 34    | BE1      | 1.9785   | 1.6707   | 2.4173   | 2.52195  | 2.29719  | 2.177128 |
| H7   | 34    | LE1      | 1.58065  | 2.30185  | 1.39801  | 1.89877  | 1.65626  | 1.767108 |
| H8   | 14    | BC1      | 0.303433 | 0.281195 | 0.333948 | 0.385289 | 0.412556 | 0.343284 |
| H8   | 14    | BC2      | 0.268175 | 0.256707 | 0.243741 | 0.2873   | 0.266889 | 0.264562 |
| H8   | 14    | BC3      | 0.220448 | 0.349561 | 0.319742 | 0.189856 | 0.260951 | 0.268112 |
| H8   | 14    | 1BC      | 0.571482 | 0.340965 | 0.443967 | 0.407871 | 0.438629 | 0.440583 |
| H8   | 14    | 2BC      | 0.298608 | 0.263224 | 0.32461  | 0.367457 | 0.306732 | 0.312126 |
| H8   | 14    | 3BC      | 0.153178 | 0.204123 | 0.231423 | 0.239837 | 0.187723 | 0.203257 |
| H8   | 14    | LC1      | 0.147394 | 0.182209 | 0.190688 | 0.178764 | 0.183177 | 0.176446 |
| H8   | 14    | LC2      | 0.188786 | 0.200449 | 0.195323 | 0.182724 | 0.186861 | 0.190829 |
| H8   | 14    | LC3      | 0.173198 | 0.122019 | 0.160398 | 0.183683 | 0.208739 | 0.169607 |
| H8   | 14    | BE1      | 1.606967 | 2.136239 | 1.732523 | 1.497076 | 0        | 1.394561 |
| H8   | 14    | LE1      | 6.756304 | 7.022901 | 3.081273 | 2.925578 | 6.097342 | 5.17668  |
| H8   | 24    | BC1      | 0.22377  | 0.29265  | 0.295069 | 0.275356 | 0.27288  | 0.271945 |
| H8   | 24    | BC2      | 0.226653 | 0.274188 | 0.251987 | 0.347759 | 0.228685 | 0.265854 |
| H8   | 24    | BC3      | 0.116097 | 0.133549 | 0.126953 | 0.171537 | 0.134103 | 0.136448 |
| H8   | 24    | 1BC      | 0.294694 | 0.322726 | 0.346167 | 0.319785 | 0.290194 | 0.314713 |
| H8   | 24    | 2BC      | 0.288589 | 0.227495 | 0.237412 | 0.368021 | 0.308679 | 0.286039 |
| H8   | 24    | 3BC      | 0.095574 | 0.096384 | 0.226824 | 0.223572 | 0.16196  | 0.160863 |
| H8   | 24    | LC1      | 0.273234 | 0.270213 | 0.267422 | 0.307426 | 0.299805 | 0.28362  |
| H8   | 24    | LC2      | 0.323285 | 0.27788  | 0.228932 | 0.340387 | 0.307043 | 0.295505 |
| H8   | 24    | LC3      | 0.289152 | 0.196482 | 0.132017 | 0.270235 | 0.274299 | 0.232437 |
| H8   | 24    | BE1      | 3.406044 | 3.125052 | 3.589757 | 3.069699 | 3.382529 | 3.314616 |
| H8   | 24    | LE1      | 1.704251 | 1.646327 | 2.083599 | 1.359984 | 0        | 1.358832 |
| H9   | 14    | BC1      | 0.202966 | 0.186354 | 0.180707 | 0.247553 | 0.215105 | 0.206537 |
| H9   | 14    | BC2      | 0.108017 | 0.151073 | 0.110819 | 0.143765 | 0.183492 | 0.139433 |
| H9   | 14    | BC3      | 0.177889 | 0.170138 | 0.205793 | 0.159426 | 0.349027 | 0.212455 |
| H9   | 14    | 1BC      | 0.210794 | 0.085963 | 0.185452 | 0.240565 | 0.079625 | 0.16048  |
| H9   | 14    | 2BC      | 0.210794 | 0.085963 | 0.185452 | 0.240565 | 0.079625 | 0.16048  |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| H9   | 14    | 3BC      | 0.217126 | 0.221001 | 0.136557 | 0.246917 | 0.231597 | 0.21064  |
| H9   | 14    | LC1      | 0.218232 | 0.207491 | 0.184085 | 0.251419 | 0.218938 | 0.216033 |
| H9   | 14    | LC2      | 0.186456 | 0.233102 | 0.167943 | 0.212389 | 0.248499 | 0.209678 |
| H9   | 14    | LC3      | *        | *        | *        | *        | *        | *        |
| H9   | 14    | BE1      | 3.02145  | 4.116423 | 2.769191 | 3.350247 | 4.481031 | 3.547668 |
| H9   | 14    | LE1      | 1.709426 | 9.057568 | 5.768068 | 2.899094 | 11.66582 | 6.219995 |
| H9   | 24    | BC1      | 0.084476 | 0.125944 | 0.083999 | 0.173227 | 0.095039 | 0.112537 |
| H9   | 24    | BC2      | 0.157634 | 0.165014 | 0.095243 | 0.19123  | 0.17047  | 0.155918 |
| H9   | 24    | BC3      | 0.21935  | 0.149352 | 0.162532 | 0.225435 | 0.189909 | 0.189315 |
| H9   | 24    | 1BC      | 0.145425 | 0.141688 | 0.134584 | 0.162624 | 0.09608  | 0.13608  |
| H9   | 24    | 2BC      | 0.150979 | 0.157357 | 0.242153 | 0.293553 | 0.252496 | 0.219308 |
| H9   | 24    | 3BC      | 0.173398 | 0.206857 | 0.22521  | 0.218858 | 0.303848 | 0.225634 |
| H9   | 24    | LC1      | 0.314583 | 0.344706 | 0.293114 | 0.272703 | 0.237707 | 0.292563 |
| H9   | 24    | LC2      | 0.222696 | 0.159952 | 0.153908 | 0.183623 | 0.211861 | 0.186408 |
| H9   | 24    | LC3      | 0.141248 | 0.111213 | 0.138067 | 0.190702 | 0.175811 | 0.151408 |
| H9   | 24    | BE1      | 6.675184 | 6.325031 | 6.7887   | 6.91722  | 7.039595 | 6.749146 |
| H9   | 24    | LE1      | 7.964743 | 10.19601 | 3.676715 | 5.159776 | 10.03558 | 7.406565 |
| L1   | 14    | BC1      | 0.31211  | 0.31746  | 0.39418  | 0.28616  | 0.34019  | 0.33002  |
| L1   | 14    | BC2      | 0.24853  | 0.27086  | 0.23638  | 0.31317  | 0.35929  | 0.285646 |
| L1   | 14    | BC3      | 0.18189  | 0.19994  | 0.17224  | 0.20119  | 0.23308  | 0.197668 |
| L1   | 14    | 1BC      | 0.31612  | 0.27789  | 0.28128  | 0.28844  | 0.24636  | 0.282018 |
| L1   | 14    | 2BC      | 0.32159  | 0.3152   | 0.21115  | 0.45913  | 0.3659   | 0.334594 |
| L1   | 14    | 3BC      | 0.31447  | 0.32413  | 0.32272  | 0.32511  | 0.29129  | 0.315544 |
| L1   | 14    | LC1      | 0.26309  | 0.39042  | 0.37475  | 0.27573  | 0.154395 | 0.291677 |
| L1   | 14    | LC2      | 0.07868  | 0.10314  | 0.11493  | 0.10767  | 0.106125 | 0.102109 |
| L1   | 14    | LC3      | 0.28967  | 0.31957  | 0.23869  | 0.3238   | 0.35527  | 0.3054   |
| L1   | 14    | BE1      | 0.523597 | 0.723048 | 0.76919  | 0.71556  | 0.661713 | 0.678622 |
| L1   | 14    | LE1      | 1.341264 | 1.673036 | 1.654925 | 1.417765 | 1.154638 | 1.448325 |
| L1   | 24    | BC1      | 0.28795  | 0.47426  | 0.32691  | 0.37334  | 0.36309  | 0.36511  |
| L1   | 24    | BC2      | 0.11545  | 0.20174  | 0.19674  | 0.17811  | 0.16336  | 0.17108  |
| L1   | 24    | BC3      | 0.15044  | 0.23833  | 0.16942  | 0.25537  | 0.26824  | 0.21636  |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L1   | 24    | 1BC      | 0.56462  | 0.56751  | 0.42505  | 0.37215  | 0.37971  | 0.461808 |
| L1   | 24    | 2BC      | 0.27594  | 0.26969  | 0.24491  | 0.24079  | 0.24685  | 0.255636 |
| L1   | 24    | 3BC      | 0.20872  | 0.19989  | 0.23542  | 0.21169  | 0.21535  | 0.214214 |
| L1   | 24    | LC1      | 0.52376  | 0.35671  | 0.32261  | 0.35305  | 0.31915  | 0.375056 |
| L1   | 24    | LC2      | 0.23513  | 0.23755  | 0.33085  | 0.27042  | 0.24714  | 0.264218 |
| L1   | 24    | LC3      | 0.18143  | 0.18296  | 0.24237  | 0.22479  | 0.17536  | 0.201382 |
| L1   | 24    | BE1      | 5.495861 | 3.979863 | 2.905608 | 5.298325 | 7.414654 | 5.018862 |
| L1   | 24    | LE1      | 5.263932 | 4.736093 | 3.601871 | 5.845152 | 6.904568 | 5.270323 |
| L2   | 14    | BC1      | 0.453992 | 0.387829 | 0.431152 | 0.415172 | 0.414463 | 0.420522 |
| L2   | 14    | BC2      | 0.201905 | 0.079238 | 0.150708 | 0.205822 | 0.101756 | 0.147886 |
| L2   | 14    | BC3      | 0.195716 | 0.238267 | 0.135895 | 0.161561 | 0.048138 | 0.155915 |
| L2   | 14    | 1BC      | 0.139864 | 0.191267 | 0.22818  | 0.206516 | 0.224823 | 0.19813  |
| L2   | 14    | 2BC      | 0.121342 | 0.104859 | 0.253208 | 0.110142 | 0.091113 | 0.136133 |
| L2   | 14    | 3BC      | 0.038647 | 0.037721 | 0.056875 | 0.047805 | 0.047805 | 0.045771 |
| L2   | 14    | LC1      | 0.334362 | 0.282203 | 0.286735 | 0.274572 | 0.270942 | 0.289763 |
| L2   | 14    | LC2      | 0.230343 | 0.22847  | 0.217332 | 0.214096 | 0.226286 | 0.223305 |
| L2   | 14    | LC3      | 0.064258 | 0.22544  | 0.103252 | 0.198824 | 0.147186 | 0.147792 |
| L2   | 14    | BE1      | 2.90882  | 4.587224 | 8.314827 | 2.645893 | 3.646667 | 4.420686 |
| L2   | 14    | LE1      | 0.688119 | 0.949131 | 1.650293 | 1.686929 | 1.247974 | 1.244489 |
| L2   | 24    | BC1      | 0.270845 | 0.222594 | 0.352754 | 0.300205 | 0.330147 | 0.295309 |
| L2   | 24    | BC2      | 0.208547 | 0.189208 | 0.221252 | 0.220591 | 0.15003  | 0.197926 |
| L2   | 24    | BC3      | 0.103262 | 0.114649 | 0.09622  | 0.099842 | 0.120805 | 0.106955 |
| L2   | 24    | 1BC      | 0.17872  | 0.241977 | 0.089583 | 0.251183 | 0.05162  | 0.162616 |
| L2   | 24    | 2BC      | 0.279401 | 0.227253 | 0.278922 | 0.251977 | 0.160207 | 0.239552 |
| L2   | 24    | 3BC      | 0.171257 | 0.080724 | 0.127279 | 0.155857 | 0.160203 | 0.139064 |
| L2   | 24    | LC1      | 0.285869 | 0.436915 | 0.394268 | 0.272472 | 0.302876 | 0.33848  |
| L2   | 24    | LC2      | 0.136467 | 0.140813 | 0.137532 | 0.211174 | 0.162557 | 0.157709 |
| L2   | 24    | LC3      | 0.144339 | 0.161567 | 0.127379 | 0.142051 | 0.127104 | 0.140488 |
| L2   | 24    | BE1      | 2.242944 | 3.659532 | 2.667331 | 2.493121 | 2.21116  | 2.654818 |
| L2   | 24    | LE1      | 7.605958 | 3.351376 | 7.773521 | 3.993367 | 6.256625 | 5.796169 |
| L3   | 14    | BC1      | 0.266314 | 0.18201  | 0.186684 | 0.252483 | 0.314763 | 0.240451 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L3   | 14    | BC2      | 0.211101 | 0.234481 | 0.300057 | 0.30026  | 0.296517 | 0.268483 |
| L3   | 14    | BC3      | 0.197327 | 0.240316 | 0.268678 | 0.282459 | 0.240735 | 0.245903 |
| L3   | 14    | 1BC      | 0.29694  | 0.339436 | 0.39503  | 0.360996 | 0.352843 | 0.349049 |
| L3   | 14    | 2BC      | 0.254704 | 0.360539 | 0.338432 | 0.281215 | 0.225448 | 0.292068 |
| L3   | 14    | 3BC      | 0.254704 | 0.360539 | 0.338432 | 0.281215 | 0.225448 | 0.292068 |
| L3   | 14    | LC1      | 0.329474 | 0.316711 | 0.297956 | 0.358774 | 0.397166 | 0.340016 |
| L3   | 14    | LC2      | 0.261154 | 0.309647 | 0.323945 | 0.290288 | 0.302389 | 0.297485 |
| L3   | 14    | LC3      | 0.246964 | 0.235272 | 0.116582 | 0.214255 | 0.211098 | 0.204834 |
| L3   | 14    | BE1      | 4.250398 | 2.64414  | 10.02955 | 10.0895  | 7.118761 | 6.826469 |
| L3   | 14    | LE1      | 3.418689 | 4.020676 | 2.242595 | 1.838895 | 5.460611 | 3.396293 |
| L3   | 24    | BC1      | 0.425409 | 0.272825 | 0.284319 | 0.305622 | 0.326209 | 0.322877 |
| L3   | 24    | BC2      | 0.250274 | 0.259336 | 0.306646 | 0.176446 | 0.232863 | 0.245113 |
| L3   | 24    | BC3      | 0.277031 | 0.209961 | 0.294772 | 0.301414 | 0.344129 | 0.285461 |
| L3   | 24    | 1BC      | 0.373752 | 0.435396 | 0.36612  | 0.434687 | 0.44127  | 0.410245 |
| L3   | 24    | 2BC      | 0.2938   | 0.272517 | 0.254    | 0.272901 | 0.382094 | 0.295062 |
| L3   | 24    | 3BC      | 0.276423 | 0.245548 | 0.169102 | 0.278437 | 0.31677  | 0.257256 |
| L3   | 24    | LC1      | 0.308305 | 0.299536 | 0.334345 | 0.291911 | 0.313475 | 0.309515 |
| L3   | 24    | LC2      | 0.269537 | 0.294541 | 0.238178 | 0.295976 | 0.308322 | 0.281311 |
| L3   | 24    | LC3      | 0.19423  | 0.238708 | 0.202757 | 0.210925 | 0.185704 | 0.206465 |
| L3   | 24    | BE1      | 6.899241 | 10.63539 | 9.454209 | 7.471824 | 10.97086 | 9.086305 |
| L3   | 24    | LE1      | 6.400523 | 5.349372 | 6.782759 | 8.585015 | 8.201199 | 7.063774 |
| L4   | 14    | BC1      | 0.219561 | 0.246495 | 0.26839  | 0.26839  | 0.4226   | 0.285087 |
| L4   | 14    | BC2      | 0.234246 | 0.22026  | 0.216534 | 0.253227 | 0.22794  | 0.230441 |
| L4   | 14    | BC3      | 0.224736 | 0.123896 | 0.267646 | 0.304824 | 0.282632 | 0.240747 |
| L4   | 14    | 1BC      | 0.312538 | 0.248171 | 0.407578 | 0.34283  | 0.278949 | 0.318013 |
| L4   | 14    | 2BC      | 0.236462 | 0.173938 | 0.294502 | 0.23658  | 0.23658  | 0.235612 |
| L4   | 14    | 3BC      | 0.236462 | 0.116548 | 0.268019 | 0.274097 | 0.290734 | 0.237172 |
| L4   | 14    | LC1      | 0.362261 | 0.377184 | 0.336333 | 0.390417 | 0.387545 | 0.370748 |
| L4   | 14    | LC2      | 0.224545 | 0.210047 | 0.198801 | 0.233495 | 0.246425 | 0.222663 |
| L4   | 14    | LC3      | 0.276722 | 0.238672 | 0.243512 | 0.281951 | 0.264322 | 0.261036 |
| L4   | 14    | BE1      | 1.641164 | 1.591207 | 3.710588 | 2.357655 | 1.924601 | 2.245043 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L4   | 14    | LE1      | 5.431523 | 7.52892  | 1.644789 | 1.205615 | 8.571104 | 4.87639  |
| L4   | 24    | BC1      | 0.320183 | 0.328824 | 0.384665 | 0.388557 | 0.350921 | 0.35463  |
| L4   | 24    | BC2      | 0.178901 | 0.212941 | 0.191797 | 0.17743  | 0.189127 | 0.190039 |
| L4   | 24    | BC3      | 0.087407 | 0.107899 | 0.105772 | 0.095491 | 0.075981 | 0.09451  |
| L4   | 24    | 1BC      | 0.237813 | 0.228989 | 0.268047 | 0.196467 | 0.361032 | 0.25847  |
| L4   | 24    | 2BC      | 0.159868 | 0.171788 | 0.166864 | 0.149611 | 0.180503 | 0.165727 |
| L4   | 24    | 3BC      | 0.153492 | 0.078516 | 0.15305  | 0.179021 | 0.146497 | 0.142115 |
| L4   | 24    | LC1      | 0.289742 | 0.323157 | 0.304242 | 0.272409 | 0.290515 | 0.296013 |
| L4   | 24    | LC2      | 0.289098 | 0.253011 | 0.255653 | 0.273838 | 0.276168 | 0.269553 |
| L4   | 24    | LC3      | 0.153159 | 0.200514 | 0.24039  | 0.146186 | 0.213961 | 0.190842 |
| L4   | 24    | BE1      | 4.103309 | 5.59747  | 8.69943  | 5.732005 | 3.870441 | 5.600531 |
| L4   | 24    | LE1      | 5.075729 | 8.970771 | 8.970771 | 1.94753  | 8.128155 | 6.618591 |
| L5   | 14    | BC1      | 0.221449 | 0.062315 | 0.163772 | 0.167655 | 0.228964 | 0.168831 |
| L5   | 14    | BC2      | 0.211972 | 0.162555 | 0.163745 | 0.300136 | 0.370353 | 0.241752 |
| L5   | 14    | BC3      | 0.314794 | 0.219211 | 0.333161 | 0.227546 | 0.321256 | 0.283194 |
| L5   | 14    | 1BC      | 0.286563 | 0.087454 | 0.248328 | 0.131619 | 0.152072 | 0.181207 |
| L5   | 14    | 2BC      | 0.261943 | 0.150747 | 0.274364 | 0.257268 | 0.182098 | 0.225284 |
| L5   | 14    | 3BC      | 0.143295 | 0.174254 | 0.184996 | 0.219791 | 0.137955 | 0.172058 |
| L5   | 14    | LC1      | 0.269342 | 0.255991 | 0.22161  | 0.245481 | 0.216635 | 0.241812 |
| L5   | 14    | LC2      | 0.452748 | 0.452748 | 0.447818 | 0.109842 | 0.312951 | 0.355222 |
| L5   | 14    | LC3      | 0.232361 | 0.31414  | 0.175783 | 0.250498 | 0.343507 | 0.263258 |
| L5   | 14    | BE1      | 2.949501 | 2.649594 | 2.26627  | 1.898107 | 2.965942 | 2.545883 |
| L5   | 14    | LE1      | 3.900521 | 3.270717 | 1.823779 | 3.589777 | 4.348357 | 3.38663  |
| L5   | 24    | BC1      | 0.129678 | 0.155973 | 0.144986 | 0.128186 | 0.197311 | 0.151227 |
| L5   | 24    | BC2      | 0.165771 | 0.157513 | 0.168704 | 0.191838 | 0.19373  | 0.175511 |
| L5   | 24    | BC3      | 0.110772 | 0.09594  | 0.087356 | 0.103462 | 0.126029 | 0.104712 |
| L5   | 24    | 1BC      | 0.243782 | 0.233928 | 0.03848  | 0.159218 | 0.245617 | 0.184205 |
| L5   | 24    | 2BC      | 0.192427 | 0.200378 | 0.160213 | 0.176976 | 0.198824 | 0.185764 |
| L5   | 24    | 3BC      | 0.203503 | 0.144962 | 0.201292 | 0.222898 | 0.194879 | 0.193507 |
| L5   | 24    | LC1      | 0.224746 | 0.157682 | 0.211007 | 0.086005 | 0.441993 | 0.224287 |
| L5   | 24    | LC2      | 0.181254 | 0.175618 | 0.140238 | 0.109893 | 0.180348 | 0.15747  |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L5   | 24    | LC3      | 0.158952 | 0.194563 | 0.165183 | 0.198203 | 0.15709  | 0.174798 |
| L5   | 24    | BE1      | 7.043129 | 5.647919 | 1.011393 | 4.173939 | 2.254766 | 4.026229 |
| L5   | 24    | LE1      | 5.684115 | 9.166631 | 3.537431 | 2.956766 | 8.844069 | 6.037802 |
| L6   | 44    | BC1      | 0.51727  | 0.33277  | 0.35724  | 0.39896  | 0.37477  | 0.396202 |
| L6   | 44    | BC2      | 0.20986  | 0.23658  | 0.23598  | 0.26978  | 0.21478  | 0.233396 |
| L6   | 44    | BC3      | 0.15232  | 0.29381  | 0.21337  | 0.23182  | 0.3752   | 0.253304 |
| L6   | 44    | 1BC      | 0.28788  | 0.31435  | 0.32178  | 0.24829  | 0.27849  | 0.290158 |
| L6   | 44    | 2BC      | 0.33093  | 0.33093  | 0.4039   | 0.41707  | 0.4261   | 0.381786 |
| L6   | 44    | 3BC      | 0.27794  | *        | 0.31114  | 0.30868  | 0.2902   | 0.29699  |
| L6   | 44    | LC1      | 0.20925  | 0.24008  | 0.2366   | 0.23682  | 0.27567  | 0.239684 |
| L6   | 44    | LC2      | 0.52012  | 0.33188  | 0.23326  | 0.36925  | 0.29173  | 0.349248 |
| L6   | 44    | LC3      | 0.46803  | 0.26878  | 0.2523   | 0.42681  | 0.2698   | 0.337144 |
| L6   | 44    | BE1      | 3.860886 | 4.298885 | 2.375353 | 8.377657 | 5.623825 | 4.907321 |
| L6   | 44    | LE1      | 1.425143 | 1.316171 | 0.692471 | 3.788409 | 2.843416 | 2.013122 |
| L6   | 34    | BC1      | 0.32568  | 0.40313  | 0.33037  | 0.45884  | 0.32621  | 0.368846 |
| L6   | 34    | BC2      | 0.36521  | 0.27827  | 0.32117  | 0.36604  | 0.37255  | 0.340648 |
| L6   | 34    | BC3      | 0.1482   | 0.09549  | 0.09983  | 0.11374  | 0.10938  | 0.113328 |
| L6   | 34    | 1BC      | 0.32627  | 0.28488  | 0.3742   | 0.36803  | 0.37206  | 0.345088 |
| L6   | 34    | 2BC      | 0.27823  | 0.28202  | 0.33228  | 0.377    | 0.35907  | 0.32572  |
| L6   | 34    | 3BC      | 0.2919   | 0.28428  | 0.27783  | 0.28963  | 0.35951  | 0.30063  |
| L6   | 34    | LC1      | 0.15833  | 0.07144  | 0.15602  | 0.15206  | 0.17537  | 0.142644 |
| L6   | 34    | LC2      | 0.31551  | 0.32261  | 0.35607  | 0.31874  | 0.31436  | 0.325458 |
| L6   | 34    | LC3      | 0.3647   | 0.36955  | 0.4182   | 0.47337  | 0.28679  | 0.382522 |
| L6   | 34    | BE1      | 6.000607 | 3.123504 | 6.024506 | 7.80933  | 7.850072 | 6.161604 |
| L6   | 34    | LE1      | 2.563821 | 3.349346 | 3.925289 | 1.962769 | 2.617645 | 2.883774 |
| L7   | 14    | BC1      | 0.207246 | 0.277763 | 0.201499 | 0.448191 | 0.540325 | 0.335005 |
| L7   | 14    | BC2      | 0.266144 | 0.418204 | 0.183518 | 0.161661 | 0.485387 | 0.302983 |
| L7   | 14    | BC3      | 0.174726 | 0.352274 | 0.352274 | 0.175832 | 0.224586 | 0.255938 |
| L7   | 14    | 1BC      | 0.339304 | 0.348927 | 0.3962   | 0.429458 | 0.467103 | 0.396199 |
| L7   | 14    | 2BC      | 0.250803 | 0.165704 | 0.191476 | 0.089759 | 0.195862 | 0.178721 |
| L7   | 14    | 3BC      | 0.126378 | 0.161783 | 0.087056 | 0.117524 | 0.209732 | 0.140494 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L7   | 14    | LC1      | 0.306471 | 0.359169 | 0.361089 | 0.415883 | 0.394236 | 0.36737  |
| L7   | 14    | LC2      | 0.21929  | 0.21001  | 0.315089 | 0.440745 | 0.338241 | 0.304675 |
| L7   | 14    | LC3      | 0.122919 | 0.117193 | 0.167331 | 0.162022 | 0.143773 | 0.142647 |
| L7   | 14    | BE1      | 1.017224 | 0.933492 | 0.984117 | 0.969929 | 1.38819  | 1.058591 |
| L7   | 14    | LE1      | 5.652793 | 4.596263 | 9.794873 | 4.462602 | 2.172505 | 5.335807 |
| L7   | 24    | BC1      | 0.434345 | 0.414843 | 0.466504 | 0.691887 | 0.424188 | 0.486353 |
| L7   | 24    | BC2      | 0.242323 | 0.24183  | 0.18173  | 0.205989 | 0.243464 | 0.223067 |
| L7   | 24    | BC3      | 0.155995 | 0.166472 | 0.106265 | 0.167272 | 0.199748 | 0.15915  |
| L7   | 24    | 1BC      | 0.342396 | 0.333854 | 0.11252  | 0.273743 | 0.300681 | 0.272639 |
| L7   | 24    | 2BC      | 0.178163 | 0.227449 | 0.22697  | 0.198425 | 0.244784 | 0.215158 |
| L7   | 24    | 3BC      | 0.135243 | 0.198387 | 0.105065 | 0.128349 | 0.099268 | 0.133262 |
| L7   | 24    | LC1      | 0.321083 | 0.359638 | 0.340615 | 0.398782 | 0.382934 | 0.36061  |
| L7   | 24    | LC2      | 0.20404  | 0.228327 | 0.185765 | 0.380892 | 0.231235 | 0.246052 |
| L7   | 24    | LC3      | 0.185871 | 0.170094 | 0.172031 | 0.257019 | 0.259294 | 0.208862 |
| L7   | 24    | BE1      | 5.467549 | 10.2496  | 12.15911 | 12.32093 | 6.132549 | 9.265948 |
| L7   | 24    | LE1      | 3.223219 | 2.612731 | 3.764037 | 4.229127 | 2.553092 | 3.276441 |
| L8   | 44    | BC1      | 0.377829 | 0.389578 | 0.376984 | 0.455786 | 0.430826 | 0.406201 |
| L8   | 44    | BC2      | 0.395759 | 0.400198 | 0.383523 | 0.364143 | 0.431495 | 0.395024 |
| L8   | 44    | BC3      | 0.318841 | 0.27825  | 0.300437 | 0.285622 | 0.291619 | 0.294954 |
| L8   | 44    | 1BC      | 0.311629 | 0.30033  | 0.207506 | 0.304944 | 0.203228 | 0.265527 |
| L8   | 44    | 2BC      | 0.286353 | 0.353681 | 0.312878 | 0.374263 | 0.336375 | 0.33271  |
| L8   | 44    | 3BC      | 0.161462 | 0.273269 | 0.21134  | 0.211086 | 0.203874 | 0.212206 |
| L8   | 44    | LC1      | 0.238921 | 0.172303 | 0.079038 | 0.18651  | 0.254445 | 0.186243 |
| L8   | 44    | LC2      | 0.30498  | 0.236274 | 0.209826 | 0.264985 | 0.287829 | 0.260779 |
| L8   | 44    | LC3      | 0.164059 | 0.184247 | 0.130017 | 0.080657 | 0.189398 | 0.149676 |
| L8   | 44    | BE1      | 0.607739 | 1.041772 | 0.873681 | 1.130055 | 0.88621  | 0.907891 |
| L8   | 44    | LE1      | 5.81412  | 7.232665 | 9.009648 | 5.761353 | 8.967053 | 7.356968 |
| L8   | 34    | BC1      | 0.322912 | 0.35807  | 0.174182 | 0.391503 | 0.295346 | 0.308403 |
| L8   | 34    | BC2      | 0.351105 | 0.162234 | 0.319282 | 0.305335 | 0.301723 | 0.287936 |
| L8   | 34    | BC3      | 0.210903 | 0.162234 | 0.319282 | 0.305335 | 0.301723 | 0.259895 |
| L8   | 34    | 1BC      | 0.271028 | 0.310909 | 0.290942 | 0.343384 | 0.304969 | 0.304246 |



