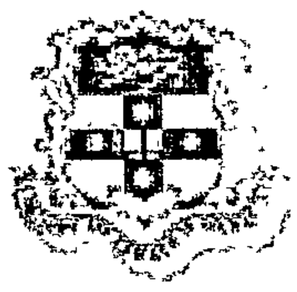

The University of Sydney

AUSTRALIA

"Physical Properties of Human Premolar Cementum - A Structural Correlation"

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B.D.S. (Hons.) F.R.A.C.D.S

A Thesis submitted in partial fulfillment

Of the requirements for the degree of

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Dedication

In memory of my late father who taught me the value of hard work and endurance, and who had allowed me every opportunity in life. Your memory is never too far from my thoughts.

To Mary, my beautiful wife, I can't begin to thank you enough for your endless encouragement, support, prayers and love. This work is truly equally shared by you.

To my three gorgeous children, Rebecca (8 years), Timothy (5 years) and Joshua (3 years) whose patience and love truly showed no limits. Their prayers and encouragement were the motivation of my every accomplishment. They have always been the focus of our joy and will continue to be forever.

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Declaration

CANDIDATE CERTIFICATE

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

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ABBREVIATIONS

µm	Micrometre (micron)
AAC	Acellular Afibrillar Cementum
AEFC	Acellular Extrinsic Fibrillar Cementum
ARE	Advancing Root Edge
BSEM	Backscattered scanning electron microscopy
cAMP	Cyclic adenomonophosphate
CEJ	Cemento-Enamel Junction
CIFC	Cellular Intrinsic Fibrillar Cementum
CMSC	Cellular Mixed Stratified Cementum
DCJ	Dento-Cemental Junction
DEJ	Dento-Enamel Junction
E	Enamel
E*	Modulus of Elasticity
EARR	External apical root resorption
EDAX	Energy dispersive analysis
ERM	Epithelial cell rest of Malassez
FF	Fibre fringe
GPa	Giga Pascal
HERS	Hertwigs Epithelial Root Sheath
KeV	Kiloelectron volts
MCA	Multichannel analyzer
MD	Mineralized Dentine
mm	Millimetre
mN	Milli-Newton
MPa	Mega Pascal
MR	X-ray micro-radiography
N	Newtons
nm	Nanometre

OM	Optical microscopy
PD	Predentine Layer
PDL	Periodontal Ligament
PPM	Parts per million
SEM	Scanning electron microscope
UMIS	Ultra Micro-Indentation Systems

ABSTRACT

Orthodontic treatment aims to move teeth as efficiently as possible with least damage to teeth and their supporting tissues. Root resorption is a pathological process initiated by specific clastic cells, which remove the organic and mineral components of dental hard tissue. Apical root resorption is a common idiopathic problem associated with orthodontic treatment and brings with it medicolegal implications. It is unpredictable, and when extending into dentine it is irreversible (Brezniak and Wasserstein 1993). The only requirement for root resorption is that the clastic cells gain access to the mineralized tissue by a breach in the naturally protective formative cell layer covering cementum (Tronstad, 1988). This unwanted side effect of orthodontic treatment can leave the affected dentition debilitated.

With the application of orthodontic force, cementum is seen to be more resistant to resorption compared with the more vulnerable bone. Our hypothesis is that the intrinsic nature of cementum renders it more resistant to resorption. The degree of cementum loss may vary from site to site and from tooth to tooth. Root resorption and its extent might be related to the physical properties of the cementum such as hardness and elasticity.

Our knowledge of the mechanisms underlying the pathological process of root resorption relies on understanding of the cells producing dental tissues. The mechanism behind root resorption is not yet fully understood. Several investigations on root resorption have been undertaken during the last century, yet physical properties of cementum were not included in these studies. The definition of these properties may help to better understand root resorption.

A new method to determine the hardness and elasticity (inverse elastic modulus) of human premolar cementum was developed. Human premolar teeth were harvested from orthodontic patients requiring extractions and mounted on a specially designed and constructed surveyor.

The objectives of this study were to develop a method for 3-dimensional analysis of hardness and elasticity on an unprocessed tooth. This enabled the formulation of 3-dimensional maps of hardness and elastic modulus of cementum using Ultra Micro-indentation Systems (UMIS), establishing baseline values. The storage conditions on samples of human premolar teeth were assessed. Accumulation of such data would enable correlation of the physical properties of the different areas of cementum to the structural composition at these sites.

UMIS was used to quantitatively evaluate hardness and elastic modulus around the root surface. Nine human premolar teeth were tested at 62 sites (60 on the root surface and 2 on enamel).

The results show that there is a significant variation in the physical properties from the apex to cervical area of the root surface. The relationship of the variables; sex, patient within sex, side, upper/lower, layer within surface, surface and calcium content are discussed.

Analysis of the effect of storage media showed that teeth stored in Milli Q varied least, with respect to their physical properties, compared to the teeth stored in alcohol, a desiccator or Miltons.

Analysis of teeth along the root surface showed that hardness was found to be significantly different between males and females ($p< 0.01$). Different individuals show significantly different hardness ($p< 0.01$). There was a significant difference between the hardness of the apex and the CEJ ($p<0.01$). There was a significant difference between the hardness of the Buccal, Mesial, Lingual and Distal surfaces ($p<0.01$). There was no difference between left and right premolar cementum hardness ($p= 0.181$). There was no significant difference found between maxillary and mandibular premolar teeth ($p>0.05$) in relation to Hardness. Hardness of cementum significantly correlated to Calcium Content ($p= 0.013$).

Elastic modulus of human premolar cementum was shown to have the following relationships to the variables assessed. Elastic modulus was significantly correlated to Sex ($p< 0.01$). Elasticity was specific to the individual Patient ($p< 0.01$). Side was significantly correlated to elastic modulus ($p= 0.01$). There was no significant difference found between maxillary and mandibular teeth ($p>0.05$) with regards to elasticity. Elastic modulus was significantly correlated to Layer within the Surface ($p<0.01$). Elastic modulus was significantly correlated to Surface ($p<0.01$). Elastic modulus was significantly correlated to Calcium ($p< 0.01$).

In conclusion, the ultra micro-indentation analysis provides an accurate method for analysis of hardness and elasticity with the newly designed 3-D location device on unprocessed teeth. Milli Q was the storage media of choice, which did not influence significantly hardness and elasticity of human teeth.

INTRODUCTION

From week 6 of intrauterine life the ectomesenchyme (of neural crest origin) is invaginated by the dental lamina, from this point the tooth develops in the three classic stages - Bud, Cap and Bell stage. The internal and external enamel epithelium form Hertwigs root sheath. The inner layer of this bi-layered sheath induces the differentiation of odontoblasts. The outer layer together with the subjacent ectomesenchymal cells form cementoblasts and the inner layer of the periodontal fibres (Melcher and Bowen 1969; Ten Cate 1994). Andreason (1988) relates the surface resistance to resorption to this inner most cellular layer of the periodontal ligament.

Root resorption is a pathological process initiated by specific clastic cells, which remove the organic and mineral components of dental hard tissue (Heithersay 1994). Apical root resorption is a common idiopathic problem associated with orthodontic treatment and brings with it medicolegal implications. It is unpredictable, and when extending into dentine it is irreversible (Brezniak and Wasserstein 1993).

The requirement for root resorption of the calcified dental tissue is only, that osteoclasts obtain access to the mineralised tissue by a breach of the naturally protective formative cell layer covering (Tronstad 1988), if the mineral and matrix coincide (Jones & Boyd 1988) or when the precementum is mechanically damaged or scrapped off (Tronstad 1988). Although most authors agree that root resorption stops after cessation of force (Rygh 1977; Reitan and Rygh 1994), the determinants of the resorption/repair sequence are not well understood.

Human and animal research demonstrates that periodontal hyalinization proceeds the root resorption process during orthodontic treatment. Three stages are described in the hyalinized zone:

- degeneration
- elimination of destroyed products and
- re-establishment (Rygh, 1977).

Brudvik and Rygh (1995) concluded that resorption appears to be associated with removal of necrotic tissue from the over compressed zone of the periodontal ligament (PDL). Repair occurs by cementoid filling in the resorbed lacunae seen after 35-70 days (Harry and Sims, 1982). However in larger defects repair cells arrive from the alveolar bone marrow derived cells leading to ankylosis.

Orthodontic tooth movement requires resorption and apposition of bone adjacent to the root structure of teeth. Since Bates in 1856 first discussed the root resorption of teeth, until recent times it was thought that the root structure was not remodeled in the same way as bone. However with the application of orthodontic force, there is seen an attack on the cementum of the root, just as there is an attack on adjacent bone, but cementum repair also occurs (Proffit 1993, Reitan 1985).

Dale (1975) is quoted to have stated that the "occlusal plane is the workbench of orthodontics," and so it is the mechanical workbench of orthodontics. However, the biological workbench occurs at two fronts, the bone/periodontal ligament (PDL) interface and the cementum/PDL interface. The latter plays a role in the undesirable effects on tooth movement, while the former allows a favorable effect.

It has been suggested that the density and hardness of cementum and dentine may retard root resorption (Andreasen 1992). This has been extrapolated from the resorption occurring in deciduous teeth during tooth eruption (Rygh and Reitan 1964), in that the hardness of the deciduous tooth substance may retard resorption process. The mechanical properties of cementum such as hardness and elasticity (inverse elastic modulus) may reveal important characteristics previously unexplored in this regard. The physical properties of cementum as well as tissue type may play an important role in root resorption. Investigation of structure, chemical composition, physical characteristics

specifically hardness and elastic modulus is required to determine whether there exists a correlation to root resorption.

2. Review of Literature

2.1 Definition of Cementum

Cementum, or simply cement from the Latin meaning "quarry stone", has been defined by the International Anatomical Nomenclature Committee (IANC 1983) - Nomina Histologica (NH) - as mineralized connective tissue covering the external surface of the root(s) of the teeth. It may also be found on enamel surface and in the apical foramina of the pulp.

2.2 Classification of Cementum

Cementum has historically been classified into acellular and cellular cementum, with thin acellular cementum covering the cervical region of the root, and thick cellular cementum covering the apical region. Listgarten and Kamin (1969) defined cementum in terms of absence or presence of a fibrillar component.

Jones (1981) suggested a classification based on the presence or absence of two main components of cementum: Cells and Sharpey's fibres, with the fibrillar component as the main functional unit of cementum. She differentiated between the collagen fibres formed outside the cementum - extrinsic fibers (Sharpey's fibers - the embedded ends of the principal periodontal fibers) and those laid down by cementoblasts - intrinsic fibers. The intrinsic fibers are the fibers of cementum proper and are arranged in parallel with the cementum surface. The classification has been summarized by Schroeder and Page (1990) as:

I) Acellular, afibrillar cementum (AAC).

