

An Investigation Of The Nature And Mechanism Of Crack Propagation For Dentine

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Abstract

Dentine fracture is a common presentation that often poses significant clinical difficulties. It is well established that teeth are particularly susceptible to fracture if the pulp has been removed. The diagnosis and management of teeth with vertical root fractures is reviewed so the clinical significance of tooth fracture would be a major focus of this thesis (Appendix A). Prior studies have primarily been laboratory experiments which have examined particular mechanical properties or attempted to compare untreated teeth directly with endodontically treated teeth. There are many difficulties in establishing similar controls and test procedures with this approach. There has been little consideration that dentine is a fluid-filled composite material and how this dynamic aqueous environment would impact on the fracture process.

This thesis examined the nature and mechanism for fracture of dentine. As the thesis was intended to have a clinical focus, the surfaces of incompletely fractured cusps from symptomatic vital teeth were fractured and then examined by scanning electron microscopy to determine the nature of the fracture. From an engineering perspective, a SEM examination may determine if the fracture process has been rapid or progressed incrementally. Cyclic fatigue has been proposed as a mechanism of fracture for dentine as there is often a period of some years between the placement of a restoration and the development of symptoms associated with incomplete cuspal fracture. If crack propagation is progressive and incremental, as would be expected by the mechanism of cyclic fatigue, re-initiation of the fracture is required and the SEM examination should reveal blunting of the crack tip or distortion at the position of crack re-initiation. As reported in Chapter 4 the surface of the fractured cusps were almost entirely covered with bacteria. Numerous bacteria, of many morphological forms, were present on the

dentinal surfaces of all fractured cusps for all teeth. The bacterial contamination extended right through the dentine to the dentin-enamel junction. No partial fractures were observed and bacteria were not present on the enamel surfaces. The findings of this study of bacterial contamination complete to the dentino-enamel junction suggest that dentine fractures catastrophically as a consequence of a single traumatic incident.

In Chapter 5, the influence of hydration on the fracture of bovine dentine was investigated. Specifically, hydrated, dehydrated, and re-hydrated dentine specimens were compared. A measure of fracture toughness, the work of fracture was used. This study investigated the nature of deformation and differences in the mechanisms of fracture and properties of dentine where there has been a loss of moisture, as may occur with removal of the pulp in the endodontic treatment of teeth. Controlled fracture toughness testing was conducted on bovine teeth to determine the influence of hydration on the work of fracture of dentine. Significant differences ($p < 0.01$) were observed between the fracture toughness of hydrated ($554 \pm 27.7 \text{ J/m}^2$) and dehydrated ($113 \pm 17.8 \text{ J/m}^2$) dentine. Observations of the crack tip region during crack extension revealed extensive ligament formation occurred behind the crack tip. These ligaments provide considerable stability to the crack by significantly increasing the work of fracture, thereby acting as a fracture toughening mechanism. Micro-cracking, reported as a fracture toughening mechanism in bone, is also clearly seen. A zone of in-elastic deformation may occur as hydrated specimens revealed upon crack extension, a region about the tip that appeared to suck water into the structure and to exude water behind the crack tip. In dehydrated dentine, no in-elastic zone was observed. Micro-cracking is present though the cracks are smaller, straighter and with less opening than hydrated dentine. Only limited ligament formation just behind the crack tip was observed. These differences resulted in a significantly lower work of fracture with unstable brittle

fracture characteristics. Based on these results, several fracture-toughening mechanisms were identified in dentine, with micro-cracking not considered the most important. These findings may be relevant for bone, a similar mineralized, hydrated tissue.

The mechanism for fracture of dentine remains unclear. However the presence of fracture toughening mechanisms, identified in bone and composite materials, has now been identified for dentine. Different fracture toughening mechanisms were identified for hydrated and dehydrated dentine, and these differences resulted in a significantly lower work of fracture for dehydrated dentine.

Declaration

Candidate’s Certificate

This thesis is the original work of the author, except where acknowledgement has been made in the text. None of the material in this thesis has been submitted for any diploma or degree.

.....
Bill Kahler, 2002

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Preface

Dentine fracture is a common presentation that often poses significant clinical difficulties. It is well established that teeth are particularly susceptible to fracture if the pulp has been removed. The diagnosis and management of teeth with vertical root fractures was reviewed so the clinical significance of tooth fracture would be a major focus of this thesis (Appendix A). The nature and mechanism of dentine fracture is not clear. In the first part of this thesis, the surfaces of incompletely fractured cusps from symptomatic vital teeth were fractured and then examined by scanning electron microscopy to determine the nature of the fracture (Chapter 4). This chapter has been published in the Australian Endodontic Journal. The second part of the thesis examined the difference in fracture toughness for dentine by measuring the work of fracture for hydrated, dehydrated and re-hydrated dentine. Differences in the mechanisms of fracture for the hydrated and dehydrated state were also investigated (Chapter 5). The manuscript for this chapter has been accepted for publication in the Journal of Biomechanics.

Each chapter based on experimental work (Chapters 4 and 5) has been written as a separate unit, in the format of a manuscript for publication. A general discussion and appendices appear at the end of the thesis, and each chapter has a separate reference list.

CHAPTER 1 INTRODUCTION

The mechanical properties of dentine are important in determining how masticatory and traumatic loads are distributed throughout the tooth (Marshall, 1993; Marshall, Marshall, Kinney & Balooch, 1997). A function of dentine is to transmit and dissipate these loads (Lin & Douglas, 1994). Dentine possesses an inherent toughness and is able to resist fracture as a result of the orientation of the collagen fibrils that counter the directional effect of the dentinal tubules, thereby exhibiting crack stopping behaviour (Renson, Boyde & Jones, 1974).

However, the mechanical forces generated by functional and parafunctional occlusion cause biomechanical changes in teeth such as tooth wear, mechanical yielding, and tooth fracture (Lin & Douglas, 1994). The mechanism of fracture is thought to be cyclic fatigue where the crack in dentine propagates in small increments in response to the occlusal load (Bell, Smith & de Pont, 1982; Arola, Huang & Sultan, 1999). Yet dentine often fractures catastrophically from a traumatic incident such as biting on a hard substance and thereby displaying a characteristic of a brittle material. Also, the mechanism of dentine fracture for vertical root fractures that involve vital and endodontically treated teeth is not known (Lertchirakarn, Palamara & Messer, 1999).

From the perspective of theoretical mechanics, the structural stability of dentine is a function of mineralisation and moisture content (Kinney, Balooch, Marshall & Marshall, 1993). Dentine, courtesy of its tubular structure, is a porous, fluid filled mineralised tissue that provides mechanical support to overlying enamel and the integrity of the tooth (Pashley, 1991). A positive pulpal pressure ensures an outward flow of fluid from the pulp along dentinal tubules (Fish, 1932; Pashley, 1992). In

restored teeth, a continuum of fluid filled channels exists between prepared tooth surfaces and restorative materials through dentinal tubules to the pulp (Brännström, 1984; 1986; Pashley, 1991; Bergenholtz, 1990; Lam & Wilson, 1999). Dentine fluid provides biomechanical integrity to the tooth and the fluid filled tubules may function to hydraulically transfer and relieve the stresses that are applied to teeth (Pashley, 1989; 1990). The influence that water plays in the biomechanical behaviour of teeth is not well understood or fully investigated (Huang, Schilder & Nathanson, 1992).

There is a clinical impression that endodontically treated teeth are more brittle (Pashley, 1990; Rosen, 1961; Johnson, Schwartz & Blackwell, 1976; Greenfeld & Marshall, 1983; Radke & Eissmann, 1991; Douglas, 1996). The reduction in tooth structure due to the carious, restorative and endodontic intervention significantly weakens the tooth structure making it more susceptible to fracture (Reeh, Messer & Douglas, 1989). This does not fully explain why endodontically treated teeth are more susceptible to fracture over time.

The perception of brittleness has also been attributed to a decrease in the moisture content. This is primarily a result of a study by Helfer, Melnick and Schilder (1972), where the moisture content of pulpless teeth from a dog were shown to have 9% less moisture content than vital teeth. Papa, Cain & Messer (1994) questioned the methodology of this study. They reported that the moisture content of vital dentine was 12.35%, in contrast to the moisture content of 12.10% from dentine of teeth that had been endodontically treated. This result was not considered statistically significant. Therefore, the moisture content of vital and endodontically treated teeth were considered similar. Huang et al. (1992) observed that as pulpless teeth exist in a water based environment of saliva in the mouth, as well as blood and tissue fluid surrounding the root, dentine should not dry out as both enamel and cementum have been

demonstrated to be permeable to water. However, enamel and cementum are relatively impermeable and act as a rate-limiting barrier to fluid with significantly slower flow rates than dentine (Pashley, 1990; Petelin, Skaleric, Cevc & Schara, 1999). Also, the removal of the pulp, pathological and iatrogenic changes to dentine, known to reduce the permeability of dentine, should logically effect the hydration of dentine with time.

A number of studies have examined the biomechanical properties of endodontically treated and vital teeth and suggest that teeth do not become more brittle following endodontic treatment. Stanford, Weigel, Paffenbarger and Sweeney (1960) examined three pairs of patient-matched vital and pulpless incisors, and reported no significant differences in the modulus of elasticity, proportional limit and strength of dentine. Taylor (1961) concluded from cantilever bending studies that the strength and modulus of elasticity of dentine from vital and endodontically treated teeth was similar. Sedgley and Messer (1992) examined the punch shear strength, toughness and load to fracture of 23 endodontically treated teeth and their contralateral pairs, and found no statistically significant differences. Huang et al. (1992) reported that the compressive and tensile strengths of dentine from pulpless teeth were statistically similar to vital teeth. Lewinstein and Grajower (1981) reported no difference in the Vickers microhardness of dentine from the teeth of 16 extracted vital teeth and 32 endodontically treated teeth extracted up to ten years after endodontic treatment. Rivera and Yamauchi (1990) reported that the collagen cross-linkage of dentine from age- and site- matched endodontically treated and vital teeth contained no statistically significant differences.

Conflicting reports also exist in the literature. Carter, Sorenson, Johnson, Teitelbaum and Levine (1983) examined 21 freshly extracted vital teeth and six teeth that had been endodontically treated, and reported a 14% reduction in the punch shear strength and toughness. Sedgley and Messer (1992) found that vital dentine was 3.5%

harder than contralateral endodontically treated teeth. Huang et al. (1992) examined 54 freshly extracted teeth and 24 pulpless teeth, and found the pulpless teeth had lower values for Young's modulus and a lower proportional limit in compression. Half of the dentine specimens from pulpless teeth exhibited greater plastic deformation than vital teeth in compression.

There are many difficulties associated with the mechanical testing of teeth and dentine due to the size and shape complexity of the test samples. Trauma may be associated with extraction and thermal damage may occur during preparation (Waters, 1980). There are difficulties in obtaining comparable test protocols and test procedures as it is impossible to maintain the original moisture content of either vital or endodontically treated teeth (Huang et al., 1992). The use of a constant water flow during specimen preparation and different storage media will affect the water content of specimens (Jameson, Tidmarsh & Hood, 1994). Most studies addressing the perceived brittleness of endodontically treated teeth have attempted to compare untreated teeth directly with root filled teeth (Jameson, Hood & Tidmarsh, 1993). They argue that the examination of biomechanical properties of endodontically treated teeth have focussed on the strength and modulus of elasticity of dentine. Strength is not a measure of toughness, being the energy required to induce fracture. Also, strain beyond the proportional limit would not be apparent from the modulus of elasticity. Therefore, calculation of stress and strain is required. An examination of fracture toughness, which is a measure of the inherent resistance of a material to crack extension and can be evaluated from a pre-cracked specimen (Vashishth, Behiri & Bonfeld, 1997), is an appropriate measure. Rasmussen, Patchin, Scott and Heuer (1976) used the work to fracture approach, which provided a direct measurement of the fracture properties of dentine.

Failure of dentine under load is a response to the presence or formation of a micro-crack, and subsequent propagation leading to macro-crack growth. The toughness of dentine, being the energy required to induce fracture, has been shown to be significantly reduced by dehydration (Jameson et al., 1993). They further observe that the changes in biomechanical properties as a result of dehydration could be completely reversed by re-hydration. This suggests that the presence or absence of fluid in dentinal tubules will alter the behaviour of dentine when mechanically loaded. They further note that dehydrated dentine exhibited a lack of plastic flow and required less energy to induce fracture than hydrated dentine. Plastic flow provides a resistance to crack propagation (Park & Lakes, 1986). Therefore, the absence of fluid has a profound influence on the fracture properties and behaviour of dentine.

This thesis aims to investigate the nature and mechanism for fracture of dentine. Firstly, in an attempt to assess the mechanism of fracture, the surfaces of fractured cusps were examined by scanning electron microscopy to determine if the fracture propagated by cyclic fatigue or, fractured catastrophically as a single incident consistent with brittle behaviour. Further investigations were conducted to quantify the difference in fracture toughness by measuring the work of fracture for hydrated, dehydrated and re-hydrated dentine. Differences in the mechanisms of fracture for the hydrated and dehydrated state were also investigated.