| No.* | Tooth | Position | H1       | H2       | H3       | H4       | H5       | Average  |
|------|-------|----------|----------|----------|----------|----------|----------|----------|
| L8   | 34    | 2BC      | 0.367384 | 0.312273 | 0.320358 | 0.309061 | 0.357755 | 0.333366 |
| L8   | 34    | 3BC      | 0.113064 | 0.076973 | 0.197069 | 0.240544 | 0.306871 | 0.186904 |
| L8   | 34    | LC1      | 0.210428 | 0.137258 | 0.158935 | 0.213792 | 0.251497 | 0.194382 |
| L8   | 34    | LC2      | 0.258114 | 0.292449 | 0.288163 | 0.363263 | 0.334067 | 0.307211 |
| L8   | 34    | LC3      | 0.29743  | 0.182985 | 0.245827 | 0.29174  | 0.243745 | 0.252345 |
| L8   | 34    | BE1      | 4.48421  | 4.908443 | 6.755312 | 7.696399 | 7.003605 | 6.169594 |
| L8   | 34    | LE1      | 6.29266  | 8.589474 | 6.400504 | 7.578207 | 11.01432 | 7.975034 |
| L9   | 14    | BC1      | 0.214417 | 0.242419 | 0.272257 | 0.284082 | 0.283299 | 0.259295 |
| L9   | 14    | BC2      | 0.318977 | 0.286796 | 0.186498 | 0.334956 | 0.308505 | 0.287146 |
| L9   | 14    | BC3      | 0.144846 | 0.064865 | 0.19456  | 0.218732 | 0.182056 | 0.161012 |
| L9   | 14    | 1BC      | 0.251315 | 0.175478 | 0.457233 | 0.365203 | 0.265788 | 0.303003 |
| L9   | 14    | 2BC      | 0.282518 | 0.241068 | 0.291884 | 0.304444 | 0.283022 | 0.280587 |
| L9   | 14    | 3BC      | 0.190994 | 0.206066 | 0.185043 | 0.257874 | 0.201742 | 0.208344 |
| L9   | 14    | LC1      | 0.290192 | 0.289623 | 0.27888  | 0.279674 | 0.267339 | 0.281142 |
| L9   | 14    | LC2      | 0.213012 | 0.162205 | 0.184279 | 0.237271 | 0.253447 | 0.210043 |
| L9   | 14    | LC3      | 0.229799 | 0.282755 | 0.179786 | 0.320789 | 0.248623 | 0.252351 |
| L9   | 14    | BE1      | 3.029568 | 4.838847 | 2.661082 | 3.576916 | 5.468926 | 3.915068 |
| L9   | 14    | LE1      | 3.33897  | 7.478969 | 6.806672 | 4.212604 | 6.836673 | 5.734778 |
| L9   | 24    | BC1      | 0.276011 | 0.301647 | 0.285713 | 0.300961 | 0.31277  | 0.29542  |
| L9   | 24    | BC2      | 0.246535 | 0.212285 | 0.228842 | 0.548858 | 0.447388 | 0.336782 |
| L9   | 24    | BC3      | 0.154624 | 0.270466 | 0.274548 | 0.237921 | 0.271117 | 0.241735 |
| L9   | 24    | 1BC      | 0.345999 | 0.401418 | 0.382592 | 0.401595 | 0.388886 | 0.384098 |
| L9   | 24    | 2BC      | 0.335397 | 0.344948 | 0.41611  | 0.408579 | 0.321247 | 0.365256 |
| L9   | 24    | 3BC      | 0.301228 | 0.187377 | 0.306781 | 0.214334 | 0.29462  | 0.260868 |
| L9   | 24    | LC1      | 0.329597 | 0.276715 | 0.330167 | 0.352949 | 0.315835 | 0.321052 |
| L9   | 24    | LC2      | 0.259015 | 0.251224 | 0.250866 | 0.243699 | 0.17187  | 0.235335 |
| L9   | 24    | LC3      | 0.157177 | 0.310218 | 0.295779 | 0.302066 | 0.225691 | 0.258186 |
| L9   | 24    | BE1      | 0.154624 | 3.504164 | 3.153413 | 4.297396 | 5.743809 | 3.370681 |
| L9   | 24    | LE1      | 5.157075 | 7.312264 | 6.94999  | 7.617976 | 5.931545 | 6.59377  |