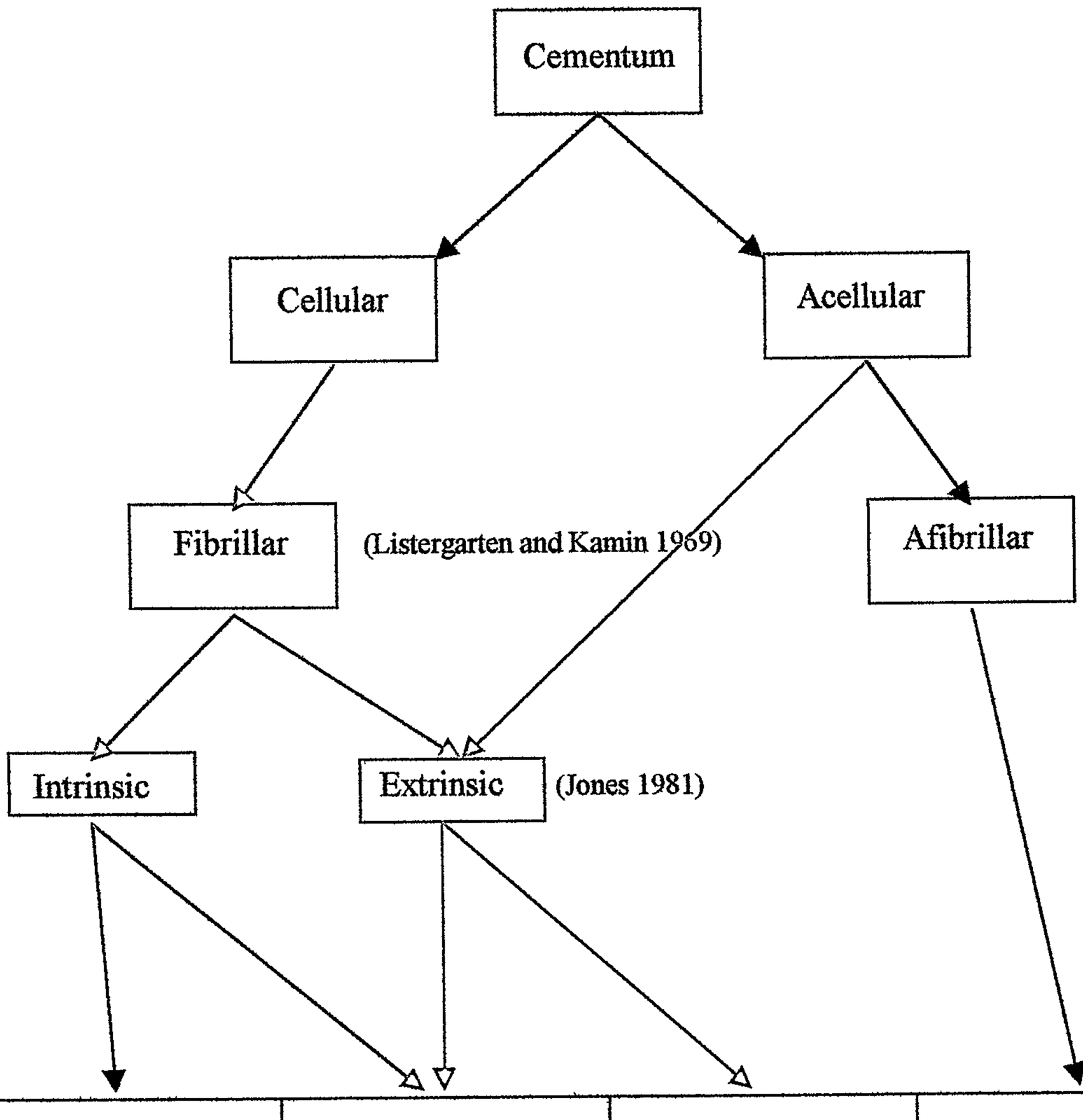
II) Acellular, fibrillar cementum (AEFC).

III) Cellular cementum containing intrinsic fibers (CIFC).

IV) Cellular cementum with intrinsic and extrinsic fibers (CMSC).

According to this classification acellular cementum is termed acellular extrinsic fiber cementum and cellular cementum is termed cellular mixed stratified cementum. The cellular cementum consists of unpredictably alternating layers of acellular intrinsic, acellular extrinsic, and cellular intrinsic fiber cementum (Bosshardt and Schroeder 1991,1992; Schroeder 1993).

Classification of Cementum.



Cellular Intrinsic Fibre Cementum (CIFC)	Cellular Mixed Stratified Cementum (CMSC)	Acellular Extrinsic Fibre Cementum (AEFC)	Acellular Afibrillar Cementum (AAC)

Figure 2. 1. Classification of Cementum (Schroeder and Page 1990, Schroeder 1993)

Schroeder (1986) describes the individual cementum types as follows:

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

Acellular extrinsic fiber cementum (AEFC) is composed almost entirely of densely packed bundles of Sharpey's fibers and lacks cells. It may be a co-product of fibroblasts and of cementoblasts providing the ground substance. It may contain patches or layers of AAC. In the human, it is found primarily on the cervical third of root(s) but it may extend further apically. Its thickness ranges between about 30 and 230 μm (Schroeder 1986) (Fig. 2.2).

Cellular, mixed stratified cementum (CMSC) is composed of extrinsic (Sharpey's) and intrinsic fibers, varying in proportion from one layer to the next, and may contain cells with uneven distribution and density. It is a co-product of cementoblasts and of fibroblasts. Its strata or layers are very irregular and patchy. In the human, it occurs primarily in the apical third of the root and the furcations. It forms the tip of the apex and accumulates in root surface concavities, extending coronally to a variable extent. Its thickness varies between 100 and 1000 μm or more (Schroeder 1993).

Figure 2. 2. Light micrograph depicting the zone of transition from cervically located pure AEFC to the more apically located CMSC. Magn. X90 [Schroeder 1993].

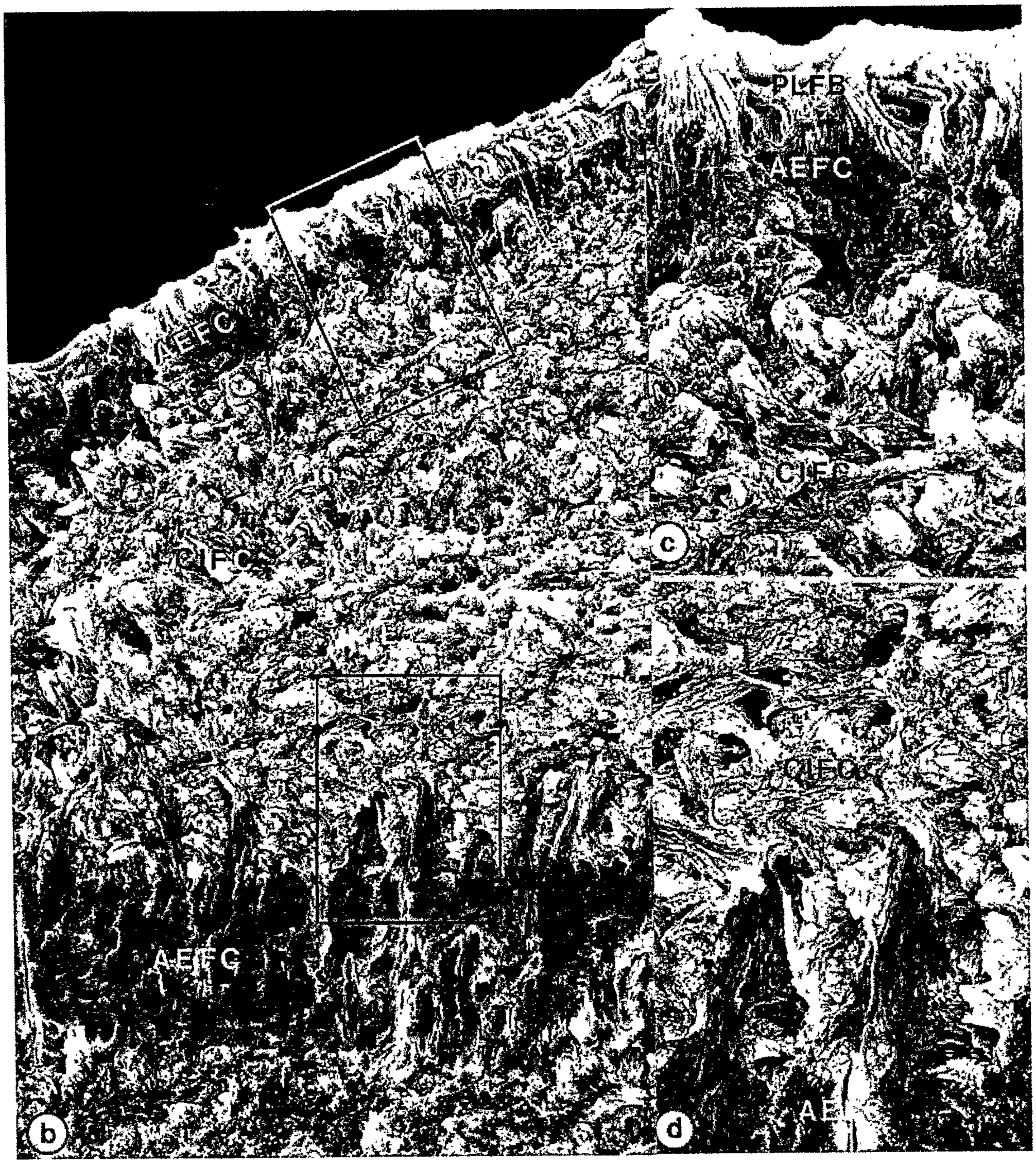


Figure 2. 3. Electron micrograph depicting CMSC. This is a haematoxilin-eosin stained celloidin section. Magnification b= X 1070, c, d= X 2670 [taken from Schroeder 1993].

Cellular intrinsic fiber cementum (CIFC) contains cells but no collagen fibers that extend into and are continuous with the periodontal ligament. It is a product of cementoblasts and in humans it is found mainly as a reparative form of cementum, deposited directly into resorption lacunae (Schroeder 1986).

In addition to these four types of cementum, there is an ill-defined layer, termed "intermediate cementum."

2.2.1 Intermediate Cementum

The term "intermediate cementum" was introduced by Bencze (1927) in order to designate a peripheral, narrow layer including cellular remains which is found between dentine and cellular root cementum in the apical half of the root (Schroeder 1986). This layer external to the granular layer of Tomes forms the apical part of the dentinocemental junction, whereas in the coronal half of the root this junction is formed by the hyaline, homogeneous layer of Hopewell-Smith (1920). This extremely narrow layer located between the granular layer of Tomes and AEFC is "entirely devoid of any histological elements" (Hopewell-Smith 1920) and has been shown in human teeth, to derive from a peripheral layer of predentine which was seen with tetracycline labeling (Owens 1972, 1973). Owens (1976) found that a layer approximately 15-35µm in thickness outside the granular layer of Tomes is of dentinal origin and contains dentinal tubules. Therefore, in the cervical root region, AEFC is deposited directly on dentine and an intermediate structure is absent (Bosshardt and Schroeder 1991).

Blackwood (1957) examined the dentinocemental junction and found intermediate cementum in all molars, premolars, and canines. However, the incisors examined showed little if any cellular cementum on their roots and appeared to be devoid of intermediate cementum.

Held (1951) described protoplasmic inclusions with connections both to the terminal dentine tubules and to the canaliculi and lacunae of cementocytes, and concluded that intermediate cementum was the result of an incomplete differentiation of the first layer of cementocytes. In contrast to this, Osborn (1965) suggested that some odontoblasts may become trapped in the developing dentine or remain on the outer surface of the growing root. "These latter cells may later become incorporated in the primary

cementum or, alternatively, grow abnormally and in conjunction with cementoblasts form the intermediate cementum."

Thus, with the intermediate cementum assumed to be either a form of cementum or a layer including a contribution of trapped odontoblasts, the origin and true nature of this ill-defined zone remained obscure (Schroeder 1986).

Intermediate cementum appears to be not a particular layer of tissue present on all human teeth, but a developmental form of external root dentine that occurs wherever thick CMSC borders the dentine, particularly so in multi-rooted teeth (Schroeder 1986). Therefore intermediate cementum may not even be classified as cementum, as it is derived from dentinal tissue (Jones 1981).