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CHAPTER 2 REVIEW OF THE LITERATURE

Fracture of dentine is a significant and common clinical occurrence for dentists. However, the nature and mechanism of crack propagation remains unclear. A focus for this literature review will be on the hydrodynamic movement of fluid within dentine, as Pashley (1990) suggested that dentine fluid provides biomechanical integrity to the tooth, and that the fluid filled tubules may function to hydraulically transfer and relieve the stresses that are applied to the teeth. Furthermore, Huang, Schilder and Nathanson (1992) noted that the influence that water plays in the biomechanical behaviour of teeth is not well understood, nor fully investigated.

This literature review includes:

1. Clinical aspects of dentine fracture
2. A discussion of theoretical fracture mechanics
3. Prior fracture toughness studies of dentine
4. Composition and structure of dentine
5. Biomechanical properties of dentine
6. Permeability of dentine
7. Effect of pathological changes and iatrogenic procedures to the permeability of dentine
8. Composition and permeability of enamel and cementum

2.1 Dentine Fracture

Tooth fracture may occur in both horizontal and vertical directions involving the crown and/or root. The fractures are a result of occlusal forces and iatrogenic

procedures (Bender & Freedland, 1983). Crown and crown-root fractures are usually incomplete fractures commencing in the crown of posterior teeth from an internal line angle at the floor of a restoration, and often involving a marginal ridge with the fracture extending in a mesiodistal direction. The fracture commences in the crown and may terminate in the vicinity of the cemento-enamel junction or extend apically into the root (Cameron, 1964; Hiatt, 1973; Walton, Michelich & Smith, 1984; Goel, Khera, Gurusami & Chen, 1992; Arola, Huang & Sultan, 1999). Vertical root fractures are longitudinally orientated fractures of the root that extend from the root canal to the periodontium (Pitts & Natkin, 1983). These fractures are usually complete and extend a variable length along the root generally in a bucco-lingual direction and may extend into the crown (Meister, Lommel & Gerstein, 1980; Walton et al., 1984; Holcomb, Pitts & Nicholls, 1987; Murgel & Walton, 1990).

2.1.1 *Clinical Presentation*

2.1.1.1 Coronal Dentine Fracture

2.1.1.1.1 *Terminology and Definition*

Tooth structure cracks should be differentiated from simple enamel cracks or vertical fractures of the crown/root complex. A crack is an incomplete fracture and can be described as a line that breaks or splits the continuity of the dentine without visible separation of the segments giving the appearance of an intact tooth (Maxwell & Braly, 1977; Abou-Rass, 1983). Gibbs (1954) first described the clinical symptoms of incomplete fracture of posterior teeth involving the cusp, naming it 'cuspal fracture odontalgia'. Incomplete fracture has also been described as 'cracked tooth syndrome' (Cameron, 1964; 1976; Stanley, 1968; Snyder, 1976; Rosen, 1982; Ehrmann & Tyas,

1990; Homewood, 1998). An incomplete crown-root fracture (Hiatt, 1973), posterior fracture (Silvestri & Singh, 1978), greenstick fracture (Sutton, 1962), coronal fracture (Talim & Gohil, 1974; Lagouvardos et al., 1989) and an incomplete tooth fracture (Maxwell & Braly, 1977; Swepston & Miller, 1986; Baxter, 1987; Gutman & Rakusin, 1994).

Incomplete fractures can be found in symptomatic and asymptomatic teeth; and are an etiological factor in pulpal disease. This can be a direct result of fracture extension to physically involve the pulp chamber or, indirectly via the microleakage of bacterial toxins (Brännström, 1986). A crack line or incomplete fracture is a precursor for complete fracture of the cusp (Abou-Rass, 1983).

2.1.1.1.2 Classification

Several authors (Talim & Gohil, 1974; Silvestri & Singh, 1978; Luebke, 1984; Clark & Caughman, 1984) have proposed classifications, and as a result considerable overlap and confusion exists (Luebke, 1984; Swepston & Miller, 1986).

Talim and Gohil (1974) proposed the following classification:

Class 1 - Fracture involving enamel

- a. Horizontal or oblique
- b. Vertical
 - 1. Complete
 - 2. Incomplete

Class 2 - Fracture involving enamel and dentine without involving pulp

- a. Horizontal or oblique
- b. Vertical
 - 1. Complete
 - 2. Incomplete

Class 3 - Fracture of enamel and dentine involving the pulp

- a. Horizontal
- b. Vertical
 - 1. Complete
 - 2. Incomplete

Class 4 - Fracture of the roots

- a. Vertical or oblique
 - 1. Involving the pulp
 - 2. Not involving the pulp
- b. Horizontal
 - 1. Cervical third
 - 2. Middle third
 - 3. Apical third

Luebke (1984) proposed that vertical crown-root fractures are classified on the basis of their nature, extent, and the condition of the bone adjacent to the defect.

Class 1 - Incomplete, supra-osseous with no periodontal defect

Class 2 - Incomplete, intra-osseous with a minor periodontal defect

Class 3 - Complete or incomplete, intra-osseous with a major periodontal defect

Diagnostically, pain should be described as

1. *Dentinal*. A brief, sharp twinge.
2. *Pulpal*. The deep, demanding, radiating pain precipitated by thermal shock to an inflamed pulp. The pain at times may be spontaneous.
3. *Periodontal*. The aggravating throbbing of a sore tooth.

2.1.1.1.3 Incidence

The presence of an incomplete fracture occurs primarily in adulthood. Cameron (1964) reported that 80% of 102 cracked teeth occurred with patients over 40 years of age. Snyder (1976) reported that most fractures occurred with patients aged between 30-59 years. Talim and Gohil (1974) reported that incomplete fracture occurred mainly in middle aged or older patients. Conversely, Eakle et al. (1986) reported that 66% of patients with complete and incomplete tooth fractures were less than 40 years of age. Geurtsen (1992) reported prevalence was highest in the 30-39 year age group. Lagouvardos (1989) reported that 82% of fractures occurred with patients less than 49 years of age. Hiatt (1973) noted that the majority of cases occur before the age of 50 years. It would appear that incomplete fracture may be present in a wide range of the population.

The incidence of fracture is highest in the mandibular molars, though there is conjecture over which tooth is the most susceptible. Cameron (1976) and Hiatt (1973) reported the second mandibular molar had the highest incidence of fracture. Other studies have shown that the mandibular first molar had the highest incidence of fracture

(Abou-Rass, 1983; Cavel, Kelsey & Blankenau, 1985; Eakle et al., 1986; Lagouvardos et al., 1989; Geurtsen, 1992). It has been suggested that the wedging effect of the prominent mesio-palatal cusp of the maxillary first molar may account for this observation (Hiatt, 1973; Geurtsen, 1992). The transverse ridge of the maxillary molars may provide structural reinforcement and account for the lower incidence of fracture in these teeth (Hiatt, 1973). The maxillary molars and premolars have a similar incidence of fracture, with the mandibular premolars being the least susceptible (Abou-Rass, 1983; Eakle et al., 1986; Lagouvardos et al., 1989; Geurtsen, 1992).

The lingual cusp of mandibular molars is the most susceptible cusp for fracture. The findings for the prevalence of cusp fracture in other teeth were not consistent (Cavel et al., 1985; Eakle et al., 1986; Lagouvardos et al., 1989). Non-functional cusps have been reported as being more susceptible to fracture than functional cusps (Cavel et al., 1985; Eakle et al., 1986). This observation may be a result of cuspal dimension as functional cusps are significantly larger in a bucco-lingual dimension and are covered with a thicker layer of enamel (Khera, Carpenter, Vetter & Staley, 1990). Functional cusps are supported on the inner and outer inclines by the opposing tooth. The non-functional cusp may be more susceptible to fracture from lateral excursive occlusal forces due to the lack of support from the outer incline (Cavel et al., 1985). Molar non-functional cusps were found to have a steeper cuspal incline. As the cuspal inclines are the guiding planes for lateral excursive movements for group function occlusal relationships, these cusps may be subjected to greater occlusal forces. If other teeth in the arch have been restored with flatter cuspal inclines, then the steeper cusps are further exposed (Khera et al., 1990). Over-carving of a restoration during placement can result in the extrusion of a tooth, altering the cusp-fossae relationship and resulting in fracture of the non-functional cusp. However, the fracture of cusps, whether

functional or non-functional, is primarily associated with large intra-coronal restorations and carious lesions (Maxwell & Braly, 1977; Braly & Maxwell, 1981; Eakle et al., 1986).

2.1.1.1.4 Clinical Symptoms

The clinical signs and symptoms vary according to the position and extent of the incomplete fracture (Chong, 1989; Ehrmann & Tyas, 1990; Geurtsen, 1992). Classically, the symptoms related to these teeth are pain on biting and sensitivity to thermal changes, particularly cold (Gibbs, 1954; Cameron, 1964; 1976; Hiatt, 1973; Abou-Rass, 1983; Brännström, 1986; Ehrmann & Tyas, 1990; Homewood, 1998; Zimet, 1998). Pain associated with the release of pressure, 'rebound pain' is also a consistent finding (Cameron, 1976; Brännström, 1986; Ehrmann & Tyas, 1990; Homewood, 1998; Zimet, 1998). Occasionally, there is sensitivity to sweets (Stanley, 1968; Hiatt, 1973; Trushkowsky, 1991; Homewood, 1998). A chronic pulpitis can exist as a result of microleakage of bacterial by-products and toxins. Pulpal and periodontal symptoms will occur when the fracture extends to involve the pulp (Brännström, 1982; 1986; Bergenholtz, 1990).

2.1.1.1.5 Diagnosis

A provisional diagnosis can generally be attained by a thorough history of the complaint. Misdiagnosis may arise due to the conflicting pain symptoms of pain on biting, usually associated with non-vital teeth, and hypersensitivity to thermal shock (Abou-Rass, 1983; Ehrmann & Tyas, 1990). Early diagnosis is important, as restorative intervention can limit propagation of the fracture, subsequent microleakage and

involvement of the pulpal or periodontal tissues, or catastrophic failure of the cusp (Agar & Weller, 1988). The ease of diagnosis will vary according to the position and extent of the fracture (Ehrmann & Tyas, 1990; Geurtsen, 1992). Dentinal fractures are not generally evident radiographically, though necessary to assess for caries, periapical status and the presence of periodontal lesions (Abou-Rass, 1983; Ehrmann & Tyas, 1990). The use of a rubber dam to isolate the suspected tooth, and the application of hot or cold water is recommended. Once the tooth is identified, the offending cusp can be located by controlled wedging so as to load test individual cusps (Cameron, 1964; 1976; Abou-Rass, 1983; Ehrmann & Tyas, 1990; Geurtsen, 1992; Homewood, 1998; Zimet, 1998). When the tooth and cusp have been identified, the tooth can be anaesthetized and all restorations removed for a thorough visual inspection so as to identify the position and extent of the fracture. The use of dyes and transillumination are useful guides. Pulp testing will assess the vitality of the tooth and may be indicative of pulpal pathology. A tooth with an incomplete fracture will not be tender to percussion in a vital tooth (Abou-Rass, 1983; Ehrmann & Tyas, 1990).

2.1.1.1.6 Mechanism of Pain

The pain associated with incomplete fracture of a cusp is due to the rapid movement of dentinal fluid in the dentinal tubules. The theory is named the 'Hydrodynamic theory of dentinal sensitivity'. Thermal changes, air, evaporation, osmotic stimuli such as sucrose, and increases in hydrostatic pressure caused by cuspal flexure as a result of occlusal forces all act as stimuli for the rapid movement of dentinal fluid. This movement stimulates A-delta nerve fibres in the vicinity of the odontoblastic process and the pulp-dentine border, resulting in a sharp pain of short duration indicative of a vital tooth. Rebound pain, indicative of a vital tooth, is similarly

explained when the pressure is released from the cusp as the tooth is free of the occlusion (Brännström, 1982; 1986). When bacterial toxins have infiltrated the pulp, 'hyperalgesia' can result. With this condition A-delta fibres are stimulated producing a sharp pain of short duration at what appears as a lower threshold than normal. The pain is due to the rapid movement of dentinal fluid and probably a result of slight pulpal inflammation. During inflammation, the stimulation threshold of the A-delta fibres is lowered (Trowbridge, 1986).

A second type of pulpal pain is produced by the stimulation of C-fibres as a response to inflammation, heat and mechanical deformation. A dull, poorly localized ache is the result (Zyväsjärvi & Kniffki, 1989). Alternatively, the pain can be a dull, aching pain with a continuous throbbing nature, or arise spontaneously and last for minutes or hours (Figdor, 1994). The C-fibres are activated by inflammatory mediators as a result of pulpal inflammation or prolonged application of heat (Zyväsjärvi, Kniffki & Mengel, 1988).

A tooth with a painful pulpitis can present with a severe, sharp pain, indicative of A-delta fibre activation followed by a prolonged, dull ache that radiates throughout the jaw, indicative of C-fibre activation as well (Figdor, 1994). The C-fibres are resistant to tissue anoxia and can remain responsive long after the A-delta fibres (Närhi, 1985). A tooth with an incomplete fracture exhibiting C-fibre activation is strongly suggestive of pulpal damage and may require endodontic intervention. A clinician needs to carefully consider the character, duration and the stimuli of pain as this has important implications for both diagnosis and treatment (Figdor, 1994).