6.3.2. ELASTIC MODULUS DATA SUMMARY

| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H1 | 14    | BC1      | 3.167346  | 3.187124  | 2.526435  | 3.263574  | *         | 3.036120  |
| H1 | 14    | BC2      | 1.087901  | 0.791070  | 1.195268  | 0.794035  | 0.608497  | 0.895354  |
| H1 | 14    | BC3      | 0.961365  | *         | *         | 0.887476  | 0.650637  | 0.833160  |
| H1 | 14    | 1BC      | 3.917250  | 3.767857  | 4.229436  | 4.539707  | 4.364530  | 4.163757  |
| H1 | 14    | 2BC      | 3.105017  | 1.852625  | 3.324311  | 3.093044  | 2.693976  | 2.740989  |
| H1 | 14    | 3BC      | 1.460540  | 1.711652  | 1.674361  | 2.371452  | 1.793490  | 1.802299  |
| H1 | 14    | LC1      | 5.991261  | 8.001984  | 3.886003  | 6.540325  | 5.982255  | 6.080365  |
| H1 | 14    | LC2      | 4.644028  | 6.010582  | 5.302996  | 3.466412  | 5.733607  | 5.031525  |
| H1 | 14    | LC3      | 2.166996  | 3.185813  | 3.191670  | 2.731190  | 3.822365  | 3.019607  |
| H1 | 14    | BE1      | 27.452791 | 30.804612 | 18.659747 | 26.188665 | 24.080435 | 25.437250 |
| H1 | 14    | LE1      | 36.938775 | 19.547716 | 53.518660 | 21.986222 | 46.053645 | 35.609003 |
| H1 | 24    | BC1      | 2.566436  | 3.352375  | 2.932358  | 4.206390  | 3.760395  | 3.363591  |
| H1 | 24    | BC2      | 2.055368  | 2.314678  | 1.784889  | 2.155825  | 2.149106  | 2.091973  |
| H1 | 24    | BC3      | 1.158565  | 0.997750  | 1.507813  | 0.893492  | 1.580844  | 1.287709  |
| H1 | 24    | 1BC      | 2.034795  | 3.573341  | 3.411212  | 3.883846  | 3.991291  | 3.378897  |
| H1 | 24    | 2BC      | 2.707591  | 2.879956  | 3.134781  | 3.976022  | 2.504449  | 3.040560  |
| H1 | 24    | 3BC      | 3.786623  | 2.702034  | 2.820492  | 3.535086  | 3.360865  | 3.241020  |
| H1 | 24    | LC1      | 4.634415  | 6.374619  | 5.920703  | 5.429020  | 6.958082  | 5.863368  |
| H1 | 24    | LC2      | 4.007363  | 6.200803  | 5.764803  | 7.341762  | 6.482859  | 5.959518  |
| H1 | 24    | LC3      | 7.706005  | 4.217721  | 4.136588  | 6.256845  | 5.221166  | 5.507665  |
| H1 | 24    | BE1      | 24.473183 | 32.385458 | 19.026775 | 28.375583 | 32.896437 | 27.431487 |
| H1 | 24    | LE1      | 28.840060 | 25.403628 | 28.629309 | 27.136256 | 30.493411 | 28.100533 |
| H2 | 14    | BC1      | 3.889630  | 6.699256  | 6.655575  | 4.792924  | 7.198629  | 5.847203  |
| H2 | 14    | BC2      | 4.537272  | 4.643111  | 5.109881  | 4.175621  | 4.339813  | 4.561139  |
| H2 | 14    | BC3      | 8.438487  | 7.534776  | 7.524646  | 6.794798  | *         | 7.573177  |
| H2 | 14    | 1BC      | 2.084788  | 2.106746  | 1.949717  | 1.800267  | 1.723664  | 1.933037  |
| H2 | 14    | 2BC      | 1.106108  | 1.214455  | 1.321660  | 1.161449  | 1.161449  | 1.214753  |
| H2 | 14    | 3BC      | 0.696175  | 0.558380  | 0.641173  | 0.434722  | 0.371797  | 0.540449  |
| H2 | 14    | LC1      | 1.310543  | 1.414627  | 1.199570  | 1.065710  | 1.279586  | 1.254007  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H2 | 14    | LC2      | 0.800157  | 0.764404  | 0.797499  | 0.814668  | 0.819260  | 0.799198  |
| H2 | 14    | LC3      | 0.400953  | 0.819260  | 0.393078  | 0.441910  | 0.398155  | 0.490671  |
| H2 | 14    | BE1      | 43.979278 | 35.754671 | 34.932943 | 36.085360 | 36.962015 | 37.542853 |
| H2 | 14    | LE1      | 36.898846 | 23.341715 | 27.736173 | 30.617764 | 30.436576 | 29.806215 |
| H2 | 24    | BC1      | 2.764695  | 2.934585  | 3.045506  | 2.955895  | 3.321665  | 3.004469  |
| H2 | 24    | BC2      | 1.574525  | 1.770331  | 1.827161  | 1.859633  | 1.933175  | 1.792965  |
| H2 | 24    | BC3      | 1.614320  | 1.569887  | 1.091114  | 1.397143  | 1.614629  | 1.457419  |
| H2 | 24    | 1BC      | 5.542314  | 5.459577  | 4.645355  | 5.794595  | 5.698849  | 5.428138  |
| H2 | 24    | 2BC      | 2.621806  | 2.938991  | 3.164213  | 3.036969  | 3.049803  | 2.962356  |
| H2 | 24    | 3BC      | 0.225783  | 0.255358  | 0.222886  | 0.241548  | 0.212820  | 0.215035  |
| H2 | 24    | LC1      | 3.664106  | 3.532509  | 3.692492  | 4.288936  | 4.107714  | 3.857151  |
| H2 | 24    | LC2      | 2.763051  | 2.582249  | 2.714648  | 2.673565  | 2.719425  | 2.690588  |
| H2 | 24    | LC3      | 0.751699  | 0.782722  | 0.702103  | 0.991212  | 0.783404  | 0.802228  |
| H2 | 24    | BE1      | 41.133008 | 31.309885 | 36.237023 | 30.823219 | 25.990627 | 33.098753 |
| H2 | 24    | LE1      | 27.759343 | 24.403179 | 29.062565 | 38.583215 | 27.801933 | 29.522047 |
| H3 | 14    | BC1      | 2.002950  | 2.184434  | 1.911254  | 2.075165  | 1.933769  | 2.021514  |
| H3 | 14    | BC2      | 2.816145  | 2.689485  | 1.424264  | 3.169587  | 3.150089  | 2.649914  |
| H3 | 14    | BC3      | 0.080463  | 0.053801  | 0.070597  | 0.136816  | 0.141023  | 0.096540  |
| H3 | 14    | 1BC      | 3.326894  | 3.079745  | 3.693572  | 2.755277  | 3.050007  | 3.181099  |
| H3 | 14    | 2BC      | 1.366248  | 2.467643  | 2.765795  | 2.734392  | 2.359367  | 2.581799  |
| H3 | 14    | 3BC      | 2.016955  | 1.911299  | 1.996497  | 1.234672  | 1.113129  | 1.654510  |
| H3 | 14    | LC1      | 1.277454  | 1.710900  | 1.574910  | 2.171198  | 1.912717  | 1.729436  |
| H3 | 14    | LC2      | 1.803769  | 2.609239  | 3.657333  | 3.341940  | 2.033614  | 2.689179  |
| H3 | 14    | LC3      | 1.606841  | 2.765403  | 2.882943  | 2.241675  | 2.508585  | 2.401089  |
| H3 | 14    | BE1      | 30.902788 | 25.660467 | 27.544494 | 41.187051 | 40.775095 | 33.213979 |
| H3 | 14    | LE1      | 19.298714 | 23.602525 | 27.301729 | 15.370678 | 19.434416 | 21.001613 |
| H3 | 24    | BC1      | 3.177065  | 2.926795  | 2.633930  | 3.056296  | 2.887501  | 2.936318  |
| H3 | 24    | BC2      | 1.311675  | 1.449504  | 1.243105  | 1.911998  | 1.902084  | 1.563673  |
| H3 | 24    | BC3      | 1.057666  | 1.144539  | 1.569328  | 1.452824  | 1.368308  | 1.318533  |
| H3 | 24    | 1BC      | 1.446799  | 1.218928  | 1.546562  | 1.574431  | 1.596401  | 1.476624  |
| H3 | 24    | 2BC      | 0.662694  | 0.658883  | 0.623288  | 0.768748  | *         | 0.678403  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H3 | 24    | 3BC      | 1.219654  | 1.217839  | 0.901102  | 1.210478  | 1.139636  | 1.137742  |
| H3 | 24    | LC1      | 3.324019  | 3.981857  | 3.790745  | 4.707581  | 4.619414  | 4.084723  |
| H3 | 24    | LC2      | 2.819300  | 1.875095  | 2.249505  | 2.969483  | 2.772295  | 2.537135  |
| H3 | 24    | LC3      | 1.384909  | 1.971661  | 1.628971  | 2.616141  | 1.691265  | 1.858589  |
| H3 | 24    | BE1      | 26.283489 | 15.242221 | 33.017104 | 25.033776 | 32.145032 | 26.344324 |
| H3 | 24    | LE1      | 21.570258 | 34.284393 | 26.508440 | 41.225717 | 41.225717 | 32.962905 |
| H4 | 14    | BC1      | 4.559608  | 4.006991  | 4.135777  | 4.713691  | 4.673630  | 4.417939  |
| H4 | 14    | BC2      | 3.804925  | 4.013920  | 4.593035  | 4.102023  | 4.355519  | 4.173885  |
| H4 | 14    | BC3      | 1.195067  | 1.160035  | 1.240733  | 1.469615  | 1.207970  | 1.254684  |
| H4 | 14    | 1BC      | 3.283845  | 2.814674  | 2.835785  | 3.051435  | 3.241658  | 3.045479  |
| H4 | 14    | 2BC      | 1.956870  | 1.579652  | 1.790575  | 1.798368  | 1.936097  | 1.776173  |
| H4 | 14    | 3BC      | 2.491555  | 1.692731  | 2.116627  | 1.789663  | 2.087220  | 2.035559  |
| H4 | 14    | LC1      | 6.302945  | 5.372905  | 5.503573  | 5.403468  | 4.510557  | 5.418690  |
| H4 | 14    | LC2      | 1.986865  | 1.674774  | 2.079440  | 2.114033  | 2.088616  | 1.988746  |
| H4 | 14    | LC3      | 0.938253  | 0.787851  | 0.921875  | 1.043178  | 0.953966  | 0.929025  |
| H4 | 14    | BE1      | 30.849855 | 41.851919 | 40.403113 | 31.110503 | 40.944367 | 37.031951 |
| H4 | 14    | LE1      | 26.106805 | 54.680895 | 43.287277 | 54.080702 | 44.155628 | 44.462261 |
| H4 | 24    | BC1      | 5.488062  | 5.153249  | 5.674531  | 5.947122  | 7.427620  | 5.938117  |
| H4 | 24    | BC2      | 3.345502  | 3.539661  | 3.541585  | 3.609615  | 3.559134  | 3.519099  |
| H4 | 24    | BC3      | 2.745609  | 2.448682  | 1.611100  | 1.770187  | 2.226714  | 2.160458  |
| H4 | 24    | 1BC      | 4.067028  | 4.038786  | 4.352658  | 4.130925  | 3.340029  | 3.985885  |
| H4 | 24    | 2BC      | 2.112815  | 2.172682  | 2.116935  | 2.263073  | 2.136310  | 2.160363  |
| H4 | 24    | 3BC      | 1.496892  | 1.306181  | 1.152864  | 1.374104  | 1.255377  | 1.317083  |
| H4 | 24    | LC1      | 4.060238  | 3.344376  | 3.449456  | 2.026536  | 2.864509  | 3.149023  |
| H4 | 24    | LC2      | 2.119727  | 1.747459  | 2.071011  | 1.995690  | 2.024975  | 1.991772  |
| H4 | 24    | LC3      | 1.372911  | 1.435849  | 1.410467  | 1.342645  | 1.483658  | 1.409106  |
| H4 | 24    | BE1      | 25.110305 | 26.937919 | 18.391545 | 22.041695 | 29.572330 | 24.410759 |
| H4 | 24    | LE1      | 27.660505 | 22.150087 | 20.412001 | 17.175611 | 27.112635 | 22.902168 |
| H5 | 14    | BC1      | 1.960043  | 2.294464  | 2.080274  | 2.183451  | 1.757944  | 2.055235  |
| H5 | 14    | BC2      | 1.434944  | 1.628626  | 1.422683  | 1.501404  | 1.551837  | 1.507899  |
| H5 | 14    | BC3      | 0.790360  | *         | 0.870658  | 0.965572  | 0.805515  | 0.858026  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H5 | 14    | 1BC      | 0.234720  | 0.221582  | 0.209624  | 0.202605  | 0.214946  | 0.216695  |
| H5 | 14    | 2BC      | 0.921607  | 0.973315  | 0.908788  | 0.982529  | 0.970492  | 0.958781  |
| H5 | 14    | 3BC      | 2.871497  | 2.767001  | 2.719441  | 2.416087  | 2.438722  | 2.642550  |
| H5 | 14    | LC1      | 4.504640  | 5.132378  | 3.508477  | 3.832682  | 2.967517  | 3.989139  |
| H5 | 14    | LC2      | 2.181078  | 3.286110  | 2.237492  | 2.520586  | 1.986907  | 2.442435  |
| H5 | 14    | LC3      | 2.285527  | 2.205811  | 2.104692  | 1.932470  | 2.522152  | 2.210130  |
| H5 | 14    | BE1      | 36.137640 | 55.689766 | 26.079324 | 45.652641 | 34.368941 | 39.585662 |
| H5 | 14    | LE1      | 51.809242 | 39.194536 | 44.203899 | 37.524941 | 37.834536 | 42.113431 |
| H5 | 24    | BC1      | 5.456591  | 4.808071  | 4.368132  | 4.998622  | 5.081929  | 4.942669  |
| H5 | 24    | BC2      | 1.446048  | 1.278568  | 1.686765  | 1.549854  | 1.443514  | 1.480950  |
| H5 | 24    | BC3      | 2.478969  | 2.323548  | 2.024638  | 2.399421  | 2.350512  | 2.315418  |
| H5 | 24    | 1BC      | 5.687295  | 5.338331  | 4.845743  | 4.630927  | 5.356342  | 5.171728  |
| H5 | 24    | 2BC      | 2.961968  | 3.428133  | 3.491145  | 3.383985  | 3.560394  | 3.365125  |
| H5 | 24    | 3BC      | 0.864966  | 0.926087  | 0.810675  | 0.871423  | 0.991709  | 0.892972  |
| H5 | 24    | LC1      | 4.350695  | 3.894494  | 3.470367  | 3.990028  | 3.891580  | 3.919433  |
| H5 | 24    | LC2      | 1.913897  | 1.436316  | 1.575909  | 1.619287  | 1.149334  | 1.538949  |
| H5 | 24    | LC3      | 0.940582  | 0.543298  | 0.988337  | 0.997852  | 0.869317  | 0.867877  |
| H5 | 24    | BE1      | 29.859803 | 39.347613 | 34.024105 | 29.246402 | 38.683224 | 34.232229 |
| H5 | 24    | LE1      | 40.504035 | 48.731398 | 52.089224 | 44.252933 | 40.175765 | 45.150671 |
| H6 | 14    | BC1      | 6.215385  | 7.461081  | 6.687631  | 6.173241  | 5.975380  | 6.502544  |
| H6 | 14    | BC2      | 1.753568  | 1.720980  | 1.668664  | 1.724483  | 1.736246  | 1.720788  |
| H6 | 14    | BC3      | 1.676517  | 1.691233  | 1.305982  | 1.836740  | 1.697449  | 1.641584  |
| H6 | 14    | 1BC      | 8.247715  | 7.655795  | 8.527160  | 8.458323  | 9.042104  | 8.386219  |
| H6 | 14    | 2BC      | 1.692296  | 1.714293  | 1.822030  | 1.822325  | 1.825499  | 1.796037  |
| H6 | 14    | 3BC      | 1.042015  | 1.070622  | 1.111275  | 1.102956  | 1.136559  | 1.092685  |
| H6 | 14    | LC1      | 5.290419  | 5.906086  | 5.750887  | 5.806996  | 5.629077  | 5.676693  |
| H6 | 14    | LC2      | 4.522630  | *         | 4.730350  | *         | 4.941287  | 4.731422  |
| H6 | 14    | LC3      | 2.756965  | 2.946206  | 3.001123  | 2.622118  | 1.935315  | 2.652345  |
| H6 | 14    | BE1      | 18.909331 | 23.745643 | 25.232852 | 16.411035 | 25.441165 | 21.948005 |
| H6 | 14    | LE1      | 38.433465 | 38.433465 | 42.941314 | 40.057845 | 34.669261 | 38.907070 |
| H6 | 24    | BC1      | 2.142489  | 1.803606  | 1.429558  | 1.891975  | 1.892556  | 1.832037  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H6 | 24    | BC2      | 5.697404  | 7.110536  | 4.540499  | 7.024196  | 5.662650  | 6.007057  |
| H6 | 24    | BC3      | 3.094985  | 3.545036  | 3.636235  | 5.395204  | 4.659597  | 4.066211  |
| H6 | 24    | 1BC      | 3.706047  | 3.931188  | 2.918932  | 4.333673  | 4.069819  | 3.791932  |
| H6 | 24    | 2BC      | 2.297285  | 2.633474  | 2.713397  | 2.486549  | 2.409375  | 2.508016  |
| H6 | 24    | 3BC      | 1.109638  | 1.370630  | 1.375642  | 1.619035  | 1.098952  | 1.314779  |
| H6 | 24    | LC1      | 2.428768  | 2.377385  | 2.152765  | 2.236853  | 2.389616  | 2.317077  |
| H6 | 24    | LC2      | 1.472558  | 1.433242  | 1.489265  | 1.512617  | 1.536839  | 1.488904  |
| H6 | 24    | LC3      | 0.903460  | 0.925122  | 0.940602  | 0.967681  | 0.971373  | 0.941647  |
| H6 | 24    | BE1      | 15.269156 | 17.330177 | 18.802602 | 20.824598 | 16.810971 | 17.807501 |
| H6 | 24    | LE1      | 15.108376 | 14.258648 | 18.245324 | 15.714954 | 16.235595 | 15.912579 |
| H7 | 44    | BC1      | 1.914940  | 1.634310  | 2.032724  | 1.559476  | 1.479151  | 1.724120  |
| H7 | 44    | BC2      | 2.076977  | 1.440491  | 1.541878  | 1.572388  | 1.292355  | 1.584818  |
| H7 | 44    | BC3      | 2.380645  | 2.597770  | 2.491518  | 3.041394  | 2.441416  | 2.590549  |
| H7 | 44    | 1BC      | 5.087628  | 4.312790  | 5.708591  | 5.755331  | *         | 5.216085  |
| H7 | 44    | 2BC      | 1.454934  | 1.169758  | 1.343118  | 1.423399  | 1.432575  | 1.342213  |
| H7 | 44    | 3BC      | 0.956625  | 0.834575  | 0.905715  | 0.862232  | 0.898000  | 0.891429  |
| H7 | 44    | LC1      | 1.350981  | 1.395615  | 1.208435  | 1.412330  | 1.571783  | 1.387829  |
| H7 | 44    | LC2      | 3.002618  | 2.731111  | 2.400938  | 2.068677  | 1.827746  | 2.406218  |
| H7 | 44    | LC3      | 0.526500  | 0.620284  | 0.327920  | 0.553198  | 0.625141  | 0.505805  |
| H7 | 44    | BE1      | 17.254805 | 4.751425  | 8.037517  | 12.888134 | 19.717281 | 12.529832 |
| H7 | 44    | LE1      | 28.110275 | 29.797207 | 20.283035 | 31.420968 | 29.074965 | 27.737290 |
| H7 | 34    | BC1      | 1.491453  | 1.676431  | 1.626759  | 0.863912  | 1.636685  | 1.459048  |
| H7 | 34    | BC2      | 1.965145  | 2.204194  | 2.093775  | 2.146959  | 2.074483  | 2.096911  |
| H7 | 34    | BC3      | 0.679226  | 1.001879  | 0.928382  | 1.099910  | 1.114003  | 0.964680  |
| H7 | 34    | 1BC      | 2.733762  | 2.274390  | 2.007898  | 3.118211  | 2.952724  | 2.617397  |
| H7 | 34    | 2BC      | 1.151936  | 1.424105  | 0.870068  | 1.230989  | 1.399075  | 1.215235  |
| H7 | 34    | 3BC      | 5.368750  | 4.532838  | 4.174415  | 5.545208  | 5.676451  | 5.059533  |
| H7 | 34    | LC1      | 1.934179  | 1.720756  | 1.537456  | 1.780383  | 2.036161  | 1.801787  |
| H7 | 34    | LC2      | 3.578135  | 3.510804  | 3.466537  | 3.502411  | 3.468099  | 3.505197  |
| H7 | 34    | LC3      | 2.550606  | 3.438492  | 3.042619  | *         | *         | 3.010572  |
| H7 | 34    | BE1      | 26.489150 | 14.294756 | 25.583243 | 27.791299 | 32.669406 | 25.365571 |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H7 | 34    | LE1      | 22.447948 | 30.513206 | 19.544431 | 27.669298 | 21.652103 | 24.365397 |
| H8 | 14    | BC1      | 4.802180  | 4.234769  | 4.782387  | 5.269489  | 5.052079  | 4.828181  |
| H8 | 14    | BC2      | 1.992603  | 1.949755  | 1.979210  | 2.191038  | 2.035060  | 2.029533  |
| H8 | 14    | BC3      | 2.186588  | 2.873601  | 2.679575  | 1.861000  | 2.046124  | 2.329378  |
| H8 | 14    | 1BC      | *         | 6.368261  | 8.907336  | 7.424594  | 8.729208  | 7.857350  |
| H8 | 14    | 2BC      | 6.076247  | 6.073451  | 6.306325  | 6.711941  | 5.339861  | 6.107895  |
| H8 | 14    | 3BC      | 2.261942  | 2.554161  | 2.891510  | 3.040458  | 2.472216  | 2.644057  |
| H8 | 14    | LC1      | 1.334326  | 1.500435  | 1.624645  | 1.580425  | 1.511754  | 1.510317  |
| H8 | 14    | LC2      | 1.193596  | 1.214569  | 1.232458  | 1.129278  | 1.153126  | 1.184606  |
| H8 | 14    | LC3      | 1.169318  | 0.924038  | 1.049674  | 1.161416  | 1.236251  | 1.108139  |
| H8 | 14    | BE1      | 11.035949 | 38.232131 | 19.280515 | 14.356985 | *         | 20.726395 |
| H8 | 14    | LE1      | 30.333716 | 29.320602 | 24.497760 | 21.445918 | 29.419438 | 27.003487 |
| H8 | 24    | BC1      | 5.107406  | 5.408720  | 5.893874  | 5.085702  | 5.383140  | 5.375768  |
| H8 | 24    | BC2      | 5.483200  | 5.870962  | 5.990273  | 7.036066  | 4.786707  | 5.833442  |
| H8 | 24    | BC3      | 1.262309  | 1.344161  | 1.300968  | 1.541804  | 1.307037  | 1.351256  |
| H8 | 24    | 1BC      | 5.031078  | 4.967822  | 5.724366  | 5.198570  | 5.043649  | 5.193097  |
| H8 | 24    | 2BC      | 3.514692  | 2.948443  | 2.975747  | 3.734417  | 3.451536  | 3.324967  |
| H8 | 24    | 3BC      | 1.414285  | 1.296840  | 2.007034  | 2.058581  | 1.669375  | 1.689223  |
| H8 | 24    | LC1      | 4.716568  | 4.449894  | 4.532068  | 4.802760  | 4.621635  | 4.624585  |
| H8 | 24    | LC2      | 3.728093  | 3.398564  | 2.998687  | 3.909713  | 3.695745  | 3.546160  |
| H8 | 24    | LC3      | 2.855380  | 2.370831  | 1.551291  | 2.786247  | 2.742264  | 2.461203  |
| H8 | 24    | BE1      | 36.628674 | 36.278260 | 31.620904 | 37.655647 | 36.359572 | 35.708611 |
| H8 | 24    | LE1      | 18.797593 | 18.797593 | 20.946576 | 10.118721 | 6.765437  | 15.085184 |
| H9 | 14    | BC1      | 3.517018  | 3.050331  | 3.148854  | 4.224297  | 3.527032  | 3.493506  |
| H9 | 14    | BC2      | 1.606252  | 1.797436  | 1.515255  | 1.694000  | 2.022622  | 1.727113  |
| H9 | 14    | BC3      | 2.890006  | 2.768075  | 2.993534  | 2.478805  | 3.372884  | 2.900661  |
| H9 | 14    | 1BC      | 3.064718  | 3.064718  | 3.439525  | 4.147742  | 3.336248  | 3.410590  |
| H9 | 14    | 2BC      | 3.550999  | 2.075836  | 3.021661  | 4.006365  | 2.153087  | 2.814237  |
| H9 | 14    | 3BC      | 0.889625  | 0.834575  | 0.905715  | 0.862232  | 0.836562  | 0.865742  |
| H9 | 14    | LC1      | 3.392967  | 3.213934  | 2.780520  | 3.628837  | 3.208777  | 3.245007  |
| H9 | 14    | LC2      | 3.571768  | 3.670731  | 2.963376  | 3.968598  | 4.715736  | 3.778042  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| H9 | 14    | LC3      | *         | *         | *         | *         | *         | *         |
| H9 | 14    | BE1      | 30.759110 | 62.145050 | 34.453243 | 50.768442 | 62.648932 | 48.154955 |
| H9 | 14    | LE1      | 26.225003 | 62.145050 | 34.453243 | 50.768442 | 62.648932 | 47.24813  |
| H9 | 24    | BC1      | 1.419334  | 1.667915  | 1.667915  | 2.283382  | 1.419923  | 1.691693  |
| H9 | 24    | BC2      | 2.459236  | 2.570978  | 1.785084  | 2.956965  | 2.501564  | 2.454765  |
| H9 | 24    | BC3      | 2.501564  | 3.236175  | 3.259384  | 3.985644  | 3.552124  | 3.306978  |
| H9 | 24    | 1BC      | 2.220562  | 2.209939  | 2.113341  | 2.318351  | 1.584985  | 2.089436  |
| H9 | 24    | 2BC      | 2.570088  | 2.411471  | 3.785674  | 4.209008  | 4.232074  | 3.441663  |
| H9 | 24    | 3BC      | 3.383381  | 3.577302  | 3.879915  | 3.971269  | 4.872055  | 3.936785  |
| H9 | 24    | LC1      | 6.713480  | 7.114892  | 5.355364  | 5.781310  | 4.760948  | 5.945199  |
| H9 | 24    | LC2      | 4.790680  | 3.660810  | 3.325405  | 3.389540  | 4.498048  | 3.932897  |
| H9 | 24    | LC3      | 1.977444  | 1.544045  | 1.489795  | 1.942677  | 1.855275  | 1.761847  |
| H9 | 24    | BE1      | 46.637580 | 50.464300 | 43.657304 | 45.636783 | 46.761612 | 46.631516 |
| H9 | 24    | LE1      | 47.304767 | 46.048216 | 30.117097 | 43.244085 | 43.313251 | 42.005483 |
| L1 | 14    | BC1      | 2.813050  | 2.919248  | 2.872359  | 2.608319  | 2.343355  | 2.711266  |
| L1 | 14    | BC2      | 1.570484  | 1.515427  | 1.476458  | 1.672454  | 1.741870  | 1.595339  |
| L1 | 14    | BC3      | 1.001822  | 0.937160  | 1.002657  | 1.045369  | 1.128250  | 1.023052  |
| L1 | 14    | 1BC      | 2.333846  | 2.283617  | 2.281120  | 2.289454  | 2.089673  | 2.255542  |
| L1 | 14    | 2BC      | 4.474385  | 4.353664  | 3.824473  | 5.926268  | 5.145387  | 4.812448  |
| L1 | 14    | 3BC      | 5.949620  | 6.299925  | 6.218870  | 6.211077  | 5.964670  | 6.128833  |
| L1 | 14    | LC1      | 4.575445  | 6.486823  | 4.897405  | 3.626430  | 2.899921  | 4.497205  |
| L1 | 14    | LC2      | *         | *         | 0.902060  | 0.987730  | 0.965873  | 0.951888  |
| L1 | 14    | LC3      | 4.954533  | 5.378791  | 4.170437  | 5.278025  | 5.851797  | 5.126717  |
| L1 | 14    | BE1      | 10.158996 | 11.609023 | 12.247524 | 10.946555 | 11.320919 | 11.256603 |
| L1 | 14    | LE1      | 9.615155  | 6.811912  | 6.106446  | 4.905479  | 8.315741  | 7.150947  |
| L1 | 24    | BC1      | 6.464787  | 9.238848  | 7.394752  | 7.702189  | 7.852976  | 7.730711  |
| L1 | 24    | BC2      | 0.935220  | 1.168234  | 1.140502  | 1.166252  | 1.119347  | 1.105911  |
| L1 | 24    | BC3      | 2.462071  | 2.661569  | 2.501317  | 2.397405  | 2.346157  | 2.473704  |
| L1 | 24    | 1BC      | 9.070855  | 9.326366  | 7.947097  | 7.317893  | 7.482987  | 8.229040  |
| L1 | 24    | 2BC      | 1.429900  | 1.357662  | 1.332680  | 1.346341  | 1.356426  | 1.364602  |
| L1 | 24    | 3BC      | 1.121245  | 1.123685  | 1.176569  | 1.172384  | 1.151776  | 1.149132  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L1 | 24    | LC1      | 5.212696  | 4.174454  | 4.282812  | 4.593073  | 3.903362  | 4.433279  |
| L1 | 24    | LC2      | 5.007005  | 4.492015  | 5.262403  | 4.366199  | 4.466407  | 4.718806  |
| L1 | 24    | LC3      | 2.472541  | 2.287365  | 2.395845  | 2.236502  | 2.061595  | 2.290770  |
| L1 | 24    | BE1      | 26.575463 | 24.950695 | 21.720235 | 28.078195 | 28.010639 | 25.867045 |
| L1 | 24    | LE1      | 24.179954 | 21.290074 | 19.660497 | 23.349668 | 24.777913 | 22.651621 |
| L2 | 14    | BC1      | 5.607507  | 5.053266  | 5.346912  | 5.679097  | 5.258301  | 5.389017  |
| L2 | 14    | BC2      | 1.259815  | 0.661828  | 1.162344  | 1.312264  | 0.958667  | 1.070983  |
| L2 | 14    | BC3      | 1.607220  | 2.090385  | 1.268128  | 1.527449  | 0.821143  | 1.462865  |
| L2 | 14    | 1BC      | 1.222392  | 1.380873  | 1.601209  | 1.564182  | 1.478158  | 1.449363  |
| L2 | 14    | 2BC      | 2.251885  | 1.764711  | 3.202595  | 2.223990  | 2.054085  | 2.311345  |
| L2 | 14    | 3BC      | 0.505838  | 0.532856  | 0.528498  | 0.543613  | 0.831928  | 0.588547  |
| L2 | 14    | LC1      | 3.218563  | 2.712601  | 2.545265  | 2.698452  | 2.887662  | 2.812508  |
| L2 | 14    | LC2      | 2.686879  | 2.594702  | 2.428551  | 2.540652  | 2.331975  | 2.516552  |
| L2 | 14    | LC3      | 0.934068  | 1.741042  | 1.207049  | 1.541148  | 1.268103  | 1.338282  |
| L2 | 14    | BE1      | 61.475225 | 47.862285 | 49.582179 | 37.779341 | 49.099066 | 49.159619 |
| L2 | 14    | LE1      | 9.645569  | 12.609131 | 15.999351 | 16.952837 | 14.683890 | 13.978156 |
| L2 | 24    | BC1      | 3.174720  | 2.641925  | 3.823910  | 3.197120  | 3.423106  | 3.252156  |
| L2 | 24    | BC2      | 1.744820  | 1.381611  | 1.548535  | 1.614261  | 1.277390  | 1.513323  |
| L2 | 24    | BC3      | 1.097855  | 1.127681  | 0.966390  | 1.012199  | 1.137510  | 1.068327  |
| L2 | 24    | 1BC      | 2.153235  | 2.451462  | 1.425505  | 2.738945  | *         | 2.192287  |
| L2 | 24    | 2BC      | 2.979457  | 2.454883  | 2.724234  | 2.628920  | 1.878896  | 2.533278  |
| L2 | 24    | 3BC      | 1.430981  | 0.967609  | 1.155255  | 1.377849  | 1.233707  | 1.284705  |
| L2 | 24    | LC1      | 3.917055  | 4.608381  | 4.134220  | 3.603329  | 3.798615  | 4.012320  |
| L2 | 24    | LC2      | 0.842445  | 0.894755  | 0.791379  | 1.079251  | 0.909270  | 0.903420  |
| L2 | 24    | LC3      | 0.703813  | 0.724969  | 0.673324  | 0.720899  | 0.659275  | 0.696456  |
| L2 | 24    | BE1      | 23.514609 | 31.528354 | 16.617836 | 21.846052 | 28.096359 | 24.320642 |
| L2 | 24    | LE1      | 29.014200 | 24.025376 | 27.070965 | 26.217601 | 26.035112 | 26.472651 |
| L3 | 14    | BC1      | 3.863507  | 2.294332  | 2.064145  | 3.242189  | 4.202953  | 3.133425  |
| L3 | 14    | BC2      | 4.903278  | 5.032275  | 6.294544  | 6.141065  | 5.910289  | 5.656290  |
| L3 | 14    | BC3      | 4.079374  | 4.533005  | 4.963079  | 5.020046  | 4.345358  | 4.588173  |
| L3 | 14    | 1BC      | 8.003111  | 8.064421  | 9.667895  | 9.243923  | 9.155843  | 8.827039  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L3 | 14    | 2BC      | 8.123129  | 7.566284  | 8.229015  | 8.525789  | 7.879895  | 8.050245  |
| L3 | 14    | 3BC      | 6.141913  | 7.564289  | 7.264989  | 6.293845  | 5.442103  | 6.541428  |
| L3 | 14    | LC1      | 7.812352  | 7.025340  | 7.463405  | 8.960795  | 8.960556  | 8.044490  |
| L3 | 14    | LC2      | 4.800776  | 5.720748  | 6.035044  | 5.551514  | 5.545934  | 5.530803  |
| L3 | 14    | LC3      | 3.870805  | 3.791065  | *         | 3.733918  | 3.472248  | 3.717009  |
| L3 | 14    | BE1      | 33.032318 | 32.065716 | 37.193571 | 51.006945 | 96.737415 | 38.324638 |
| L3 | 14    | LE1      | 37.582137 | 52.512408 | 24.170340 | 24.277050 | 49.727503 | 37.653888 |
| L3 | 24    | BC1      | 3.269866  | 2.986134  | 3.171367  | 3.207012  | 3.194862  | 3.165848  |
| L3 | 24    | BC2      | 1.754125  | 1.780636  | 1.989014  | 1.394677  | 1.654923  | 1.714675  |
| L3 | 24    | BC3      | 2.844715  | 2.661000  | 3.203625  | 3.183619  | 3.405483  | 3.059688  |
| L3 | 24    | 1BC      | 6.635096  | 6.690500  | 6.113899  | 6.490918  | 6.587613  | 6.503605  |
| L3 | 24    | 2BC      | 4.022225  | 3.703777  | 3.615201  | 3.750136  | 4.504370  | 3.919142  |
| L3 | 24    | 3BC      | 3.233472  | 3.031876  | 2.327490  | 2.999937  | 3.314545  | 2.981464  |
| L3 | 24    | LC1      | 3.754850  | 3.606117  | 3.942170  | 3.569378  | 3.888897  | 3.752283  |
| L3 | 24    | LC2      | 6.892880  | 6.964124  | 5.392691  | 7.162611  | 7.785782  | 6.839617  |
| L3 | 24    | LC3      | 3.584146  | 4.600298  | 4.146970  | 4.723696  | 4.629107  | 4.336844  |
| L3 | 24    | BE1      | 42.859083 | 63.155110 | 57.054907 | 48.670269 | 52.942693 | 52.936412 |
| L3 | 24    | LE1      | 28.259385 | 27.421475 | 29.378746 | 31.036574 | 28.158151 | 28.850866 |
| L4 | 14    | BC1      | 3.719652  | 4.546696  | 4.625524  | 5.889845  | 6.907942  | 5.137932  |
| L4 | 14    | BC2      | 3.739128  | 3.685960  | 3.749875  | 4.094752  | 3.848335  | 3.823610  |
| L4 | 14    | BC3      | 3.291975  | *         | 3.531174  | 3.939008  | 3.570238  | 3.583099  |
| L4 | 14    | 1BC      | 5.562674  | 4.991939  | 6.891288  | 6.032218  | 5.301926  | 5.756009  |
| L4 | 14    | 2BC      | 3.676634  | 2.849238  | 4.385336  | 3.278644  | 3.790373  | 3.575898  |
| L4 | 14    | 3BC      | 3.607603  | 2.078054  | 3.623300  | 3.563085  | 3.614686  | 3.297345  |
| L4 | 14    | LC1      | 6.649676  | 6.703208  | 6.551347  | 7.082663  | 6.888215  | 6.775022  |
| L4 | 14    | LC2      | 3.007534  | 2.639845  | 2.886331  | 3.338876  | 3.299008  | 3.034319  |
| L4 | 14    | LC3      | 3.098951  | 2.831277  | 2.743242  | 3.045623  | 2.994010  | 2.942621  |
| L4 | 14    | BE1      | 16.671061 | 11.996561 | 37.538085 | 23.246296 | 3.848335  | 18.660067 |
| L4 | 14    | LE1      | 37.537040 | 39.533835 | *         | 20.483678 | 39.749616 | 34.326042 |
| L4 | 24    | BC1      | 7.821954  | 7.584792  | 8.671388  | 8.845975  | 7.992539  | 8.183329  |
| L4 | 24    | BC2      | 1.302773  | 1.492017  | 1.399051  | 1.274075  | 1.342253  | 1.362034  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L4 | 24    | BC3      | 0.662261  | 0.657843  | 0.613575  | 0.607191  | 0.549414  | 0.618057  |
| L4 | 24    | 1BC      | 2.431837  | 2.556107  | 2.715139  | 2.182755  | 2.927527  | 2.562673  |
| L4 | 24    | 2BC      | 1.264708  | 1.282794  | 1.296872  | 1.190336  | 1.331581  | 1.273258  |
| L4 | 24    | 3BC      | 0.957234  | 0.705386  | 0.988383  | 1.028810  | 0.911082  | 0.918179  |
| L4 | 24    | LC1      | 8.369270  | 8.433811  | 7.958994  | 7.121249  | 8.479748  | 8.072614  |
| L4 | 24    | LC2      | 6.578165  | 5.755654  | 5.751146  | 5.983881  | 6.267695  | 6.067308  |
| L4 | 24    | LC3      | 2.266714  | 2.448272  | 2.553664  | 2.170265  | 2.462707  | 2.380324  |
| L4 | 24    | BE1      | 17.864913 | 17.672158 | 16.495044 | 18.858622 | 12.246027 | 16.627353 |
| L4 | 24    | LE1      | 47.442016 | 43.260704 | 61.169641 | 23.349356 | 47.849000 | 44.614143 |
| L5 | 14    | BC1      | 1.683615  | 0.787224  | 1.528512  | 1.416715  | 1.866031  | 1.456419  |
| L5 | 14    | BC2      | 3.194843  | 2.541345  | 3.272448  | 4.211651  | 5.879208  | 3.819899  |
| L5 | 14    | BC3      | 4.694124  | 4.300323  | 5.899000  | 3.546845  | 4.159352  | 4.519929  |
| L5 | 14    | 1BC      | 2.848497  | *         | 2.461662  | 1.864269  | 1.851590  | 2.256505  |
| L5 | 14    | 2BC      | 2.948573  | 1.582251  | 2.575665  | 2.378516  | 1.713225  | 2.062415  |
| L5 | 14    | 3BC      | 1.267033  | 1.382191  | 1.448493  | 1.596946  | 1.235734  | 1.386079  |
| L5 | 14    | LC1      | 2.949171  | 2.910945  | 2.611292  | 2.929847  | 2.758206  | 2.831892  |
| L5 | 14    | LC2      | 6.044118  | 5.260369  | 5.913282  | 2.130843  | 3.862787  | 4.642280  |
| L5 | 14    | LC3      | 3.397495  | 4.521878  | 2.657875  | 3.033737  | 4.183390  | 3.558875  |
| L5 | 14    | BE1      | 21.727078 | 22.726912 | 19.866956 | 18.959479 | 29.303443 | 22.516774 |
| L5 | 14    | LE1      | 43.250674 | 36.980505 | 18.292501 | 36.251883 | 47.338667 | 36.422846 |
| L5 | 24    | BC1      | 1.064187  | 1.227865  | 1.155063  | 1.026558  | 1.429015  | 1.180538  |
| L5 | 24    | BC2      | 1.637235  | 1.433725  | 1.442669  | 1.708567  | 1.776173  | 1.599674  |
| L5 | 24    | BC3      | 0.916121  | 0.956817  | 1.092095  | 1.344899  | 1.427043  | 1.147395  |
| L5 | 24    | 1BC      | 3.813538  | 3.539816  | *         | *         | 3.996592  | 3.783315  |
| L5 | 24    | 2BC      | 2.564481  | 2.360425  | 2.270000  | 2.133625  | 2.831431  | 2.431993  |
| L5 | 24    | 3BC      | 2.095020  | 1.646811  | 2.006392  | 2.140620  | 1.726655  | 1.923100  |
| L5 | 24    | LC1      | 2.251727  | 1.579064  | 2.026502  | 1.243188  | 4.143871  | 2.248870  |
| L5 | 24    | LC2      | 2.476614  | 2.289341  | 1.690000  | 1.733482  | 2.613430  | 2.160573  |
| L5 | 24    | LC3      | 1.748515  | 1.884807  | 1.609733  | 1.856075  | 1.733020  | 1.766430  |
| L5 | 24    | BE1      | 45.551740 | 36.039941 | 9.614685  | 41.315525 | 24.699799 | 31.444338 |
| L5 | 24    | LE1      | 43.061364 | 39.545870 | 27.461236 | 32.741204 | 45.087198 | 37.579374 |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L6 | 44    | BC1      | 3.425182  | 3.082085  | 3.022344  | 3.185307  | 3.207563  | 3.184496  |
| L6 | 44    | BC2      | 1.602515  | 1.630473  | 1.610053  | 1.696994  | 1.652198  | 1.638447  |
| L6 | 44    | BC3      | 1.025558  | 1.281661  | 1.132229  | 1.099543  | 1.344978  | 1.176794  |
| L6 | 44    | 1BC      | 2.833495  | 2.906737  | 2.789012  | 3.072054  | 2.795870  | 2.879434  |
| L6 | 44    | 2BC      | 4.752755  | 4.512725  | 5.309145  | 5.730580  | 5.300778  | 5.213307  |
| L6 | 44    | 3BC      | 3.787654  | 3.620985  | 4.053888  | 4.145895  | 4.162943  | 3.954273  |
| L6 | 44    | LC1      | 2.029370  | 2.389007  | 2.220406  | 2.230848  | 2.433283  | 2.260583  |
| L6 | 44    | LC2      | 5.961583  | 5.065342  | 3.760880  | 5.359778  | 4.951628  | 5.019842  |
| L6 | 44    | LC3      | 2.536617  | 2.299755  | 2.329355  | 2.389304  | 2.426073  | 2.396221  |
| L6 | 44    | BE1      | 24.591165 | 36.228989 | 39.421429 | 40.102005 | 40.717695 | 36.212257 |
| L6 | 44    | LE1      | 19.826837 | 23.814872 | 12.287589 | 27.034953 | 25.039548 | 21.600760 |
| L6 | 34    | BC1      | 4.975971  | 5.730126  | 5.039395  | 5.971802  | 4.963156  | 5.336090  |
| L6 | 34    | BC2      | 4.111491  | 3.769683  | 4.044734  | 4.336255  | 4.389579  | 4.130348  |
| L6 | 34    | BC3      | 0.838540  | 0.717085  | 0.821472  | 0.788854  | 0.783807  | 0.904835  |
| L6 | 34    | 1BC      | 4.926070  | 4.570849  | 5.564432  | 5.838674  | 6.065637  | 5.393132  |
| L6 | 34    | 2BC      | 4.762631  | 4.649441  | 5.435046  | 6.060089  | 5.590005  | 5.299442  |
| L6 | 34    | 3BC      | 7.475885  | 6.305133  | 6.305133  | 7.036811  | 7.614789  | 6.947550  |
| L6 | 34    | LC1      | 2.001934  | 1.002023  | 1.718980  | 1.886449  | 1.892775  | 1.700432  |
| L6 | 34    | LC2      | 4.038371  | 3.903431  | 3.849120  | 3.505638  | 3.551285  | 3.769569  |
| L6 | 34    | LC3      | 6.195105  | 6.234816  | 6.622690  | 7.549192  | 5.167032  | 6.353767  |
| L6 | 34    | BE1      | 38.648140 | 32.822765 | 33.850421 | 46.125193 | 37.847926 | 37.858889 |
| L6 | 34    | LE1      | 20.220339 | 29.178109 | 38.077318 | 22.219882 | *         | 27.423912 |
| L7 | 14    | BC1      | 2.904862  | 3.597836  | 2.636419  | 4.501501  | 5.013387  | 3.730801  |
| L7 | 14    | BC2      | 3.532427  | 4.588752  | 2.583723  | 2.745925  | 5.119669  | 3.714099  |
| L7 | 14    | BC3      | 1.838124  | 2.692033  | 1.334498  | 1.903548  | 1.965747  | 1.946790  |
| L7 | 14    | 1BC      | 4.226705  | 4.410333  | 4.856730  | 5.026293  | 5.134531  | 4.730918  |
| L7 | 14    | 2BC      | 1.581328  | 1.253558  | 1.254143  | 0.908660  | 1.330137  | 1.265565  |
| L7 | 14    | 3BC      | 1.513995  | 1.497715  | 1.013448  | 1.326357  | 1.795215  | 1.429346  |
| L7 | 14    | LC1      | 6.455528  | 7.466522  | 7.512293  | 8.142593  | 7.778952  | 7.471177  |
| L7 | 14    | LC2      | 3.348715  | 3.154077  | 4.440171  | 5.148466  | 4.453639  | 4.109014  |
| L7 | 14    | LC3      | 0.709287  | 0.700473  | 0.812544  | 0.741205  | 0.768428  | 0.746387  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L7 | 14    | BE1      | 9.707353  | 8.345366  | 9.575567  | 10.089994 | 16.788041 | 10.901264 |
| L7 | 14    | LE1      | 48.315080 | 41.947520 | 54.882506 | 39.955990 | 36.035655 | 44.227350 |
| L7 | 24    | BC1      | 4.742244  | 4.535592  | 4.982884  | 6.472394  | 4.511128  | 5.048848  |
| L7 | 24    | BC2      | 1.229975  | 1.239345  | 1.144666  | 1.202129  | 1.212636  | 1.205750  |
| L7 | 24    | BC3      | 0.823965  | 0.866379  | 0.705676  | 0.822829  | 0.891285  | 0.822027  |
| L7 | 24    | 1BC      | 2.150530  | 2.184520  | 1.340505  | 1.912094  | 1.967585  | 1.911047  |
| L7 | 24    | 2BC      | 1.061144  | 1.237665  | 1.247216  | 1.181403  | 1.294654  | 1.204416  |
| L7 | 24    | 3BC      | 0.932018  | 1.054999  | 0.770797  | 0.926218  | 0.687803  | 0.874367  |
| L7 | 24    | LC1      | 3.588847  | 3.883531  | 3.779105  | 4.070990  | 4.056684  | 3.875831  |
| L7 | 24    | LC2      | 2.122683  | 2.284795  | 2.070353  | 2.882203  | 2.047265  | 2.281459  |
| L7 | 24    | LC3      | 1.646964  | 1.437929  | 1.542095  | 1.978305  | 2.050635  | 1.731186  |
| L7 | 24    | BE1      | 40.570632 | 43.615874 | 52.457055 | 62.181014 | 47.261313 | 49.217177 |
| L7 | 24    | LE1      | 22.175185 | 23.473125 | 30.978663 | 31.112626 | 27.225134 | 26.992946 |
| L8 | 44    | BC1      | 8.015355  | 7.886951  | 7.612708  | 8.522941  | 8.548125  | 8.117216  |
| L8 | 44    | BC2      | 6.105982  | 5.930485  | 5.679619  | 5.439195  | 6.062385  | 5.843533  |
| L8 | 44    | BC3      | 4.739629  | 4.189424  | 4.388907  | 4.559631  | 4.397423  | 4.455003  |
| L8 | 44    | 1BC      | 5.260897  | 4.929382  | 4.871957  | 5.410494  | 3.992314  | 4.893009  |
| L8 | 44    | 2BC      | 3.362586  | 3.915434  | 3.566145  | 4.052062  | 3.586591  | 3.696563  |
| L8 | 44    | 3BC      | 1.965965  | 2.692868  | 2.309755  | 2.221293  | 2.108487  | 2.259674  |
| L8 | 44    | LC1      | 2.883915  | 2.300565  | 1.647084  | 2.557257  | 3.076085  | 2.492981  |
| L8 | 44    | LC2      | 2.863334  | 2.289866  | 2.118894  | 2.453878  | 2.582793  | 2.461753  |
| L8 | 44    | LC3      | 1.229283  | 1.268226  | 0.972935  | 0.716405  | 1.204180  | 1.078206  |
| L8 | 44    | BE1      | 7.516514  | 13.611655 | 7.186762  | 11.378205 | 8.650398  | 9.668707  |
| L8 | 44    | LE1      | 31.271733 | 36.241768 | 38.059825 | 34.964491 | 36.737255 | 35.455014 |
| L8 | 34    | BC1      | 5.013860  | 4.997259  | 3.169020  | 5.236401  | 3.961663  | 4.475641  |
| L8 | 34    | BC2      | 6.625667  | 3.895423  | 6.204729  | 5.780195  | 5.574176  | 5.616038  |
| L8 | 34    | BC3      | 2.114632  | 1.765592  | 2.355036  | 2.359869  | 2.373492  | 2.193724  |
| L8 | 34    | 1BC      | 3.475249  | 3.776599  | 3.794407  | 4.247580  | 3.702861  | 3.799339  |
| L8 | 34    | 2BC      | 3.239767  | 2.958392  | 2.973453  | 2.919921  | 3.179686  | 3.054244  |
| L8 | 34    | 3BC      | 1.291597  | 0.912556  | 1.785646  | 1.964564  | 2.448709  | 1.680615  |
| L8 | 34    | LC1      | 2.235394  | 1.836019  | 1.920500  | 2.308473  | 2.638018  | 2.187681  |