2.3 Development of Cementum

2.3.1 Formation

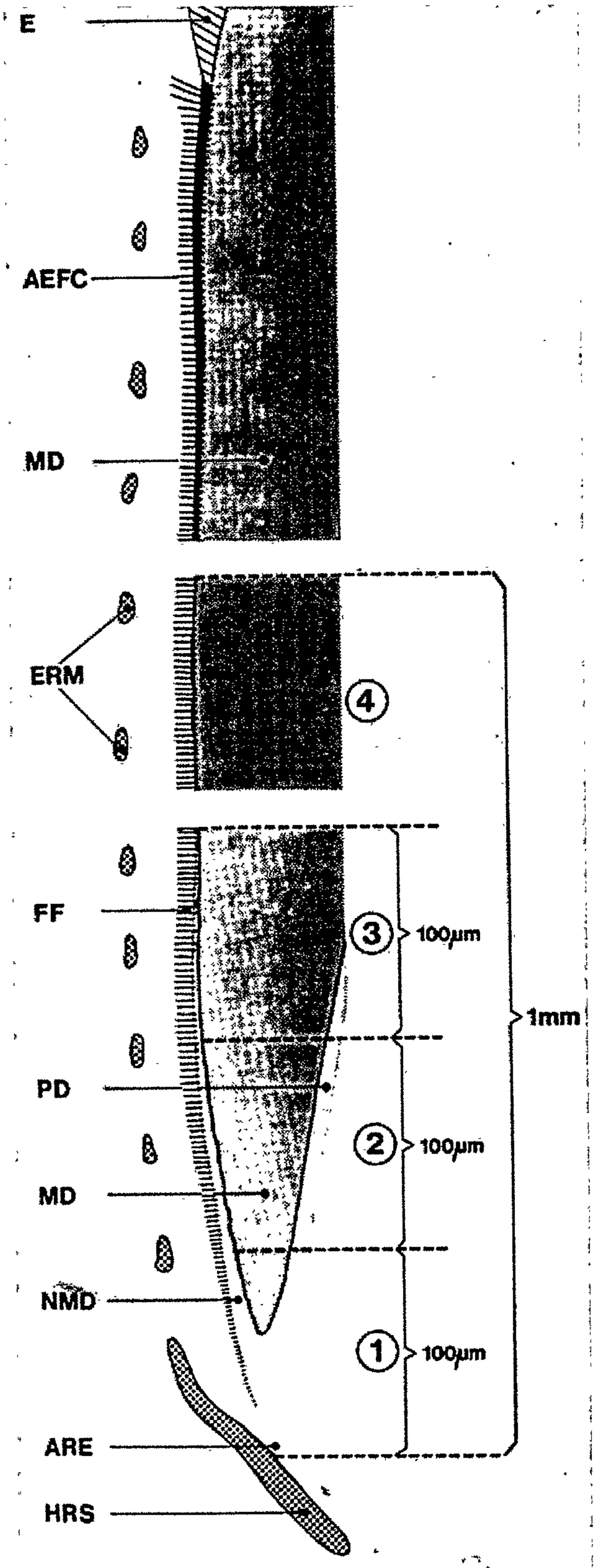
The formation of cementum can be subdivided into a pre-functional and functional developmental stage. The pre-functional portion of cementum is formed during root development. The formation of human tooth roots occurs over an extended period of time ranging between 3.75 and 7.75 years for permanent teeth (Bosshardt and Selvig 1997). Therefore the pre-functional development of cementum is an extremely long-lasting process. The functional development of cementum, on the other hand, commences when the tooth is about to reach the occlusal level, is associated with the attachment of the root to the surrounding bone and continues throughout life. It is mainly during the functional development that adaptive and reparative processes are carried out by the biological responsiveness of cementum, which in turn, influences the alterations in the distribution and appearance of the cementum varieties on the root surface with time (Bosshardt and Selvig 1997).

Root formation commences when the enamel organ has reached its final size and the inner and outer cell layers of the enamel epithelium, which delineate the enamel organ, proliferate from the cervical loop to form Hertwig's epithelial root sheath (HERS) (Diamond and Applebaum 1942). Continuous cell mitotic activity at the apical termination of Hertwig's root sheath leads to a coronoapical growth of this double cell layer. Its most apical portion, the diaphragm, separates the dental papilla from the dental follicle. The inner and outer cell layer of Hertwig's root sheath is surrounded by a basement membrane. Once the first matrix of radicular mantle dentin is formed by the maturing odontoblasts and before the mineralization of the dentin matrix reaches the inner epithelial cells, Hertwig's root sheath becomes discontinuous. Epithelial cell remnants of Hertwig's root sheath persist in the still developing and, later in time, in the aging periodontal ligament at an approximate distance of 30-60 μm remote from the root surface, where they are referred to as the epithelial rests of Malassez (Bosshardt and Selvig 1997) (Fig. 2.4).

There are however, diverging opinions on HERS participation in the formation of cementum. Paynter and Puty (1958) described its disintegration, Armitage (1986) described its fenestration and Listegarten (1968) wrote on its displacement and perforation by collagen producing cells. Following root formation, the epithelial cells remain in the form of strands in the Periodontal Ligament (PDL) and their role as the Epithelial Cells of Malassez remains unclear.

Historically it was believed that exposure of the newly formed dentine to the mesenchymal cells of the dental follicle led to the differentiation of cementoblasts (Armitage 1986). However, Thomas and Kollar (1988) showed that this was not a significant stimulus for cementoblast differentiation. Hammarstrom (1997) suggested that the development of acellular cementum seems to be preceded by a stage of secretion of enamel related proteins. He also suggested that the formation of cellular cementum seems to be induced by the exposure to the inner layer of HERS. These processes are influenced by or associated with the mineralisation of dentine. The precise method of initiation remains obscure.

Root development and formation is characterised by a simultaneous PDL fibre attachment. Bosshardt and Selvig (1997) described the cemental development of human teeth as being of two types AEFC and CMSC. The advancing root edge is confined to a zone of 200-300 μm in length (Fig. 2.4).



Schematic diagram depicting the gradual development of acellular extrinsic fiber cementum during its pre-functional genesis along a human premolar root developed to about 50% of its final length. 1. Attachment of the acellular extrinsic fiber cementum matrix to the not yet mineralized matrix of the radicular mantle dentin (NMD). The latter is continuous with the pulpal predentin layer (PD) and tapers in the coronal direction. Note that Hertwig's epithelial root sheath (HERS) is associated with the non-mineralized matrix of the radicular mantle dentin for an extremely short distance at the advancing root edge (ARE); 2. Establishment of the acellular extrinsic fiber cementum matrix on the root surface in form of a short collagenous fiber fringe (FF); 3. When the fiber fringe has attained its maximum numerical density, a cell-fiber fringe meshwork establishes on the root surface. 1-3. The external mineralization front in dentin (mineralized dentin, MD) is gradually approaching the base of the fiber fringe implantation on the root surface. 4. The external mineralization front in dentin has reached the future dentinocemental junction. E: enamel; ERM: epithelial cell rests of Malassez. Source: Bosshardt and Schroeder (1991).

Figure 2. 4. Schematic diagram depicting the gradual development of acellular extrinsic fiber cementum.

2.3.1.1 Acellular Afibrillar Cementum (AAC)

The cells responsible for the formation of acellular afibrillar cementum have still not been determined with precision. Its formation commences at the end of enamel maturation and continues for an unknown period of time. It is believed that connective tissue cells are responsible for the acellular afibrillar cementum formation when they come in contact with the enamel surface (Schroeder 1986). To make this possible, cells of the reduced enamel epithelium, must be lost or detached from the enamel. Bosshardt and Selvig (1997) suggested it cannot be completely ruled out that acellular afibrillar cementum is an epithelial product initially produced when the ameloblasts transform into the reduced enamel epithelium and when the cells of the inner enamel epithelium are about to generate the inner cells of Hertwig's root sheath. Therefore AAC may not even be considered cementum if it is found to be of epithelial origin as opposed to having connective tissue origin.

Beertsen and Van Den Bos (1991) showed that calcified layers, which morphologically resembled acellular afibrillar cementum, formed around demineralized dentin slices immersed in serum-containing culture medium supplemented with alkaline phosphatase and an organic source for phosphate such as the monophosphate ester '3-glycerophosphate. This suggested that such acellular afibrillar cementum-like layers formed also in the absence of cells, is a matrix of a co-precipitate of medium- or serum-derived components and mineral. However, alkaline phosphatase is required for mineralization to occur. In the, *in vivo* situation, this enzyme is associated with periodontal ligament cells in the vicinity to bone and cementum (Bosshardt and Selvig 1997).

2.3.1.2 Acellular Extrinsic Fiber Cementum (AEFC)

The acellular extrinsic fiber cementum is usually confined to the coronal half of the root. Its formation commences therefore shortly after crown formation is complete and always before cellular intrinsic fiber cementum starts to form on the apical aspect of the root.

The cementoblasts producing acellular extrinsic fiber cementum commence their cell differentiation about 20 to 30 μm coronal to the first deposited dentinal matrix (Bosshardt and Selvig 1997). These cells have been described as resembling fibroblasts, revealing a well-developed rough endoplasmic reticulum, and are interconnected by desmosome-like junctions and commence to produce and attach the collagenous cementum matrix as close as 50 μm coronal to the root edge (Bosshardt and Selvig 1997). Collagen deposition results in a complete covering of the not yet mineralized dentinal matrix along the next 100 μm of the root surface. About 200 to 300 μm coronal to the advancing root edge, the initial acellular extrinsic fiber cementum matrix is established on the dentinal matrix (Fig. 2.4). The acellular extrinsic fiber cementum matrix consists of a dense fringe of short collagenous fibers that are implanted into the dentinal matrix and oriented approximately perpendicular to the root surface. The outwardly progressing mineralization front in dentin does not reach the future dentinocemental junction until the collagenous interdigitation of the two fibril populations are established. The mineralization of the dentinal matrix commences about 100 μm coronal to the advancing root edge. With the onset of cementum mineralization, the acellular extrinsic fiber cementum, commences to grow in thickness (Sequeira et al 1992). The extrinsic fibers remain short until the tooth is about to reach the occlusal level (Bosshardt and Selvig 1997). It is not known how the short fiber fringe becomes elongated and eventually continuous with the principal periodontal ligament fibers (Bosshardt and Selvig 1997).

Incremental lines appear to represent the periodic deposition of cementum layers in frequent association with an abrupt change in the direction of Sharpey's fibers. Growth rates are reported faster on the distal surface (4.3 μm/year) than on the mesial surface (1.4 μm/year) (Dastmalchi et al 1990). Acellular extrinsic fiber cementum has the potential to adapt to functionally dictated alterations such as mesial tooth drift (Bosshardt and Selvig 1997).

2.3.1.3 Cellular Intrinsic Fiber Cementum (CIFC)

The initiation of cellular intrinsic fiber cementum formation commences in close proximity to the advancing root edge (Bosshardt and Schroeder 1992). Free cementoblasts differentiate along the not yet mineralized dentinal matrix. They project numerous cytoplasmic processes into the loose dentinal matrix and immediately commence to implant the initial collagen fibrils among those of the dentinal matrix. Additional cementoblasts, which are remote from the dentinal surface, deposit their cementum matrix at various locations around themselves. This multipolar and fast matrix deposition, which occurs in the space between deviating epithelial cells of Hertwig's root sheath and the dentinal surface, appears to be the reason for the incorporation of some of the cementoblasts (Bosshardt and Schroeder 1992). The cells entrapped in the mineralized cementum are referred to as cementocytes and occupy lacunae, which are interconnected through canaliculi. The cementoblasts attain their full synthetic activity approximately 100 μm coronal to the advancing root edge. The collagen fibrils produced during the fast, multipolar cellular intrinsic fiber cementum initiation show a more random orientation than those of the subsequently deposited matrix. Therefore, the bulk of the intrinsic collagen fibrils form discrete bundles oriented mainly parallel to the root surface. (Bosshardt and Schroeder 1992) (Fig. 2.3 and 2.4).

2.3.1.4 Cellular Mixed Stratified Cementum (CMSC)

In humans, the extrinsic fibers are oriented about perpendicularly to the root surface and traverse the intrinsic cementum variety either sporadically or densely arrayed in parallel (Fig. 2.3). Although the numerical density of these highly aggregated extrinsic fibers may be distinctly less than in pure acellular extrinsic fiber cementum (Schroeder 1986), they are considered as the matrix of acellular extrinsic fiber cementum that intermingles or alternates with the intrinsic fibers. This mixed cementum is referred to as cellular mixed stratified cementum. When the extrinsic fibers are continuous with the functionally oriented principal fibers of the periodontal ligament, they are regarded as Sharpey's fibers. As layers of acellular extrinsic fiber cementum and cellular and

acellular intrinsic fiber cementum develop unpredictably in time, space and thickness (Schroeder 1986), particular root surface areas covered with cellular mixed stratified cementum may temporarily remain unsupported by periodontal fibers (Schroeder 1986). Cellular mixed stratified cementum may deposit up to 30-times faster than the more regular acellular extrinsic fiber cementum. The patch-wise deposition of cellular mixed stratified cementum results in great circumferential variations in cementum thickness and reflects periods of accelerated deposition of cellular intrinsic fiber cementum, which are probably due to functional demands in order to reposition the tooth when it is shifting in its bony socket during its post-eruptive tooth movements. Bosshardt and Selvig (1997) suggested that the dynamic tissue alternations and the variations in growth rates are reflected by a tissue layering of cellular mixed stratified cementum with layers of acellular extrinsic fiber cementum and incremental lines interfacing layers of cellular and acellular intrinsic fiber cementum.