2.1.1.2 Root Dentine Fracture

The clinical, radiographic and diagnostic aspects of vertical root fracture have been comprehensively reviewed in: Moule, A.J., and Kahler, B. Diagnosis and management of teeth with vertical root fractures. *Aust Dent J* 1999; 44: 75-87. Refer to Appendix A.

2.1.2 Cause of Fracture

The use of high speed rotary instruments (Bender & Freedland, 1983; Xu et al., 1998; Arola et al., 1999), the placement of retentive pins (Silvestri, 1976), intraradicular post selection (Milot & Stein, 1995), forces associated with obturation (Dang & Walton, 1989; Saw & Messer, 1995), and post cementation pressure may result in the formation of microcracks that then propagate to produce a fracture. Extensive restorations, steep cuspal inclines resulting in tight cusp-fossae interdigitation, thermal cycling, functional and parafunctional forces, and masticatory accidents all make a tooth susceptible to fracture (Cameron, 1964; 1976; Hiatt, 1973; Maxwell, Braly & Eakle, 1986; Schweitzer, Gutmann & Bliss, 1989).

2.1.2.1 Coronal Fracture

The most common cause of coronal tooth fracture is the high impact force of biting on a hard object. This can result in a complete or incomplete fracture of the cusp (Cameron, 1964; Talim & Gohil, 1974). Teeth can be subjected to significant occlusal loads. During normal masticatory function, loads can range between 2.4-14.9 kg (23.5-146 N) on molar teeth (Anderson, 1956a; 1956b; De Boever, McCall, Holden & Ash, 1978). A maximum load of 90kg (880N) for a first molar has been reported (Howell & Manly, 1948). Helkimo (1978) found that maximum biting forces on molar

teeth ranged from 10-73 kg (98-715 N) with the average force being 45.7kg (448N) for males and 36.4kg (357N) for females. Forces on molar teeth are generally double those of the premolars (Arnold, 1981). These forces can potentially be exceeded during parafunction (Attanasio, 1991). Predisposing factors include large internally retained restorations, wear, steep cuspal inclines and/or grooves in the occlusal morphology of the tooth (Maxwell & Braly, 1977). Non-functional cusps have been reported as being more susceptible to fracture (Cavel et al., 1985; Eakle et al., 1986a). This observation may be a result of cuspal dimension, as functional cusps are significantly larger in the bucco-lingual dimension with a thicker layer of enamel (Khera et al., 1990). However, the presence of large restorations or carious lesions is primarily associated with most fractures (Eakle et al., 1986a; Hood, 1991).

The pioneering study by Vale (1956) demonstrated that conservative cavity preparation increased the strength of the restored tooth. When the isthmus width was extended from one-quarter to one-third of the intercuspal distance, the force required for fracture was two-thirds that of the intact control. Isthmus widths of one-quarter required a fracture force similar to control teeth. Mondelli, Steagall, Ishikiriama, Navarro and Soares (1980) demonstrated a decrease in strength even for narrow Class 1 preparations. The preparation of MOD cavities where the marginal ridge is lost results in the greatest loss of tooth strength (Reeh, Messser & Douglas, 1989; Hansen, Asmussen & Christiansen, 1990; Hood, 1991; Panitvisai & Messer, 1995). The presence of sharp internal line angles does not appear to weaken the tooth (Re & Norling, 1980; Eakle & Braly, 1985). Blaser, Lund, Cochran and Potter (1983) reported that teeth with narrow isthmus / deep pulpal floor preparations were significantly weaker than those with a wide isthmus and shallow floor. Re, Draheim and Norling (1982) also noted that the severity of the fracture was associated with the depth of the

restoration. Malcolm and Hood (1977) demonstrated that the increased removal of tooth structure resulted in increased cuspal flexure. Hood (1991) reported that the cuspal deflection is 11 μ m for an intact tooth, 16 μ m for a minimal Class 1 cavity, 20 μ m for a conservative Class II MO cavity, 24 μ m for a conservative MOD cavity and 32.5 μ m for extensive MOD cavities. Endodontic access resulted in a 2-3 fold increase in cuspal deflection. However, Reeh et al. (1989) reported that endodontic access reduced tooth stiffness by only 5%. The methodology of this study was questioned as the endodontic access was cut within the confines of the occlusal cavity floor. Panitvisai and Messer (1995) reported that cuspal deflection was greatest following endodontic access. In this study, endodontic access included the removal of all dentine between the pulp chamber and the proximal boxes. As a result, the depth of the cavity is the floor of the pulp chamber. Hood (1991) suggested that cusps behave like cantilever beams where the deflection of the unsupported cusp is proportional to the cube of its length. Hood's cantilever hypothesis may be the primary explanation for the higher incidence of fracture in endodontically treated teeth. Therefore, teeth that have not been restored with cuspal overlays are more susceptible to fracture (Tidmarsh, 1976; Salis, Hood, Kirk & Stokes, 1987; Morin, Douglass, Cross & DeLong, 1988; Hansen et al., 1990; Hood, 1991; Linn & Messer, 1994; Panitvisai & Messer, 1995).

2.1.2.2 Root Fracture

Vertical root fracture is usually associated with endodontically treated teeth (Gher, Dunlap, Anderson & Kuhl, 1987; Meister et al., 1980; Pitts & Natkin, 1983; Moule & Kahler, 1999), although occurrence in non-restored teeth has been described (Yang, Rivera & Walton, 1995; Yeh, 1997; Chan, Tseng, Lin, Huang, Tsai & Chen, 1998). It

is reported that endodontically treated teeth are more brittle and at risk of fracture as a result of decreased moisture content (Helfer, Melnick & Schilder, 1972). Carter, Sorenson, Johnson, Teitelbaum and Levine (1983) reported that dentine from endodontically treated teeth showed a reduction in punch shear strength and toughness relative to vital teeth. These results have been qualified by other studies. Papa, Cain and Messer (1994) reported no significant water loss in contra-lateral pairs of teeth where one tooth had been endodontically treated. Stanford, Weigel, Paffenbarger and Sweeney (1960) reported no significant differences in modulus of elasticity, proportional limit and strength of dentine between pulpless and vital teeth. The hardness of dentine was found not to be altered by endodontic treatment (Lewinstein & Grajower, 1981). The compressive and tensile strengths of dentine from endodontically treated and vital teeth is reported to be similar (Huang et al., 1992). Sedgley and Messer (1992) reported that the punch shear strength, toughness and load to fracture is similar for endodontically treated teeth and their contra-lateral pairs.

Excessive enlargement of the root canal may weaken the tooth and increase the susceptibility for vertical root fracture (Bender & Freedland, 1983). Wilcox, Roskelley and Sutton (1997) have demonstrated that the more root dentine that is removed then there is an increased likelihood of fracture. McCann, Keller and LaBounty (1990) reported that 13% of mandibular molars had the thickness of dentine reduced to less than 0.3mm.

Wedging forces used in lateral condensation when the tooth is obturated is considered a common cause for vertical root fracture (Meister et al., 1980; Tamse, 1988; Saw & Messer, 1995). Lateral condensation has been shown to induce stresses and strains in the root of the tooth (Harvey, White & Leeb, 1981; Gimlin, Parr & Aguirre-Ramirez, 1986; Dang & Walton, 1989; Saw & Messer, 1995; Telli & Gülkan,

1998). These stresses are highest at the tip of the spreader and the apical third of the root (Gimlin et al., 1986; Telli, Gunel & Gunel, 1994). Canals that have a greater flare in their preparation will be subjected to more condensation force in the apical third of the root (Harvey et al., 1981). Lertchirakarn, Palamara and Messer (1999) suggested that vertical root fracture is initiated in the apical third of the root as a result of spreader induced strains. The fracture then propagates both apically and coronally. Hand spreaders, such as the D11T have been shown to produce significantly more strains in the root than finger pluggers (Dang & Walton, 1989; Lertchirakarn et al., 1999). Dang and Walton (1989) observed that vertical root fractures are observed months or years after obturation of the tooth and suggested that obturation resulted in a root surface strain that was incorporated into the root, creating micro-fractures. Vertical root fracture resulted from the additional stresses that were applied from occlusal forces applied to the restored tooth. Telli et al. (1994) suggested that areas of high stress and strain occur in local irregularities within the wall of the root canal from which the fracture is initiated. The maximum stress produced by lateral condensation in over instrumented canals is along the external facial plane (Ricks-Williamson, Fotos, Goel, Spivey, Rivera & Khera, 1995).

The load applied during lateral condensation was found to range from 1-3 kg (Harvey et al., 1981; Holcomb et al., 1987; Saw & Messer, 1995; Lertchirakarn et al., 1999). Pitts, Matheny and Nicholls (1983) reported that a spreader load of 7.2kg resulted in a vertical root fracture of a maxillary incisor, with 16% of the teeth tested fracturing at loads less than 10kg. Holcomb et al. (1987) found that with the smaller mandibular incisors, a load of only 1.5kg resulted in fracture, with 13% of the teeth tested fracturing at loads less than 3.5kg. However, the mean load required to induce fracture ranges from 10-20 kg (Pitts et al., 1983; Saw & Messer, 1995; Lertchirakarn et

al., 1999). The loads and strain recorded at obturation are significantly lower than those recorded at fracture (Saw & Messer, 1995; Lertchirakarn et al., 1999). Finite element analysis concludes that the maximum stresses transferred to dentine are considerably lower than the tensile strength of dentine (Telli & Gülkan, 1998; Telli, Gülkan & Raab, 1999). These results suggest that lateral condensation should not be considered as the primary cause of vertical root fracture.

Restorative procedures, particularly post and core restoration can result in vertical root fractures. These fractures often have an angular direction and commence at the apical end of the post (Sorensen & Martinoff, 1984; Vire, 1991). Preservation of the maximum amount of sound tooth structure is required to reduce the risk of vertical root fracture (Guzy & Nicholls, 1979; Trope, Maltz & Tronstad, 1985; Sorensen & Martinoff, 1984). An adequate ferrule is required to bind the coronal tooth structure when the tooth is restored (Eissmann & Radke, 1976; Rosen & Partrida-Rivera, 1986; Barkhordar, Radke & Abbasi, 1989). Conversely, over enlargement of the post space weakens the root and increases the risk of fracture (Sorensen & Martinoff, 1984). The use of threaded posts (Ross, Nicholls & Harrington, 1991) and tapered posts (Sorensen & Martinoff, 1984; Deutsch, Cavallari, Musikant, Lepley & Petroni, 1985a; Deutsch et al., 1985b; Sorensen & Engleman, 1990) were associated with higher incidence of fracture. Tamse (1988) reported that vertical root fracture could be caused by cementation of posts in the root canal.

2.1.3 *Mechanisms of Fracture*

2.1.3.1 Coronal Fracture

Dentine fracture as a result of occlusal load is a result of microcrack initiation and propagation with subsequent macrocrack growth (Jameson, Hood & Tidmarsh, 1993). Mastication and parafunctional activity produce cyclic stresses that promote fatigue crack propagation. Fracture is often associated with far greater loads than those that occur during mastication. Fracture initiation begins from a defect or a small flaw and is due to a localization of high stress concentration (Arola et al., 1999). Artificial cleavage planes and sub-surface cracks are created during cavity preparation (Maxwell & Braly, 1977; Bell, Smith & de Pont, 1982; Xu et al., 1998). Finite element analysis has found that tensile stresses are greatest in the dentine at the base of the cavity where the sub-surface cracks may be found (Bell et al., 1982; Goel et al., 1992; Arola et al., 1999). Cuspal failure occurs due to crack propagation from repeated occlusal loading; the mechanism being progressive cyclic fatigue (Bell et al., 1982; Douglas, 1996; Arola et al., 1999).

Dentine possesses an inherent toughness and is able to resist fracture. This is due to the orientation and bonding of the collagen fibrils to the hydroxyapatite that counter the directional effect of the dentinal tubules. The dentinal tubules may act as a weak interface, thereby exhibiting a crack stopping behavior. Propagation of the fracture would require sufficient energy to re-initiate the fracture process (Renson, Boyde & Jones, 1974).

Toughness, being the energy required to induce fracture, has been shown to be significantly reduced by dehydration. In the dehydrated state, dentine demonstrates a

lack of plastic flow. This suggested that the presence of fluid in dentine increases the energy that is required to induce fracture (Jameson et al., 1993). Flow provides a resistance to crack propagation (Parkes & Lakes, 1986). Dentinal fluid provides biomechanical integrity to the tooth and the fluid-filled tubules may function to hydraulically transfer and relieve the stresses that are applied to a tooth (Pashley, 1989; 1990).

Fracture occurs by either brittle or ductile failure. Both modes of fracture may involve incremental crack propagation (Mencik, 1992). A brittle fracture generally occurs catastrophically with little or no plastic deformation and with low energy absorption. Ductile failure generally occurs over a long period of time with substantial plastic deformation and high energy absorption. Plastic deformation leads to a blunting of the crack tip, increasing the fracture strength (Callister, 1997). Hydrated dentine subjected to three-point bend tests demonstrated considerable plastic flow and resistance to fracture. In contrast, dehydrated dentine fractured with a complete absence of plastic flow (Jameson et al., 1993).