| No | Tooth | Position | H1        | H2        | H3        | H4        | H5        | Average   |
|----|-------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| L8 | 34    | LC2      | 2.544067  | 2.742756  | 2.818699  | 2.982288  | 2.903862  | 2.798335  |
| L8 | 34    | LC3      | 1.792829  | 1.281992  | 1.616810  | 1.800057  | 1.515035  | 1.601345  |
| L8 | 34    | BE1      | 40.318316 | 37.790055 | 43.396079 | 33.477889 | 45.132694 | 40.023007 |
| L8 | 34    | LE1      | 29.764826 | 36.451379 | 30.312890 | 34.551865 | 33.433878 | 32.902968 |
| L9 | 14    | BC1      | 3.371549  | 3.619148  | 3.932399  | 4.032793  | 3.871435  | 3.765465  |
| L9 | 14    | BC2      | 2.405279  | 2.269941  | 1.830814  | 2.452061  | 2.279425  | 2.247504  |
| L9 | 14    | BC3      | 1.034788  | *         | 1.172677  | 1.227858  | 1.134261  | 1.142396  |
| L9 | 14    | 1BC      | 3.260988  | *         | 4.900209  | 4.182989  | 3.345600  | 3.922447  |
| L9 | 14    | 2BC      | 2.302420  | 1.895913  | 2.238895  | 2.320856  | 2.310231  | 2.213663  |
| L9 | 14    | 3BC      | 1.177695  | 1.165955  | 1.128165  | 1.325183  | 1.325183  | 1.224436  |
| L9 | 14    | LC1      | 2.716278  | 2.575645  | 2.608843  | 2.618669  | 2.440689  | 2.592025  |
| L9 | 14    | LC2      | 1.480516  | 1.250048  | 1.373671  | 1.608655  | 1.599425  | 1.462463  |
| L9 | 14    | LC3      | 1.795878  | 2.102960  | 1.627631  | 2.187388  | 1.961058  | 1.934983  |
| L9 | 14    | BE1      | 19.562046 | 29.287459 | 16.009323 | 24.202274 | 45.502475 | 26.912715 |
| L9 | 14    | LE1      | 26.796007 | 29.273702 | 28.502035 | 26.143294 | 25.492806 | 27.241569 |
| L9 | 24    | BC1      | 5.470319  | 5.992389  | 5.338427  | 5.532258  | 5.826421  | 5.631963  |
| L9 | 24    | BC2      | 6.554787  | 5.011862  | 5.452165  | 12.057969 | 8.050026  | 7.425362  |
| L9 | 24    | BC3      | 2.838749  | 4.832422  | 4.560905  | 3.836380  | 3.724155  | 3.958522  |
| L9 | 24    | 1BC      | 9.725094  | 9.627964  | 9.160961  | 10.462083 | 9.716885  | 9.738597  |
| L9 | 24    | 2BC      | 7.526296  | 7.432944  | 8.247725  | 8.095050  | 5.963706  | 7.453144  |
| L9 | 24    | 3BC      | 4.936960  | 3.051738  | 4.630914  | 3.670295  | 4.744766  | 4.206935  |
| L9 | 24    | LC1      | 3.785389  | 3.447028  | 4.064724  | 4.043254  | 3.794116  | 3.826902  |
| L9 | 24    | LC2      | 2.905646  | 2.876638  | 2.792966  | 2.743749  | 2.166565  | 2.697113  |
| L9 | 24    | LC3      | 1.767931  | 2.224792  | 2.244398  | 2.254037  | 1.885682  | 2.075368  |
| L9 | 24    | BE1      | 40.802467 | 40.642295 | 45.146856 | 43.115727 | 42.999150 | 42.541299 |
| L9 | 24    | LE1      | 30.399691 | 35.749213 | 34.575614 | 30.870485 | 27.981024 | 31.915205 |



## 6.4 GLOSSARY OF TERMS

1 N/m<sup>2</sup> = 1 Pascal (Pa)

1 kg/mm<sup>2</sup> = 100 kg/cm<sup>2</sup>

1 GPa = 10<sup>9</sup> Pascal

(From: Craig RG. Restorative Dental Materials. 9<sup>th</sup> edition, St. Louis; Mosby Year Book, 1993).



6.5 STATISTICAL DATA

6.5.1 PART I

Means (not including enamel)

HARDC Hardness (control) ELASTC Elasticity (control) HARDE Hardness (experimental) ELASTE Elasticity (experimental) \* POS Position on tooth

| POS Position on tooth |                    | HARDC<br>Hardness<br>(control) | ELASTC<br>Elasticity<br>(control) | HARDE<br>Hardness<br>(experimental) | ELASTE<br>Elasticity<br>(experimental) |
|-----------------------|--------------------|--------------------------------|-----------------------------------|-------------------------------------|----------------------------------------|
| 11 buccal-top         | N                  | 36                             | 36                                | 36                                  | 36                                     |
|                       | Mean               | .28002                         | 4.21653                           | .29128                              | 4.02592                                |
|                       | Std. Deviation     | 8.3775E-02                     | 2.11298                           | 8.0981E-02                          | 2.08483                                |
|                       | Std. Error of Mean | 1.3962E-02                     | .35216                            | 1.3497E-02                          | .34747                                 |
| 12 buccal-mid         | N                  | 36                             | 36                                | 36                                  | 36                                     |
|                       | Mean               | .24444                         | 2.88178                           | .24795                              | 2.91096                                |
|                       | Std. Deviation     | 6.8107E-02                     | 1.79655                           | 7.7661E-02                          | 1.72458                                |
|                       | Std. Error of Mean | 1.1351E-02                     | .29943                            | 1.2943E-02                          | .28743                                 |
| 13 buccal-low         | N                  | 36                             | 36                                | 36                                  | 36                                     |
|                       | Mean               | .17520                         | 2.09014                           | .20351                              | 2.36505                                |
|                       | Std. Deviation     | 6.8237E-02                     | 1.46203                           | 8.1624E-02                          | 1.78283                                |
|                       | Std. Error of Mean | 1.1373E-02                     | .24367                            | 1.3604E-02                          | .29714                                 |
| 21 lingual-top        | N                  | 18                             | 18                                | 18                                  | 18                                     |
|                       | Mean               | .25663                         | 3.87070                           | .25671                              | 3.89274                                |
|                       | Std. Deviation     | 7.5933E-02                     | 1.61405                           | 7.5997E-02                          | 2.19145                                |
|                       | Std. Error of Mean | 1.7898E-02                     | .38043                            | 1.7913E-02                          | .51653                                 |
| 22 lingual-mid        | N                  | 18                             | 18                                | 18                                  | 18                                     |
|                       | Mean               | .24985                         | 3.30152                           | .23848                              | 3.04291                                |
|                       | Std. Deviation     | 5.9469E-02                     | 1.67573                           | 7.4765E-02                          | 1.51748                                |
|                       | Std. Error of Mean | 1.4017E-02                     | .39497                            | 1.7622E-02                          | .35767                                 |
| 23 lingual-low        | N                  | 18                             | 18                                | 18                                  | 17                                     |
|                       | Mean               | .22494                         | 2.48585                           | .18264                              | 2.12683                                |
|                       | Std. Deviation     | 7.9710E-02                     | 1.66580                           | 9.0067E-02                          | 1.29695                                |
|                       | Std. Error of Mean | 1.8788E-02                     | .39263                            | 2.1229E-02                          | .31456                                 |
| Total                 | N                  | 162                            | 162                               | 162                                 | 161                                    |
|                       | Mean               | .23675                         | 3.11500                           | .24037                              | 3.07992                                |
|                       | Std. Deviation     | 8.0979E-02                     | 1.90573                           | 8.6838E-02                          | 1.92707                                |
|                       | Std. Error of Mean | 6.3623E-03                     | .14973                            | 6.8226E-03                          | .15187                                 |



HARDC Hardness (control) ELASTC Elasticity (control) HARDE Hardness (experimental) ELASTE Elasticity (experimental) \* STR Strength of Force

| STR Strength of Force |                    | HARDC Hardness (control) | ELASTC Elasticity (control) | HARDE Hardness (experimental) | ELASTE Elasticity (experimental) |
|-----------------------|--------------------|--------------------------|-----------------------------|-------------------------------|----------------------------------|
| 1 light               | N                  | 81                       | 81                          | 81                            | 81                               |
|                       | Mean               | .25296                   | 3.33477                     | .26442                        | 3.44988                          |
|                       | Std. Deviation     | 8.8172E-02               | 2.19690                     | 7.6041E-02                    | 1.94355                          |
|                       | Std. Error of Mean | 9.7969E-03               | .24410                      | 8.4490E-03                    | .21595                           |
| 2 heavy               | N                  | 81                       | 81                          | 81                            | 80                               |
|                       | Mean               | .22053                   | 2.89523                     | .21631                        | 2.70533                          |
|                       | Std. Deviation     | 6.9930E-02               | 1.54430                     | 9.0675E-02                    | 1.84758                          |
|                       | Std. Error of Mean | 7.7700E-03               | .17159                      | 1.0075E-02                    | .20657                           |
| Total                 | N                  | 162                      | 162                         | 162                           | 161                              |
|                       | Mean               | .23675                   | 3.11500                     | .24037                        | 3.07992                          |
|                       | Std. Deviation     | 8.0979E-02               | 1.90573                     | 8.6838E-02                    | 1.92707                          |
|                       | Std. Error of Mean | 6.3623E-03               | .14973                      | 6.8226E-03                    | .15187                           |

Univariate Analysis of Variance

Between-Subjects Factors

|                             |    | Value Label       | N  |
|-----------------------------|----|-------------------|----|
| STR Strength of Force       | 1  | light             | 72 |
|                             | 2  | heavy             | 81 |
| POS Position on tooth       | 11 | buccal-top        | 34 |
|                             | 12 | buccal-mid        | 34 |
|                             | 13 | buccal-low        | 34 |
|                             | 21 | lingual-top       | 17 |
|                             | 22 | lingual-mid       | 17 |
|                             | 23 | lingual-low       | 17 |
| BIRTH Birthplace of subject | 1  | Born in Australia | 81 |
|                             | 2  | Born overseas     | 72 |



Tests of Between-Subjects Effects

Dependent Variable: HARDC Hardness (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F        | Sig. |
|-----------------|-------------------------|-----|-------------|----------|------|
| Corrected Model | .263 <sup>a</sup>       | 7   | 3.756E-02   | 7.409    | .000 |
| Intercept       | 7.795                   | 1   | 7.795       | 1537.511 | .000 |
| STR             | 7.480E-02               | 1   | 7.480E-02   | 14.754   | .000 |
| POS             | .188                    | 5   | 3.761E-02   | 7.418    | .000 |
| BIRTH           | 2.326E-02               | 1   | 2.326E-02   | 4.588    | .034 |
| Error           | .735                    | 145 | 5.070E-03   |          |      |
| Total           | 9.654                   | 153 |             |          |      |
| Corrected Total | .998                    | 152 |             |          |      |

a. R Squared = .263 (Adjusted R Squared = .228)

Estimated Marginal Means

Birthplace of subject

Dependent Variable: HARDC Hardness (control)

| Birthplace of subject | Mean | Std. Error | 95% Confidence Interval |             |
|-----------------------|------|------------|-------------------------|-------------|
|                       |      |            | Lower Bound             | Upper Bound |
| 1 Born in Australia   | .254 | .009       | .237                    | .272        |
| 2 Born overseas       | .225 | .009       | .207                    | .244        |



Univariate Analysis of Variance

Between-Subjects Factors

|                             |    | Value Label       | N  |
|-----------------------------|----|-------------------|----|
| STR Strength of Force       | 1  | light             | 72 |
|                             | 2  | heavy             | 81 |
| POS Position on tooth       | 11 | buccal-top        | 34 |
|                             | 12 | buccal-mid        | 34 |
|                             | 13 | buccal-low        | 34 |
|                             | 21 | lingual-top       | 17 |
|                             | 22 | lingual-mid       | 17 |
|                             | 23 | lingual-low       | 17 |
| BIRTH Birthplace of subject | 1  | Born in Australia | 81 |
|                             | 2  | Born overseas     | 72 |

Tests of Between-Subjects Effects

Dependent Variable: ELASTC Elasticity (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F       | Sig. |
|-----------------|-------------------------|-----|-------------|---------|------|
| Corrected Model | 86.264 <sup>a</sup>     | 7   | 12.323      | 4.244   | .000 |
| Intercept       | 1301.951                | 1   | 1301.951    | 448.382 | .000 |
| STR             | 7.629                   | 1   | 7.629       | 2.627   | .107 |
| POS             | 78.419                  | 5   | 15.684      | 5.401   | .000 |
| BIRTH           | 1.130                   | 1   | 1.130       | .389    | .534 |
| Error           | 421.032                 | 145 | 2.904       |         |      |
| Total           | 1970.762                | 153 |             |         |      |
| Corrected Total | 507.296                 | 152 |             |         |      |

a. R Squared = .170 (Adjusted R Squared = .130)



Estimated Marginal Means

Birthplace of subject

Dependent Variable: ELASTC Elasticity (control)

| Birthplace of subject | Mean  | Std. Error | 95% Confidence Interval |             |
|-----------------------|-------|------------|-------------------------|-------------|
|                       |       |            | Lower Bound             | Upper Bound |
| 1 Born in Australia   | 3.202 | .215       | 2.776                   | 3.627       |
| 2 Born overseas       | 2.999 | .222       | 2.560                   | 3.438       |

Univariate Analysis of Variance

Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |
| SEX                   | 1  | Male        | 90 |
|                       | 2  | Female      | 72 |



Tests of Between-Subjects Effects

Dependent Variable: HARDC Hardness (control)

| Source          | Type III<br>Sum of<br>Squares | df  | Mean<br>Square | F        | Sig. |
|-----------------|-------------------------------|-----|----------------|----------|------|
| Corrected Model | .281 <sup>a</sup>             | 7   | 4.008E-02      | 7.964    | .000 |
| Intercept       | 8.012                         | 1   | 8.012          | 1591.765 | .000 |
| STR             | 5.395E-02                     | 1   | 5.395E-02      | 10.718   | .001 |
| POS             | .219                          | 5   | 4.373E-02      | 8.688    | .000 |
| SEX             | 1.934E-02                     | 1   | 1.934E-02      | 3.843    | .052 |
| Error           | .775                          | 154 | 5.034E-03      |          |      |
| Total           | 10.136                        | 162 |                |          |      |
| Corrected Total | 1.056                         | 161 |                |          |      |

a. R Squared = .266 (Adjusted R Squared = .232)

Estimated Marginal Means

SEX

Dependent Variable: HARDC Hardness (control)

| SEX      | Mean | Std. Error | 95% Confidence Interval |                |
|----------|------|------------|-------------------------|----------------|
|          |      |            | Lower<br>Bound          | Upper<br>Bound |
| 1 Male   | .249 | .008       | .233                    | .264           |
| 2 Female | .226 | .009       | .209                    | .243           |

Univariate Analysis of Variance



Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |
| SEX                   | 1  | Male        | 90 |
|                       | 2  | Female      | 72 |

Tests of Between-Subjects Effects

Dependent Variable: ELASTC Elasticity (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F       | Sig. |
|-----------------|-------------------------|-----|-------------|---------|------|
| Corrected Model | 111.648 <sup>a</sup>    | 7   | 15.950      | 5.192   | .000 |
| Intercept       | 1392.035                | 1   | 1392.035    | 453.148 | .000 |
| STR             | 9.416                   | 1   | 9.416       | 3.065   | .082 |
| POS             | 101.482                 | 5   | 20.296      | 6.607   | .000 |
| SEX             | 2.342                   | 1   | 2.342       | .762    | .384 |
| Error           | 473.076                 | 154 | 3.072       |         |      |
| Total           | 2156.643                | 162 |             |         |      |
| Corrected Total | 584.724                 | 161 |             |         |      |

a. R Squared = .191 (Adjusted R Squared = .154)

Estimated Marginal Means

SEX

Dependent Variable: ELASTC Elasticity (control)

| SEX      | Mean  | Std. Error | 95% Confidence Interval |             |
|----------|-------|------------|-------------------------|-------------|
|          |       |            | Lower Bound             | Upper Bound |
| 1 Male   | 3.251 | .193       | 2.870                   | 3.633       |
| 2 Female | 3.003 | .215       | 2.578                   | 3.428       |



Means (including enamel)

HARDC Hardness (control) ELASTC Elasticity (control) HARDE Hardness (experimental) ELASTE Elasticity (experimental) \* POS Position on tooth

| POS Position on tooth |                    | HARDC Hardness (control) | ELASTC Elasticity (control) | HARDE Hardness (experimental) | ELASTE Elasticity (experimental) |
|-----------------------|--------------------|--------------------------|-----------------------------|-------------------------------|----------------------------------|
| 11 buccal-top         | N                  | 36                       | 36                          | 36                            | 36                               |
|                       | Mean               | .28002                   | 4.21653                     | .29128                        | 4.02592                          |
|                       | Std. Deviation     | 8.3775E-02               | 2.11298                     | 8.0981E-02                    | 2.08483                          |
|                       | Std. Error of Mean | 1.3962E-02               | .35216                      | 1.3497E-02                    | .34747                           |
| 12 buccal-mid         | N                  | 36                       | 36                          | 36                            | 36                               |
|                       | Mean               | .24444                   | 2.88178                     | .24795                        | 2.91096                          |
|                       | Std. Deviation     | 6.8107E-02               | 1.79655                     | 7.7661E-02                    | 1.72458                          |
|                       | Std. Error of Mean | 1.1351E-02               | .29943                      | 1.2943E-02                    | .28743                           |
| 13 buccal-low         | N                  | 36                       | 36                          | 36                            | 36                               |
|                       | Mean               | .17520                   | 2.09014                     | .20351                        | 2.36505                          |
|                       | Std. Deviation     | 6.8237E-02               | 1.46203                     | 8.1624E-02                    | 1.78283                          |
|                       | Std. Error of Mean | 1.1373E-02               | .24367                      | 1.3604E-02                    | .29714                           |
| 21 lingual-top        | N                  | 18                       | 18                          | 18                            | 18                               |
|                       | Mean               | .25663                   | 3.87070                     | .25671                        | 3.89274                          |
|                       | Std. Deviation     | 7.5933E-02               | 1.61405                     | 7.5997E-02                    | 2.19145                          |
|                       | Std. Error of Mean | 1.7898E-02               | .38043                      | 1.7913E-02                    | .51653                           |
| 22 lingual-mid        | N                  | 18                       | 18                          | 18                            | 18                               |
|                       | Mean               | .24985                   | 3.30152                     | .23848                        | 3.04291                          |
|                       | Std. Deviation     | 5.9469E-02               | 1.67573                     | 7.4765E-02                    | 1.51748                          |
|                       | Std. Error of Mean | 1.4017E-02               | .39497                      | 1.7622E-02                    | .35767                           |
| 23 lingual-low        | N                  | 18                       | 18                          | 18                            | 17                               |
|                       | Mean               | .22494                   | 2.48585                     | .18264                        | 2.12683                          |
|                       | Std. Deviation     | 7.9710E-02               | 1.66580                     | 9.0067E-02                    | 1.29695                          |
|                       | Std. Error of Mean | 1.8788E-02               | .39263                      | 2.1229E-02                    | .31456                           |
| 34 enamel             | N                  | 36                       | 36                          | 36                            | 36                               |
|                       | Mean               | 5.05864                  | 31.31327                    | 4.15459                       | 29.77024                         |
|                       | Std. Deviation     | 1.91512                  | 9.55731                     | 1.86939                       | 11.80632                         |
|                       | Std. Error of Mean | .31919                   | 1.59288                     | .31156                        | 1.96772                          |
| Total                 | N                  | 198                      | 198                         | 198                           | 197                              |
|                       | Mean               | 1.11346                  | 8.24195                     | .95205                        | 7.95734                          |
|                       | Std. Deviation     | 2.03306                  | 11.75085                    | 1.70815                       | 11.61275                         |
|                       | Std. Error of Mean | .14448                   | .83510                      | .12139                        | .82737                           |