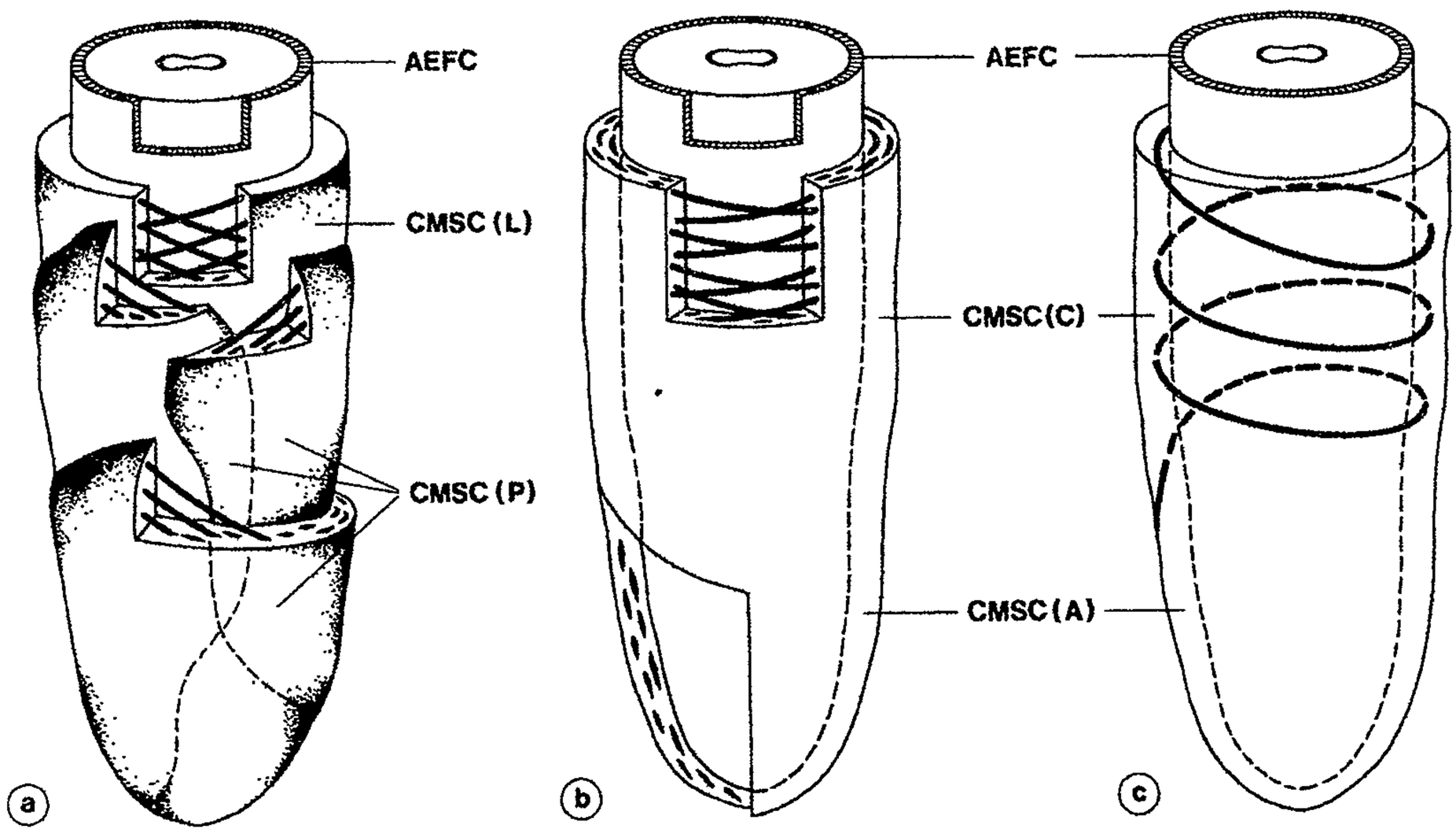


Figure 2. 5. The orientation and course taken by intrinsic fibers of cellular, mixed stratified cementum *(CMSC)* in human permanent teeth, either erupted (a) or retained and impacted (b, c). (Schroeder 1986 adapted from Keller 1964; b, C adapted from Imgrüth 1959)

In the cervical region of erupted teeth (Fig. 2.5a), 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 scales 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 (Fig. 2.5b, c). (Schroeder 1986, adapted from Keller 1964, Imgrüth 1959)

2.3.2 Mineralization

Mineralization begins in the depth of precementum. Fine hydroxyapatite crystals are deposited, first between and, secondly, within the collagen fibrils by a process which is identical to the mineralization of bone tissue. Zander and Hurzeler (1958) examined the thickness of cementum on human teeth extracted from individuals of varying ages. From their data it can be calculated that the mean, linear rate of cementum deposition on single-rooted teeth is about 3 μm per year, but varying with tooth type, root surface area, and type of cementum being formed. A similar rate has been found for acellular extrinsic fiber cementum in young human premolars and in nonfunctioning, impacted teeth (Azaz et al 1974).

The width of the precementum layer in the human is about 3-5 μm (Selvig 1968). The mineral crystals reach mature size similar to mineral crystals in bone and dentin within 1 to 4 μm from the calcification front (Selvig 1968). Therefore the processes of crystallization in cementum normally is extremely slow and extend over a period of several months (Bosshardt and Selvig 1997).

The distribution of mineral within the mature tissue shows a great deal of variability. Studies by microradiography, using a technique that reflects the distribution of calcium in the tissue, have shown that cellular mixed stratified cementum generally has a lower mineral content than acellular extrinsic fiber cementum (Soni et al 1962). This difference can in part be accounted for by the non-mineralized structures present in cellular intrinsic fiber cementum. These may include cementocyte lacunae as well as larger inclusions of cellular elements. In addition, the Sharpey's fibers of cellular mixed

stratified cementum generally retain an unmineralized core (Selvig 1968). The latter feature is in contrast to the intrinsic fibers and to the Sharpey's fibers in acellular extrinsic fiber cementum which exhibit a more complete degree of mineralization. Selvig (1968) pointed out that Sharpey's fibers are derived from periodontal fibers which are not calcifiable in this location. These fibers will calcify only after they have become embedded in bone and cementum. For calcification to occur they require the concentration of inorganic ions for calcification and the removal of inhibiting substances. Therefore when formation progresses at a rapid rate, such as during formation of cellular mixed stratified cementum there would be less opportunity for calcium deposition. Wang et al (1980) indicated that these fibers of Sharpey have a coating type III collagen, which may prevent mineralization of the type I collagen in the core.

Although additional cementum is laid down throughout life, the mineral content of this tissue once formed, does not seem to change significantly with age (Nakata 1972, Selvig and Selvig 1962, Stepnick and Gettleman 1975). This is in contrast to dentine, which increases in mineral content and transparency with age by obliteration of the dentine tubules.

2.3.3 Age

Cementum, at the Cementoenamel junction is thin measuring 20 to 50 μm in thickness. As the apex is approached, the cementum becomes progressively thicker 150 to 200 μm (Ten Cate 1994).

Ruatiola and Craig (1961) reported marked variation in the thickness of cementum among the different areas of the root. There appeared to be a general increase in thickness near the apex of all the teeth studied. Except for the extremely thin cementum (in some instances less than 4 microns) near the cemento-enamel junction, the cementum covering most of the root is fairly uniform in thickness, varying from 15 to 30 microns. Near the apex, the cementum became markedly thicker and increased to 150 μm.

Mariotti (1993) described the thickness of cementum as varying from 20μm to 200μm. Cementum being mineralized organic matrix that covers the anatomic root surface of the tooth. He goes on to describe cementum as an avascular, alymphatic, non-innervated tissue that is asymmetrically populated by cells, called cementocytes, in lacunae. As early as 1878, Magitot stated that cementum appears to increase in thickness with age, and refers to a "continuous increase in volume." Black (1887) compared teeth from people aged 30 years with those of age 50 and a third group aged 70. In view of his observations, he stated that cementum grows continuously (Zander and Hurzeler 1958).

Cementum formation on the roots of human teeth continues throughout life unless disturbed by periapical or periodontal pathology. More cementum is formed apically than cervically. In addition, cementum thickness shows characteristic variations among tooth groups and tooth surfaces (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 multirooted teeth. The rate of cementum formation may vary from time to time. The reasons for these variations are not completely clear. However, changes in tooth position may exert temporal and spatial variations in pressure and tension on root and bone surfaces. The biological responsiveness of cementoblasts to these stimuli may influence the rate as well as pattern of cementum deposition (Schroeder 1986).

The first quantitative data for erupted and functioning teeth are derived from an extensive study of Zander and Hurzeler (1958). These authors collected 230 single-rooted (incisors, canines, premolars) teeth with a healthy periodontium from patients aged from 11 to 76 years. Weighed and measured paper-cuts of the cementum profiles traced in serial horizontal sections were used to determine average thickness for the whole root as well as average data for cervical, middle of root, and apical segments. Data revealed an overall and site-specific cementum thickness increase about three-fold over a full life span. This increase was linear, with the thickness of cervical cementum (AEFC) rising much more slowly than that of apical cementum (CMSC).

Similar data have been obtained for nonfunctioning, impacted teeth (Azaz et al. 1974). Using buccolingual, axial ground sections of 60 canines and premolars from patients aged between 9 and 70 years, Azaz et al. (1974) demonstrated an age-dependent increase of cementum thickness in cervical as well as mid-root areas. Their data was very similar to those of Zander and Hurzeler (1958), implying that similar phenomena may be responsible for increasing cementum thickness in both functioning and nonfunctioning, erupted and impacted teeth. In the latter study, all cementum measured at cervical and middle root sites was of the acellular variety (AEFC). In the apical region, impacted teeth showed several different types of cementum (i.e., 33% totally acellular, 27% totally cellular, 40% variably mixed and stratified), and 23% of all teeth investigated revealed hypercementosis (Azaz et al. 1974). These data may favor the assumption that the increase in cementum thickness is directly related to aging of teeth rather than the result of masticatory function.

Nonfunctioning, impacted teeth generally appear to have thicker cementum than functioning teeth (Azaz et al 1974), and the structural architecture is different. In the cementum of impacted teeth, Sharpey's fibers may be nearly completely absent, and the cementum is built up mainly by intrinsic fibers arranged parallel to the root surface. In the periodontal ligament of such teeth as well, the fiber arrangement may be predominantly parallel to the root surface (Bosshardt and Selvig 1997).

However, several authors believed that masticatory function and the forces exerted have a role in stimulating cementum apposition. Geppert and Mueller (1951) examined a sample of 21 maxillary and 21 mandibular first incisors and of 6 maxillary as well as 20 mandibular canines from patients over 25 years of age. Using labiolingual axial sections, they measured cementum thickness at five different levels both on labial and lingual root aspects. Thickness was determined separately for three morphologically distinct layers, i.e., an inner layer of acellular cementum covering the dentin (intermediate cementum), an outer layer of acellular cementum loaded with fibers of Sharpey, and an intermediate layer of cellular cementum. Their data tend to show that cementum thickness assumes a site-specific maximum, i.e., both in maxillary incisors and canines maximum thickness

occurs at the oral aspect cervically and at the labial aspect apically. In contrast, in mandibular incisors and canines, maximum thickness occurs at the oral aspect apically and at the labial aspect cervically.

2.4 Function of Cementum

Cementum is a component of the tooth itself, but belongs functionally to the dental attachment apparatus, the periodontium. One of the main functions of cementum is to anchor the principal collagen fibres of the periodontal ligament to the root surface (Bosshardt and Selvig 1997). Despite the minor physical tissue volume occupied by cementum, the apposition of cementum to the surface of root dentin is necessary for the attachment of the tooth to the alveolar bone, repair of root fractures and resorption as well as functional adaptation of teeth (Mariotti 1993).

2.4.1 Function of Acellular Afibrillar Cementum (AAC)

The acellular afibrillar cementum consists of a mineralized matrix, which appears similar to the interfibrillar matrix of acellular extrinsic fiber cementum, but contains neither collagen fibrils nor embedded cells. The lack of collagen fibrils indicates that this cementum variety has no function in tooth attachment. Acellular afibrillar cementum is deposited as isolated patches over minor areas of enamel and dentin (Bosshardt and Selvig 1997).

2.4.2 Function of Acellular Extrinsic Fiber Cementum (AEFC)

The acellular extrinsic fiber cementum is usually confined to the coronal half of the root. Its formation commences therefore shortly after crown formation is completed and always before cellular intrinsic fiber cementum starts to form on more apical root portion. The acellular extrinsic fiber cementum continues to grow as long as the adjacent

periodontal ligament remains undisturbed. The extraordinarily high numerical density of fibers inserting into acellular extrinsic fiber cementum (approximately 30,000/mm^2, (Schroeder 1986)) is a reflection of the significant function of this cementum variety for tooth anchorage to the surrounding bone. Due to post-eruptive tooth movements, changes can occur in the direction of the Sharpey's fibers. These changes are accentuated by individual acellular extrinsic fiber cementum layers interfaced by incremental lines (Bosshardt and Selvig 1997).