Brittle fracture occurs as a result of spontaneous and rapid crack propagation with little or no plastic deformation. Rasmussen, Patchin, Scott and Heuer (1976) examined fractured dentine where the crack growth was either parallel or perpendicular to the dentinal tubules. The work to fracture (W_f) for fracture parallel to the tubular direction was 550Jm^{-2} and for fracture perpendicular to tubular direction was 270Jm^{-2} . The difference in the values for W_f for the two modes of fracture was thought to be due to the different orientation of the collagen fibres. As these fibres are arranged perpendicular to the tubules, the energy required for crack propagation is greatest for parallel fracture. The W_f values are a ten fold increase on many ceramic materials, but many hundred times lower than ductile materials (Waters, 1980). Rasmussen et al.

(1976) concluded that dentine behaved as a brittle material and that forces generated in function and parafunction had the potential to initiate fracture in teeth with cavity preparations. Scanning electron microscopic examination of the fractured dentinal surfaces found there was no evidence of blunting of the crack tip or macroscopic displacement prior to crack initiation. These observations are consistent with brittle and spontaneous failure. It has been shown with catastrophic failure with high propagation rates such as impact forces, the direction of fracture is not affected by tubular orientation (Renson et al., 1974). Therefore, two modes of fracture may exist where the stress relaxation mechanisms, such as hydration and the visco-elastic properties of dentine, that are present at the crack tip at low rates of propagation may be virtually absent for catastrophic failure (Waters, 1980).

The mechanism of cuspal fracture is still not fully understood. A major difficulty is that the methodology of most laboratory studies examining cuspal loading and fracture have utilized slow load rates and rigidly mounted teeth. Slow load rates do not simulate the in vivo situation where fracture of the cusp is associated with the rapid application of force to an internal cusp plane (Salis et al., 1987). Crack propagation is spontaneous at the time of failure and may have propagated by cyclic fatigue failure after restoration placement.

2.1.3.2 Root Fracture

Gher et al. (1987) reported that 71% of fractured teeth have been endodontically treated. Lateral condensation is considered to be a cause of vertical root fracture (Meister et al., 1980; Pitts et al., 1983; Holcomb et al., 1987; Tamse, 1988). A high concentration of stress associated with the spreader may initiate the fracture point

(Walton et al., 1984; Gimlin et al., 1986; Telli et al., 1994; Saw & Messer, 1995). Finite element analysis has shown that the highest stresses occur near the tip of the spreader and at the apex (Gimlin et al., 1986). Surface irregularities and grooves in the canal could also contribute to a high concentration of stresses in the root (Pitts et al., 1983; Telli & Gülkan, 1998). Saw and Messer (1995) suggested that strains are generated as a result of the wedging action of the spreader. Dang and Walton (1989) suggested that strains may be introduced into root dentine during obturation that result in subsequent fracture as the tooth is subjected to occlusal forces.

Post selection and cementation are also implicated as further causes of vertical root fracture (Tamse, 1988; Sorensen & Engleman, 1990). Finite element analyses show that the highest concentration of stresses occur in the dentine immediately surrounding the post apex (Pao, Reinherdt & Krejci, 1987).

The literature is inconclusive as to the mechanism of fracture. A high concentration of stress associated with the use of spreaders or posts particularly in areas of canal irregularities are most likely the position of fracture initiation.

2.1.4 *Treatment of Fracture*

2.1.4.1 Coronal Fracture

Treatment of incomplete fracture should involve recognition of predisposing factors for prevention, recognition of signs and symptoms and the provision of adequate restorations that protect the tooth from fracture (Braly & Maxwell, 1981). Early diagnosis is most important in the treatment of incomplete fracture so as to limit the propagation of the crack, subsequent microleakage and involvement of the pulpal and periodontal tissues (Cameron, 1964; Hiatt, 1973; Agar & Weller, 1988; Ehrmann &

Tyas, 1990). The treatment requirement of a cracked cusp is dependent on the position and extent of the fracture (Silvestri & Singh, 1978; Ehrmann & Tyas, 1990; Geurtsen, 1992). An assessment of the stimuli, character and duration of the pain is also an influential guide for treatment (Figdor, 1994). The classification proposed by Luebke (1984) is particularly useful as it assesses:

1. The extent of the fracture being complete or incomplete.
2. Whether the fracture extends into the periodontal attachment apparatus or is supra-osseous.
3. The character and duration of pain suggestive of either dentinal sensitivity indicative of a vital tooth or pulpal and periodontal pain where endodontic intervention may be required.

Teeth that have complete fractures which are intra-osseous with periodontal type pain often involving the mesial and distal aspects of the tooth and the cavity floor have a hopeless prognosis (Clark & Caughman, 1984; Gutman & Rakusin, 1994). A multi-disciplinary approach involving endodontic, periodontic, prosthodontic and surgical intervention may be required (Pitts & Natkin, 1983)

Clark and Caughman (1984) have categorized the prognosis of the cracked tooth as excellent, good, poor and hopeless.

1. Excellent: (a) Cuspal fracture confined within the dentine that angles from the facio-pulpal or linguo-pulpal line angle of a cusp to the cemento-enamel junction or slightly below.
(b) Horizontal fracture of a cusp not involving the pulp.
2. Good: A coronal vertical fracture that runs mesio-distally into the dentine but not into the pulp.

3. Poor: A coronal vertical fracture that runs mesio-distally into the dentine and pulp but confined to the crown.
4. Hopeless: A coronal vertical fracture that runs mesio-distally through the pulp and extends into the root.

Gutman and Rakusin (1994) suggested that treatment consist of an initial investigative and sedative stage followed by definitive treatment and restoration. Initial treatment involves the removal of all existing restorations to fully assess the extent of the fracture. Transillumination is a useful guide (Abou-Rass, 1983). In the absence of irreversible pulpitis, many techniques have been described to bind or remove the fracture so as to prevent flexure of the cusp, crack propagation and bacterial microleakage.

In the initial diagnostic phase, the use of copper or stainless steel bands (Geursten, 1992; Ehrmann & Tyas, 1990; Homewood, 1998), stainless steel crowns (Chong, 1989), and acrylic resin crowns (Guthrie & DiFiore, 1991) have been advocated.

Definitive treatment has included pin retained amalgams (Silvestri & Singh, 1987; Clark & Caughman, 1984), bonded amalgams (Trushkowsky, 1991; Bearn, Saunders & Saunders, 1994), bonded composite (Eakle 1985; 1986b; Baxter, 1987; Hansen, 1988; Burke, Wilson & Watts, 1994), cusp overlay restorations (Morin et al., 1988; Hansen et al., 1990; Linn & Messer, 1994; Panitvisai & Messer, 1995), and full coverage crowns (Cameron, 1976; Ehrmann & Tyas, 1990; Guthrie & DiFiore, 1991; Geurtsen, 1992; Homewood, 1998)

The preparation of teeth for restorations reduces their fracture resistance. Teeth restored with intra-coronal amalgam restorations are no stronger than unrestored teeth

(Vale, 1956; Salis et al., 1987). Cusp overlay (Morin et al., 1988) and bonded composite restorations (Eakle 1985; 1986b) improve the fracture resistance of the teeth. A retrospective in vivo study of endodontically treated teeth reported that one-third of premolars restored with MOD amalgams had fractured within three years, in contrast the 40 premolar teeth restored with MOD composite had not fractured (Hansen, 1988). However, the enamel/composite bond will be subjected to fatigue failure with time (Hood, 1991). Teeth restored with cuspal amalgam overlays had fracture energies, measured as the force required to fracture, equal to that of an intact tooth whereas gold crowns increased the fracture energy by more than three fold (Salis et al., 1987).

Fractures that involve the pulp will require endodontic intervention (Viener, 1965; Ehrmann & Tyas, 1990; Gutman & Rakusin, 1994). Fractures that involve the periodontal attachment may require extraction, though hemisection may be appropriate for multi-rooted teeth (Pitts & Natkin, 1983; Burke, 1992).

The provision of an acrylic splint is recommended for prevention of further fractures in patients with parafunctional occlusal activity or a history of incomplete fracture in other teeth (Zimet, 1998).

2.1.4.2 Root Fracture

The treatment of vertical root fractures is comprehensively reviewed in: Moule, A.J., and Kahler, B. Diagnosis and management of teeth with vertical root fractures. *Aust Dent J* 1999; 44: 75-87. Refer to Appendix A.

2.1.5 *Comparison of Root Filled and Vital Teeth*

There is a clinical impression that endodontically treated teeth are more brittle (Rosen, 1961; Johnson, Schwartz & Blackwell, 1976; Greenfeld & Marshall, 1983; Pashley, 1990; Radke & Eissmann, 1991; Douglas, 1996). The reduction in tooth structure due to the carious, restorative and endodontic intervention significantly weakens the tooth structure making it more susceptible to fracture (Reeh et al., 1989). The perception of brittleness has been attributed to a decreased moisture content. This is primarily as a result of a study by Helfer et al. (1972), where the moisture content of pulpless teeth from a dog was shown to have 9% less moisture than vital teeth. More recently, Papa et al. (1994) have questioned the methodology of this study. These authors reported that the moisture content of vital dentine was 12.35% in contrast to the moisture content of 12.10% from dentine of teeth that had been endodontically treated. This result was not considered statistically significant.

Studies examining the biomechanical properties of endodontically treated and vital teeth suggest that teeth do not become more brittle following endodontic treatment. Stanford et al. (1960) examined three pairs of patient matched vital and pulpless incisor teeth and reported no significant differences in the modulus of elasticity, proportional limit and strength of dentine. Taylor (1961) concluded from cantilever bending studies that the strength and modulus of elasticity of dentine from vital and endodontically treated teeth was similar. Sedgley and Messer (1992) examined the punch shear strength, toughness and load to fracture of 23 endodontically treated teeth and their contralateral pairs, and found no statistically significant differences. Huang et al. (1992) reported that the compressive and tensile strengths of dentine from pulpless teeth were statistically similar to vital teeth. Lewinstein and Grajower (1981) reported no difference in the Vickers microhardness of dentine from the teeth of 16 extracted vital

teeth and 32 endodontically treated teeth extracted up to ten years after endodontic treatment. Rivera and Yamauchi (1990) reported that the collagen cross-linkage of dentine from age- and site- matched endodontically treated and vital teeth contained no statistically significant differences.

However, conflicting reports do exist in the literature. Carter et al. (1983) examined 21 freshly extracted vital teeth and six teeth that had been endodontically treated, and reported a 14% reduction in the punch shear strength and toughness. Sedgley and Messer (1992) found that vital dentine was 3.5% harder than contralateral endodontically treated teeth. Huang et al. (1992) examined 54 freshly extracted teeth and 24 pulpless teeth, and found the pulpless teeth had lower values for Young's modulus and a lower proportional limit in compression. Half of the dentine specimens from pulpless teeth exhibited greater plastic deformation than vital teeth in compression.

Jameson et al. (1993) note that most studies addressing the perceived brittleness of endodontically treated teeth have attempted to compare untreated teeth with root filled teeth. They draw attention to the difficulties of establishing similar controls and test procedures, and suggest these may have contributed to the conflicting evidence in the literature. They further suggest that the examination of biomechanical properties of endodontically treated teeth have focussed on the strength and modulus of elasticity of dentine. Strength is not a measure of toughness, being the energy required to induce fracture. Also, strain beyond the proportional limit would not be apparent from the modulus of elasticity. Further studies assessing stress, strain and fracture toughness are required. Huang et al. (1992) also note difficulties in obtaining comparable test protocols and procedures as it is impossible to maintain the original moisture content of either vital or endodontically treated teeth. The use of a constant water flow during specimen preparation and different storage medium will affect the water content of

specimens. The biomechanical changes induced by dehydration have been shown to be reversed by rehydration (Jameson et al., 1993). Therefore, results of studies that have involved specimen preparation have to be questioned.

2.1.6 Dentine Desiccation

Jameson et al. (1993) examined the effects of dehydration and rehydration on the biomechanical properties of dentine. Dehydration of human dentine over seven days at 20°C and 50% relative humidity resulted in a 3.3% reduction in weight, which comprised 30% of total moisture. Dehydrated specimens had similar results in tensile and bending strengths, but were shown to be brittle and underwent no plastic deformation in contrast to the hydrated and rehydrated specimens. The biomechanical properties of the dehydrated specimens could be reversed to the values of the hydrated specimens by rehydration. Dentine that has been air dried has been found to show decreased stress relaxation suggesting that the properties of dentine are changed by air drying (Trengrrove, Carter & Hood, 1995). Kinney, Balooch, Marshall and Marshall (1993) found that drying of dentine resulted in microstrains probably as a result of contraction of the collagen fibrils. These strains were found to be small and well within the elastic limits of dentine. Helfer et al. (1972) reported that the moisture content of pulpless teeth from a dog had 9% less moisture than vital teeth. This study was conducted on only one dog where teeth were stored in saliva before the analysis of moisture content. The pulps were removed at short intervals before the teeth were analyzed. No correlation between moisture content and the time elapsed since pulp removal was noted. More recently, Papa et al. (1994) have questioned the methodology of this study. They reported that the moisture content of vital dentine was 12.35% in contrast to the moisture content of 12.10% from dentine of teeth that have been

endodontically treated. The result was not considered statistically significant. They concluded that the lack of difference in moisture content indicated that desiccation is not responsible for the higher incidence of fracture for endodontically treated teeth. Huang et al. (1992) observed that as pulpless teeth exist in a water-based environment of saliva in the mouth, as well as blood and tissue fluid surrounding the root, dentine should not dry out as both enamel and cementum have been shown to be permeable to water.