**HARDC Hardness (control) ELA STC Elasticity (control) HARDE Hardness (experimental) ELA STE Elasticity (experimental) \* STR Strength of Force**

| STR Strength of Force |                    | HARDC Hardness (control) | ELASTC Elasticity (control) | HARDE Hardness (experimental) | ELASTE Elasticity (experimental) |
|-----------------------|--------------------|--------------------------|-----------------------------|-------------------------------|----------------------------------|
| 1 light               | N                  | 99                       | 99                          | 99                            | 99                               |
|                       | Mean               | 1.23350                  | 8.79147                     | .95465                        | 7.68797                          |
|                       | Std. Deviation     | 2.26277                  | 12.47907                    | 1.68371                       | 10.65277                         |
|                       | Std. Error of Mean | .22742                   | 1.25419                     | .16922                        | 1.07064                          |
| 2 heavy               | N                  | 99                       | 99                          | 99                            | 98                               |
|                       | Mean               | .99341                   | 7.69244                     | .94944                        | 8.22945                          |
|                       | Std. Deviation     | 1.77751                  | 11.01076                    | 1.74081                       | 12.55755                         |
|                       | Std. Error of Mean | .17865                   | 1.10662                     | .17496                        | 1.26850                          |
| Total                 | N                  | 198                      | 198                         | 198                           | 197                              |
|                       | Mean               | 1.11346                  | 8.24195                     | .95205                        | 7.95734                          |
|                       | Std. Deviation     | 2.03306                  | 11.75085                    | 1.70815                       | 11.61275                         |
|                       | Std. Error of Mean | .14448                   | .83510                      | .12139                        | .82737                           |

**HARDC Hardness (control) ELASTC Elasticity (control) HARDE Hardness (experimental) ELASTE Elasticity (experimental) \* BLE Buccal Lingual Enamel**

| BLE Buccal Lingual Enamel |                    | HARDC Hardness (control) | ELASTC Elasticity (control) | HARDE Hardness (experimental) | ELASTE Elasticity (experimental) |
|---------------------------|--------------------|--------------------------|-----------------------------|-------------------------------|----------------------------------|
| 1 buccal                  | N                  | 108                      | 108                         | 108                           | 108                              |
|                           | Mean               | .23322                   | 3.06282                     | .24758                        | 3.10064                          |
|                           | Std. Deviation     | 8.5136E-02               | 1.99813                     | 8.7140E-02                    | 1.97902                          |
|                           | Std. Error of Mean | 8.1922E-03               | .19227                      | 8.3850E-03                    | .19043                           |
| 2 lingual                 | N                  | 54                       | 54                          | 54                            | 53                               |
|                           | Mean               | .24380                   | 3.21935                     | .22594                        | 3.03769                          |
|                           | Std. Deviation     | 7.2187E-02               | 1.71915                     | 8.5201E-02                    | 1.83432                          |
|                           | Std. Error of Mean | 9.8233E-03               | .23395                      | 1.1594E-02                    | .25196                           |
| 3 enamel                  | N                  | 36                       | 36                          | 36                            | 36                               |
|                           | Mean               | 5.05864                  | 31.31327                    | 4.15459                       | 29.77024                         |
|                           | Std. Deviation     | 1.91512                  | 9.55731                     | 1.86939                       | 11.80632                         |
|                           | Std. Error of Mean | .31919                   | 1.59288                     | .31156                        | 1.96772                          |
| Total                     | N                  | 198                      | 198                         | 198                           | 197                              |
|                           | Mean               | 1.11346                  | 8.24195                     | .95205                        | 7.95734                          |
|                           | Std. Deviation     | 2.03306                  | 11.75085                    | 1.70815                       | 11.61275                         |
|                           | Std. Error of Mean | .14448                   | .83510                      | .12139                        | .82737                           |

**Means (incl enamel)**



| Report                         |                    |                                |                                   |                                     |                                        |
|--------------------------------|--------------------|--------------------------------|-----------------------------------|-------------------------------------|----------------------------------------|
| STSUBLE -<br>Strength-Subj-BLE |                    | HARDC<br>Hardness<br>(control) | ELASTC<br>Elasticity<br>(control) | HARDE<br>Hardness<br>(experimental) | ELASTE<br>Elasticity<br>(experimental) |
| 111                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | .28659                         | 3 67552                           | .29373                              | 3 08775                                |
|                                | Std. Deviation     | .10725                         | 3 37489                           | 7 3239E-02                          | 1.97724                                |
|                                | Std. Error of Mean | 4 3785E-02                     | 1.37779                           | 2 8900E-02                          | .80720                                 |
| 112                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .26743                         | 3 81428                           | .30536                              | 3.52261                                |
|                                | Std. Deviation     | .14276                         | 1 32710                           | 5 8670E-02                          | 2.25530                                |
|                                | Std. Error of Mean | 8 2422E-02                     | .76620                            | 3.3873E-02                          | 1 30210                                |
| 113                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 4 52269                        | 24 25933                          | 3 46022                             | 9.20377                                |
|                                | Std. Deviation     | 2.31778                        | 2.27365                           | 2.04651                             | 2 90314                                |
|                                | Std. Error of Mean | 1.63891                        | 1.60771                           | 1.44710                             | 2 05283                                |
| 121                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | .19024                         | 1 97401                           | .18406                              | 2 07645                                |
|                                | Std. Deviation     | 6 9063E-02                     | .83687                            | .12620                              | 1 70308                                |
|                                | Std. Error of Mean | 2.8195E-02                     | .34185                            | 5.1521E-02                          | .69528                                 |
| 122                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | 21223                          | 1.87073                           | 22029                               | 2.22245                                |
|                                | Std. Deviation     | 10968                          | 1.85755                           | 7 1034E-02                          | .77988                                 |
|                                | Std. Error of Mean | 6 3323E-02                     | 1.07246                           | 4 1011E-02                          | .45026                                 |
| 123                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 4.22549                        | 25 39665                          | 2.83259                             | 31.56889                               |
|                                | Std. Deviation     | 2.22127                        | 1 52170                           | 2.24591                             | 24.87705                               |
|                                | Std. Error of Mean | 1.57068                        | 1 07600                           | 1 58810                             | 17.59073                               |
| 131                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | .30267                         | 3 55740                           | .29157                              | 6.13277                                |
|                                | Std. Deviation     | 5 9515E-02                     | 1.60869                           | 4.9734E-02                          | 2.13128                                |
|                                | Std. Error of Mean | 2 4297E-02                     | .65674                            | 2 0304E-02                          | .87009                                 |
| 132                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | 30011                          | 4 97625                           | .28078                              | 5.76410                                |
|                                | Std. Deviation     | 1.8283E-02                     | 1 63998                           | 6 9122E-02                          | 2.17315                                |
|                                | Std. Error of Mean | 9 4012E-03                     | .94684                            | 3 9908E-02                          | 1.25467                                |
| 133                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 8 07504                        | 40 89364                          | 5 11138                             | 37.98926                               |
|                                | Std. Deviation     | 1.43015                        | 17.03105                          | 2.42550                             | .47429                                 |
|                                | Std. Error of Mean | 1 01127                        | 12 04277                          | 1.71509                             | .33538                                 |
| 141                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | 20092                          | 2 48626                           | .25785                              | 4 19565                                |
|                                | Std. Deviation     | 9 2819E-02                     | 2 86868                           | 3 5573E-02                          | 1 00273                                |
|                                | Std. Error of Mean | 3 7893E-02                     | 1.17114                           | 1.4523E-02                          | .40936                                 |
| 142                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .25214                         | 5.50675                           | .28482                              | 4 25065                                |
|                                | Std. Deviation     | 5.4706E-02                     | 2 88725                           | 7 6853E-02                          | 2.18665                                |
|                                | Std. Error of Mean | 3.1585E-02                     | 1.66895                           | 4.4371E-02                          | 1 26246                                |
| 143                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 6 10956                        | 30 62075                          | 3 56072                             | 28 49305                               |
|                                | Std. Deviation     | .71988                         | 19 78965                          | 1 86064                             | 11.07752                               |
|                                | Std. Error of Mean | .50903                         | 13.99340                          | 1.31567                             | 7 83299                                |
| 151                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | 16582                          | 2 01100                           | 21205                               | 2 58354                                |
|                                | Std. Deviation     | 3.3297E-02                     | .99305                            | 4.5907E-02                          | 1 29314                                |
|                                | Std. Error of Mean | 1 3593E-02                     | .40541                            | 1.8742E-02                          | .52792                                 |
| 152                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .18552                         | 2.05862                           | .28676                              | 3 67768                                |
|                                | Std. Deviation     | 3 4674E-02                     | 25687                             | 6 0248E-02                          | .91102                                 |
|                                | Std. Error of Mean | 2.0019E-02                     | .14830                            | 3 4784E-02                          | .52598                                 |
| 153                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 5 03202                        | 34 51186                          | 2 96626                             | 29.46981                               |
|                                | Std. Deviation     | 1 42240                        | 4 33813                           | 59450                               | 9 83308                                |
|                                | Std. Error of Mean | 1 00579                        | 3 06752                           | 42037                               | 6 95304                                |
| 161                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | .28659                         | 4.66857                           | .29373                              | 3 00779                                |
|                                | Std. Deviation     | .10725                         | 2 05025                           | 7.3239E-02                          | 1.48563                                |
|                                | Std. Error of Mean | 4.3785E-02                     | .83701                            | 2.8900E-02                          | .60651                                 |
| 162                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .26743                         | 3 94126                           | .30536                              | 3 22555                                |
|                                | Std. Deviation     | .14276                         | 2.33141                           | 5 8670E-02                          | 1.55538                                |
|                                | Std. Error of Mean | 8 2422E-02                     | 1.34604                           | 3 3873E-02                          | .89800                                 |
| 163                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 4.52269                        | 32.64140                          | 3.46022                             | 28 90651                               |
|                                | Std. Deviation     | 2.31778                        | 7.37864                           | 2.04651                             | 10 33189                               |
|                                | Std. Error of Mean | 1.63891                        | 5 21749                           | 1.44710                             | 7 30575                                |
| 171                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | 24827                          | 1 84441                           | 26822                               | 2.80292                                |
|                                | Std. Deviation     | .12663                         | 1 61719                           | 9 6459E-02                          | 1.44163                                |
|                                | Std. Error of Mean | 5.1697E-02                     | .66022                            | 3 9379E-02                          | .58854                                 |
| 172                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .27184                         | 2.62949                           | .27156                              | 4.10886                                |
|                                | Std. Deviation     | 7.9093E-02                     | 1.11388                           | .11596                              | 3 36240                                |
|                                | Std. Error of Mean | 4 5665E-02                     | .64310                            | 6 6951E-02                          | 1.94128                                |
| 173                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 6 27119                        | 38 10506                          | 3.19720                             | 27 56431                               |
|                                | Std. Deviation     | 4.23522                        | 15.71490                          | 3.02445                             | 23 56510                               |
|                                | Std. Error of Mean | 2.99475                        | 11.1212                           | 2.13861                             | 16 66304                               |
| 181                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | 28013                          | 3.46993                           | .31777                              | 4 87750                                |
|                                | Std. Deviation     | 5 1723E-02                     | 1.46485                           | 7.5372E-02                          | 1.99275                                |
|                                | Std. Error of Mean | 2.1116E-02                     | .59802                            | 3 0771E-02                          | .81354                                 |
| 182                            | N                  | 3                              | 3                                 | 3                                   | 3                                      |
|                                | Mean               | .25131                         | 2.19579                           | .19890                              | 2.01098                                |
|                                | Std. Deviation     | 5 6422E-02                     | 59854                             | 5 6622E-02                          | 80796                                  |
|                                | Std. Error of Mean | 3 2575E-02                     | .34556                            | 3.2691E-02                          | .46647                                 |
| 183                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |
|                                | Mean               | 7.07231                        | 36 46299                          | 7.13243                             | 22.56186                               |
|                                | Std. Deviation     | 1.27664                        | 5 03463                           | .31754                              | 18.23367                               |
|                                | Std. Error of Mean | .90272                         | 3 56002                           | .22454                              | 12.89315                               |
| 191                            | N                  | 6                              | 6                                 | 6                                   | 6                                      |
|                                | Mean               | .31403                         | 6 40242                           | .24990                              | 2.41832                                |
|                                | Std. Deviation     | 5.7359E-02                     | 2.22112                           | 5 4526E-02                          | 1.20013                                |
|                                | Std. Error of Mean | 2.3417E-02                     | .90677                            | 2.2260E-02                          | .48895                                 |
|                                | N                  | -                              | -                                 | -                                   | -                                      |
|                                | Mean               | .27152                         | 2.86846                           | 24784                               | 1.99649                                |
|                                | Std. Deviation     | 4.4388E-02                     | .88796                            | 3 5763E-02                          | .56729                                 |
|                                | Std. Error of Mean | 2.5627E-02                     | .51267                            | 2.0648E-02                          | .32752                                 |
| 193                            | N                  | 2                              | 2                                 | 2                                   | 2                                      |



Univariate Analysis of Variance

Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 18 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |
|                       |    |             |    |

Tests of Between-Subjects Effects

Dependent Variable: HARDC Hardness (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F        | Sig. |
|-----------------|-------------------------|-----|-------------|----------|------|
| Corrected Model | .480 <sup>a</sup>       | 22  | 2.184E-02   | 5.276    | .000 |
| Intercept       | 8.192                   | 1   | 8.192       | 1979.125 | .000 |
| STR             | 4.260E-02               | 1   | 4.260E-02   | 10.293   | .002 |
| SUBJ(STR)       | .219                    | 16  | 1.370E-02   | 3.309    | .000 |
| POS             | .219                    | 5   | 4.373E-02   | 10.565   | .000 |
| Error           | .575                    | 139 | 4.139E-03   |          |      |
| Total           | 10.136                  | 162 |             |          |      |
| Corrected Total | 1.056                   | 161 |             |          |      |

a. R Squared = .455 (Adjusted R Squared = .369)



Estimated Marginal Means

1. Strength of Force

Estimates

Dependent Variable: HARDC Hardness (control)

| Strength of Force | Mean | Std. Error | 95% Confidence Interval |             |
|-------------------|------|------------|-------------------------|-------------|
|                   |      |            | Lower Bound             | Upper Bound |
| 1 light           | .255 | .007       | .240                    | .269        |
| 2 heavy           | .222 | .007       | .208                    | .237        |

Pairwise Comparisons

Dependent Variable: HARDC Hardness (control)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | 3.243E-02*            | .010       | .002              | 1.245E-02                                           | 5.242E-02   |
| 2 heavy                                     | 1 light | -3.243E-02*           | .010       | .002              | -5.242E-02                                          | -1.245E-02  |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: HARDC Hardness (control)

|          | Sum of Squares | df  | Mean Square | F      | Sig. |
|----------|----------------|-----|-------------|--------|------|
| Contrast | 4.260E-02      | 1   | 4.260E-02   | 10.293 | .002 |
| Error    | .575           | 139 | 4.139E-03   |        |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth



Estimates

Dependent Variable: HARDC Hardness (control)

| Position on tooth | Mean | Std. Error | 95% Confidence Interval |             |
|-------------------|------|------------|-------------------------|-------------|
|                   |      |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | .280 | .011       | .259                    | .301        |
| 12 buccal-mid     | .244 | .011       | .223                    | .266        |
| 13 buccal-low     | .175 | .011       | .154                    | .196        |
| 21 lingual-top    | .257 | .015       | .227                    | .287        |
| 22 lingual-mid    | .250 | .015       | .220                    | .280        |
| 23 lingual-low    | .225 | .015       | .195                    | .255        |



Pairwise Comparisons

Dependent Variable: HARDC Hardness (control)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | 3.559E-02                   | .015       | .305              | -9.705E-03                                             | 8.088E-02      |
|                       | 13 buccal-low         | .105*                       | .015       | .000              | 5.954E-02                                              | .150           |
|                       | 21 lingual-top        | 2.339E-02                   | .019       | 1.000             | -3.208E-02                                             | 7.887E-02      |
|                       | 22 lingual-mid        | 3.018E-02                   | .019       | 1.000             | -2.529E-02                                             | 8.565E-02      |
|                       | 23 lingual-low        | 5.508E-02                   | .019       | .053              | -3.873E-04                                             | .111           |
| 12 buccal-mid         | 11 buccal-top         | -3.559E-02                  | .015       | .305              | -8.088E-02                                             | 9.705E-03      |
|                       | 13 buccal-low         | 6.924E-02*                  | .015       | .000              | 2.395E-02                                              | .115           |
|                       | 21 lingual-top        | -1.219E-02                  | .019       | 1.000             | -6.766E-02                                             | 4.328E-02      |
|                       | 22 lingual-mid        | -5.410E-03                  | .019       | 1.000             | -6.088E-02                                             | 5.006E-02      |
|                       | 23 lingual-low        | 1.950E-02                   | .019       | 1.000             | -3.597E-02                                             | 7.497E-02      |
| 13 buccal-low         | 11 buccal-top         | -.105*                      | .015       | .000              | -.150                                                  | -5.954E-02     |
|                       | 12 buccal-mid         | -6.924E-02*                 | .015       | .000              | -.115                                                  | -2.395E-02     |
|                       | 21 lingual-top        | -8.143E-02*                 | .019       | .000              | -.137                                                  | -2.596E-02     |
|                       | 22 lingual-mid        | -7.465E-02*                 | .019       | .001              | -.130                                                  | -1.918E-02     |
|                       | 23 lingual-low        | -4.974E-02                  | .019       | .124              | -.105                                                  | 5.727E-03      |
| 21 lingual-top        | 11 buccal-top         | -2.339E-02                  | .019       | 1.000             | -7.887E-02                                             | 3.208E-02      |
|                       | 12 buccal-mid         | 1.219E-02                   | .019       | 1.000             | -4.328E-02                                             | 6.766E-02      |
|                       | 13 buccal-low         | 8.143E-02*                  | .019       | .000              | 2.596E-02                                              | .137           |
|                       | 22 lingual-mid        | 6.782E-03                   | .021       | 1.000             | -5.727E-02                                             | 7.083E-02      |
|                       | 23 lingual-low        | 3.169E-02                   | .021       | 1.000             | -3.236E-02                                             | 9.574E-02      |
| 22 lingual-mid        | 11 buccal-top         | -3.018E-02                  | .019       | 1.000             | -8.565E-02                                             | 2.529E-02      |
|                       | 12 buccal-mid         | 5.410E-03                   | .019       | 1.000             | -5.006E-02                                             | 6.088E-02      |
|                       | 13 buccal-low         | 7.465E-02*                  | .019       | .001              | 1.918E-02                                              | .130           |
|                       | 21 lingual-top        | -6.782E-03                  | .021       | 1.000             | -7.083E-02                                             | 5.727E-02      |
|                       | 23 lingual-low        | 2.491E-02                   | .021       | 1.000             | -3.915E-02                                             | 8.896E-02      |
| 23 lingual-low        | 11 buccal-top         | -5.508E-02                  | .019       | .053              | -.111                                                  | 3.873E-04      |
|                       | 12 buccal-mid         | -1.950E-02                  | .019       | 1.000             | -7.497E-02                                             | 3.597E-02      |
|                       | 13 buccal-low         | 4.974E-02                   | .019       | .124              | -5.727E-03                                             | .105           |
|                       | 21 lingual-top        | -3.169E-02                  | .021       | 1.000             | -9.574E-02                                             | 3.236E-02      |
|                       | 22 lingual-mid        | -2.491E-02                  | .021       | 1.000             | -8.896E-02                                             | 3.915E-02      |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: HARDC Hardness (control)

|          | Sum of Squares | df  | Mean Square | F      | Sig. |
|----------|----------------|-----|-------------|--------|------|
| Contrast | .219           | 5   | 4.373E-02   | 10.565 | .000 |
| Error    | .575           | 139 | 4.139E-03   |        |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Univariate Analysis of Variance

Between-Subjects Factors

|                          |    | Value<br>Label | N  |
|--------------------------|----|----------------|----|
| STR Strength<br>of Force | 1  | light          | 81 |
|                          | 2  | heavy          | 81 |
| SUBJ Subject             | 1  |                | 18 |
|                          | 2  |                | 18 |
|                          | 3  |                | 18 |
|                          | 4  |                | 18 |
|                          | 5  |                | 18 |
|                          | 6  |                | 18 |
|                          | 7  |                | 18 |
|                          | 8  |                | 18 |
|                          | 9  |                | 18 |
| POS Position<br>on tooth | 11 | buccal-top     | 36 |
|                          | 12 | buccal-mid     | 36 |
|                          | 13 | buccal-low     | 36 |
|                          | 21 | lingual-top    | 18 |
|                          | 22 | lingual-mid    | 18 |
|                          | 23 | lingual-low    | 18 |



Tests of Between-Subjects Effects

Dependent Variable: ELASTC Elasticity (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F       | Sig. |
|-----------------|-------------------------|-----|-------------|---------|------|
| Corrected Model | 233.432 <sup>a</sup>    | 22  | 10.611      | 4.198   | .000 |
| Intercept       | 1420.764                | 1   | 1420.764    | 562.172 | .000 |
| STR             | 7.824                   | 1   | 7.824       | 3.096   | .081 |
| SUBJ(STR)       | 124.126                 | 16  | 7.758       | 3.070   | .000 |
| POS             | 101.482                 | 5   | 20.296      | 8.031   | .000 |
| Error           | 351.292                 | 139 | 2.527       |         |      |
| Total           | 2156.643                | 162 |             |         |      |
| Corrected Total | 584.724                 | 161 |             |         |      |

a. R Squared = .399 (Adjusted R Squared = .304)

Estimated Marginal Means

1. Strength of Force

Estimates

Dependent Variable: ELASTC Elasticity (control)

| Strength of Force | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------------|-------|------------|-------------------------|-------------|
|                   |       |            | Lower Bound             | Upper Bound |
| 1 light           | 3.361 | .182       | 3.001                   | 3.721       |
| 2 heavy           | 2.921 | .182       | 2.561                   | 3.281       |

Pairwise Comparisons

Dependent Variable: ELASTC Elasticity (control)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | .440                  | .250       | .081              | -5.437E-02                                          | .933        |
| 2 heavy                                     | 1 light | -.440                 | .250       | .081              | -.933                                               | 5.437E-02   |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: ELASTC Elasticity (control)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 7.824          | 1   | 7.824       | 3.096 | .081 |
| Error    | 351.292        | 139 | 2.527       |       |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth

Estimates

Dependent Variable: ELASTC Elasticity (control)

| Position on tooth | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------------|-------|------------|-------------------------|-------------|
|                   |       |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | 4.217 | .265       | 3.693                   | 4.740       |
| 12 buccal-mid     | 2.882 | .265       | 2.358                   | 3.406       |
| 13 buccal-low     | 2.090 | .265       | 1.566                   | 2.614       |
| 21 lingual-top    | 3.871 | .375       | 3.130                   | 4.612       |
| 22 lingual-mid    | 3.302 | .375       | 2.561                   | 4.042       |
| 23 lingual-low    | 2.486 | .375       | 1.745                   | 3.227       |