2.4.3 Function of Cellular Intrinsic Fiber Cementum (CIFC)

Although the intrinsic cementum alone has no immediate function in tooth attachment, its important role as an adaptive tissue (Schroeder 1986) that brings and maintains the tooth in its proper position. In addition, only cellular intrinsic fiber cementum can repair a resorptive defect of the root in a reasonable time due to its capacity to grow much faster than any other known cementum type. Functional stimuli, that is, the force generated by tooth contact and mastication, are widely held responsible for the onset and appositional growth of cellular intrinsic fiber cementum. This assumption probably originates from observations showing that the genesis of this cementum variety coincides with the first occlusal tooth contact (Diab 1965, Hoffman 1940) and that functioning teeth appear to have thicker cementum layers than teeth which are not in function. Several observations, however, are not in keeping with this concept. As suggested by Kronfeld (1938) mastication is apparently not a prerequisite for cellular intrinsic fiber cementum genesis, since:

i) the furcations of human teeth are covered with thick cementum layers before they emerge into the oral cavity (Kronfeld 1938),

ii) impacted and erupted teeth without antagonists appear to have thicker cementum layers than fully erupted and functioning teeth (Azaz et al 1974, Kronfeld 1938, Sicher et al 1972), and

iii) over-compression of the periodontal ligament causes root resorption. (Brudvik and Rygh 1995).

Thus, it seems that the initiation of cellular intrinsic fiber cementum genesis does not depend on stimuli transmitted by masticatory forces and that influence of pressure may reduce the rate of matrix deposition (Bosshardt and Selvig 1997).

2.4.4 Function of Cellular Mixed Stratified Cementum (CMSC)

Like pure acellular extrinsic fiber cementum on the coronal half of the root, cellular mixed stratified cementum increases in thickness throughout life (Zander et al 1958). The patch-wise deposition of cellular mixed stratified cementum results in great circumferential variations in cementum thickness and reflects periods of accelerated deposition of cellular intrinsic fiber cementum, which are probably due to functional demands in order to reposition the tooth when it is shifting in its bony socket during its post-eruptive tooth movements (Bosshardt and Selvig 1997).

Table 2. 1. Summary of the characteristics of the main cementum types.

	CIFC	CMSC	AEFC	AAC
Structure	• Cells • Intrinsic Fibers	• Cells • Intrinsic Fibers • Extrinsic (Sharpey's)	• No Cells • Bundles of Sharpey's fibres	• No Cells • No Intrinsic or Extrinsic Fibres
Product of:	Cementoblasts	Cementoblasts Fibroblasts	Cementoblasts Fibroblasts	Cementoblasts
Position on Root	• Resorption lacunae • CMSC	• Apical 1/3rd • Furcations	• Cervical 1/3rd • CMSC	Covers enamel surface
Thickness (µm)	Dependant on depth of resorption lacunae	100 - 1000µm	30 - 230µm	1 - 5µm
Function	Repair	Repositioning of tooth to compensate for shifting in its bony socket	Anchorage	Unclear

2.5 Composition of Cementum

Cementum is a non-uniform, mineralized connective tissue. The different cementum varieties differ with respect to location, structure, function, rate of formation, chemical composition and degree of mineralization. In fully formed functioning teeth, cementum is firmly attached to radicular dentine and covers the entire surface of the root (Bosshardt and Selvig 1997).

Biochemical studies have shown that the chemical composition to cementum is similar to bone (Mariotti 1993). The inorganic hydroxyapatite crystals comprise 50% of the dry mass, the remaining organic matrix contains largely collagen and to a lesser degree glycoproteins and proteoglycans. Cementum is generally less mineralized than the root dentine (Selvig and Selvig 1962, Nieders et al 1972, Hals and Selvig 1977). Ninety percent of the organic matrix is type I collagen and approximately 5% type III collagen (Chistner et al 1977).

Cementum is similar to bone in its organic fibrous framework, ground substance, crystal type, developmental processes, reorganizational capabilities and chemical composition (Hassel 1993). There are, however, some important differences between bone and cementum;

i) about 70% of bone is made up of inorganic salts, where as cellular cementum has only 46%
ii) only type I collagen is found in bone, whereas cementum contains type I plus about 5% type III collagen in its organic matrix.
iii) Cementum contains a proteoglycan interfibrilar substance that appears to be a gene product unique to cementoblasts.
iv) Unlike bone and tooth enamel, cementum is relatively permeable.

About 50% of mature cementum contains organic materials, which include collagens, glycoproteins and proteoglycans. Biochemically the organic corpus of cementum is

composed primarily of collagens. Both types I and III collagen have been identified in cementum, with type I collagen comprising 90% and type III collagen comprising approximately 5% of the organic matrix (Mariotti 1993).

The remaining components of the organic matrix are accounted for by noncollagen proteins. Many of the noncollagen proteins are similar to those found in bone and dentin, although the total cementum organic matrix contains a larger proportion of noncollagen proteins than do bone and dentin (Mariotti 1993).

From the point of view of function, cementum differs fundamentally from bone in that cementum does not undergo the extensive remodeling that is characteristically observed in histological sections through the alveolar processes. Some re-modeling of cementum does occur, however, as evidenced by the presence of resorption lacunae observed on extracted human teeth (Henry and Weinmann 1951) and by the ability of cementocytes to resorb the organic cemental matrix (Hassel 1993).

2.5.1 Calcium Content

Acellular extrinsic fiber cementum is more mineralized than cellular intrinsic fiber cementum and cellular mixed stratified cementum. The difference can in part be explained by the presence of uncalcified spaces, such as lacunae and by the uncalcified core of Sharpey's fibers. In addition, the matrix of acellular extrinsic fiber cementum may be more completely mineralized because its formation is a slow process that allows longer direct contact of tissue fluids (Soni et al 1962).

The minute size of the mineral crystals compared with enamel results in a much larger specific surface area of the mineral component. As a consequence, cementum has a greater capacity for adsorption of fluoride and other elements over time but also more readily decalcifies in the presence of acidic conditions (Bosshardt and Selvig 1997).

There are a range of techniques available for the biochemical analysis of calcium. The Calcium composition of cementum has been studied in rhesus monkeys by quantitative microradiography (Röckert 1958) and in the seal and human cementum by a chemical method. Röckert examined cementum of monkey teeth by quantitative X-ray microscopy and found that the concentration of Calcium (Ca) varied within a wide range, from 0.10 to 0.83 mg Ca/mm^3. This variation confirms that cementum is not a completely mineralized or a homogeneously mineralized tissue. In the studies on human cementum by Selvig and Selvig (1962) the analysis was determined for combined Ca and Mg. In patients under 20 years of age, the combined Ca and Mg content was 26.0 ± 0.3 and 26.3 ± 0.2% in the cervical and mid-root portions of the root, respectively. The mean values for all samples obtained by Neiders et al 1972 for Ca alone were slightly lower (cervical 25.6%, midroot 26.0%). However, combined Ca and Mg composition was comparable (cervical 26.1%, midroot 26.6%).

Neiders et al (1972) studied 5 teeth to determine mineral content using an electron microprobe with scanning electron microscope attachment to obtain data on the chemical composition of small selected regions of the tooth. They found that the Ca composition of the cementum in the cervical and midroot regions showed statistically significant differences in only one tooth with higher Ca composition in the midroot region. The Ca values in the hypermineralized zone did not show statistically significant differences in individual teeth, except in one, where the highest Ca level was in the cervical portion.

Calcium content has been related to enamel and bone (Davidson et al., 1974; Weaver, 1966). Davidson correlated micro-hardness of enamel to calcium after slow decalcification and etching. Weaver (1966) investigated the microscopic hardness of bone and using micro-radiography found that microhardness is a direct measure of the degree of mineralization. Carlström (1954), was first to note that microhardness of bone was a direct function of the degree of osseous mineralization as determined by microradiography.

2.5.2 Phosphorus Composition.

Neiders et al 1972 obtained percentage composition of phosphorous (P) with the electron microprobe (cervical 12.9%, midroot 13.5%). These were higher than those by Selvig and Selvig (1962), who found with chemical analysis that the mean composition of cementum was 12.3 ± 0.2 in the cervical region and 12.3 ± 0.1% in the midroot region. The P composition in cementum generally corresponded to the Ca composition (Neiders et al 1972).

A number of trace elements may also be present in normal cementum in concentrations detectable by electron microprobe analysis, in particular, Sulfur, Copper, Zinc and Sodium (Brudevold et al 1960). However, their distribution and significance do not seem to have been studied in any detail.

2.5.3 Fluoride Concentration

Cementum appears to have a high fluoride (F) content compared with other hard tissues. Concentrations up to 0.9% ash weight have been reported (Bosshardt and Selvig 1997). Fluoride concentration in cementum shows a general increase with age and varies with the nutritional fluoride supply to the individual (Yoon 1960).

A direct relationship has been demonstrated between the deposition of fluoride in human bone and the fluoride concentration in the drinking water up to 4.0ppm (Zipkin 1958).

The fluoride content has been extensively studied (Yoon *et at.*, 1960; Singer and Armstrong, 1960; Stepnick *et* at., 1975; Nakata *et at.*, 1972). Although the analytical methods do not allow for direct comparison of results, it seems that fluoride accumulates with age in cementum, and that, as in other mineralized tissues, there is a distribution gradient from the surface inward, suggesting an uptake over time from the immediately surrounding fluids. This uptake of ions from the surroundings has also been thought to

explain why root cementum exposed to the oral environment was more mineralized than non-exposed surfaces (Selvig and Zander, 1962; Hals and Selvig, 1977).

With the exception of Yoon et al, all the studies indicated that cementum contained a higher concentration of fluoride than any other calcified tissue. Indeed, where comparative studies involving both teeth and bone (Yoon 1960, Brudevold et al 1960 and Singer and Armstrong 1960) have been made, the fluoride concentration of cementum exceeded that in bone. Tohda (1996) used electron-microprobe analysis and found that there was a gradient in fluoride concentration with a decrease toward the inner layers of cementum.

Fluoride accumulates in the surface layer of cementum, which is exposed to the circulating tissue fluids in the periodontal ligament. Since the F^- ion reacts aggressively with hydroxyapatite, fluoride concentrates near the surface and shows limited diffusion into deeper layers of the tissue. Thus, the mean fluoride content of the fine layer of cervical cementum is higher than that of the thicker apical cementum (Brudevold et al 1960, Stepnick et al 1975). As a consequence of its longevity, cementum appears to be the most fluoride-rich tissue of the body. By contrast, the bone tissue facing the periodontal ligament is constantly being remodeled and, therefore, has no chance to accumulate the same amount of fluoride. For the same reason, the fluoride concentration of alveolar bone is lower than that of the cortical lamellae of the maxilla and mandible (Yoon 1960) and of most other bones in the body. The relatively high fluoride content of the surface layer compared with deeper layers of cementum and root dentin may help explain why any root resorption tends to be of an undermining character (Bosshardt and Selvig 1997).

2.6 Tooth movement and Resorption

Root resorption after orthodontic treatment is intimately associated with the biological processes that occur during tooth movement. The displacement of a tooth in its socket by

an orthodontic load results in the death of many cells in the region of the compressed periodontal ligament (PDL); removal of this necrotic tissue is required before tooth movement can occur. Severe external root resorption may result when the process of removal penetrates into the cementum. Resorption at the root apex of the tooth may progress through the root width to produce permanent loss of root length and is termed *external apical root resorption* (EARR) (Gibilaro and Proffit 1996). It remains a challenge to identify the mechanical and biological factors that are responsible for enhancing resorption.

Studies investigating the cause of EARR have focused on treatment-related factors such as force levels, direction or amount of tooth movement, length of treatment, type of appliance used, and whether extractions were performed (Rudolph 1936, Blake, Woodside and Pharoah 1995, Linge 1983, Katona 1994,Alexander 1996,Brezniak and Wasserstein 1993). Biological factors that have been examined include gender and the age at the commencement of treatment. Brezniak and Wasserstein (1993) reviewed over 100 studies on external root resorption only to reveal a lack of consensus on the causative factors of this phenomenon and an inability to predict the susceptibility of individuals.

Using a cellular biology approach, Davidovitch et al (1996) questioned whether inflammatory mediators generated outside of the PDL influenced cellular interactions involved in root resorption, by attracting and/or activating cementoclast progenitors.