2.1.7 *Fracture Mechanics*

Fracture mechanics is an aspect of engineering that deals with the failure of bodies containing cracks. All fractures involve crack formation and propagation. The mode of fracture may be either ductile or brittle. The mode of fracture is highly dependent on the mechanism of crack propagation. Ductile materials exhibit substantial plastic deformation with high energy absorption before fracture. Generally, ductile failure occurs slowly and over a relatively long time as the crack length is extended. The crack is extended when there is an increase in the applied stress. In contrast, with brittle fracture the crack will propagate rapidly with little or no plastic deformation and with low energy absorption. The crack will continue to propagate without an increase in the applied stress. Brittle failure usually occurs suddenly and catastrophically. There is little or no plastic deformation because of the spontaneous and rapid crack propagation. The mode of fracture is also dependent on the temperature and the rate of loading (Callister, 1997).

A crack will reduce the fracture strength as the applied stress can be amplified at the crack tip. Fracture toughness is a measure of a material's resistance to brittle

fracture when a crack is present. Stress in the area of the crack tip can be defined as the stress intensity factor (K), which is a function of the applied stress, the size and position of the crack. The critical value of the stress intensity factor, termed as fracture toughness (K_c), is a material property that is determined experimentally (Mencik, 1992):

$$K_c = Y\sigma(\pi a)^{1/2}$$

where: Y = a dimensionless parameter that depends upon the specimen and the crack geometries

a = the length of the crack

σ = the magnitude of the applied tensile strength

Fracture mechanics provides quantitative solutions to specific problems caused by cracks in a material (Ewalds & Wanhill, 1984). For brittle materials, linear fracture mechanics is appropriate, which is based on the assumption that the material exhibits elastic behaviour obeying Hooke's law up to fracture where all plastic deformations are restricted to the vicinity of the crack tip (Mencik, 1992). Linear fracture mechanics uses two criteria for failure: Irwin's and Griffith's. The former is based on analysis of stresses at the crack tip, the latter on energy balance. However, both criteria are equivalent (Mencik, 1992).

With the Irwin criterion for brittle fracture, the fracture is usually initiated from the crack tip where stress is concentrated under load. The stresses in this elastically deformed region determine the behaviour of the crack. Since these stresses can be characterised by means of the stress intensity factor (K), then the crack will propagate if the stress intensity factor (K) reaches the critical value (K_c).

With the Griffith criterion for brittle fracture, as an elastic body with a crack is loaded, elastic energy is stored in it. If the crack size increases then part of this energy is released as some energy is used to form the new fracture surface. A crack can propagate spontaneously without an increase in the load if the energy released during crack growth equals or exceeds the energy required for this growth. The amount of energy released by unit increment of fracture surface is termed the strain energy release rate (G). Therefore, the crack will propagate if the energy release rate (G) reaches a critical value (G_c). This critical value corresponds to the energy necessary for the creation of a unit area of fracture surface. This is a material property referred to as toughness (Mencik, 1992)

The growth of a crack is controlled by stresses that act in the vicinity of the crack tip. When a crack is present, the stress close to the crack (σ_{local}) is greater than the average stress (σ) that is applied to the material. Therefore, the crack acts to concentrate the stress (Ashby & Jones, 1986). The local stress becomes higher as it gets closer to the crack tip until, at some distance (r_y) from the tip of the crack, the stress reaches the yield stress (σ_y) of the material when plastic flow occurs. A plastic zone surrounds the crack tip as the material deforms plastically above the yield stress. The size of the plastic zone relative to the thickness of the body influences the crack tip state of stress (Ewalds & Wanhill, 1984). This plastic zone that surrounds the crack tip is a significant factor in crack propagation as plastic flow at the crack tip blunts the crack tip. Crack blunting decreases the stress at the crack tip (σ_{local}). Brittle materials have very high yield strengths with very little plastic deformation occurring at the crack tip (Mencik, 1992).

Arola et al. (1999) proposed that a crack initiated by a cavity preparation flaw may be extended by cyclic crack propagation. As many cuspal failures are noted many years after placement of the restorations, cyclic fatigue is considered as the mechanism of fracture (Bell et al., 1982; Douglas, 1996; Arola et al., 1999). The fracture of brittle materials is usually initiated at a crack where stress is concentrated when the material is loaded. Fracture mechanics examines the conditions that are appropriate for a crack to propagate. If the crack has a negligible root radius, linear elastic fracture mechanics is an appropriate method to analyze the incremental fatigue crack growth rate. This rate may be determined by Paris law according to:

$$\frac{da}{dN} = C(\Delta K)^m$$

where: $\frac{da}{dN}$ = the cyclic crack growth rate

a = the incremental crack length

N = the number of fatigue cycles

C and m = empirical constants which are dependant on material properties

ΔK is expressed in terms of stress state and crack length according to:

$$\Delta K = F \Delta \sigma (\pi a)^{1/2}$$

where: $\Delta \sigma$ = the stress range ($G_{\max} - G_{\min}$)

F = a geometry factor which accounts for geometry and boundary conditions. It is a function of flaw length and changes with crack growth however, it is assumed that the geometry factor does not change appreciably with crack growth.

The final crack length a_f is the critical flaw length which promotes failure at the maximum applied stress:

$$a_f = \frac{1}{\pi} \left[\frac{K_{Ic}}{F\sigma_{\max}} \right]^2$$

where: K_{Ic} = the plane strain fracture toughness of dentine

An application of the Paris law to dental restorations requires that the opening mode global stress (σ), resulting from occlusal loading, can be determined. However, appropriate Paris law constants C and m have not been reported for dentine or enamel (Arola et al., 1999).

Fracture of dentine is a function of crack initiation and crack propagation (Arola et al., 1999). Crack growth resistance of a material is a consequence of intrinsic micro-structural damage mechanisms operating ahead of the crack tip, and extrinsic crack tip shielding mechanisms that operate behind the crack tip. Intrinsic mechanisms are an inherent property of the material that control crack initiation. Extrinsic mechanisms, which include crack deflection, inelastic or dilated zones that surround the crack wake, and bridge formation (ligament toughening) between the crack surfaces acting in the crack wake, are responsible for resistance-curve behaviour (R-curve). They are the primary toughening mechanisms in brittle materials (Evans & Faber, 1984; Ritchie, Gilbert & McNaney, 2000).

2.1.8 *Prior Studies of Dentine Fracture Toughness*

For relatively brittle materials such as dentine, resistance to fracture is best quantified by fracture mechanics. However, few studies have examined fracture

toughness of dentine. There are many difficulties associated with the mechanical testing of teeth and dentine due to the size and shape complexity of the test samples. Trauma may be associated with extraction and thermal damage may occur during preparation (Waters, 1980). There are difficulties in obtaining comparable test protocols and test procedures, as it is impossible to maintain the original moisture content (Huang et al., 1992). The use of a constant water flow during specimen preparation and different storage media will affect the water content of specimens (Jameson, Tidmarsh & Hood, 1994).

Most studies addressing the perceived brittleness of endodontically treated teeth have attempted to compare untreated teeth directly with root filled teeth (Jameson et al., 1993). They argue that the examination of biomechanical properties of endodontically treated teeth have focussed on the strength and modulus of elasticity of dentine. Strength is not a measure of toughness, being the energy required to induce fracture. Also, strain beyond the proportional limit would not be apparent from the modulus of elasticity. Therefore, calculation of stress and strain is required. An examination of fracture toughness, which is a measure of the inherent resistance of a material to crack extension, which can be evaluated from a pre-cracked specimen (Vashishth, Behiri & Bonfeld, 1997), is an appropriate measure.

Rasmussen et al. (1976), using the work of fracture (W_f) approach, provided a direct measurement of the fracture properties of human enamel and dentine. This approach has been used in controlled fracture studies on bone, ceramics and composites (Tattersall & Tappin, 1966; Zioupos, 1998). A notched specimen is subjected to loading in flexure or tension using a constant deformation rate testing apparatus so that the crack stably extends from the notch. The (W_f) is determined from the area under the

load versus extension curve, that is, the work done, which is divided by the area of the two fractured surfaces.

Rasmussen et al. (1976) reported that the W_f for dentine fracture parallel to the tubular direction was 550Jm^{-2} , and 270Jm^{-2} for fracture at right angles to the tubules. The higher W_f for parallel fracture was a result of the microstructure of dentine as fracture in this direction required fracture of the collagenous framework. They concluded that dentine was a brittle material, as though considerable non-recoverable energy absorbing processes were occurring, as they were small when compared to those that occur during fracture of ductile materials. Further support for this conclusion was obtained by scanning electron micrographs where no blunting of the crack tip was observed.

A fracture mechanics approach was used by El Mowafy and Watts (1986) where the fracture toughness of dentine (K_{Ic}) was determined by compact-tension tests. K_{Ic} was found to be $3.08\text{MPa}\sqrt{\text{m}}$. These experiments were with machined notches rather than atomically sharp (e.g., fatigued) precracked specimens.

Jameson et al. (1993) used a fracture energy approach testing small dentine bars that had not been notched which were loaded by three point bending and tension until fracture, which was usually unstable. The fracture energy was determined from the area under the stress-strain curve. Strain at fracture and fracture energy was significantly greater for hydrated and re-hydrated than for dehydrated dentine.

2.2 Dentine

2.2.1 *Composition*

Dentine is a complex hydrated composite compound that consists of orientated tubules. The tubules are surrounded by a highly mineralized peritubular layer and are contained in an intertubular matrix that primarily consists of Type I collagen which has embedded apatite crystals. The tubules contain dentinal fluid and to a varying extent, an odontoblastic process (Marshall, 1993). Dentine is formed by these odontoblastic cells which secrete an organic matrix which becomes mineralized to form dentine (Ten Cate, 1998).

Dentine is composed of approximately 70% inorganic material, 18% organic material and 12% water, by weight. By volume, the inorganic material makes up 50%, organic matrix accounts for 30% and 20% consists of water (Mjör & Fejerskov, 1979; Driessens & Verbeeck, 1990; Van Meerbeek, Lambrechts, Inokoshi, Braem & Vanherle, 1992). Differences in the specific gravity of the organic and inorganic materials account for the discrepancy between weight and volume (Ten Cate, 1998). Other organic components are present in small amounts and consist of proteoglycan, non-collagenous protein, citrate, lactate, and lipid, which accounts for approximately 2% by weight (Trowbridge & Kim, 1998). It has been calculated that in dentine 75.2% of the water is in the tubules and 24.8% is in the mineralized matrix (Van Der Graaf & Ten Bosch, 1990). Hydroxyapatite crystals are the main inorganic material and this provides the strength to dentine; the collagen matrix provides the toughness (Marshall, 1993).

2.2.2 *Structure*

2.2.2.1 Dentinal Tubules

The presence of dentinal tubules is the most characteristic structural feature of dentine (Gage, Francis & Triffitt, 1989). The tubules are surrounded by highly mineralized peritubular dentine and embedded in an intratubular matrix (Marshall, 1993). Dentinal tubules comprise a profuse anastomosing canalicular structure that branches throughout the dentine (Ten Cate, 1998). Branches have been categorized as major branches, fine branches and microbranches. Major branches are between 0.5µm and 1.0µm in diameter and are primarily found near the dentino-enamel and cemento-enamel junction. They are typically Y-shaped and terminate in a delta-forming configuration. This is more often seen in coronal dentine than in root dentine. Fine branches are 0.3µm to 0.7µm in diameter and extend peripherally from the tubules at an angle of approximately 45°. These branches are found mostly in root dentine. They anastomose with adjacent tubules and may cross several tubules (Mjör & Nordahl, 1996; Ten Cate, 1998). Microbranches are between 0.05µm and 0.1µm in diameter and extend at an angle of approximately 90° to the dentinal tubule. They anastomose with adjacent microbranches and are found in the intertubular dentine (Jones & Boyde, 1984; Mjör & Nordahl, 1996).

Dentine, as a result of its tubular structure, is very porous (Pashley, 1989). The tubular framework of dentine may contribute to the physical properties of dentine, as the fluid filled dentinal tubules could function to hydraulically transfer and dissipate the occlusal forces that are applied to a tooth (Pashley, 1990).

2.2.2.2 Tubular Orientation

The tubules in coronal dentine have a gentle S shape, and run continuously between the pulp and the dentino-enamel junction (Pashley, 1989). The S shape curvature is a result of crowding when odontoblasts converge toward the pulp (Trowbridge & Kim, 1998). At the incisal edge, cusps, and in root dentine, the tubules are almost straight (Gage et al., 1989).

2.2.2.3 *Tubular Density*

The density of dentinal tubules varies throughout dentine, being 1% just beneath the enamel to more than 22% near the pulp (Pashley, 1989). This is a result of the convergence of tubules towards the pulp (Pashley, 1984). There are between 40,000 and 65,000 tubules/mm² near the pulp, 29,500 tubules/mm² midway to the pulp, and 15,000 tubules/mm² at the dentino-enamel junction (Garberoglio & Brännström, 1976). In coronal dentine the ratio of the number of tubules/mm² at the pulpal and the dentino-enamel junction is 4:1 (Fogel, Marshall & Pashley, 1988).