Pairwise Comparisons

Dependent Variable: ELASTC Elasticity (control)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | 1.335*                      | .375       | .008              | .216                                                   | 2.454          |
|                       | 13 buccal-low         | 2.126*                      | .375       | .000              | 1.007                                                  | 3.246          |
|                       | 21 lingual-top        | .346                        | .459       | 1.000             | -1.025                                                 | 1.717          |
|                       | 22 lingual-mid        | .915                        | .459       | .722              | -.456                                                  | 2.286          |
|                       | 23 lingual-low        | 1.731*                      | .459       | .004              | .360                                                   | 3.101          |
| 12 buccal-mid         | 11 buccal-top         | -1.335*                     | .375       | .008              | -2.454                                                 | -.216          |
|                       | 13 buccal-low         | .792                        | .375       | .546              | -.328                                                  | 1.911          |
|                       | 21 lingual-top        | -.989                       | .459       | .493              | -2.360                                                 | .382           |
|                       | 22 lingual-mid        | -.420                       | .459       | 1.000             | -1.790                                                 | .951           |
|                       | 23 lingual-low        | .396                        | .459       | 1.000             | -.975                                                  | 1.767          |
| 13 buccal-low         | 11 buccal-top         | -2.126*                     | .375       | .000              | -3.246                                                 | -1.007         |
|                       | 12 buccal-mid         | -.792                       | .375       | .546              | -1.911                                                 | .328           |
|                       | 21 lingual-top        | -1.781*                     | .459       | .002              | -3.151                                                 | -.410          |
|                       | 22 lingual-mid        | -1.211                      | .459       | .139              | -2.582                                                 | .159           |
|                       | 23 lingual-low        | -.396                       | .459       | 1.000             | -1.766                                                 | .975           |
| 21 lingual-top        | 11 buccal-top         | -.346                       | .459       | 1.000             | -1.717                                                 | 1.025          |
|                       | 12 buccal-mid         | .989                        | .459       | .493              | -.382                                                  | 2.360          |
|                       | 13 buccal-low         | 1.781*                      | .459       | .002              | .410                                                   | 3.151          |
|                       | 22 lingual-mid        | .569                        | .530       | 1.000             | -1.014                                                 | 2.152          |
|                       | 23 lingual-low        | 1.385                       | .530       | .149              | -.198                                                  | 2.968          |
| 22 lingual-mid        | 11 buccal-top         | -.915                       | .459       | .722              | -2.286                                                 | .456           |
|                       | 12 buccal-mid         | .420                        | .459       | 1.000             | -.951                                                  | 1.790          |
|                       | 13 buccal-low         | 1.211                       | .459       | .139              | -.159                                                  | 2.582          |
|                       | 21 lingual-top        | -.569                       | .530       | 1.000             | -2.152                                                 | 1.014          |
|                       | 23 lingual-low        | .816                        | .530       | 1.000             | -.767                                                  | 2.398          |
| 23 lingual-low        | 11 buccal-top         | -1.731*                     | .459       | .004              | -3.101                                                 | -.360          |
|                       | 12 buccal-mid         | -.396                       | .459       | 1.000             | -1.767                                                 | .975           |
|                       | 13 buccal-low         | .396                        | .459       | 1.000             | -.975                                                  | 1.766          |
|                       | 21 lingual-top        | -1.385                      | .530       | .149              | -2.968                                                 | .198           |
|                       | 22 lingual-mid        | -.816                       | .530       | 1.000             | -2.398                                                 | .767           |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: ELASTC Elasticity (control)

|          | Sum of<br>Squares | df  | Mean<br>Square | F     | Sig. |
|----------|-------------------|-----|----------------|-------|------|
| Contrast | 101.482           | 5   | 20.296         | 8.031 | .000 |
| Error    | 351.292           | 139 | 2.527          |       |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Means (not including enamel)



Report

| STRSUB |                    | HARDC<br>Hardness<br>(control) | HARDE<br>Hardness<br>(experimental) |
|--------|--------------------|--------------------------------|-------------------------------------|
| 11     | Mean               | .28020                         | .29761                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | .11125                         | 6.5167E-02                          |
|        | Std. Error of Mean | 3.7083E-02                     | 2.1722E-02                          |
| 12     | Mean               | .19757                         | .19614                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 7.8162E-02                     | .10744                              |
|        | Std. Error of Mean | 2.6054E-02                     | 3.5814E-02                          |
| 13     | Mean               | .30182                         | .28797                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 4.7767E-02                     | 5.2626E-02                          |
|        | Std. Error of Mean | 1.5922E-02                     | 1.7542E-02                          |
| 14     | Mean               | .21799                         | .26684                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 8.2394E-02                     | 4.9491E-02                          |
|        | Std. Error of Mean | 2.7465E-02                     | 1.6497E-02                          |
| 15     | Mean               | .17239                         | .23696                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 3.3023E-02                     | 6.0166E-02                          |
|        | Std. Error of Mean | 1.1008E-02                     | 2.0055E-02                          |
| 16     | Mean               | .28020                         | .29761                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | .11125                         | 6.5167E-02                          |
|        | Std. Error of Mean | 3.7083E-02                     | 2.1722E-02                          |
| 17     | Mean               | .25613                         | .26934                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | .10828                         | 9.5812E-02                          |
|        | Std. Error of Mean | 3.6094E-02                     | 3.1937E-02                          |
| 18     | Mean               | .27052                         | .27815                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 5.1725E-02                     | 8.8796E-02                          |
|        | Std. Error of Mean | 1.7242E-02                     | 2.9599E-02                          |
| 19     | Mean               | .29986                         | .24921                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 5.4777E-02                     | 4.6679E-02                          |
|        | Std. Error of Mean | 1.8259E-02                     | 1.5560E-02                          |
| 21     | Mean               | .24992                         | .21710                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 7.5785E-02                     | 8.2054E-02                          |
|        | Std. Error of Mean | 2.5262E-02                     | 2.7351E-02                          |
| 22     | Mean               | .21585                         | .25880                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 9.2631E-02                     | .13612                              |
|        | Std. Error of Mean | 3.0877E-02                     | 4.5373E-02                          |
| 23     | Mean               | .18208                         | .18384                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 5.7517E-02                     | 6.7174E-02                          |
|        | Std. Error of Mean | 1.9172E-02                     | 2.2391E-02                          |
| 24     | Mean               | .20929                         | .20837                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 3.7286E-02                     | 6.0349E-02                          |
|        | Std. Error of Mean | 1.2422E-02                     | 2.0116E-02                          |
| 25     | Mean               | .24915                         | .21596                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 7.0543E-02                     | 7.1325E-02                          |
|        | Std. Error of Mean | 2.3514E-02                     | 2.3775E-02                          |
| 26     | Mean               | .25155                         | .27714                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 6.3499E-02                     | 8.4983E-02                          |
|        | Std. Error of Mean | 2.1166E-02                     | 2.8328E-02                          |
| 27     | Mean               | .19177                         | .14460                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 7.7268E-02                     | 7.4195E-02                          |
|        | Std. Error of Mean | 2.5756E-02                     | 2.4732E-02                          |
| 28     | Mean               | .24971                         | .26320                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 6.1814E-02                     | 9.0426E-02                          |
|        | Std. Error of Mean | 2.0605E-02                     | 3.0142E-02                          |
| 29     | Mean               | .18546                         | .17781                              |
|        | N                  | 9                              | 9                                   |
|        | Std. Deviation     | 5.4812E-02                     | 7.3729E-02                          |
|        | Std. Error of Mean | 1.8271E-02                     | 2.4576E-02                          |
| Total  | Mean               | .23675                         | .24037                              |
|        | N                  | 162                            | 162                                 |
|        | Std. Deviation     | 8.0979E-02                     | 8.6838E-02                          |
|        | Std. Error of Mean | 6.3623E-03                     | 6.8226E-03                          |



Univariate Analysis of Variance

Between-Subjects Factors

|                       |   | Value Label | N  |
|-----------------------|---|-------------|----|
| STR Strength of Force | 1 | light       | 81 |
|                       | 2 | heavy       | 81 |
| SUBJ Subject          | 1 |             | 18 |
|                       | 2 |             | 18 |
|                       | 3 |             | 18 |
|                       | 4 |             | 18 |
|                       | 5 |             | 18 |
|                       | 6 |             | 18 |
|                       | 7 |             | 18 |
|                       | 8 |             | 18 |
|                       | 9 |             | 18 |
| LAY Tooth Layer       | 1 | top         | 54 |
|                       | 2 | middle      | 54 |
|                       | 3 | bottom      | 54 |

Tests of Between-Subjects Effects

Dependent Variable: HARDC Hardness (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F        | Sig. |
|-----------------|-------------------------|-----|-------------|----------|------|
| Corrected Model | .444 <sup>a</sup>       | 19  | 2.336E-02   | 5.420    | .000 |
| Intercept       | 9.080                   | 1   | 9.080       | 2106.964 | .000 |
| STR             | 4.260E-02               | 1   | 4.260E-02   | 9.886    | .002 |
| SUBJ(STR)       | .219                    | 16  | 1.370E-02   | 3.179    | .000 |
| LAY             | .182                    | 2   | 9.102E-02   | 21.121   | .000 |
| Error           | .612                    | 142 | 4.309E-03   |          |      |
| Total           | 10.136                  | 162 |             |          |      |
| Corrected Total | 1.056                   | 161 |             |          |      |

a. R Squared = .420 (Adjusted R Squared = .343)

Estimated Marginal Means

1. Strength of Force



Estimates

Dependent Variable: HARDC Hardness (control)

| Strength of Force | Mean | Std. Error | 95% Confidence Interval |             |
|-------------------|------|------------|-------------------------|-------------|
|                   |      |            | Lower Bound             | Upper Bound |
| 1 light           | .253 | .007       | .239                    | .267        |
| 2 heavy           | .221 | .007       | .206                    | .235        |

Pairwise Comparisons

Dependent Variable: HARDC Hardness (control)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | 3.243E-02*            | .010       | .002              | 1.204E-02                                           | 5.282E-02   |
| 2 heavy                                     | 1 light | -3.243E-02*           | .010       | .002              | -5.282E-02                                          | -1.204E-02  |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: HARDC Hardness (control)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 4.260E-02      | 1   | 4.260E-02   | 9.886 | .002 |
| Error    | .612           | 142 | 4.309E-03   |       |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Tooth Layer

Estimates

Dependent Variable: HARDC Hardness (control)

| Tooth Layer | Mean | Std. Error | 95% Confidence Interval |             |
|-------------|------|------------|-------------------------|-------------|
|             |      |            | Lower Bound             | Upper Bound |
| 1 top       | .272 | .009       | .255                    | .290        |
| 2 middle    | .246 | .009       | .229                    | .264        |
| 3 bottom    | .192 | .009       | .174                    | .209        |



Pairwise Comparisons

Dependent Variable: HARDC Hardness (control)

|                 |                 | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------|-----------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Tooth Layer | (J) Tooth Layer |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 1 top           | 2 middle        | 2.599E-02                   | .013       | .125              | -4.622E-03                                             | 5.659E-02      |
|                 | 3 bottom        | 8.045E-02*                  | .013       | .000              | 4.984E-02                                              | .111           |
| 2 middle        | 1 top           | -2.599E-02                  | .013       | .125              | -5.659E-02                                             | 4.622E-03      |
|                 | 3 bottom        | 5.446E-02*                  | .013       | .000              | 2.385E-02                                              | 8.507E-02      |
| 3 bottom        | 1 top           | -8.045E-02*                 | .013       | .000              | -.111                                                  | -4.984E-02     |
|                 | 2 middle        | -5.446E-02*                 | .013       | .000              | -8.507E-02                                             | -2.385E-02     |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: HARDC Hardness (control)

|          | Sum of<br>Squares | df  | Mean<br>Square | F      | Sig. |
|----------|-------------------|-----|----------------|--------|------|
| Contrast | .182              | 2   | 9.102E-02      | 21.121 | .000 |
| Error    | .612              | 142 | 4.309E-03      |        |      |

The F tests the effect of Tooth Layer. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Univariate Analysis of Variance



Between-Subjects Factors

|                       |   | Value Label | N  |
|-----------------------|---|-------------|----|
| STR Strength of Force | 1 | light       | 81 |
|                       | 2 | heavy       | 81 |
| SUBJ Subject          | 1 |             | 18 |
|                       | 2 |             | 18 |
|                       | 3 |             | 18 |
|                       | 4 |             | 18 |
|                       | 5 |             | 18 |
|                       | 6 |             | 18 |
|                       | 7 |             | 18 |
|                       | 8 |             | 18 |
|                       | 9 |             | 18 |
| LAY Tooth Layer       | 1 | top         | 54 |
|                       | 2 | middle      | 54 |
|                       | 3 | bottom      | 54 |

Tests of Between-Subjects Effects

Dependent Variable: ELASTC Elasticity (control)

| Source          | Type III Sum of Squares | df  | Mean Square | F       | Sig. |
|-----------------|-------------------------|-----|-------------|---------|------|
| Corrected Model | 228.004 <sup>a</sup>    | 19  | 12.000      | 4.777   | .000 |
| Intercept       | 1571.919                | 1   | 1571.919    | 625.736 | .000 |
| STR             | 7.824                   | 1   | 7.824       | 3.115   | .080 |
| SUBJ(STR)       | 124.126                 | 16  | 7.758       | 3.088   | .000 |
| LAY             | 96.053                  | 2   | 48.027      | 19.118  | .000 |
| Error           | 356.720                 | 142 | 2.512       |         |      |
| Total           | 2156.643                | 162 |             |         |      |
| Corrected Total | 584.724                 | 161 |             |         |      |

a. R Squared = .390 (Adjusted R Squared = .308)

Estimated Marginal Means

1. Strength of Force



Estimates

Dependent Variable: ELASTC Elasticity (control)

| Strength of Force | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------------|-------|------------|-------------------------|-------------|
|                   |       |            | Lower Bound             | Upper Bound |
| 1 light           | 3.335 | .176       | 2.987                   | 3.683       |
| 2 heavy           | 2.895 | .176       | 2.547                   | 3.243       |

Pairwise Comparisons

Dependent Variable: ELASTC Elasticity (control)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | .440                  | .249       | .080              | -5.279E-02                                          | .932        |
| 2 heavy                                     | 1 light | -.440                 | .249       | .080              | -.932                                               | 5.279E-02   |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: ELASTC Elasticity (control)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 7.824          | 1   | 7.824       | 3.115 | .080 |
| Error    | 356.720        | 142 | 2.512       |       |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Tooth Layer

Estimates

Dependent Variable: ELASTC Elasticity (control)

| Tooth Layer | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------|-------|------------|-------------------------|-------------|
|             |       |            | Lower Bound             | Upper Bound |
| 1 top       | 4.101 | .216       | 3.675                   | 4.528       |
| 2 middle    | 3.022 | .216       | 2.595                   | 3.448       |
| 3 bottom    | 2.222 | .216       | 1.796                   | 2.648       |



Pairwise Comparisons

Dependent Variable: ELASTC Elasticity (control)

|                 |                 | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------|-----------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Tooth Layer | (J) Tooth Layer |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 1 top           | 2 middle        | 1.080*                      | .305       | .002              | .341                                                   | 1.819          |
|                 | 3 bottom        | 1.879*                      | .305       | .000              | 1.140                                                  | 2.618          |
| 2 middle        | 1 top           | -1.080*                     | .305       | .002              | -1.819                                                 | -.341          |
|                 | 3 bottom        | .800*                       | .305       | .029              | 6.067E-02                                              | 1.539          |
| 3 bottom        | 1 top           | -1.879*                     | .305       | .000              | -2.618                                                 | -1.140         |
|                 | 2 middle        | -.800*                      | .305       | .029              | -1.539                                                 | -6.067E-02     |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: ELASTC Elasticity (control)

|          | Sum of<br>Squares | df  | Mean<br>Square | F      | Sig. |
|----------|-------------------|-----|----------------|--------|------|
| Contrast | 96.053            | 2   | 48.027         | 19.118 | .000 |
| Error    | 356.720           | 142 | 2.512          |        |      |

The F tests the effect of Tooth Layer. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Univariate Analysis of Variance



Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 18 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |

Tests of Between-Subjects Effects

Dependent Variable: HARDE Hardness (experimental)

| Source          | Type III Sum of Squares | df  | Mean Square | F        | Sig. |
|-----------------|-------------------------|-----|-------------|----------|------|
| Corrected Model | .520 <sup>a</sup>       | 22  | 2.361E-02   | 4.726    | .000 |
| Intercept       | 8.072                   | 1   | 8.072       | 1615.473 | .000 |
| STR             | 9.374E-02               | 1   | 9.374E-02   | 18.760   | .000 |
| SUBJ(STR)       | .217                    | 16  | 1.354E-02   | 2.710    | .001 |
| POS             | .209                    | 5   | 4.183E-02   | 8.371    | .000 |
| Error           | .695                    | 139 | 4.997E-03   |          |      |
| Total           | 10.574                  | 162 |             |          |      |
| Corrected Total | 1.214                   | 161 |             |          |      |

a. R Squared = .428 (Adjusted R Squared = .337)

Estimated Marginal Means

1. Strength of Force



Estimates

Dependent Variable: HARDE Hardness (experimental)

| Strength of Force | Mean | Std. Error | 95% Confidence Interval |             |
|-------------------|------|------------|-------------------------|-------------|
|                   |      |            | Lower Bound             | Upper Bound |
| 1 light           | .261 | .008       | .245                    | .277        |
| 2 heavy           | .213 | .008       | .197                    | .229        |

Pairwise Comparisons

Dependent Variable: HARDE Hardness (experimental)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | 4.811E-02*            | .011       | .000              | 2.615E-02                                           | 7.007E-02   |
| 2 heavy                                     | 1 light | -4.811E-02*           | .011       | .000              | -7.007E-02                                          | -2.615E-02  |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: HARDE Hardness (experimental)

|          | Sum of Squares | df  | Mean Square | F      | Sig. |
|----------|----------------|-----|-------------|--------|------|
| Contrast | 9.374E-02      | 1   | 9.374E-02   | 18.760 | .000 |
| Error    | .695           | 139 | 4.997E-03   |        |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth



Estimates

Dependent Variable: HARDE Hardness (experimental)

| Position on tooth | Mean | Std. Error | 95% Confidence Interval |             |
|-------------------|------|------------|-------------------------|-------------|
|                   |      |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | .291 | .012       | .268                    | .315        |
| 12 buccal-mid     | .248 | .012       | .225                    | .271        |
| 13 buccal-low     | .204 | .012       | .180                    | .227        |
| 21 lingual-top    | .257 | .017       | .224                    | .290        |
| 22 lingual-mid    | .238 | .017       | .206                    | .271        |
| 23 lingual-low    | .183 | .017       | .150                    | .216        |



Pairwise Comparisons

Dependent Variable: HARDE Hardness (experimental)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | 4.333E-02                   | .017       | .155              | -6.431E-03                                             | 9.310E-02      |
|                       | 13 buccal-low         | 8.777E-02*                  | .017       | .000              | 3.801E-02                                              | .138           |
|                       | 21 lingual-top        | 3.457E-02                   | .020       | 1.000             | -2.638E-02                                             | 9.551E-02      |
|                       | 22 lingual-mid        | 5.281E-02                   | .020       | .160              | -8.141E-03                                             | .114           |
|                       | 23 lingual-low        | .109*                       | .020       | .000              | 4.769E-02                                              | .170           |
| 12 buccal-mid         | 11 buccal-top         | -4.333E-02                  | .017       | .155              | -9.310E-02                                             | 6.431E-03      |
|                       | 13 buccal-low         | 4.444E-02                   | .017       | .128              | -5.326E-03                                             | 9.420E-02      |
|                       | 21 lingual-top        | -8.766E-03                  | .020       | 1.000             | -6.971E-02                                             | 5.218E-02      |
|                       | 22 lingual-mid        | 9.474E-03                   | .020       | 1.000             | -5.147E-02                                             | 7.042E-02      |
|                       | 23 lingual-low        | 6.531E-02*                  | .020       | .026              | 4.359E-03                                              | .126           |
| 13 buccal-low         | 11 buccal-top         | -8.777E-02*                 | .017       | .000              | -.138                                                  | -3.801E-02     |
|                       | 12 buccal-mid         | -4.444E-02                  | .017       | .128              | -9.420E-02                                             | 5.326E-03      |
|                       | 21 lingual-top        | -5.320E-02                  | .020       | .152              | -.114                                                  | 7.744E-03      |
|                       | 22 lingual-mid        | -3.496E-02                  | .020       | 1.000             | -9.591E-02                                             | 2.598E-02      |
|                       | 23 lingual-low        | 2.087E-02                   | .020       | 1.000             | -4.008E-02                                             | 8.182E-02      |
| 21 lingual-top        | 11 buccal-top         | -3.457E-02                  | .020       | 1.000             | -9.551E-02                                             | 2.638E-02      |
|                       | 12 buccal-mid         | 8.766E-03                   | .020       | 1.000             | -5.218E-02                                             | 6.971E-02      |
|                       | 13 buccal-low         | 5.320E-02                   | .020       | .152              | -7.744E-03                                             | .114           |
|                       | 22 lingual-mid        | 1.824E-02                   | .024       | 1.000             | -5.214E-02                                             | 8.862E-02      |
|                       | 23 lingual-low        | 7.407E-02*                  | .024       | .031              | 3.696E-03                                              | .144           |
| 22 lingual-mid        | 11 buccal-top         | -5.281E-02                  | .020       | .160              | -.114                                                  | 8.141E-03      |
|                       | 12 buccal-mid         | -9.474E-03                  | .020       | 1.000             | -7.042E-02                                             | 5.147E-02      |
|                       | 13 buccal-low         | 3.496E-02                   | .020       | 1.000             | -2.598E-02                                             | 9.591E-02      |
|                       | 21 lingual-top        | -1.824E-02                  | .024       | 1.000             | -8.862E-02                                             | 5.214E-02      |
|                       | 23 lingual-low        | 5.583E-02                   | .024       | .288              | -1.454E-02                                             | .126           |
| 23 lingual-low        | 11 buccal-top         | -.109*                      | .020       | .000              | -.170                                                  | -4.769E-02     |
|                       | 12 buccal-mid         | -6.531E-02*                 | .020       | .026              | -.126                                                  | -4.359E-03     |
|                       | 13 buccal-low         | -2.087E-02                  | .020       | 1.000             | -8.182E-02                                             | 4.008E-02      |
|                       | 21 lingual-top        | -7.407E-02*                 | .024       | .031              | -.144                                                  | -3.696E-03     |
|                       | 22 lingual-mid        | -5.583E-02                  | .024       | .288              | -.126                                                  | 1.454E-02      |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: HARDE Hardness (experimental)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | .209           | 5   | 4.183E-02   | 8.371 | .000 |
| Error    | .695           | 139 | 4.997E-03   |       |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Univariate Analysis of Variance

Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 80 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 17 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 17 |



Tests of Between-Subjects Effects

Dependent Variable: ELASTE Elasticity (experimental)

| Source          | Type III<br>Sum of<br>Squares | df  | Mean<br>Square | F       | Sig. |
|-----------------|-------------------------------|-----|----------------|---------|------|
| Corrected Model | 230.188 <sup>a</sup>          | 22  | 10.463         | 3.967   | .000 |
| Intercept       | 1325.938                      | 1   | 1325.938       | 502.711 | .000 |
| STR             | 23.044                        | 1   | 23.044         | 8.737   | .004 |
| SUBJ(STR)       | 128.152                       | 16  | 8.010          | 3.037   | .000 |
| POS             | 79.686                        | 5   | 15.937         | 6.042   | .000 |
| Error           | 363.985                       | 138 | 2.638          |         |      |
| Total           | 2121.403                      | 161 |                |         |      |
| Corrected Total | 594.174                       | 160 |                |         |      |

a. R Squared = .387 (Adjusted R Squared = .290)

Estimated Marginal Means

1. Strength of Force

Estimates

Dependent Variable: ELASTE Elasticity (experimental)

| Strength of Force | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------------|-------|------------|-------------------------|-------------|
|                   |       |            | Lower Bound             | Upper Bound |
| 1 light           | 3.435 | .186       | 3.067                   | 3.803       |
| 2 heavy           | 2.678 | .188       | 2.306                   | 3.050       |

Pairwise Comparisons

Dependent Variable: ELASTE Elasticity (experimental)

| (I) Strength of Force (J) Strength of Force |         | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------------|------------|-------------------|--------------------------------------------------------|-------------|
|                                             |         |                             |            |                   | Lower Bound                                            | Upper Bound |
| 1 light                                     | 2 heavy | .757*                       | .256       | .004              | .251                                                   | 1.264       |
| 2 heavy                                     | 1 light | -.757*                      | .256       | .004              | -1.264                                                 | -.251       |

Based on estimated marginal means

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

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: ELASTE Elasticity (experimental)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 23.044         | 1   | 23.044      | 8.737 | .004 |
| Error    | 363.985        | 138 | 2.638       |       |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth

Estimates

Dependent Variable: ELASTE Elasticity (experimental)

| Position on tooth | Mean  | Std. Error | 95% Confidence Interval |             |
|-------------------|-------|------------|-------------------------|-------------|
|                   |       |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | 4.026 | .271       | 3.491                   | 4.561       |
| 12 buccal-mid     | 2.911 | .271       | 2.376                   | 3.446       |
| 13 buccal-low     | 2.365 | .271       | 1.830                   | 2.900       |
| 21 lingual-top    | 3.893 | .383       | 3.136                   | 4.650       |
| 22 lingual-mid    | 3.043 | .383       | 2.286                   | 3.800       |
| 23 lingual-low    | 2.103 | .395       | 1.321                   | 2.884       |