2.6.1 Cementum reactions to physiological tooth movement and occlusal forces

The distribution of cementum on impacted teeth tends to indicate that occlusal forces are 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). It has been suggested that cementum is thicker in areas exposed to tensional forces on labial and lingual surfaces of incisors

(Geppert and Mueller 1951, Schroeder 1986). The deposition of considerably more new cementum has been noted on the tension side compared with the pressure side of the root surface of teeth undergoing orthodontic tooth movement in rhesus monkeys (Polson et al 1984). This finding correlates with the observation of appositional layers of bone lining the distal wall of alveolar sockets, and indicates that cementum, like bone tissue, has the potential to be dynamically responsive and that its growth may be stimulated by tension (Dastmalchi et al 1990, Bosshardt and Selvig 1997).

2.6.2 Root Resorption

Although physiological root resorption is a normal phenomenon of deciduous teeth during tooth shedding, permanent teeth do not undergo physiological resorption. A variety of other factors however, induce root resorption. These factors can be either pathological (infectious and systemic diseases as well as tumors) or non-pathological. Trauma (mechanical, chemical or thermal) or sustained over compression of the periodontal ligament resulting in the resorption of cementum and dentin. In vast majority of cases, however, idiopathic resorption does occur (Massler and Malone 1954). Root resorption can be classified by location into internal and external, and by the degree of persistence into transient or progressive.

Root resorption is a pathological process initiated by specific clastic cells, which remove the organic and mineral components of dental hard tissue. (Heithersay, 1994). Apical root resorption is a common idiopathic problem associated with orthodontic treatment. It is unpredictable, and when extending into dentine it is irreversible (Brezniak and Wasserstein 1993).

The requirement for root resorption of the calcified dental tissue is only, that osteoclasts obtain access to the mineralised tissue by a breach of the naturally protective formative cell layer covering (Tronstad 1988), if the mineral and matrix coincide (Jones and Boyd 1988) or when the precementum is mechanically damaged or scrapped off (Tronstad 1988). Although most authors agree that root resorption stops after cessation of force

(Rygh, 1977; Reitan and Rygh, 1994), the determinants of the resorption/repair sequence are not well understood.

2.6.2.1 Prevalence:

The prevalence of physiological root resorption of the untreated population ranges from 0% to 90.5% (Plets et al., 1974). However in the treated group, root resorption increased from 4% to 77% (Goldson and Henrikson, 1975), 15% to73% (Lupi et al., 1996).

Bosshardt and Schroeder (1994) observed resorption lacunae were very superficial and therefore too small to be detected radiographically. As most of them were undergoing repair, they can be classified as transient phenomena of no clinical significance. Such resorptions have been found frequently on roots of human permanent teeth. In a histological study including 261 non-orthodontically treated teeth from 15 dentitions, Henry and Weinmann (1951) found that 90.5% of these teeth showed signs of resorption to some degree. The resorption areas were usually small and shallow (average size: 0.7 mm in length and 0.1 mm in depth), and 76.8% of them occurred in the apical, 19.2% in the middle, and 4% in the cervical third of the root. The number of resorption areas increased with age (average number of resorptions per tooth: 1.4-3.5 in the age range between 16 and 3 years, and 2.8-8.6 in that between 36 and 58 years). Independent of age, the respective values for premolars alone were 2.7, 3.1, and 2.8, 3.3 for the maxillary and the mandibular first and second premolars, respectively (Henry and Weinmann, 1951).

Bosshardt and Schroeder (1994), found about 15% of all available teeth (being in the age range between 9 and 27 years and with roots developed to 30-100% of their final length) showed resorptions. On average, 2.7 resorptions were found per tooth, most of them being located at the apical root surface. It seems likely that with the onset of occlusal contact, i.e. with the commencement of functional demand, resorptions may begin to occur and later on increase in number with age (Bosshardt and Selvig 1997).

It is well known that resorption is a frequent consequence of forced orthodontic tooth movement, whereby resorptions occur on the pressure site (Bosshardt and Selvig 1997).

2.6.2.2 Types of Resorption:

Andreason (1988) describes two types of root resorption: internal and external.

External resorption can be subdivided into:

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. Gharfari (1994) described this type of resorption as due to inflammation in the immediate area of the root surface. Clinically this may be observed radiographically by slight irregularities in the root surface not accompanied by a corresponding radiolucency in the adjacent bone. The periodontal ligament remains unchanged (Heithersay, 1994).

2. ***Replacement resorption*** – occurs when bone replaces the resorbed tissue and leads to ankylosis. Radiographically resorption is detected by a loss of periodontal ligament space and signs of tooth substance being replaced by bone (Andreason 1988).

3. ***Inflammatory resorption*** – occurs when initial root resorption reaches the dentinal tubules of an infected necrotic pulpal tissue or an infected leukocyte zone. That is inflammatory mediators and phagocytic cells colonise mineralised or denuded cemental surface and later dentinal or pulpal tissues (Gharfari, 1994). Clinically this is characterised by bowl-like radiolucencies in both the root surface and the adjacent bone. If extensive, may involve the root canal space (Heithersay, 1994).

Tronstad (1988) divides inflammatory resorption further into:

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

2. *Progressive inflammatory resorption* occurs when stimulation is for a long period. This is tissue pressure related, therefore when force is removed resorption should be arrested as the stimulation of the resorbing cells stop. Clinically this is seen as a shortening of the roots.

Internal Resorption will not be described here.

2.6.2.3 Biological Aspects:

The active cell in resorption of tooth is the "clastic cell" (Heithersay 1994). In response to mechanical or chemical stimuli, periodontal ligament cells synthesize prostaglandin E with concomitant increase in cAMP (Ngan et al, 1988). This process is regulated by hormones neurotransmitters, cytokines and monokines (Brezniak and Wasserstein 1993). On stimulation, motile blood borne cells derived from haematopoietic stem cell precursors from bone marrow, migrate as mononuclear pre-osteoclasts to resorption sites and fuse with other similar cells to form mature multinucleated resorbing cell. The central reactive area has a characteristic ruffled border. Here the mineral and organic components are degraded and removed both extracellularly through exocytosis of enzymes and H+ ions and intracellularly through phagocytosis. The pH of the microenvironment is as low as 4.75 (Silver et al., 1988).

Human and animal research demonstrated that periodontal hyalinization preceeds the root resorption process during orthodontic treatment. Three stages are described in the hyalinized zone:

- degeneration
- elimination of destroyed products, and
- re-establishment (Rygh, 1977).

Brudvik and Rygh (1995) concluded that resorption appears to be associated with removal of necrotic tissue from the over-compressed zone of the PDL. Repair occurs by cementoid filling in the resorbed lacunae seen after 35-70 days (Harry and Sims, 1982). However in larger defects, repair cells arrive from the alveolar bone marrow derived cells leading to ankylosis.

2.6.2.4 Clinical Aspects

Common to most identified risk factors is the presence of 'jiggling'. The forces involved in orthodontic movement are characterised by; increased stress, frequent local trauma through over compression of the PDL followed by diminution of stress down to zero before reactivation begins again. This causes external apical root resorption (EARR) of cementum that exposes dentine to clastic destruction (Linge, 1994).

The clinical eitiology can be divided several factors (Brezniak and Wasserstein 1993):

1. Biological,
2. Mechanical and
3. Causal.

2.6.2.5 Biological Factors:

Biological Factors can be considered as:

1. *Individual susceptibility* – incidence of root resorption varies among different people and on different teeth (Rygh, 1977).

2. *Genetics* – Harris (1997) found heritability estimates averaged 70% for 3 rooted teeth, but low for mandibular incisors. He postulated that biochemical factors control the familial differences in susceptibility.

3. *Systemic* – Endocrine problems have been related to root resorption, for example; Hyperthyroidism (Goultschin et al., 1982), Paget's disease (Smith, 1978), hypophosphatemia (Tangney, 1979), hypothyroidism, hypo and hyper pituitarism (Becks, 1939; Hemley, 1941).

4. *Asthma / Allergy*– According to recent observations, allergic (especially asthmatic) patients, seem to have a tendency for root resorptions (Davidovitch, 1997).

Conditions that were implicated in contributing to the production of such mediators were gingivitis, asthma, and alcoholism. Davidovitch et al[3] 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 panoral films, concluded a statistically significant increase in root resorption post orthodontics in asthmatics when compared to non-asthmatics. However this increase was only associated with grade 1 (root blunting).

5. *Nutrition* – Linge and Linge (1983) suggested malnutrition as a major influence.

6. *Chronological age* – Younger patients seem to be less prone to root resorption Linge and Linge, 1991). The relationship between root resorption and orthodontic treatment was investigated by Shafer et al., (1983) and Reitan (1985). They concluded that root resorption was more prevalent in adults.

7. *Dental age* – Rosenberg (1972) reported that incompletely formed roots showed less resorption and still reached their normal root length than those with completely formed roots. Roots that are partially formed appear to develop normally during orthodontic treatment although if treated vigorously root development may be stunted (Rudolph, 1936, 1940).

8. *Gender* – Harris (1997) reported that sex is not a factor affecting root resorption, although a statistically significant correlation has been suggested by Baumrind (1996). Newman (1975) reported a ratio of 3.7 to 1 (females to males).

9. *Presence of root resorption before orthodontic treatment.*

10. *Habits* – Finger sucking persisting beyond 7yrs and lip tongue dysfunction are significant risk factors for root resorption (Linge, 1994). Nail biting has also been implicated (Odenrick, 1985).

11. *Tooth morphology* – Long, narrow, abnormal root shapes are significant risk factors (Mirabella, 1995; Kjaer, 1995) as with convergent apical root canal (Kinsella, 1971), and blunt or pipette shaped roots (Levander, 1988). Patients with dental agenesis, invaginations, and taurodontism are reported to have an increased risk of root resorption (Kjaer 1995).

12. *Previous trauma* - Linge and Linge (1991) significantly related trauma to root resorption. Andreason (1988) suggested orthodontic treatment could initiate the process in teeth with a previous history of root resorption.

13. *Endodontic treatment* – Mirabella (1995) stated that endodontic treatment was a preventive factor. Reitan (1985) showed increased resistance was due to increased dentine hardness and density.

14. *Alveolar bone density* – More resorption occurs with dense alveolar bone than with less dense alveolar bone (Reitan, 1985). The same resorption occurs with strong continuous force on less dense bone as a mild continuous force on highly dense alveolar bone (Reitan, 1985).

15. *Malocclusion* – Harris (1997) demonstrated greater ANB values and low angle cases are associated with greater external root resorption. Linge and Linge (1991) noted significant resorption related to increased overjet and impacted canines. Kaley and Phillips (1991) reported significant root resorption associated with Class III surgical cases, ranging from 1.6 to 20.8% in maxillary and mandibular incisors. Gharfari (1994) proposed Orthognathic surgery influences root resorption by affecting the blood supply to the periodontal ligament, bone and cementum.

16. *Specific Tooth* – the most frequently affected teeth are the maxillary laterals then centrals, followed by the mandibular incisors, distal root of the lower first molar, second premolars and the maxillary second premolars (Brezniak and Wasserstein, 1993).

2.6.2.6 Mechanical Factors:

Mechanical Factors include (Brezniak and Wasserstein 1993):

1. *Appliances,*
2. *Movement type,*
3. *Force* and
4. *Treatment duration.*

Katona (1994) showed that compression of periodontal ligament that was associated with intrusion and pure translation resulted in root resorption. Although all types of tooth movement can cause resorption, intrusion produced significant decrease in root length (Beck and Harris 1994)

Exceeding the optional force can cause periodontal ischemia leading to root resorption (Brezniak and Wasserstein 1993). Although a pause provided by intermittent force can allow resorbed cementum to heal (Reitan 1964), detrimental effects have been linked to the jiggling force generated (Stuteville 1937, Goz and Radosi 1989). Increased resorption due to elastics wear and occlusal trauma may be due to unbalanced chewing pattern causing muscular forces (Ghafari 1994).

Most studies indicated that the severity is directly related to treatment duration (Brezniak and Wasserstein 1993). Rudolph (1936) found root resorption increases with treatment duration with 100% of patients demonstrating the process after 7 years of active treatment. The amount of root loss during treatment is 0.9mm/year according to Goldin (1989). Levander and Malmgren (1988) have demonstrated minor resorption or irregular contour of root seen 6-9 months after last radiograph indicate an increased risk of further root resorption.