The number of dentinal tubules decreases in an apical direction (Carrigan, Morse, Furst & Sinai, 1984; Fogel et al., 1988). There are significantly less tubules in the apical portion of the root (Whittaker & Kneale, 1979). In root dentine there are $40,691 \pm 7,107$ tubules/mm² and $20,895 \pm 2,817$ tubules/mm² at the cemento-enamel junction. In root dentine the ratio of the number of tubules/mm² at the pulpal and cemento-enamel junction is 2:1 (Fogel et al., 1988).

2.2.2.4 *Tubular Dentine*

Dentinal tubules are slightly tapered as a result of the progressive deposition of peritubular dentine. This causes a progressive decrease in the diameter of the tubule towards the dentino-enamel and cemento-dentinal junction (Trowbridge & Kim, 1998). The diameter of the tubules is $2.5\mu\text{m}$ near the pulp, $1.2\mu\text{m}$ in the middle of dentine, and $0.9\mu\text{m}$ near the dentino-enamel junction (Garberoglio & Brännström, 1976). In root dentine, the diameter of the tubule near the pulp is $1.56 \pm 0.29 \mu\text{m}$, and $1.07 \pm 0.18 \mu\text{m}$ near the cemento-enamel junction (Fogel et al., 1988). The functional diameter of dentinal tubules is less than the anatomical diameter and is between 0.04 and $0.19\mu\text{m}$. This may be due to irregularities in the tubular wall, and the presence of collagen and odontoblastic processes (Michelich, Pashley & Whitford, 1978).

As a consequence of this narrowing of the tubular diameter peripherally, dentine is relatively dry near the dentino-enamel and cemento-dentinal junction, and is composed primarily of intertubular dentine, whereas pulpal dentine is relatively moist and consists of peritubular dentine (Pashley, 1991).

2.2.2.5 Peritubular Dentine

Peritubular dentine surrounds the dentinal tubule. It is highly mineralized, consisting mainly of hydroxyapatite and containing less organic matrix than intertubular dentine. It is also harder than intertubular dentine, and may provide structural support for the intertubular dentine (Trowbridge & Kim, 1998). Intratubular mineralization results in thickening of the peritubular dentine and therefore a constriction of the tubular diameter. This can occur as a response to the carious process (Ten Cate, 1998).

2.2.2.6 Intertubular Dentine

Intertubular dentine is located between the dentinal tubules and consists of a tightly interwoven mesh of primarily Type I collagen in which apatite crystals are embedded. The fibrils are orientated approximately perpendicular to the dentinal tubules (Trowbridge & Kim, 1998; Ten Cate, 1998). The area of dentine that consists of intertubular dentine is highest at the dentino-enamel junction and lowest at the pulpal border (Pashley, 1989).

2.2.2.7 The Odontoblastic Process

The odontoblasts are responsible for the formation and mineralisation of dentine. The odontoblasts are found on the inner surface of the dentine and at the periphery of the pulp. The dentinal tubules, a characteristic of dentine, are a result of these extraordinarily numerous and regularly arranged cell processes. This is important for the physical properties of dentine and is responsible for the permeability of the dentine (Schroeder, 1991). The extent that the odontoblastic process extends into the tubules is a matter of considerable controversy. The dentinal tubules are occupied by the odontoblastic process for a variable distance and also filled with fluid (Marshall, Marshall, Kinney & Balooch, 1997).

2.2.2.8 Dentinal Fluid

Dentinal fluid is a transudate of pulp blood plasma, and contains many plasma proteins including antibody containing gamma globulins (Pashley, 1991; Bergenholtz, Jontell, Tuttle & Knutson, 1993). The concentration of plasma proteins in dentinal fluid is approximately 20% of that found in plasma (Pashley et al., 1983a; Maita,

Simpson, Tao & Pashley, 1991). The contents of dentinal fluid have been described as a transparent fluid that is devoid of cells and having a lower protein and sugar content than plasma. It is considered similar to synovial fluid (Berggren & Brännström, 1965).

2.2.3 *Biomechanical Properties of Dentine*

2.2.3.1 Introduction

There are significant differences in the structural elements of dentine as the tubules progress from the dentino-enamel and cemento-enamel junctions towards the pulp, and thus may mean that the properties of dentine could vary with location (Marshall, 1993).

Wide discrepancies in the values for mechanical properties have been reported (Waters, 1980; Pashley, 1996; Marshall et al., 1997). The hardness of dentine has been demonstrated to be dependent on location (Craig, Gehring & Payton, 1959; Pashley, O'Meara, Williams & Kepler, 1985; Kinney, Balooch, Marshall, Marshall & Weihs, 1996). This has also applied to punch shear strength (Roydhouse, 1970; Smith & Cooper, 1971).

2.2.3.2 Anisotropy of Dentine

Anisotropic materials have the property of directionality, where the measured properties are dependent on the direction of measurement (Rees & Jacobson, 1995). Materials where physical properties are independent of the direction of measurement are considered isotropic (Callister, 1997). In dentine, the orientation of the tubules to the long axis of the tooth and the orientation of collagen fibers to the tubules could influence the measurement of the biomechanical properties.

Rasmussen et al. (1976) and, Rasmussen and Patchin (1984) reported that dentine is anisotropic. This suggests that fracture toughness will be dependent on the orientation of the dentinal tubules. However, many studies have concluded that dentine is an isotropic material (Craig & Peyton, 1958; Tyldesley, 1959; Stanford et al., 1960; Renson et al., 1974). Renson et al. (1974) examined dentine fractured in bending and torsion tests by scanning electron microscopy, and reported that the fracture plane was dependent upon the mode of deformation rather than on the tubule orientation. However, Rasmussen et al. (1976) reported that less work to fracture (W_f) was required for the direction perpendicular to the dentinal tubules. Watanabe, Marshall and Marshall (1996) reported only a weak dependence on tubule orientation when shear strength was examined in relation to tubule orientation. Other studies have reported similar findings (Kinney et al., 1999; Lertchirakarn et al., 2001).

2.2.3.3 Viscoelastic and Time Dependent Properties of Dentine

Craig and Peyton (1958) examined the elastic and mechanical properties of dentine, and demonstrated that loading below the proportional limit increased the strain when the load was maintained. Deformation of dentine was recovered when the load was released. If dentine is loaded above the proportional limit, permanent deformation occurs. Löst et al. (1992) used longitudinal sound velocity to demonstrate visco-elastic behavior of dentine. Trengrove et al. (1995) demonstrated that dentine exhibited a linear stress relaxation with the logarithm of time. Dentine that had been air-dried demonstrated decreased stress relaxation suggesting that the properties of dentine are changed by air-drying.

The elastic properties of dentine are of considerable importance in understanding the elastic response of dentine to external loading. Visco-elastic materials exhibit continued deformation under a constant load with a progressive reduction in stress while the material is under constant deformation.

Stress relaxation is the only area of time-dependent behavior reported in detail in the literature (Duncanson and Korostoff, 1975; Korostoff et al., 1975; Tengrove et al. 1995; Jantararat et al., 2002). Jantararat et al. (2002) reported time-dependent properties for dentine where linear visco-elastic behaviour was demonstrated under various conditions of compressive loading. The visco-elastic nature of dentine may impact on the mechanism of fracture at the crack tip.

2.2.3.4 *Hardness of Dentine*

Hardness is a measure of deformation. Craig et al. (1959) reported Knoop Hardness Number (KHN) varied from 35 to 83 KHN. Fusayama, Okuse and Hosoda (1966) reported the range to vary from 20 to 70 KHN. In both studies, the KHN of dentine was lower for dentine closest to the pulp. Pashley et al. (1995) suggest that the lower values are due to a decrease in the amount of intertubular dentine and an increase in tubular diameter.

Kinney et al. (1996) measured the hardness of peritubular and intertubular dentine using a modified atomic-force microscope, which is location specific. They reported that the hardness of peritubular dentine was not location dependent. However, the hardness of intertubular dentine was significantly greater near the dentino-enamel junction (0.49 to 0.52 GPa) than near the pulp (0.12 to 0.18 GPa). They suggest that it

is the lower value of intertubular dentine hardness, rather than tubular density, that is responsible for the decrease in hardness for dentine near the pulp.

Transparent (sclerotic) dentine is harder than normal dentine as it is more calcified (Craig et al., 1959).

2.2.3.5 Compressive Strength of Dentine

Craig and Peyton (1958) reported a proportional limit and ultimate compressive strength of 167MPa and 297MPa respectively. Stanford et al. (1960) reported lower values but showed no significant differences between the coronal dentine of different teeth, and that orientation of the coronal dentine did not affect the compressive properties. However, root dentine has a lower compressive strength, proportional limit, and modulus of elasticity. There were no significant differences in the compressive properties of the root dentine from vital and pulpless teeth.

2.2.3.6 Tensile Strength of Dentine

The tensile strength of dentine was found to be 41.4MPa, which is lower than the compressive strength (Lehman, 1967). Tyldesley (1959) measured the flexural strength of dentine and reported a value of 267.5MPa. This value is close to the compressive strength. Flexural strength is a measure of the maximum tensile strength in bending. Dentine was reported to behave elastically and demonstrated isotropic behavior in 4 point bending tests. Sano, Ciucchi, Matthews and Pashley (1994) found that the ultimate tensile strength of dentine was 104MPa, which is much larger than previously reported. Lertchirakarn et al. (2001) reported that ultimate tensile strength was lowest

(36.7MPa) when the tensile force was parallel to tubule orientation and greatest at 90 degrees to tubule orientation (60.3 MPa) where the fracture was parallel to tubule direction. Huang et al. (1992) reported that the ultimate tensile strength of wet root dentine, of both vital and endodontically treated teeth, was not significantly different.

2.2.3.7 *Shear Strength of Dentine*

Roydhouse (1970) reported the shear strength of dentine ranged between 70 and 150 MPa. The value was dependant on the location, type of tooth and the direction of the punch. Smith and Cooper (1971) also reported that the shear strength of dentine was dependant on its location relative to the pulp chamber. Much lower shear strength values were reported for dentine close to the pulp. A value of 39MPa was recorded near the pulp compared to a value of 132MPa near the dentino-enamel junction. The shear strength also varied with the thickness of the section and appeared to vary in relation to the orientation of the tubules. However, Watanabe et al. (1996) measured the shear strength of mid-coronal dentine where the force was applied both parallel and perpendicular to the tubule orientation, and reported no statistically significant difference.

2.2.4 *Permeability*

2.2.4.1 *Introduction*

Dentine, by nature of its tubular structure is both porous and permeable. Fluid movement through dentine has been demonstrated (Anderson & Ronning, 1962; Anderson, Matthews & Gorretta, 1967; Brännström, Lindén & Åström, 1967). Quantitative investigations of coronal dentine (Merchant, Livingston & Pashley, 1977;

Pashley, Livingston & Outhwaite, 1977; Reeder, Walton, Livingston & Pashley, 1978; Pashley, Livingston & Greenhill, 1978a; Pashley & Livingston, 1978) and radicular dentine (Fogel et al., 1988) have been published.

Dentine may also be considered a barrier to fluid movement as the tubules are embedded in a relatively impermeable mineralized matrix (Pashley, Livingston & Outhwaite, 1978b). Fluid movement or filtration through dentine is determined by the variables of the Poiseuille-Hagen equation:

$$V = \frac{\pi \Delta P r^4}{8 \eta l}$$

where: V = volume flow ($\mu\text{L min}^{-1}$)

ΔP = hydrostatic pressure difference across dentine

η = viscosity of fluid

r = radius of tubule

l = length of tubules

Hydraulic conductance (L_p) is a measure of fluid movement through dentine across a hydrostatic or osmotic pressure gradient. Hydraulic conductance can be calculated from the following equation (Pashley, Kepler, Williams & Okabe, 1983a):

$$L_p = \frac{J_v}{A \Delta P t}$$

where: J_v = fluid flow in microlitres

A = surface area which fluid permeates

ΔP = hydrostatic pressure gradient in cm's of water

t = time in minutes

L_p = hydraulic conductance in microlitres, cm^{-2} , minutes^{-1} , $\text{cmH}_2\text{O}^{-1}$

Dentine and the pulp can be considered as a physiological continuum that can be referred to as the pulpo-dentine complex. Dentine permeability is a direct consequence of the presence of tubules and proportional to their number, diameter and length (Tagami, Tao, Pashley & Horner, 1989).

The number and diameter of the dentinal tubules have a significant impact on the rate at which fluid flows through them. As filtration varies with the fourth power of the radius of the tubule, small changes in tubular diameter will have a significant effect on fluid flow. Tubular density is greater nearest the pulp and less dense in the peripheral dentine (Bhasker, 1976). Tubules are wider near the pulp with a diameter of 3-4 μm , and narrower at the dentino-enamel junction with a diameter of approximately 1 μm (Garberoglio & Brännström, 1976). Therefore, the ratio of the number of tubules per unit area at the pulpal and peripheral tooth surfaces is approximately 4:1 in coronal dentine (Fogel et al., 1988; Pashley 1989). As a result peripheral dentine is less permeable than pulpal dentine.

Fluid filtration through dentine is also dependent on tubular length, being directly proportional to dentine thickness (Fogel et al., 1988). As the thickness of dentine decreases, there is an exponential increase in filtration (Reeder et al., 1978; Pashley, 1989).