Pairwise Comparisons

Dependent Variable: ELASTE Elasticity (experimental)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | 1.115                       | .383       | .063              | -2.851E-02                                             | 2.258          |
|                       | 13 buccal-low         | 1.661*                      | .383       | .000              | .517                                                   | 2.804          |
|                       | 21 lingual-top        | .133                        | .469       | 1.000             | -1.267                                                 | 1.534          |
|                       | 22 lingual-mid        | .983                        | .469       | .568              | -.417                                                  | 2.383          |
|                       | 23 lingual-low        | 1.923*                      | .479       | .001              | .492                                                   | 3.354          |
| 12 buccal-mid         | 11 buccal-top         | -1.115                      | .383       | .063              | -2.258                                                 | 2.851E-02      |
|                       | 13 buccal-low         | .546                        | .383       | 1.000             | -.598                                                  | 1.689          |
|                       | 21 lingual-top        | -.982                       | .469       | .571              | -2.382                                                 | .419           |
|                       | 22 lingual-mid        | -.132                       | .469       | 1.000             | -1.532                                                 | 1.269          |
|                       | 23 lingual-low        | .808                        | .479       | 1.000             | -.623                                                  | 2.239          |
| 13 buccal-low         | 11 buccal-top         | -1.661*                     | .383       | .000              | -2.804                                                 | -.517          |
|                       | 12 buccal-mid         | -.546                       | .383       | 1.000             | -1.689                                                 | .598           |
|                       | 21 lingual-top        | -1.528*                     | .469       | .021              | -2.928                                                 | -.127          |
|                       | 22 lingual-mid        | -.678                       | .469       | 1.000             | -2.078                                                 | .723           |
|                       | 23 lingual-low        | .263                        | .479       | 1.000             | -1.169                                                 | 1.694          |
| 21 lingual-top        | 11 buccal-top         | -.133                       | .469       | 1.000             | -1.534                                                 | 1.267          |
|                       | 12 buccal-mid         | .982                        | .469       | .571              | -.419                                                  | 2.382          |
|                       | 13 buccal-low         | 1.528*                      | .469       | .021              | .127                                                   | 2.928          |
|                       | 22 lingual-mid        | .850                        | .541       | 1.000             | -.767                                                  | 2.467          |
|                       | 23 lingual-low        | 1.790*                      | .550       | .021              | .147                                                   | 3.434          |
| 22 lingual-mid        | 11 buccal-top         | -.983                       | .469       | .568              | -2.383                                                 | .417           |
|                       | 12 buccal-mid         | .132                        | .469       | 1.000             | -1.269                                                 | 1.532          |
|                       | 13 buccal-low         | .678                        | .469       | 1.000             | -.723                                                  | 2.078          |
|                       | 21 lingual-top        | -.850                       | .541       | 1.000             | -2.467                                                 | .767           |
|                       | 23 lingual-low        | .940                        | .550       | 1.000             | -.703                                                  | 2.584          |
| 23 lingual-low        | 11 buccal-top         | -1.923*                     | .479       | .001              | -3.354                                                 | -.492          |
|                       | 12 buccal-mid         | -.808                       | .479       | 1.000             | -2.239                                                 | .623           |
|                       | 13 buccal-low         | -.263                       | .479       | 1.000             | -1.694                                                 | 1.169          |
|                       | 21 lingual-top        | -1.790*                     | .550       | .021              | -3.434                                                 | -.147          |
|                       | 22 lingual-mid        | -.940                       | .550       | 1.000             | -2.584                                                 | .703           |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: ELASTE Elasticity (expperimental)

|          | Sum of<br>Squares | df  | Mean<br>Square | F     | Sig. |
|----------|-------------------|-----|----------------|-------|------|
| Contrast | 79.686            | 5   | 15.937         | 6.042 | .000 |
| Error    | 363.985           | 138 | 2.638          |       |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Means



| Report |                    |                                |                                   |                                     |                                        |                                  |                                     |
|--------|--------------------|--------------------------------|-----------------------------------|-------------------------------------|----------------------------------------|----------------------------------|-------------------------------------|
| STRSUB |                    | HARDC<br>Hardness<br>(control) | ELASTC<br>Elasticity<br>(control) | HARDE<br>Hardness<br>(experimental) | ELASTE<br>Elasticity<br>(experimental) | DHARD<br>Hardness<br>(cont-expt) | DELAST<br>Elasticity<br>(cont-expt) |
| 11     | Mean               | .28020                         | 3.72177                           | .29761                              | 3.23270                                | -1.740E-02                       | .48907                              |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | .11125                         | 2.75023                           | 6.5167E-02                          | 1.93966                                | 8.9249E-02                       | 3.87380                             |
|        | Std. Error of Mean | 3.7083E-02                     | .91674                            | 2.1722E-02                          | .64655                                 | 2.9750E-02                       | 1.29127                             |
| 12     | Mean               | .19757                         | 1.93959                           | .19614                              | 2.12511                                | 1.4314E-03                       | -.18553                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 7.8162E-02                     | 1.14149                           | .10744                              | 1.40363                                | 7.7420E-02                       | 1.11368                             |
|        | Std. Error of Mean | 2.6054E-02                     | .38050                            | 3.5814E-02                          | .46788                                 | 2.5807E-02                       | .37123                              |
| 13     | Mean               | .30182                         | 4.03035                           | .28797                              | 6.00988                                | 1.3844E-02                       | -1.87953                            |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 4.7767E-02                     | 1.67125                           | 5.2626E-02                          | 2.01335                                | 5.8841E-02                       | 2.18703                             |
|        | Std. Error of Mean | 1.5922E-02                     | .55708                            | 1.7542E-02                          | .67112                                 | 1.9814E-02                       | .72901                              |
| 14     | Mean               | .21799                         | 3.49309                           | .26884                              | 4.21398                                | -4.885E-02                       | -.72090                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 8.2394E-02                     | 3.08354                           | 4.9491E-02                          | 1.35075                                | 6.7598E-02                       | 2.54477                             |
|        | Std. Error of Mean | 2.7465E-02                     | 1.02785                           | 1.6497E-02                          | .45025                                 | 2.2533E-02                       | .84826                              |
| 15     | Mean               | .17239                         | 2.02688                           | .23898                              | 2.94825                                | -6.457E-02                       | -.92138                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 3.3023E-02                     | .79587                            | 6.0166E-02                          | 1.24575                                | 7.7700E-02                       | 1.62814                             |
|        | Std. Error of Mean | 1.1008E-02                     | .26529                            | 2.0055E-02                          | .41525                                 | 2.5900E-02                       | .54271                              |
| 16     | Mean               | .28020                         | 4.42613                           | .29761                              | 3.08038                                | -1.740E-02                       | 1.34575                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | .11125                         | 2.02937                           | 6.5167E-02                          | 1.41283                                | 8.9249E-02                       | 1.85197                             |
|        | Std. Error of Mean | 3.7083E-02                     | .67646                            | 2.1722E-02                          | .47094                                 | 2.9750E-02                       | .61732                              |
| 17     | Mean               | .25613                         | 2.10810                           | .26934                              | 3.23823                                | -1.321E-02                       | -1.13213                            |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | .10828                         | 1.44874                           | 9.5812E-02                          | 2.13348                                | 8.7753E-02                       | 1.70508                             |
|        | Std. Error of Mean | 3.6094E-02                     | .48291                            | 3.1937E-02                          | .71116                                 | 2.9251E-02                       | .56836                              |
| 18     | Mean               | .27052                         | 3.04522                           | .27815                              | 3.92199                                | -7.626E-03                       | -.87678                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 5.1725E-02                     | 1.35519                           | 8.8796E-02                          | 2.16780                                | 6.7677E-02                       | 1.31965                             |
|        | Std. Error of Mean | 1.7242E-02                     | .45173                            | 2.9599E-02                          | .72260                                 | 2.2559E-02                       | .43988                              |
| 19     | Mean               | .29986                         | 5.22377                           | .24921                              | 2.27838                                | 5.0646E-02                       | 2.94539                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 5.4777E-02                     | 2.53105                           | 4.6679E-02                          | 1.01259                                | 2.7319E-02                       | 2.04300                             |
|        | Std. Error of Mean | 1.8259E-02                     | .84368                            | 1.5560E-02                          | .33753                                 | 9.1084E-03                       | .68100                              |
| 21     | Mean               | .24992                         | 3.74826                           | .21710                              | 3.08702                                | 3.2821E-02                       | .68124                              |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 7.5785E-02                     | 1.66954                           | 8.2054E-02                          | 1.78737                                | 5.0668E-02                       | .96458                              |
|        | Std. Error of Mean | 2.5262E-02                     | .55651                            | 2.7351E-02                          | .59579                                 | 1.6889E-02                       | .32153                              |
| 22     | Mean               | .21585                         | 2.46782                           | .25880                              | 2.69040                                | -4.296E-02                       | -.22259                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 9.2631E-02                     | 1.60474                           | .13612                              | 2.62580                                | .13490                           | 3.13303                             |
|        | Std. Error of Mean | 3.0877E-02                     | .53491                            | 4.5373E-02                          | .87527                                 | 4.4968E-02                       | 1.04434                             |
| 23     | Mean               | .18208                         | 1.95464                           | .18384                              | 2.11168                                | -1.759E-03                       | -.15704                             |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 5.7517E-02                     | 1.05662                           | 6.7174E-02                          | .90109                                 | 8.7618E-02                       | 1.41192                             |
|        | Std. Error of Mean | 1.9172E-02                     | .35221                            | 2.2391E-02                          | .30036                                 | 2.9206E-02                       | .47064                              |
| 24     | Mean               | .20929                         | 2.84788                           | .20837                              | 2.78224                                | 9.1610E-04                       | 6.5636E-02                          |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 3.7266E-02                     | 1.47806                           | 6.0349E-02                          | 1.56523                                | 3.4819E-02                       | 1.14299                             |
|        | Std. Error of Mean | 1.2422E-02                     | .49269                            | 2.0116E-02                          | .52174                                 | 1.1606E-02                       | .38100                              |
| 25     | Mean               | .24915                         | 2.72168                           | .21596                              | 1.87565                                | 3.3181E-02                       | .84603                              |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 7.0543E-02                     | 1.68331                           | 7.1325E-02                          | 1.13379                                | 8.8278E-02                       | 2.23738                             |
|        | Std. Error of Mean | 2.3514E-02                     | .58110                            | 2.3775E-02                          | .37793                                 | 2.9426E-02                       | .74579                              |
| 26     | Mean               | .25155                         | 2.69841                           | .27714                              | 3.80004                                | -2.559E-02                       | -1.10363                            |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 6.3499E-02                     | 1.63591                           | 8.4983E-02                          | 2.60699                                | 6.0757E-02                       | 3.19166                             |
|        | Std. Error of Mean | 2.1166E-02                     | .54530                            | 2.8328E-02                          | .86900                                 | 2.0252E-02                       | 1.06389                             |
| 27     | Mean               | .19177                         | 2.41448                           | .14460                              | 1.98101                                | 4.7169E-02                       | .45348                              |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 7.7268E-02                     | 1.29960                           | 7.4195E-02                          | 1.38567                                | .11915                           | 2.02856                             |
|        | Std. Error of Mean | 2.5756E-02                     | .43320                            | 2.4732E-02                          | .46189                                 | 3.9717E-02                       | .67619                              |
| 28     | Mean               | .24971                         | 3.71108                           | .26320                              | 3.28883                                | -1.349E-02                       | .42225                              |
|        | N                  | 9                              | 9                                 | 9                                   | 9                                      | 9                                | 9                                   |
|        | Std. Deviation     | 6.1814E-02                     | 1.64703                           | 9.0426E-02                          | 2.40978                                | 9.0486E-02                       | 2.42339                             |
|        | Std. Error of Mean | 2.0605E-02                     | .54901                            | 3.0142E-02                          | .80326                                 | 3.0162E-02                       | .80780                              |
| 29     | Mean               | .18546                         | 3.49481                           | .17781                              | 2.77936                                | 7.6544E-03                       | .57056                              |
|        | N                  | 9                              | 9                                 | 9                                   | 8                                      | 9                                | 8                                   |
|        | Std. Deviation     | 5.4812E-02                     | 1.32670                           | 7.3729E-02                          | .99339                                 | 8.2154E-02                       | 1.69967                             |
|        | Std. Error of Mean | 1.8271E-02                     | .44223                            | 2.4576E-02                          | .35122                                 | 2.7385E-02                       | .60092                              |
| Total  | Mean               | .23675                         | 3.11500                           | .24037                              | 3.07992                                | -3.621E-03                       | 2.5520E-02                          |
|        | N                  | 162                            | 162                               | 162                                 | 161                                    | 162                              | 161                                 |
|        | Std. Deviation     | 8.0979E-02                     | 1.90573                           | 8.6838E-02                          | 1.92707                                | 8.2955E-02                       | 2.32436                             |
|        | Std. Error of Mean | 6.3623E-03                     | .14973                            | 6.8228E-03                          | .15187                                 | 6.5176E-03                       | .18319                              |



Univariate Analysis of Variance

Between-Subjects Factors

|                          |    | Value<br>Label | N  |
|--------------------------|----|----------------|----|
| STR Strength<br>of Force | 1  | light          | 81 |
|                          | 2  | heavy          | 81 |
| SUBJ Subject             | 1  |                | 18 |
|                          | 2  |                | 18 |
|                          | 3  |                | 18 |
|                          | 4  |                | 18 |
|                          | 5  |                | 18 |
|                          | 6  |                | 18 |
|                          | 7  |                | 18 |
|                          | 8  |                | 18 |
|                          | 9  |                | 18 |
| POS Position<br>on tooth | 11 | buccal-top     | 36 |
|                          | 12 | buccal-mid     | 36 |
|                          | 13 | buccal-low     | 36 |
|                          | 21 | lingual-top    | 18 |
|                          | 22 | lingual-mid    | 18 |
|                          | 23 | lingual-low    | 18 |

Tests of Between-Subjects Effects

Dependent Variable: DHARD Hardness (cont-expt)

| Source          | Type III<br>Sum of<br>Squares | df  | Mean<br>Square | F     | Sig. |
|-----------------|-------------------------------|-----|----------------|-------|------|
| Corrected Model | .220 <sup>a</sup>             | 22  | 9.993E-03      | 1.564 | .063 |
| Intercept       | 4.405E-04                     | 1   | 4.405E-04      | .069  | .793 |
| STR             | 9.953E-03                     | 1   | 9.953E-03      | 1.558 | .214 |
| SUBJ(STR)       | .144                          | 16  | 8.976E-03      | 1.405 | .148 |
| POS             | 6.628E-02                     | 5   | 1.326E-02      | 2.075 | .072 |
| Error           | .888                          | 139 | 6.389E-03      |       |      |
| Total           | 1.110                         | 162 |                |       |      |
| Corrected Total | 1.108                         | 161 |                |       |      |

a. R Squared = .198 (Adjusted R Squared = .072)

Estimated Marginal Means



1. Strength of Force

Estimates

Dependent Variable: DHARD Hardness (cont-expt)

| Strength of Force | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 1 light           | -6.09E-03 | .009       | -2.419E-02              | 1.201E-02   |
| 2 heavy           | 9.587E-03 | .009       | -8.513E-03              | 2.769E-02   |

Pairwise Comparisons

Dependent Variable: DHARD Hardness (cont-expt)

| (I) Strength of Force (J) Strength of Force |         | Mean Difference (I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval for Difference <sup>a</sup> |             |
|---------------------------------------------|---------|-----------------------|------------|-------------------|-----------------------------------------------------|-------------|
|                                             |         |                       |            |                   | Lower Bound                                         | Upper Bound |
| 1 light                                     | 2 heavy | -1.568E-02            | .013       | .214              | -4.051E-02                                          | 9.157E-03   |
| 2 heavy                                     | 1 light | 1.568E-02             | .013       | .214              | -9.157E-03                                          | 4.051E-02   |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Univariate Tests

Dependent Variable: DHARD Hardness (cont-expt)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 9.953E-03      | 1   | 9.953E-03   | 1.558 | .214 |
| Error    | .888           | 139 | 6.389E-03   |       |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth



Estimates

Dependent Variable: DHARD Hardness (cont-expt)

| Position on tooth | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | -1.13E-02 | .013       | -3.760E-02              | 1.508E-02   |
| 12 buccal-mid     | -3.51E-03 | .013       | -2.985E-02              | 2.283E-02   |
| 13 buccal-low     | -2.83E-02 | .013       | -5.466E-02              | -1.976E-03  |
| 21 lingual-top    | -8.62E-05 | .019       | -3.734E-02              | 3.716E-02   |
| 22 lingual-mid    | 1.137E-02 | .019       | -2.588E-02              | 4.862E-02   |
| 23 lingual-low    | 4.230E-02 | .019       | 5.046E-03               | 7.955E-02   |



Pairwise Comparisons

Dependent Variable: DHARD Hardness (cont-ex pt)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | -7.746E-03                  | .019       | 1.000             | -6.402E-02                                             | 4.853E-02      |
|                       | 13 buccal-low         | 1.706E-02                   | .019       | 1.000             | -3.921E-02                                             | 7.333E-02      |
|                       | 21 lingual-top        | -1.117E-02                  | .023       | 1.000             | -8.009E-02                                             | 5.775E-02      |
|                       | 22 lingual-mid        | -2.263E-02                  | .023       | 1.000             | -9.155E-02                                             | 4.629E-02      |
|                       | 23 lingual-low        | -5.356E-02                  | .023       | .326              | -.122                                                  | 1.536E-02      |
| 12 buccal-mid         | 11 buccal-top         | 7.746E-03                   | .019       | 1.000             | -4.853E-02                                             | 6.402E-02      |
|                       | 13 buccal-low         | 2.480E-02                   | .019       | 1.000             | -3.147E-02                                             | 8.107E-02      |
|                       | 21 lingual-top        | -3.427E-03                  | .023       | 1.000             | -7.234E-02                                             | 6.549E-02      |
|                       | 22 lingual-mid        | -1.488E-02                  | .023       | 1.000             | -8.380E-02                                             | 5.403E-02      |
|                       | 23 lingual-low        | -4.581E-02                  | .023       | .736              | -.115                                                  | 2.311E-02      |
| 13 buccal-low         | 11 buccal-top         | -1.706E-02                  | .019       | 1.000             | -7.333E-02                                             | 3.921E-02      |
|                       | 12 buccal-mid         | -2.480E-02                  | .019       | 1.000             | -8.107E-02                                             | 3.147E-02      |
|                       | 21 lingual-top        | -2.823E-02                  | .023       | 1.000             | -9.715E-02                                             | 4.069E-02      |
|                       | 22 lingual-mid        | -3.969E-02                  | .023       | 1.000             | -.109                                                  | 2.923E-02      |
|                       | 23 lingual-low        | -7.061E-02*                 | .023       | .040              | -.140                                                  | -1.694E-03     |
| 21 lingual-top        | 11 buccal-top         | 1.117E-02                   | .023       | 1.000             | -5.775E-02                                             | 8.009E-02      |
|                       | 12 buccal-mid         | 3.427E-03                   | .023       | 1.000             | -6.549E-02                                             | 7.234E-02      |
|                       | 13 buccal-low         | 2.823E-02                   | .023       | 1.000             | -4.069E-02                                             | 9.715E-02      |
|                       | 22 lingual-mid        | -1.146E-02                  | .027       | 1.000             | -9.104E-02                                             | 6.812E-02      |
|                       | 23 lingual-low        | -4.238E-02                  | .027       | 1.000             | -.122                                                  | 3.720E-02      |
| 22 lingual-mid        | 11 buccal-top         | 2.263E-02                   | .023       | 1.000             | -4.629E-02                                             | 9.155E-02      |
|                       | 12 buccal-mid         | 1.488E-02                   | .023       | 1.000             | -5.403E-02                                             | 8.380E-02      |
|                       | 13 buccal-low         | 3.969E-02                   | .023       | 1.000             | -2.923E-02                                             | .109           |
|                       | 21 lingual-top        | 1.146E-02                   | .027       | 1.000             | -6.812E-02                                             | 9.104E-02      |
|                       | 23 lingual-low        | -3.093E-02                  | .027       | 1.000             | -.111                                                  | 4.865E-02      |
| 23 lingual-low        | 11 buccal-top         | 5.356E-02                   | .023       | .326              | -1.536E-02                                             | .122           |
|                       | 12 buccal-mid         | 4.581E-02                   | .023       | .736              | -2.311E-02                                             | .115           |
|                       | 13 buccal-low         | 7.061E-02*                  | .023       | .040              | 1.694E-03                                              | .140           |
|                       | 21 lingual-top        | 4.238E-02                   | .027       | 1.000             | -3.720E-02                                             | .122           |
|                       | 22 lingual-mid        | 3.093E-02                   | .027       | 1.000             | -4.865E-02                                             | .111           |

Based on estimated marginal means  
\*. The mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: DHARD Hardness (cont-expt)

|          | Sum of Squares | df  | Mean Square | F     | Sig. |
|----------|----------------|-----|-------------|-------|------|
| Contrast | 6.628E-02      | 5   | 1.326E-02   | 2.075 | .072 |
| Error    | .888           | 139 | 6.389E-03   |       |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

Univariate Analysis of Variance

Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 80 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 17 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 17 |



Tests of Between-Subjects Effects

Dependent Variable: DELAST Elasticity (cont-expt)

| Source          | Type III<br>Sum of<br>Squares | df  | Mean<br>Square | F     | Sig. |
|-----------------|-------------------------------|-----|----------------|-------|------|
| Corrected Model | 197.443 <sup>a</sup>          | 22  | 8.975          | 1.857 | .017 |
| Intercept       | .594                          | 1   | .594           | .123  | .727 |
| STR             | 3.410                         | 1   | 3.410          | .706  | .402 |
| SUBJ(STR)       | 188.082                       | 16  | 11.755         | 2.432 | .003 |
| POS             | 6.323                         | 5   | 1.265          | .262  | .933 |
| Error           | 666.983                       | 138 | 4.833          |       |      |
| Total           | 864.532                       | 161 |                |       |      |
| Corrected Total | 864.427                       | 160 |                |       |      |

a. R Squared = .228 (Adjusted R Squared = .105)

Estimated Marginal Means

1. Strength of Force

Estimates

Dependent Variable: DELAST Elasticity (cont-expt)

| Strength of Force | Mean      | Std. Error | 95% Confidence Interval |                |
|-------------------|-----------|------------|-------------------------|----------------|
|                   |           |            | Lower<br>Bound          | Upper<br>Bound |
| 1 light           | -8.09E-02 | .252       | -.579                   | .417           |
| 2 heavy           | .210      | .254       | -.293                   | .714           |

Pairwise Comparisons

Dependent Variable: DELAST Elasticity (cont-expt)

| (I) Strength of Force (J) Strength of Force |         | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|---------------------------------------------|---------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
|                                             |         |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 1 light                                     | 2 heavy | -.291                       | .347       | .402              | -.977                                                  | .394           |
| 2 heavy                                     | 1 light | .291                        | .347       | .402              | -.394                                                  | .977           |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: DELAST Elasticity (cont-expt)

|          | Sum of<br>Squares | df  | Mean<br>Square | F    | Sig. |
|----------|-------------------|-----|----------------|------|------|
| Contrast | 3.410             | 1   | 3.410          | .706 | .402 |
| Error    | 666.983           | 138 | 4.833          |      |      |

The F tests the effect of Strength of Force. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.

2. Position on tooth

6.5.2 PART II

Univariate Analysis of Variance



Between-Subjects Factors

|                          |   | Value<br>Label | N  |
|--------------------------|---|----------------|----|
| LOC Location<br>on Tooth | 1 |                | 18 |
|                          | 2 |                | 18 |
|                          | 3 |                | 18 |
|                          | 4 |                | 18 |
|                          | 5 |                | 18 |
|                          | 6 |                | 18 |
|                          | 7 |                | 18 |
|                          | 8 |                | 18 |
|                          | 9 |                | 18 |
| STR Strength<br>of Force | 1 | light          | 81 |
|                          | 2 | heavy          | 81 |
| SUBJ Subject             | 1 |                | 18 |
|                          | 2 |                | 18 |
|                          | 3 |                | 18 |
|                          | 4 |                | 18 |
|                          | 5 |                | 18 |
|                          | 6 |                | 18 |
|                          | 7 |                | 18 |
|                          | 8 |                | 18 |
|                          | 9 |                | 18 |



Tests of Between-Subjects Effects

Dependent Variable: DHARD Hardness (cont-expt)

| Source    |            | Type III<br>Sum of<br>Squares | df  | Mean<br>Square         | F     | Sig. |
|-----------|------------|-------------------------------|-----|------------------------|-------|------|
| Intercept | Hypothesis | 2.125E-03                     | 1   | 2.125E-03              | .321  | .587 |
|           | Error      | 5.294E-02                     | 8   | 6.618E-03 <sup>a</sup> |       |      |
| LOC       | Hypothesis | 8.782E-02                     | 8   | 1.098E-02              | 1.651 | .115 |
|           | Error      | .957                          | 144 | 6.647E-03 <sup>b</sup> |       |      |
| STR       | Hypothesis | 9.953E-03                     | 1   | 9.953E-03              | 1.497 | .223 |
|           | Error      | .957                          | 144 | 6.647E-03 <sup>b</sup> |       |      |
| SUBJ      | Hypothesis | 5.294E-02                     | 8   | 6.618E-03              | .996  | .442 |
|           | Error      | .957                          | 144 | 6.647E-03 <sup>b</sup> |       |      |

a. MS(SUBJ)

b. MS(Error)

Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |            |                        |
|-----------|--------------------|------------|------------------------|
|           | Var(SUBJ)          | Var(Error) | Quadratic<br>Term      |
| Intercept | 18.000             | 1.000      | Intercept,<br>LOC, STR |
| LOC       | .000               | 1.000      | LOC                    |
| STR       | .000               | 1.000      | STR                    |
| SUBJ      | 18.000             | 1.000      |                        |
| Error     | .000               | 1.000      |                        |

- a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.
- b. Expected Mean Squares are based on the Type III Sums of Squares.