2.6.2.7 Casual Factors

Casual Factors include (Brezniak and Wasserstein 1993):

1. Physiological,
2. Orthodontic tooth movement,
3. Pressure from impacted teeth, tumors or cysts, periapical or periodontal infection, tooth implantation or
4. Re-implantation,
5. Occlusal trauma,
6. Metabolic, systemic and idiopathic factors.

An improved knowledge of the biological and clinical aspects of root resorption will lead to better prevention, diagnosis and treatment to decrease the biological cost to the patient. It is widely accepted that the root surface is more resistant to resorption than alveolar bone. It is also known that the number and the severity of resorptions are markedly increased by orthodontic treatment (Massler and Malone 1954) (Bosshardt and Selvig 1997).

2.6.3 Repair

Following the detachment of odontoclasts from the root surface, cementogenic cells repopulate the Howship's lacunae and attach the initial repair matrix to thin decalcified layer of residual and exposed collagen fibrils (Bosshardt and Selvig 1997).

Bosshardt and Schroeder (1994) described the mechanism by which the new repair matrix becomes attached to the resorbed root surface. The results can be summarized as follows:

(1) Following the resorptive phase, the odontoclasts withdraw from the resorbed root surface, and the bottom of Howship's lacunae left behind is lined by an about 1- to 2-μm-thick seam of exposed collagen fibrils representing demineralized, residual dentinal matrix.

(2) The periphery of resorption lacunae becomes populated by a particular class of mononuclear cells that closely adapt to the residual matrix.

(3) These mononuclear cells produce a collagenous fiber fringe (FF), the base of which is intermingled with the collagen fibrils of the residual dentinal matrix.

(4) Advanced stages of FF formation resemble the matrix of AEFC. Fibroblast-like cells, interspersed among the FF matrix, partition the extracellular space into discrete, fiber-containing compartments.

(5) Following the establishment of this fiber attachment, the junctional zone between the initial repair matrix, i.e. the FF and the residual dentinal or cemental matrix, becomes obscured by a basophilic, fine granular and electron-dense material. However, the junctional zone later attains exceptionally strong electron density and basophilia and then represents a reversal line.

(6) Further apposition of repair matrix is usually performed by cementoblasts and results in the formation of CIFC.

2.7 Physical Properties of Cementum

Cementum composition determines, at least to a certain degree, the biophysical properties of this tissue (Schroeder 1986). The physical properties considered here, will be limited to hardness and elastic modulus (inversely proportional to elasticity).

2.7.1. Hardness

Hardness is defined by Greener (1972) as the resistance to deformation caused by penetration, scratching or bouncing an object on a test surface of various degrees of polish.

Boyer (1987) defines hardness as the ability of a material to withstand permanent deformation through indentation. Hodge and McKay (1933) also consider scratching, cutting, elastic impact and permanent deformation as a means for determining hardness. Resistance to scratching was developed for mineralogical use by Mohs, who arranged a hardness scale of ten minerals by placing the material that scratches into the other in a higher series (Hodge, 1936).

Hardness is not a fundamental property of a material, however it is a cheap and relatively simple means of acquiring information on the mechanical properties of materials (Boyer 1987), such as cementum. 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).

There is a basic relationship between hardness and some other properties in metals, namely modulus and yield stress. An indentation on metal is permanent and the result obtained can be related to yield stress in compression (Tabor *1951;* Johnson 1985; Ashby and Jones 1986).

2.7.1.1 Micro-Indentation

Indentation testing can be classified into two categories. The first is macro-indention where loads greater than 1 kg are applied. The second are micro- indentation tests that use loads less than 1 kg. Micro- indentation tests are commonly used in testing dental materials (Willems *et al,* 1993). Weaver (1966) suggested no firm definition of microhardness but 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.

In static indentation tests, a load is applied to a conical or pyramidal indenter (Fig. 2.6) 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 (Boyer 1987). The hardness tests commonly used are Brinell, Knoop, Rockwell and Vickers and they are employed in different circumstances depending on the test materials. However, 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 (Boyer 1987). 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 two most common micro-indentation tests were the Knoop and Vickers micro-indentation tests (Ryge *et al,* 1961). The Vickers test applied a load of 10-500 g, which resulted in diagonals of 10-100 μm at depths of 1-10 μm (Willems *et al,* 1993). To measure the physical properties of a small layered surface 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 1μm of penetration produced.

In the case of Knoop and Vickers measurements, the hardness reported is a result of plastic deformation. Willems et al (1993) however, defines hardness that is measured by nano-indentation tests as the resistance to permanent (plastic) and non-permanent (elastic) deformation caused by indentation and cautions against the comparison of the results obtained by different.

The commonly used micro-indentation hardness tests for teeth are Knoop and Vickers hardness tests. 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. A cutting action occurs along the major axis of the indentation and spreading takes place along the minor axis. The stress is therefore distributed in such a manner that primarily only the dimension of the minor axis is subject to change by relaxation (Phillips 1996) (Fig. 2.6).

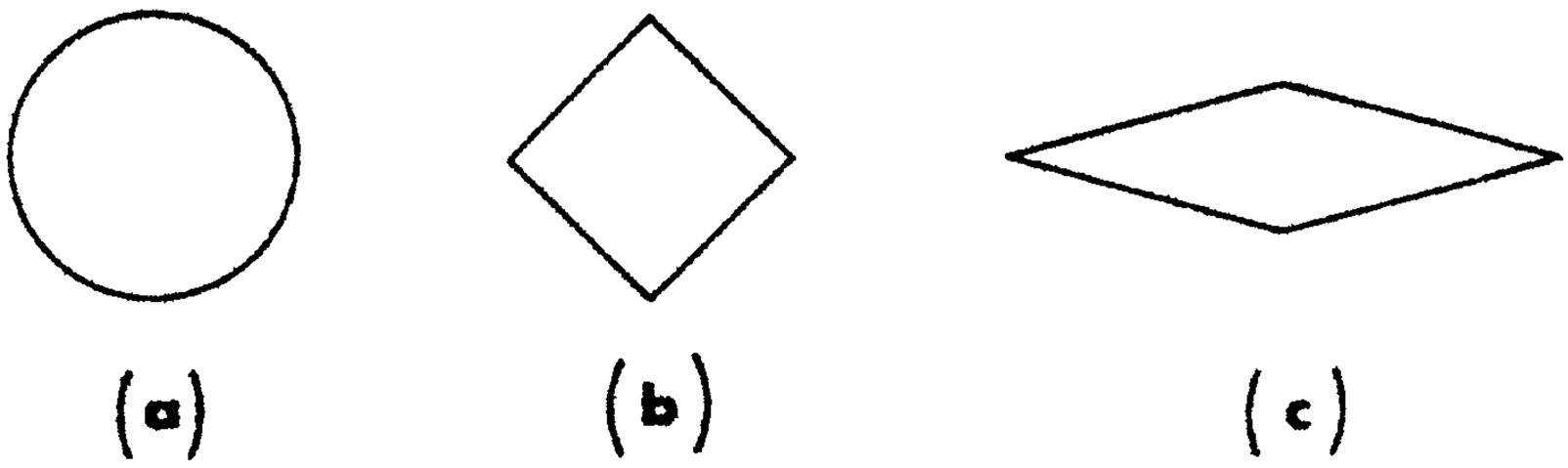


Figure 2. 6. Shape of indentations produced by hardness testers. (a) Brinell and Rockwell, (b) Vickers, (c) Knoop.

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:

$$KHN = P/Cl^2$$

where P is the load applied, l is the length of the long diagonal of the indentation and C is a constant relating l to the projected area of the indentation. The unit for KHN is kg/mm^2 (Boyer 1987, Askeland 1992).

The Vickers hardness 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. The resultant diagonals are measured and a Vickers hardness number (VHN) is then reported. The Vickers indenter appears to penetrate deeper than the Knoop for the same load and thus it is less sensitive to the surface conditions. Optical measurement errors are easily made with the Vickers indenter because of its small diagonal length (Boyer 1987).

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

$$VHN = 2P\sin(\theta/2)/d^2$$

where P is the load applied, d is the average length of the two diagonals and θ is 136°. The unit for VHN is kg/mm^2 (Boyer 1987, Askeland 1992).

The Vickers hardness test is useful where a small area and a hard material is 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.

The Brinell system uses a steel or tungsten carbide ball typically 1.6 mm in diameter. 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:

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

where P is the load in kg, D is the diameter of the ball in mm and d is the diameter of the indentation in mm (Boyer 1987; Askeland 1992). The BHN unit is kg/mm^2. The size of the ball indenter makes it unsuitable for a small area characterisation. For brittle ceramic materials such large indenters introduce Hertzian cone cracks rather than plastic deformation (Tabor 1986).

These traditional testing methods required direct imaging of the indentations to obtain a value of hardness. From these images the diagonals or diameters of the indentations were measured. This however, introduces the possibility of human error, which is the

inaccuracy of measurement that is possible when very small indentations are to be measured. The use of optical instrumentation was then used in an attempt to improve the measurement, however the tendency of one extreme of the indentation to be in focus while the other was not meant that this technique was still prone to errors, though not as great as previous errors. Throughout the refining of the testing process many other difficulties were encountered such as tester error in loading, rate of load application, duration of a contact period and impact (Boyer 1987). This reliability problem is somewhat overcome with the use of depth sensing and high resolution microscopy (Doerner and Nix 1986). Depending on the testing methods used various units of hardness are available. In this study the units given are gigaNewtons per square meter (GN/m^2), or gigaPascals (GPa). This property is indirectly related to other mechanical properties (Phillips 1996).

The interpretation of these more conventional hardness methods is governed by the fact that an indentor of known geometry is pressed into a material under a known load for a measured length of time. The hardness is calculated either by measurement of depth or area of indentation. A deep indentation indicates a soft material, and visa versa (Combe 1986). Various tests are listed in Table 2.2 and the respective indentors are seen in Figure 2.6.

Table 2. 2. Common Indenter Types

TEST	INDENTOR	MEASUREMENT	UNITS
Brinell	Steel ball	Area of indentation	BHN
Vickers	Diamond	Area of indentation	VHN
Knoop	Diamond	Area of indentation	KHN
Rockwell	Steel ball or diamond point	Depth of indentation	Rockwell*

*Rockwell hardness is expressed as a letter and a number, e.g.:
M105. The letter indicates the condition of testing, such as the load on the indentor, and the number indicates the hardness. For other testers, only a number is quoted.

2.7.1.2 Umis 2000

The Ultra Micro Indentation System (UMIS) is a nano-indentation instrument for the investigation of the material properties of coatings, thin films and the near surface region of materials. UMIS was developed at the National Measurement Laboratory in CSIRO *(Commonwealth Scientific and Industralial research Organisation (CSIRO), Sydney, Australia)*. UMIS has application for the investigation of very hard thin films such as cementum.

In the present study the nano-indentation technique developed by Bell et *al. (1991/1992)* is used.

The UMIS 2000 is a 'force-driven static measuring' ultra micro-indentation instrument for investigating the mechanical properties of near surface regions of materials. It has applications in surface engineering and in the development of surface modification processes.

It is 'force-driven' in that the indenter is driven into the surface until a resistance equal to a set force is met. It is 'static measuring' in that penetration is measured under conditions of force equilibrium at each of a series of force steps (Fig. 2.7).

Information is derived from the penetration on loading and also from the elastic recovery of the indentation on unloading.