Factors that modify dentine permeability have been confirmed in in vitro experiments in coronal dentine (Outhwaite, Livingston & Pashley, 1976; Fogel et al., 1988). Other factors are associated with variations in in vitro permeability of teeth such as tubular irregularities due to mineral deposits, the organic components of the

odontoblastic processes, intratubular deposits of collagen, and the storage conditions for the teeth prior to experimentation (Marshall et al., 1997). The functional diameter of the tubule was found to be less than the anatomical diameter (Michelich et al., 1978).

2.2.4.2 *Rate of Permeation*

A continuous liquid phase exists between the pulp and saliva (Lindén & Brännström, 1967; Brännström, 1984), as well as blood and tissue fluid that surround the root (Huang et al., 1992). The free fluid phase comprises 2% by volume of enamel, and 25% by volume of dentine. The mobility of this liquid is high in dentine, and low in enamel (Lindén & Brännström, 1967; Petelin, Skaleric, Cevc & Schara, 1999) and cementum (Lindén, 1968; Pashley, 1990; Petelin et al., 1999). Complete permeation of tracer across dentine, the cemento-dentinal junction and cementum has been shown to be slow. It was observed that the cemento-dentinal junction functioned in a rate limiting capacity (Petelin et al., 1999).

The velocity of the spontaneous flow of fluid through enamel in vitro is approximately 0.1mm per hour (Bergmen & Siljestrand, 1963). A similar flow rate was registered in vivo (Bergman & Lindén, 1965). The diffusion co-efficient for diffusion of tritiated water across enamel is $1 \times 10^{-10} \text{cm}^2/\text{s}$ (Burke & Moreno, 1975).

On the basis of capillary experiments where it was assumed that the physical properties of tubular fluid were similar to those of synovial fluid (Spreter Von Kreudenstein, 1958) it was calculated that the rate of flow in a dentinal tubule is approximately 4mm/sec at a distance of 2mm from the pulp (Berggren & Brännström, 1965). The movement of water depended on dentine thickness and varied from $0.40 \mu\text{L}/\text{min per cm}^2$ for dentine with a thickness of 0.40mm (Potts, Cunningham,

Finkelstein & Silverberg-Strumfeld, 1985). In teeth of anaesthetized cats, it was calculated that the average flow rate per tubule ranged from 0.1 to 1.3 μLsec^{-1} (mean 0.6; standard deviation 0.5). The average flow velocity at the mouths of the tubules was calculated to vary from 0.2 to 4.4 μmsec^{-1} (mean 1.4; standard deviation 1.2) (Vongsavan & Matthews, 1990).

The diffusion co-efficient for diffusion of tritiated water across dentine is $1 \times 10^{-6} \text{cm}^2/\text{sec}$ (Petelin et al., 1999).

The diffusion co-efficient for cementum was $1 \times 10^{-8} \text{cm}^2/\text{sec}$, and at the cemento-dentinal junction it was $0.3 - 1 \times 10^{-10} \text{cm}^2/\text{sec}$ (Petelin et al., 1999).

To summarize the findings of Petelin et al. (1999), it was found that compared to enamel, fluid transport across cementum is approximately 100 times faster ($1 \times 10^{-8} \text{cm}^2/\text{sec}$). Diffusion across dentine was in the order of 1,000 times faster ($1 \times 10^{-6} \text{cm}^2/\text{sec}$). The diffusion rates of enamel and the cemento-enamel junction were in the same range ($1 \times 10^{-10} \text{cm}^2/\text{sec}$). The cemento-dentinal junction behaved as a rate-limiting barrier.

2.2.4.3 *Regional Difference*

Maroli et al. (1992) investigated regional differences in dentine permeability by examining the hydraulic conductance values from the cervical and occlusal area of teeth. The cervical area was significantly more permeable than the occlusal area. This observation was attributed to the fact that cervical dentine is closer to the pulp and a greater number of dentinal tubules are present.

Dentine permeability is greater near the pulp and pulp horns, which is attributed to differences in tubular density and a greater diameter of tubules that are closest to the pulp (Pashley, Andringa, Derkson, Derkson & Kalathoor, 1987; Fogel et al., 1988; Pashley, 1991).

2.2.4.4 Coronal and Radicular Dentine

Fogel et al. (1988) examined the hydraulic conductance of radicular dentine and found it to be much lower than coronal dentine. In this study, roots were sectioned in halves that were approximately equal and the hydraulic conductance of the inner (pulpal) and outer (peripheral) root slabs were measured.

The mean L_p for the inner root dentine was 2.69×10^{-2} (range 1.01 to 3.76) and for outer root dentine was 0.28×10^{-2} (range 0.14 to 0.49) $\mu\text{Lcm}^{-2}\text{min}^{-1}\text{cmH}_2\text{O}^{-1}$. The difference between these means was considered to be statistically significant. When this data is compared to studies measuring the hydraulic conductance of coronal dentine (Pashley, Nelson & Pashley, 1981b; Pashley, Nelson & Williams, 1981c; Pashley, Thompson & Stewart, 1983b; Pashley, Galloway & Stewart, 1984; Pashley, Kalathoor & Burnham, 1986), it was found that the hydraulic conductance of inner radicular dentine was approximately 20% that of coronal dentine, which has a mean value of $1.29 \times 10^{-1} \mu\text{Lcm}^{-2}\text{min}^{-1}\text{cmH}_2\text{O}^{-1}$. The L_p of outer radicular dentine was approximately 2% that of coronal dentine.

The difference in permeability may be accounted for by a difference in the number and diameter of tubules. Whereas Garberoglio and Brännström (1976) found

approximately 45,000 tubules per square millimeter with a diameter of 2.5 μ m, Fogel et al. (1988) observed only 40,691 tubules per square millimeter with a diameter of only 1.56 μ m. As discussed previously, permeability is proportional to the fourth power of the radius, so the variation in diameter is significant. Also, the ratio of the number of tubules per unit area at the pulpal and peripheral root surfaces was only 2:1 in comparison to the 4:1 observed in coronal dentine.

The results of Carrigan et al. (1984) were similar to those of Garberoglio and Brännström (1976). They observed a decrease in the number of tubules in the apical direction from approximately 42,000 tubules per square millimeter in cervical dentine to approximately 8,000 tubules per square millimeter in apical root dentine.

Fogel et al. (1988) also reported that when cementum was removed, there was not a marked increase in the hydraulic conductance of the peripheral dentine slabs. They noted that several tenths of a millimeter of peripheral dentine was required to be removed before any noticeable increase in L_p could be observed. They postulated that the low intrinsic permeability of root dentine would be protective for the pulp from plaque and periodontal disease.

Cervical and middle root dentine has significantly higher permeability than apical dentine (Marshall et al., 1997; Tao, Anderson & Pashley, 1991). Apical dentine consists of more sclerotic dentine (Vasiliades, Darling & Levers, 1983) and has a more atubular structure. It is therefore less permeable despite apical root dentine having dentine thinner than middle cervical regions (Tao et al., 1991).

2.2.4.5 Effect of Root Canal Procedures

It would be expected that endodontic preparation of the root canal surface would increase dentine permeability as there would be an increase in the intracanal surface area and a subsequent reduction in the thickness of the root dentine. Dentine permeability has been shown to increase with decreased dentine thickness or with an increase in surface area (Reeder et al., 1978). However, instrumentation with K files alone or in combination with Gates Glidden drills did not significantly alter the permeability of root dentine. Irrigation with EDTA and 2.5% NaOCl, to remove the smear layer, did not significantly increase root permeability. This study demonstrated that endodontic procedures did not significantly alter the permeability of root dentine when the cementum layer was present. It was concluded that cementum behaved as an effective barrier because when cementum was removed there was a significant increase in the permeability of root dentine (Tao et al., 1991).

2.2.4.6 *Bovine Permeability*

Bovine teeth are frequently used as a substitute for human dentine for in vitro studies in biomechanics and adhesion, due to their larger size and ready availability (Rueggeberg, 1991; Jameson et al., 1994).

Tagami et al. (1989) investigated bovine incisor dentine and reported the number of tubules in deep dentine to be $30,381 \pm 7,269$ per mm^2 , and in superficial dentine to be $16,445 \pm 4,576$ per mm^2 . The diameter of the tubule in deep dentine was $1.8 \pm 0.3\mu\text{m}$, and in superficial dentine it was $1.2 \pm 0.1\mu\text{m}$.

Jameson et al. (1994) demonstrated that there is significantly greater water loss in bovine teeth, when compared to human dentine, if specimens are allowed to dehydrate.

It is important to maintain their hydration throughout any in vitro experimental procedure. They demonstrated that water loss as a result of dehydration at room temperature in in vitro studies of bovine and human dentine can be fast and non-linear.

The hydraulic conductance (L_p) of bovine incisor dentine ranged from 3×10^{-3} to $1.8 \times 10^{-1} \mu\text{Lcm}^{-2}\text{min}^{-1}\text{cmH}_2\text{O}^{-1}$, dependent upon dentine thickness. Reeder et al. (1978) investigated human third molar dentine and reported hydraulic conductance values that ranged from 7.02×10^{-2} to $4.2 \times 10^{-1} \mu\text{Lcm}^{-2}\text{min}^{-1}\text{cmH}_2\text{O}^{-1}$.

Therefore, the permeability of human occlusal molar dentine is approximately six to eight times greater than that of bovine incisor dentine (Tagami et al., 1989). Bovine incisor dentine and human radicular dentine have a similar permeability, consistent with similar tubular density and diameter. The percentage of the area occupied by tubules in human radicular dentine was 7.8% for inner dentine and 1.9% for peripheral dentine, whereas in bovine incisor teeth it was 7.7% for inner dentine and 1.9% for peripheral dentine (Fogel et al., 1988).

2.2.4.7 *Tooth Vitality*

Schroeder (1991) defined vitality as the ability of a tissue to react to physiological and pathological stimuli. The vitality of dentine can be demonstrated by the perception of pain and by processes of functional adaptation. These responses are controlled by odontoblasts. The fluid filled tubules are sensitive to external stimuli and can move fluid in either direction, which can trigger mechanoreceptor nerve endings in close proximity to the odontoblasts. Pain is a direct result of a hydrodynamic stimulus (Brännström, 1982; 1986).

Dentine undergoes adaptive processes where there is further mineralization as a result of physiologic (aging) and pathologic (caries, abrasion) processes (Schroeder, 1991). Secondary, tertiary, sclerotic, and transparent dentine refer to various forms of dentine that have been affected by physiological aging or disease processes (Marshall et al., 1997).

Secondary dentine, as a result of aging, produces a gradual narrowing of the pulp chamber. There is a regular tubular structure, though there is a change in alteration of the tubules. Tertiary dentine, which has also been termed reparative, irregular secondary, or reactionary dentine (Cox, White, Ramus, Farmer & Snuggs, 1992), is deposited on the inside of the pulp in specific localized areas. This dentine has a less regular structure with fewer and less well aligned tubules (Ten Cate, 1998; Avery, 1990). It is thought to be a protective response by the pulp as it is often observed under cut dentinal tubules or teeth that have been chronically inflamed (Schroeder, 1991).

2.2.4.8 Cariious Dentine

Cariious dentine consists of an outer 'infected' layer and an inner 'affected' layer with zones further differentiating the layers having been described (Fusayama, 1993; Schafer, Hine & Levy, 1974; Hoffman, 1980). In the outer layer the majority of the dentine structure is obliterated by the carious process. In the inner layer Fusayama (1993) has described a turbid or discoloured layer, a transparent and a sub-transparent zone. Transparent dentine is sclerotic with hyper-mineralization and occlusion of the dentinal tubules as a result of the carious process (Marshall et al., 1997). Apatite crystals are frequently deposited in the lumen of tubules in transparent dentine (Shimuzu, Yamashita, Ichijo & Fusayama, 1981). These inorganic crystals, which

initially consist of large, rhombohedral crystals of whitlockite that are subsequently converted to apatite (Frank & Voegel, 1980), are also present further occluding tubules (Pashley 1991; Frank, 1990; Michelich et al., 1978). Pathologic stimuli can result in the complete obliteration of more than 90% of the dentinal tubules (Schroeder, 1991)

This layer acts as a barrier to the penetration of substances (Ten Cate, 1998; Avery, 1990, Schafer et al., 1974). The permeability of sclerotic dentine is significantly reduced as a result of the occlusion of the dentinal tubules (Fish, 1932; Miller & Massler, 1962; Sarnat & Messler, 1965; Brännström, 1982). Pashley, Talman, Horner and Pashley (1991) reported that carious lesions have only 2.3% the permeability of the control teeth. Young carious molars exhibited only 14% the permeability of normal dentine (Tagami, Hosoda, Burrow & Nakajima, 1992).

2.2.4.9 Non-Carious Cervical Lesions

The transparent, irritation and sclerotic dentine have also been described tinnon-carious cervical lesions (Marshall et al., 1997). Weber (1974), using microradiographic techniques, reported physiologic sclerosis and pathologic sclerosis with increased intraluminal mineralization. Yagi and Suga, (1990) examining cervical abrasion lesions observed cuboidal, rhomboid shaped, short rod, and droplet-like crystals that were smaller than crystals associated with carious lesions. Yoshiyama, Masada, Uchida and Ishida (1989) reported that approximately 75% of the tubules appeared closed.