Univariate Analysis of Variance



Between-Subjects Factors

|                          |   |       | Value<br>Label | N  |
|--------------------------|---|-------|----------------|----|
| LOC Location<br>on Tooth | 1 |       |                | 18 |
|                          | 2 |       |                | 18 |
|                          | 3 |       |                | 18 |
|                          | 4 |       |                | 18 |
|                          | 5 |       |                | 18 |
|                          | 6 |       |                | 18 |
|                          | 7 |       |                | 18 |
|                          | 8 |       |                | 18 |
|                          | 9 |       |                | 17 |
| STR Strength<br>of Force | 1 | light |                | 81 |
|                          | 2 | heavy |                | 80 |
| SUBJ Subject             | 1 |       |                | 18 |
|                          | 2 |       |                | 18 |
|                          | 3 |       |                | 18 |
|                          | 4 |       |                | 18 |
|                          | 5 |       |                | 18 |
|                          | 6 |       |                | 18 |
|                          | 7 |       |                | 18 |
|                          | 8 |       |                | 18 |
|                          | 9 |       |                | 17 |

Tests of Between-Subjects Effects

Dependent Variable: DELAST Elasticity (cont-expt)

| Source    |            | Type III<br>Sum of<br>Squares | df    | Mean<br>Square      | F     | Sig. |
|-----------|------------|-------------------------------|-------|---------------------|-------|------|
| Intercept | Hypothesis | .253                          | 1     | .253                | .022  | .885 |
|           | Error      | 90.864                        | 8.002 | 11.355 <sup>a</sup> |       |      |
| LOC       | Hypothesis | 10.285                        | 8     | 1.286               | .242  | .982 |
|           | Error      | 761.017                       | 143   | 5.322 <sup>b</sup>  |       |      |
| STR       | Hypothesis | 3.854                         | 1     | 3.854               | .724  | .396 |
|           | Error      | 761.017                       | 143   | 5.322 <sup>b</sup>  |       |      |
| SUBJ      | Hypothesis | 90.852                        | 8     | 11.356              | 2.134 | .036 |
|           | Error      | 761.017                       | 143   | 5.322 <sup>b</sup>  |       |      |

a. 1.000 MS(SUBJ) + 3.197E-04 MS(Error)

b. MS(Error)



Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |            |                     |
|-----------|--------------------|------------|---------------------|
|           | Var(SUBJ)          | Var(Error) | Quadratic Term      |
| Intercept | 17.876             | 1.000      | Intercept, LOC, STR |
| LOC       | .000               | 1.000      | LOC                 |
| STR       | .000               | 1.000      | STR                 |
| SUBJ      | 17.882             | 1.000      |                     |
| Error     | .000               | 1.000      |                     |

- a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.
- b. Expected Mean Squares are based on the Type III Sums of Squares.

General Linear Model



Between-Subjects Factors

|                          |   | Value<br>Label | N  |
|--------------------------|---|----------------|----|
| LOC Location<br>on Tooth | 1 |                | 18 |
|                          | 2 |                | 18 |
|                          | 3 |                | 18 |
|                          | 4 |                | 18 |
|                          | 5 |                | 18 |
|                          | 6 |                | 18 |
|                          | 7 |                | 18 |
|                          | 8 |                | 18 |
|                          | 9 |                | 17 |
| STR Strength<br>of Force | 1 | light          | 81 |
|                          | 2 | heavy          | 80 |
| SUBJ Subject             | 1 |                | 18 |
|                          | 2 |                | 18 |
|                          | 3 |                | 18 |
|                          | 4 |                | 18 |
|                          | 5 |                | 18 |
|                          | 6 |                | 18 |
|                          | 7 |                | 18 |
|                          | 8 |                | 18 |
|                          | 9 |                | 17 |



Multivariate Tests<sup>c</sup>

| Effect    |                    | Value | F                  | Hypothesis<br>df | Error df | Sig. |
|-----------|--------------------|-------|--------------------|------------------|----------|------|
| Intercept | Pillai's Trace     | .007  | .497 <sup>a</sup>  | 2.000            | 142.000  | .609 |
|           | Wilks' Lambda      | .993  | .497 <sup>a</sup>  | 2.000            | 142.000  | .609 |
|           | Hotelling's Trace  | .007  | .497 <sup>a</sup>  | 2.000            | 142.000  | .609 |
|           | Roy's Largest Root | .007  | .497 <sup>a</sup>  | 2.000            | 142.000  | .609 |
| LOC       | Pillai's Trace     | .095  | .894               | 16.000           | 286.000  | .576 |
|           | Wilks' Lambda      | .905  | .905 <sup>a</sup>  | 16.000           | 284.000  | .564 |
|           | Hotelling's Trace  | .104  | .915               | 16.000           | 282.000  | .552 |
|           | Roy's Largest Root | .096  | 1.723 <sup>b</sup> | 8.000            | 143.000  | .098 |
| STR       | Pillai's Trace     | .009  | .668 <sup>a</sup>  | 2.000            | 142.000  | .514 |
|           | Wilks' Lambda      | .991  | .668 <sup>a</sup>  | 2.000            | 142.000  | .514 |
|           | Hotelling's Trace  | .009  | .668 <sup>a</sup>  | 2.000            | 142.000  | .514 |
|           | Roy's Largest Root | .009  | .668 <sup>a</sup>  | 2.000            | 142.000  | .514 |
| SUBJ      | Pillai's Trace     | .183  | 1.799              | 16.000           | 286.000  | .031 |
|           | Wilks' Lambda      | .824  | 1.809 <sup>a</sup> | 16.000           | 284.000  | .030 |
|           | Hotelling's Trace  | .206  | 1.819              | 16.000           | 282.000  | .028 |
|           | Roy's Largest Root | .157  | 2.804 <sup>b</sup> | 8.000            | 143.000  | .006 |

- a. Exact statistic
- b. The statistic is an upper bound on F that yields a lower bound on the significance level.
- c. Design: Intercept+LOC+STR+SUBJ



Tests of Between-Subjects Effects

| Source          | Dependent Variable               | Type III<br>Sum of<br>Squares | df  | Mean<br>Square | F     | Sig. |
|-----------------|----------------------------------|-------------------------------|-----|----------------|-------|------|
| Corrected Model | DHARD Hardness<br>(cont-expt)    | .132 <sup>a</sup>             | 17  | 7.753E-03      | 1.165 | .301 |
|                 | DELAST Elasticity<br>(cont-expt) | 103.410 <sup>b</sup>          | 17  | 6.083          | 1.143 | .320 |
| Intercept       | DHARD Hardness<br>(cont-expt)    | 2.701E-03                     | 1   | 2.701E-03      | .406  | .525 |
|                 | DELAST Elasticity<br>(cont-expt) | .253                          | 1   | .253           | .048  | .828 |
| LOC             | DHARD Hardness<br>(cont-expt)    | 7.914E-02                     | 8   | 9.893E-03      | 1.486 | .167 |
|                 | DELAST Elasticity<br>(cont-expt) | 10.285                        | 8   | 1.286          | .242  | .982 |
| STR             | DHARD Hardness<br>(cont-expt)    | 8.721E-03                     | 1   | 8.721E-03      | 1.310 | .254 |
|                 | DELAST Elasticity<br>(cont-expt) | 3.854                         | 1   | 3.854          | .724  | .396 |
| SUBJ            | DHARD Hardness<br>(cont-expt)    | 4.729E-02                     | 8   | 5.911E-03      | .888  | .528 |
|                 | DELAST Elasticity<br>(cont-expt) | 90.852                        | 8   | 11.356         | 2.134 | .036 |
| Error           | DHARD Hardness<br>(cont-expt)    | .952                          | 143 | 6.657E-03      |       |      |
|                 | DELAST Elasticity<br>(cont-expt) | 761.017                       | 143 | 5.322          |       |      |
| Total           | DHARD Hardness<br>(cont-expt)    | 1.087                         | 161 |                |       |      |
|                 | DELAST Elasticity<br>(cont-expt) | 864.532                       | 161 |                |       |      |
| Corrected Total | DHARD Hardness<br>(cont-expt)    | 1.084                         | 160 |                |       |      |
|                 | DELAST Elasticity<br>(cont-expt) | 864.427                       | 160 |                |       |      |

a. R Squared = .122 (Adjusted R Squared = .017)

b. R Squared = .120 (Adjusted R Squared = .015)



Univariate Analysis of Variance

Between-Subjects Factors

|                          |    | Value<br>Label | N  |
|--------------------------|----|----------------|----|
| STR Strength<br>of Force | 1  | light          | 99 |
|                          | 2  | heavy          | 99 |
| SUBJ Subject             | 1  |                | 22 |
|                          | 2  |                | 22 |
|                          | 3  |                | 22 |
|                          | 4  |                | 22 |
|                          | 5  |                | 22 |
|                          | 6  |                | 22 |
|                          | 7  |                | 22 |
|                          | 8  |                | 22 |
|                          | 9  |                | 22 |
| LOC Location<br>on Tooth | 1  |                | 18 |
|                          | 2  |                | 18 |
|                          | 3  |                | 18 |
|                          | 4  |                | 18 |
|                          | 5  |                | 18 |
|                          | 6  |                | 18 |
|                          | 7  |                | 18 |
|                          | 8  |                | 18 |
|                          | 9  |                | 18 |
|                          | 10 |                | 18 |
|                          | 11 |                | 18 |



Tests of Between-Subjects Effects

Dependent Variable: DHARD Hardness (cont-expt)

| Source    |            | Type III<br>Sum of<br>Squares | df    | Mean<br>Square     | F     | Sig. |
|-----------|------------|-------------------------------|-------|--------------------|-------|------|
| Intercept | Hypothesis | 5.159                         | 1     | 5.159              | 1.598 | .239 |
|           | Error      | 28.465                        | 8.816 | 3.229 <sup>a</sup> |       |      |
| STR       | Hypothesis | 2.731                         | 1     | 2.731              | 2.639 | .106 |
|           | Error      | 184.194                       | 178   | 1.035 <sup>b</sup> |       |      |
| SUBJ      | Hypothesis | 8.275                         | 8     | 1.034              | 1.000 | .438 |
|           | Error      | 184.194                       | 178   | 1.035 <sup>b</sup> |       |      |
| LOC       | Hypothesis | 32.292                        | 10    | 3.229              | 3.121 | .001 |
|           | Error      | 184.194                       | 178   | 1.035 <sup>b</sup> |       |      |

a. 1.000 MS(SUBJ) + MS(LOC) - 1.000 MS(Error)

b. MS(Error)

Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |          |            |                   |
|-----------|--------------------|----------|------------|-------------------|
|           | Var(SUBJ)          | Var(LOC) | Var(Error) | Quadratic<br>Term |
| Intercept | 22.000             | 18.000   | 1.000      | Intercept,<br>STR |
| STR       | .000               | .000     | 1.000      | STR               |
| SUBJ      | 22.000             | .000     | 1.000      |                   |
| LOC       | .000               | 18.000   | 1.000      |                   |
| Error     | .000               | .000     | 1.000      |                   |

a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.

b. Expected Mean Squares are based on the Type III Sums of Squares.

Univariate Analysis of Variance



Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 18 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |

Tests of Between-Subjects Effects

Dependent Variable: DHARD Hardness (cont-expt)

| Source    |            | Type III Sum of Squares | df    | Mean Square       | F     | Sig. |
|-----------|------------|-------------------------|-------|-------------------|-------|------|
| Intercept | Hypothesis | .000                    | 1     | .000              | .035  | .860 |
|           | Error      | .060                    | 4.745 | .013 <sup>a</sup> |       |      |
| STR       | Hypothesis | .010                    | 1     | .010              | 1.495 | .223 |
|           | Error      | .979                    | 147   | .007 <sup>b</sup> |       |      |
| SUBJ      | Hypothesis | .053                    | 8     | .007              | .994  | .443 |
|           | Error      | .979                    | 147   | .007 <sup>b</sup> |       |      |
| POS       | Hypothesis | .066                    | 5     | .013              | 1.991 | .083 |
|           | Error      | .979                    | 147   | .007 <sup>b</sup> |       |      |

a. .889 MS(SUBJ) + .909 MS(POS) - .798 MS(Error)

b. MS(Error)



Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |          |            |                       |
|-----------|--------------------|----------|------------|-----------------------|
|           | Var(SUBJ)          | Var(POS) | Var(Error) | Quadratic Term        |
| Intercept | 16.000             | 24.000   | 1.000      | Intercept, STR<br>STR |
| STR       | .000               | .000     | 1.000      |                       |
| SUBJ      | 18.000             | .000     | 1.000      |                       |
| POS       | .000               | 26.400   | 1.000      |                       |
| Error     | .000               | .000     | 1.000      |                       |

- a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.
- b. Expected Mean Squares are based on the Type III Sums of Squares.

Univariate Analysis of Variance

Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 81 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 18 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 18 |



Tests of Between-Subjects Effects

Dependent Variable: DHARD Hardness (cont-expt)

| Source    |            | Type III<br>Sum of<br>Squares | df    | Mean<br>Square         | F     | Sig. |
|-----------|------------|-------------------------------|-------|------------------------|-------|------|
| Intercept | Hypothesis | 4.405E-04                     | 1     | 4.405E-04              | .035  | .860 |
|           | Error      | 5.988E-02                     | 4.745 | 1.262E-02 <sup>a</sup> |       |      |
| STR       | Hypothesis | 9.953E-03                     | 1     | 9.953E-03              | 1.495 | .223 |
|           | Error      | .979                          | 147   | 6.658E-03 <sup>b</sup> |       |      |
| SUBJ      | Hypothesis | 5.294E-02                     | 8     | 6.618E-03              | .994  | .443 |
|           | Error      | .979                          | 147   | 6.658E-03 <sup>b</sup> |       |      |
| POS       | Hypothesis | 6.628E-02                     | 5     | 1.326E-02              | 1.991 | .083 |
|           | Error      | .979                          | 147   | 6.658E-03 <sup>b</sup> |       |      |

- a. .889 MS(SUBJ) + .909 MS(POS) - .798 MS(Error)
- b. MS(Error)

Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |          |            |                   |
|-----------|--------------------|----------|------------|-------------------|
|           | Var(SUBJ)          | Var(POS) | Var(Error) | Quadratic<br>Term |
| Intercept | 16.000             | 24.000   | 1.000      | Intercept,<br>STR |
| STR       | .000               | .000     | 1.000      | STR               |
| SUBJ      | 18.000             | .000     | 1.000      |                   |
| POS       | .000               | 26.400   | 1.000      |                   |
| Error     | .000               | .000     | 1.000      |                   |

- a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.
- b. Expected Mean Squares are based on the Type III Sums of Squares.

Estimated Marginal Means



1. Strength of Force

Dependent Variable: DHARD Hardness (cont-expt)

| Strength of Force | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 1 light           | -6.09E-03 | .009       | -2.456E-02              | 1.238E-02   |
| 2 heavy           | 9.587E-03 | .009       | -8.881E-03              | 2.806E-02   |

2. Subject

Dependent Variable: DHARD Hardness (cont-expt)

| Subject | Mean      | Std. Error | 95% Confidence Interval |             |
|---------|-----------|------------|-------------------------|-------------|
|         |           |            | Lower Bound             | Upper Bound |
| 1       | 1.308E-02 | .019       | -2.519E-02              | 5.135E-02   |
| 2       | -1.54E-02 | .019       | -5.366E-02              | 2.288E-02   |
| 3       | 1.141E-02 | .019       | -2.686E-02              | 4.968E-02   |
| 4       | -1.86E-02 | .019       | -5.687E-02              | 1.968E-02   |
| 5       | -1.03E-02 | .019       | -4.860E-02              | 2.795E-02   |
| 6       | -1.61E-02 | .019       | -5.440E-02              | 2.215E-02   |
| 7       | 2.235E-02 | .019       | -1.592E-02              | 6.062E-02   |
| 8       | -5.19E-03 | .019       | -4.346E-02              | 3.309E-02   |
| 9       | 3.452E-02 | .019       | -3.751E-03              | 7.279E-02   |

3. Position on tooth

Dependent Variable: DHARD Hardness (cont-expt)

| Position on tooth | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | -1.13E-02 | .014       | -3.813E-02              | 1.562E-02   |
| 12 buccal-mid     | -3.51E-03 | .014       | -3.039E-02              | 2.336E-02   |
| 13 buccal-low     | -2.83E-02 | .014       | -5.519E-02              | -1.439E-03  |
| 21 lingual-top    | -8.62E-05 | .019       | -3.809E-02              | 3.792E-02   |
| 22 lingual-mid    | 1.137E-02 | .019       | -2.664E-02              | 4.938E-02   |
| 23 lingual-low    | 4.230E-02 | .019       | 4.288E-03               | 8.031E-02   |

Univariate Analysis of Variance



Between-Subjects Factors

|                       |    | Value Label | N  |
|-----------------------|----|-------------|----|
| STR Strength of Force | 1  | light       | 81 |
|                       | 2  | heavy       | 80 |
| SUBJ Subject          | 1  |             | 18 |
|                       | 2  |             | 18 |
|                       | 3  |             | 18 |
|                       | 4  |             | 18 |
|                       | 5  |             | 18 |
|                       | 6  |             | 18 |
|                       | 7  |             | 18 |
|                       | 8  |             | 18 |
|                       | 9  |             | 17 |
| POS Position on tooth | 11 | buccal-top  | 36 |
|                       | 12 | buccal-mid  | 36 |
|                       | 13 | buccal-low  | 36 |
|                       | 21 | lingual-top | 18 |
|                       | 22 | lingual-mid | 18 |
|                       | 23 | lingual-low | 17 |

Tests of Between-Subjects Effects

Dependent Variable: DELAST Elasticity (cont-expt)

| Source    |            | Type III Sum of Squares | df    | Mean Square        | F     | Sig. |
|-----------|------------|-------------------------|-------|--------------------|-------|------|
| Intercept | Hypothesis | .873                    | 1     | .873               | .121  | .745 |
|           | Error      | 28.570                  | 3.975 | 7.188 <sup>a</sup> |       |      |
| STR       | Hypothesis | 3.854                   | 1     | 3.854              | .736  | .392 |
|           | Error      | 764.213                 | 146   | 5.234 <sup>b</sup> |       |      |
| SUBJ      | Hypothesis | 90.852                  | 8     | 11.356             | 2.170 | .033 |
|           | Error      | 764.213                 | 146   | 5.234 <sup>b</sup> |       |      |
| POS       | Hypothesis | 7.088                   | 5     | 1.418              | .271  | .928 |
|           | Error      | 764.213                 | 146   | 5.234 <sup>b</sup> |       |      |

a. .883 MS(SUBJ) + .904 MS(POS) - .786 MS(Error)

b. MS(Error)



Expected Mean Squares<sup>a,b</sup>

| Source    | Variance Component |          |            |  | Quadratic Term |
|-----------|--------------------|----------|------------|--|----------------|
|           | Var(SUBJ)          | Var(POS) | Var(Error) |  |                |
| Intercept | 15.781             | 23.671   | 1.000      |  | Intercept, STR |
| STR       | .000               | .000     | 1.000      |  | STR            |
| SUBJ      | 17.882             | .000     | 1.000      |  |                |
| POS       | .000               | 26.195   | 1.000      |  |                |
| Error     | .000               | .000     | 1.000      |  |                |

- a. For each source, the expected mean square equals the sum of the coefficients in the cells times the variance components, plus a quadratic term involving effects in the Quadratic Term cell.
- b. Expected Mean Squares are based on the Type III Sums of Squares.

Estimated Marginal Means

1. Strength of Force

Dependent Variable: DELAST Elasticity (cont-expt)

| Strength of Force | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 1 light           | -7.64E-02 | .262       | -.594                   | .442        |
| 2 heavy           | .233      | .265       | -.290                   | .756        |



2. Subject

Dependent Variable: DELAST Elasticity (cont-expt)

| Subject | Mean      | Std. Error | 95% Confidence Interval |             |
|---------|-----------|------------|-------------------------|-------------|
|         |           |            | Lower Bound             | Upper Bound |
| 1       | .624      | .543       | -.449                   | 1.697       |
| 2       | -.165     | .543       | -1.239                  | .908        |
| 3       | -1.030    | .543       | -2.103                  | 4.370E-02   |
| 4       | -.289     | .543       | -1.362                  | .784        |
| 5       | 1.069E-03 | .543       | -1.072                  | 1.074       |
| 6       | .160      | .543       | -.913                   | 1.233       |
| 7       | -.301     | .543       | -1.374                  | .773        |
| 8       | -.189     | .543       | -1.262                  | .885        |
| 9       | 1.894     | .561       | .784                    | 3.003       |

3. Position on tooth

Dependent Variable: DELAST Elasticity (cont-expt)

| Position on tooth | Mean      | Std. Error | 95% Confidence Interval |             |
|-------------------|-----------|------------|-------------------------|-------------|
|                   |           |            | Lower Bound             | Upper Bound |
| 11 buccal-top     | .191      | .381       | -.563                   | .944        |
| 12 buccal-mid     | -2.92E-02 | .381       | -.783                   | .724        |
| 13 buccal-low     | -.275     | .381       | -1.029                  | .479        |
| 21 lingual-top    | -2.20E-02 | .539       | -1.088                  | 1.044       |
| 22 lingual-mid    | .259      | .539       | -.807                   | 1.324       |
| 23 lingual-low    | .347      | .556       | -.751                   | 1.446       |

Descriptives

Descriptive Statistics

|                               | N         | Minimum   | Maximum   | Mean      |            | Std.      |
|-------------------------------|-----------|-----------|-----------|-----------|------------|-----------|
|                               | Statistic | Statistic | Statistic | Statistic | Std. Error | Statistic |
| DHARD Hardness (cont-expt)    | 162       | -.300     | .265      | -3.6E-03  | 6.52E-03   | 8.30E-02  |
| DELAST Elasticity (cont-expt) | 161       | -6.116    | 5.973     | 2.55E-02  | .18319     | 2.32436   |
| Valid N (listwise)            | 161       |           |           |           |            |           |

Descriptives



Descriptive Statistics

|                                  | N         | Mean      |            | Std.      |
|----------------------------------|-----------|-----------|------------|-----------|
|                                  | Statistic | Statistic | Std. Error | Statistic |
| DHARD Hardness<br>(cont-expt)    | 162       | -3.6E-03  | 6.52E-03   | 8.30E-02  |
| DELAST Elasticity<br>(cont-expt) | 161       | 2.55E-02  | .18319     | 2.32436   |
| Valid N (listwise)               | 161       |           |            |           |



Pairwise Comparisons

Dependent Variable: DELAST Elasticity (cont-expt)

|                       |                       | Mean<br>Difference<br>(I-J) | Std. Error | Sig. <sup>a</sup> | 95% Confidence Interval<br>for Difference <sup>a</sup> |                |
|-----------------------|-----------------------|-----------------------------|------------|-------------------|--------------------------------------------------------|----------------|
| (I) Position on tooth | (J) Position on tooth |                             |            |                   | Lower<br>Bound                                         | Upper<br>Bound |
| 11 buccal-top         | 12 buccal-mid         | .220                        | .518       | 1.000             | -1.328                                                 | 1.768          |
|                       | 13 buccal-low         | .466                        | .518       | 1.000             | -1.082                                                 | 2.013          |
|                       | 21 lingual-top        | .213                        | .635       | 1.000             | -1.683                                                 | 2.108          |
|                       | 22 lingual-mid        | -6.800E-02                  | .635       | 1.000             | -1.964                                                 | 1.828          |
|                       | 23 lingual-low        | -7.437E-02                  | .648       | 1.000             | -2.012                                                 | 1.863          |
| 12 buccal-mid         | 11 buccal-top         | -.220                       | .518       | 1.000             | -1.768                                                 | 1.328          |
|                       | 13 buccal-low         | .246                        | .518       | 1.000             | -1.302                                                 | 1.794          |
|                       | 21 lingual-top        | -7.131E-03                  | .635       | 1.000             | -1.903                                                 | 1.889          |
|                       | 22 lingual-mid        | -.288                       | .635       | 1.000             | -2.184                                                 | 1.608          |
|                       | 23 lingual-low        | -.294                       | .648       | 1.000             | -2.231                                                 | 1.643          |
| 13 buccal-low         | 11 buccal-top         | -.466                       | .518       | 1.000             | -2.013                                                 | 1.082          |
|                       | 12 buccal-mid         | -.246                       | .518       | 1.000             | -1.794                                                 | 1.302          |
|                       | 21 lingual-top        | -.253                       | .635       | 1.000             | -2.149                                                 | 1.643          |
|                       | 22 lingual-mid        | -.534                       | .635       | 1.000             | -2.429                                                 | 1.362          |
|                       | 23 lingual-low        | -.540                       | .648       | 1.000             | -2.477                                                 | 1.397          |
| 21 lingual-top        | 11 buccal-top         | -.213                       | .635       | 1.000             | -2.108                                                 | 1.683          |
|                       | 12 buccal-mid         | 7.131E-03                   | .635       | 1.000             | -1.889                                                 | 1.903          |
|                       | 13 buccal-low         | .253                        | .635       | 1.000             | -1.643                                                 | 2.149          |
|                       | 22 lingual-mid        | -.281                       | .733       | 1.000             | -2.470                                                 | 1.908          |
|                       | 23 lingual-low        | -.287                       | .745       | 1.000             | -2.512                                                 | 1.938          |
| 22 lingual-mid        | 11 buccal-top         | 6.800E-02                   | .635       | 1.000             | -1.828                                                 | 1.964          |
|                       | 12 buccal-mid         | .288                        | .635       | 1.000             | -1.608                                                 | 2.184          |
|                       | 13 buccal-low         | .534                        | .635       | 1.000             | -1.362                                                 | 2.429          |
|                       | 21 lingual-top        | .281                        | .733       | 1.000             | -1.908                                                 | 2.470          |
|                       | 23 lingual-low        | -6.366E-03                  | .745       | 1.000             | -2.231                                                 | 2.219          |
| 23 lingual-low        | 11 buccal-top         | 7.437E-02                   | .648       | 1.000             | -1.863                                                 | 2.012          |
|                       | 12 buccal-mid         | .294                        | .648       | 1.000             | -1.643                                                 | 2.231          |
|                       | 13 buccal-low         | .540                        | .648       | 1.000             | -1.397                                                 | 2.477          |
|                       | 21 lingual-top        | .287                        | .745       | 1.000             | -1.938                                                 | 2.512          |
|                       | 22 lingual-mid        | 6.366E-03                   | .745       | 1.000             | -2.219                                                 | 2.231          |

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.



Univariate Tests

Dependent Variable: DELAST Elasticity (cont-expt)

|          | Sum of<br>Squares | df  | Mean<br>Square | F    | Sig. |
|----------|-------------------|-----|----------------|------|------|
| Contrast | 6.323             | 5   | 1.265          | .262 | .933 |
| Error    | 666.983           | 138 | 4.833          |      |      |

The F tests the effect of Position on tooth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.