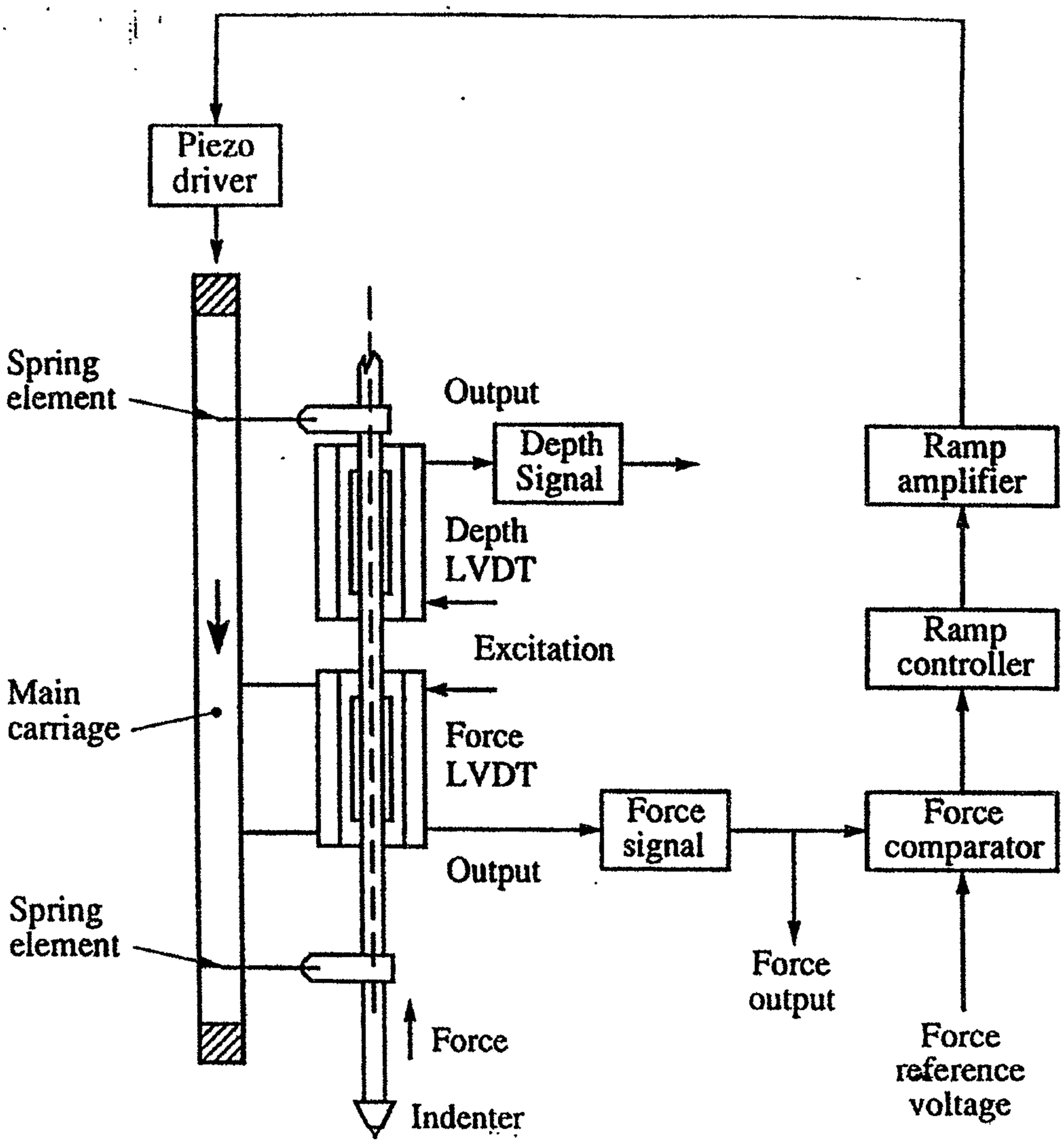


Figure 2. 7. Schematic diagram depicting the principle operation of the servo system and the depth measuring system in the UMIS.

There are two modes of operation available (CSIRO, 1993). These are:

1. Data acquisition by continuous load cycle
2. Data acquisition by partial unload cycle.

The UMIS 2000 can acquire data by either method other than insertion of the appropriate indenter. The indenting mechanism operates under the control of a computer program and requires only the appropriate software to perform either data acquisition sequence.

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

Indentation techniques have enabled the hardness and more recently the Modulus of Elasticity to be estimated (Swain 1999). A major limitation of continuous plots of force-displacement data is that only one value of contact pressure and elastic modulus is determined. A simple partial-unload procedure throughout the force / displacement curve enables a near continuous assessment of contact pressure and modulus of the specimen throughout the test. 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.

Numerical output includes:

a) hardness at maximum depth, H

b) composite elastic modulus, E^* in the form

$$\frac{1}{E^*} = \frac{1-Vm^2}{E_m} + \frac{1-v_i^2}{E_i}$$

Where Elasticity (E^*), Vm and Em are Poisson's ratio and elastic modulus of the material and Vi and E_i are Poisson's ratio and elastic modulus for the indenter.

2.7.2 Elasticity. Modulus Of Elasticity (Young's Modulus)

Modulus Of Elasticity and Young's Modulus are designated by the letter *E*. The slope of the straight-line region (elastic range) of the stress-strain diagram is a measure of the relative *rigidity* or *stress* of a material (Phillips 1996).

According to Craig (1993), the Modulus Of Elasticity (Young's Modulus) is related to the interatomic bonding forces within the material and usually is the same when the material is subjected to tension or compression.

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. For example, if one wire is much more difficult to bend than another of the same shape and size, considerably higher stress must be induced before a desired strain or deformation can be produced in the stiffer wire. Such a material would possess a comparatively high modulus of elasticity. Modulus of elasticity is given in units of force per unit area, typically, gigaNewtons per square meter (GN/m^2), or gigaPascals (GPa). This property is indirectly related to other mechanical properties (Phillips 1996).

2.7.3 Mechanical Testing of Teeth

Hardness testing is widely used to determine mechanical properties of materials. The structure of the test material may influence the hardness. Few materials are completely homogeneous. Defects such as microcracks and voids often exist (CSIRO 1993). 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) (Poolthong 1998).

2.7.4 Hardness of Cementum

Hodge and McKay (1933) where the first workers to consider the hardness of cementum. Hodge and McKay (1933) tested a sagittal section of a cuspid. The average hardness of cementum was found to be 85 Brinell Hardness numbers.

Craig and Peyton (1960) reported on the compressive properties of enamel, dental cements and gold. They mounted teeth in a cup containing impression compound such that the cusp or side of the tooth selected for sampling was parallel to the proposed axis of the specimen. The cup was designed so that it could be mounted on a jeweller's lathe. A hollow, diamond core was placed in the head stock of the lathe and a cylindrical blank was cut out of the tooth, using water as a coolant. These blanks were 0.060 inch in diameter and consisted of enamel on one end and dentine on the other. The core drill cut into the surface of the tooth at a right angle, and therefore the general direction of the enamel rods was parallel to the long axis of the cylinder.

The Compression testing involved the determination of the proportional limit, compressive strength, and elastic modulus of the various samples. The specimens were placed between two steel plungers, the deformation was obtained from optical strain gauges, and the load indicated by a reliable testing machine. The stress-strain curves for enamel were obtained, using a discontinuous loading rate. The load was increased in increments and the strain measured at these intervals. This procedure was possible, since no flow of enamel was observed, as had been the case with human dentine (Craig and Peyton 1960).

Rautiola and Craig (1961) obtained eighteen freshly extracted teeth. Patients were selected on the basis of no previous history to scaling. Four teeth were embedded directly

in casting plastic within 20 minutes after extraction. The remaining fourteen 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 was reported to have no apparent effect on microhardness of dentin and cementum (Rautiola and Craig 1961).

Rautiola and Craig (1961) used an "MO" Tukon hardness tester with a Knoop diamond indenter. A 25 gram load was used with a 15 second contact time. They obtained a total of 1640 indentations were completed spanning over 26 sections of 18 teeth. The data indicated that exposed and unexposed cementum are of equal hardness. For all teeth the mean KHN was 39.6 (±6.1) for unexposed cementum and 39.3 (±5.3) for exposed cementum. No measurable difference was observed in the microhardness of exposed and unexposed cementum. That is to say there was no recorded trend in hardness with respect to the age of the patient or to the depth of the periodontal pocket.

Measured in KHN (Knoop hardness numbers), fresh root cementum (i.e., both AEFC and CMSC), is very much softer than dentine, 39.6 ± 6.1 versus 69 ± 7 respectively (Rautiola and Craig 1961). Measured in VH (Vickers hardness, with a pressure of 25 p), cementum reveals an average hardness of 49.6 kg/ mm^2, ranging between 38.7 and 61.3 kg/mm^2 (Schemel et al. 1984).

Rautiola and Craig (1961) reported extremely wide variations in hardness among different locations of the same tissue of the same tooth. Some teeth, however, showed little variation in hardness among different locations. These variations account for the large standard deviations reported for some teeth and low standard deviations for other teeth. In eight teeth they were able to test the difference in microhardness between inner and outer layers of cementum. Microhardness values for outer and inner cementum was reported as the mean KHN for outer cementum was 41 (±6) and for inner cementum was 39 (±7). The difference between the means is not statistically significant, and therefore they concluded outer and inner cementum are not different in hardness apart from the

normal wide variations in hardness found throughout cementum. They could not explain the variation in hardness in their study (Table 2.3).

Table 2. 3. Microhardness of Cementum.

COMPARISON OF KHN FOR SURFACE CEMENTUM AND LONGITUDINALLY SECTIONED CEMENTUM RAUTIOLA AND CRAIG (1961)						
	Unexposed Cementum			Exposed Cementum		
Preparation of		No.	Std.		No.	Std.
Specimen	KHN	Read.	Dev.	KHN	Read.	Dev.
Sectioned	40	13	5.6	36	10	5.9
Surface	37	25	6.2	36	9	5.1

Rautiola and Craig (1961) used a Knoop hardness test and reported a hardness value of 40 KHN.

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) used the UMIS to measure the hardness and elasticity of human premolar teeth. They reported that the cementum in the apical third (H= 0.82 ± 0.08 GPa, E= 9.3 ± 0.23) gave lower hardness and elasticity values when compared to the cervical third (H= 1.5 ± 0.09 GPa, E= 12.3 ± 0.43).

Poolthong et al (1998) obtained different results. Hardness ranged between 0.57 - 0.63 GPa (Equivalent to 52 - 58 Vickers hardness numbers). Elasticity was reported ranging from 8.6 - 12.0 GPa. The elastic modulus of cementum was higher in the middle third than the apical third.

Clark (1997), using the UMIS 2000, found the mean value of hardness of cementum

from the apical third of premolar teeth to be 0.36 ± 0.08 GPa. The mean value of elasticity of cementum from the apical third of premolar teeth was 12.31 ± 2.03 GPa. 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 this difference but the most likely is that air storage of the female specimens allowed them to dehydrate causing an increase in the hardness value.

Clark (1997) found no statistical differences between the hardness of cementum from maxillary teeth when compared to those of either the mandible or the buccal surface when compared to the lingual surface nor when the premolar was in the first or second position. Also there were no statistical differences between the elasticity of cementum when all the variables were compared. Gender, arch, tooth position and tooth surface seemed not to affect the elasticity of the teeth measured.

Table 2. 4. Microhardness of Cementum – Summary.

AUTHOR	*YEAR*	*STORAGE MEDIA*	*TOOTH NO.*	*HARDNESS (ELASTIC MOD.)*	*LOCATION TESTED*
Hodge & McKay	1933		Cuspid	85 BHNs	Sagittal Section
Ichiro	1959	?	?	14-21 VHNs	?
Rautiola & Craig	1961	Formalin		40 KHNs	
Poolthong et al	1996	Saline	Premolar	1.5 GPa. (12.3 GPa)	Cervical Third
Poolthong et al	1996	Saline	Premolar	0.82 GPa. (9.3 GPa)	Apical Third
Clark et al	1997	10% Formalin. Sulphonic Acid. 70% Alcohol	Premolar	0.36 GPa. (12.3 ± 2.03 GPa)	Apical Third
Poolthong et al	1998	24hrs Miltons. Deionized Water.	Premolar	0.57-0.63 GPa. (8.6-12.0 GPa)	Middle Third. Apical Third

Elastic Modulus is reported in Brackets.

2.7.5 Hardness of Enamel

Enamel has been reported to behave anisotropically, ie., differently in different direction, with respect to stiffness (van Noort et al., 1991; Spears 1997, Lees and Rollins 1972).

Craig and Peyton (1961) 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.

Davidson et al (1974), reported human enamel hardness in KNH. The hardness recorded with the load applied parallel to the direction of the prism axis was 367 ±17 KHN. The hardness recorded with the load applied perpendicular to the direction of the prism axis was less at 327 ±34 KHN.

Willems et al (1993) reported enamel hardness as 3.4 GPa , which he obtained using a nano-indentation tip. He used loads of 0.2N applied to a pyramidal diamond indenter, having a triangular base.

Craig (1993) reported enamel hardness as 3.4 GPa. While more recently Poolthong (1998) reported enamel hardness as 3,4 ± 0.07 GPa.

2.7.6 Elasticity of Enamel

Differing values of proportional limit, elastic modulus, and ultimate compressive strength have been reported for enamel and dentine, depending on the area of the tooth from which they were obtained. The proportional limit, ultimate compressive strength, and elastic modulus of enamel are greater than the corresponding values for dentine. The elastic modulus of enamel is about three times greater than that of dentine and, depending on the study cited, it can be as much as seven times higher (Phillips 1996).