2.2.4.10 Cavity Preparation and The Smear Layer

A reduction on the permeability of dentine by 76% was observed following cavity preparation, with further reductions being reported with time (Pashley et al., 1983a). Reductions in dentine permeability in the order of 80 to 90% for coronal dentine have been reported when dentine was instrumented with abrasive paper or burs (Pashley, 1984). Instrumentation of root dentine with K files reduced dentine permeability in the order of 25 to 49% (Fogel & Pashley, 1990). This is attributed to the presence of a smear layer that penetrates several micrometers into the tubules to form smear plugs and is a direct result of dental instrumentation (Marshall et al., 1997). This layer has been reported to be 1-2 μ m thick with the smear plugs having a depth of up to 40 μ m (Foster, Kulid & Weller, 1993; Mader, Baumgartner & Peters, 1984). It is composed of a partly denatured collagen, and mineral (Eick, Wilko, Anderson & Sorenson, 1970; Pashley, Tao, Boyd, King & Horner, 1988; Pashley, 1992). The composition of the dentine substrate and the smear layer is very similar, as determined by X-ray photoelectron spectroscopy (Ruse & Smith, 1991). Pashley (1992) suggests that the depth of smear plugs will vary according to the diameter of the dentinal tubule. Scanning electron microscopic examination of dentinal smear layers demonstrated a uniform, amorphous layer, which completely occluded the dentinal tubules (Pashley, Michelich & Kehl, 1981a). It has been suggested that the smear layer is responsible for 86% of the total resistance to fluid movement across dentine in vitro. The smear layer can be removed by acid, and maximum permeability of the dentine sample can be returned after 15 seconds of etching with 6% citric acid (Pashley et al., 1978a).

Though endodontic treatment creates a smear layer, many studies have shown that NaOCl (sodium hypochlorite) is unable to completely remove the smear layer (McComb & Smith 1975; Goldman, Goldman, Kronman & Liu, 1981; Mader et al., 1984; Fogel & Pashley, 1990; Koskinen, Meurman & Stenvall, 1980; McComb, Smith

& Beagrie, 1976). Irrigation with EDTA resulted in only a slight increase in root dentine permeability indicating that it may only be effective in removing superficial parts of the smear layer (Hampson & Atkinson, 1964; Tao et al., 1991).

As mentioned previously, carious lesions exhibit only a slight degree of permeability ($2.3 \pm 0.6\%$) of controls, even after the excavation of the caries. There was a significant increase in the permeability of these excavated lesions to $6.9 \pm 3.2\%$ when the smear layer was removed. In this study, there was only a slight increase in permeability when a control cavity of similar size and depth of the carious lesion was prepared. However, the removal of the smear layer from this test cavity resulted in a 91% increase in the permeability of dentine. Therefore, the permeability of dentine affected by caries is low, even after the excavation of caries and the removal of the smear layer (Pashley et al., 1991).

This phenomenon occurs because the pulp reacts to the carious process and subsequent cavity preparation as if it has sustained a wound (Pashley, 1991). Pulpal tissue pressure is significantly increased and may even double during pulpal inflammation, which then doubles the rate of transudation from the pulpal blood vessels in to the tubules. As the carious process approaches the pulp, this flow would substantially increase, as the diameter of the tubule is larger. The content of dentinal tubules is essentially a transudate of plasma and contains many plasma proteins, including antibody containing gamma globulins (Pashley, 1991). There is an increased permeability to large molecules from the pulpal circulation through to the dentine, when there is a disruption to the odontoblastic cells (Turner, Marfurt & Sattelberg, 1989). Hydronic stimuli disrupt the odontoblastic layer with the cells being aspirated into the dentinal tubules as a result of the outward flow in the tubules produced by a

physiological pressure gradient (Johnson, Olgart & Brännström, 1973; Brännström, 1982). Therefore, in vital teeth there is a progressive reduction in permeability after the carious process or cavity preparation (Pashley et al., 1983a). An investigation of the permeability of dentine from non-vital and vital teeth from a dog revealed a progressive reduction in dentine permeability of vital dentine from cavity preparation, whereas the non-vital teeth demonstrated a slight increase in permeability. However, when the dogs were depleted of fibrinogen, a large plasma protein, the reduction in permeability was significantly reduced (Pashley, 1979). Permeability of dentine is, therefore, significantly reduced by the leakage of fluid and plasma proteins, especially fibrinogen, as fibrin seals are formed between damaged odontoblasts and the dentinal tubules (Pashley, 1991).

2.2.4.11 Pulpal Pressure and Inflammation

The pulpal interstitial fluid is under a positive tissue pressure (Heyeraas, 1989) that forces dentinal fluid from the pulp through the dentinal tubules (Johnson et al., 1973; Brännström, 1982; Pashley, 1996). The diffusion of exogenous toxins into dentine is opposed by the slow outward flow of the dentinal fluid (Vongsavan & Matthews, 1992). The rate at which this occurs depends on the pulpal tissue pressure, the hydraulic conductance of the dentine and the degree of marginal integrity of the restorative material, and the cavity margin (Pashley, 1991). Pulpal tissue pressures have been measured by several techniques (Kim, 1990), and have been found to be approximately between 10mm Hg and 28mm Hg (Vongsavan & Matthews, 1992; Beveridge & Brown, 1965; Van Hassel, 1971). These pressures can double during pulpal inflammation, which then doubles the rate of local transudation between the odontoblastic cells and into the dentinal tubules (Turner et al., 1989).

The rate of flow is higher in the absence of a smear layer. It is higher for dentine that is thin as a result of restorative intervention (Pashley, 1991) and for restorations that lack marginal integrity by not providing an adequate seal (Terkla, Brown, Hainisch & Mitchem, 1987). Despite these observations in vivo dentine permeability falls progressively with time after cavity preparation (Pashley et al., 1983a). Vital teeth exhibited a progressive reduction in dentine permeability after cavity preparation, whereas non-vital teeth resulted in an increased permeability. This reduction in permeability was attributed to an increased permeability to large molecules such as fibrinogen and antibody containing immunoglobulins that entered the dentinal tubules from the pulpal vasclature (Pashley et al., 1984). In vivo, bacterial toxins are also diluted and removed from the pulpal vasclature in a healthy pulp maintaining tooth vitality (Pashley, 1979; Bergenholtz, 1990). However, pulpal health can be disrupted by changes in microleakage, dentine permeability, and reductions in blood flow which can increase the permeation of microbial products across dentine that then accumulate in the pulp. This can further trigger inflammatory reactions in the pulp (Pashley, 1979), with further changes to pulpal pressure. There is a dynamic and changing relationship that exists in the pulp complex, as a result of tooth restoration, that may impact on the vitality of the tooth (Pashley, 1985). The formation of sclerotic dentine as a result of the carious injury, cavity preparation, and the presence of a smear layer will reduce the permeability of dentine (Pashley & Livingston, 1978; Pashley, Livingston, Reeder & Horner, 1978c; Pashley et al., 1981a; Pashley, Nelson & Kepler, 1982; Pashley et al., 1981c; 1983a; 1984; 1985; 1986; 1991). Therefore, the availability of fluid and protective plasma proteins will be altered.

2.2.4.12 *Comparison of In Vivo and Laboratory Experiments*

As the contents of dentinal tubular fluid is essentially a transudate of plasma, in vivo dentine permeability falls after cavity preparation due to the biological activity of the plasma proteins, whereas the in vitro permeability of dentine remains relatively constant (Pashley, 1983a).

A conflicting report exists as a comparison of the rate of permeation of ^{131}I in the dentine of a dog in an in vivo and in vitro study of the same teeth revealed very similar results. However, the authors cautioned that the observation may not be true for larger molecules or for lipid soluble substances (Pashley et al., 1981b).

2.2.4.13 *Storage Conditions and Post Extraction Time*

Various storage mediums for teeth have been used including saline buffered with Krebs-Ringer phosphate (Outhwaite et al. 1976; Pashley et al., 1977; 1978b; Greenhill & Pashley, 1981; Reeder et al., 1978), buffered saline with sodium azide (Derkson, Pashley & Derkson, 1986; Fogel et al., 1988; Tao et al., 1991), formalin (Wenner, Fairhurst, Morris, Hawkins & Ringle, 1988; Sandoval, Cooley & Barnwell, 1989), ethanol (Boyde 1984; Gwinnett, 1988), and distilled water (Öilo, 1981; Barkmeier, Shafter & Gwinnett, 1986; Barakat & Powers, 1986; Barkmeier, Gwinnett & Shafter, 1987; Addy & Mostafa, 1988) and tap water (Le Fevre & Manly, 1938; Jørgensen, Itoh, Munksgaard & Asmussen, 1985).

Outhwaite et al. (1976) reported only a slight increase in dentine permeability in the first hour after extraction, with no further change being detected in the subsequent 3 to 4 weeks. They concluded that post-extraction time had no significant influence on hydraulic conductance of dentine. Sedgley and Messer (1992) reported that three

months storage in sterile buffered saline plus 0.05 sodium azide did not affect the punch shear strength, toughness or load to fracture. When composite/dentine bond strengths were assessed, five years post extraction time was found to have no significant effect (Peddey, 1981; Williams & Svare, 1985).

Jameson et al. (1994) reported no significant difference in tensile tests on human dentine, stored in deionised water or neutral buffered formalin, on the fracture stress, fracture strain or energy to fracture. They further reported that there were no significant differences with three-point bending tests evaluating the modules of elasticity, fracture stress, fracture strain, plastic energy, or energy to fracture, for human dentine in similar storage conditions. Different storage media had no significant effect on the strength or toughness of dentine.

Goodis, Marshall and White (1991) demonstrated increased permeability of human dentine over a 22-day period when the teeth were stored in 70 % ethanol, 10% formalin, distilled water with thymol, or phosphate-buffered saline with thymol. However, 10% formalin was the most effective storage solution for limiting changes in dentine permeability over time (Goodis et al., 1991; Jameson et al., 1994).

2.3 Enamel

2.3.1 Introduction

The composition and physical properties of enamel are vastly different from dentine, cementum and bone (Schroeder, 1991).

2.3.2 *Composition*

Enamel is the most highly mineralized tissue in the body, composed of 96% inorganic minerals, 1% organic matter, and 3% water by weight (Simmelink, 1994; Simmer & Fincham, 1995). The inorganic component of enamel is principally apatite in hydroxy-, fluoro-, or carbonate forms (Brudevold, Steadman & Smith, 1960; Gwinnett, 1992). The inorganic crystallites are embedded in an organic matrix that strengthens the enamel tissue and reduces the tendency of the crystals to separate (Simmelink, 1994). The organic component consists of two kinds of proteins, a soluble glycoprotein and a more insoluble protein (Mjör & Pindborg, 1973). During maturation of enamel, the more soluble amelogenin is almost entirely removed from the enamel while enamelin is tightly bound to the crystallites (Osborne & Ten Cate, 1976).

Water has been reported to be present in enamel to the amount of 1-2% by weight (Ferguson & Chestnut, 1978), or between 3-4% (Stack & Fearnhead, 1965). Most of the water in enamel is bound to apatite crystals as a hydration shell with only one quarter of the water freely available (Little, Cueto & Rowley, 1962; Ferguson & Chestnut, 1978; Gwinnett, 1992). Loosely bound water is thought to be present on micropores, adsorbed on the enamel crystallite surfaces, or present in the organic matrix (Corcia & Moody, 1974). This water can be removed from enamel by heating or chemically exchanged with ethanol (Little et al., 1962; Holager, 1972). Although enamel is highly mineralized it is selectively permeable, allowing the passage of small molecules and water (Darling, Mortimer, Poole & Ollis, 1961; Poole, Tailby & Berry, 1963; Bergman & Siljestrand, 1963; Bergman & Lindén, 1965).

2.3.3 *Structure*

Enamel is comprised of mineralized rods or prisms, which are separated by interrod enamel (Simmelink, 1994; Simmer & Fincham, 1995). Enamel rods commence at an acute angle from the dentino-enamel junction and follow a torturous path in the inner two thirds becoming parallel in the outer third of enamel (Gwinnett, 1992). The prisms are approximately 3µm in size at the dentino-enamel junction and enlarge to 6µm at the enamel surface (Osborne & Ten Cate, 1976). Not all rods reach the surface and this 'rodless' or 'prismless' enamel is commonly present in the pit, fissure and cervical enamel (Ripa, Gwinnett & Buonocore, 1966). Enamel rods have a key-hole appearance when examined in cross section with scanning electron microscopy (Meckel, Griebstein & Neal, 1965). The central mass of the key, named the body, is composed of crystallites, while the tail consists mainly of interrod or interprismatic material (Gwinnett, 1992). This geometry is dependent on the plane that the enamel is sectioned. Each prism is surrounded by a sheath which consists of submicroscopic fibrils and crystallites (Gustafson & Gustafson, 1967). Enamel rods are arranged in a three-dimensional pattern where each rod is parallel to the long axis of the rod though perpendicular to the enamel surface. However, the interrod crystallites will deviate at an angle up to 40-65° from the rod direction (Meckel et al., 1965; Simmelink, 1994). This discontinuous network of crystals strengthens the enamel (Simmelink, 1994), and influences the propagation of cracks in enamel (Xu et al., 1998). Enamel is an anisotropic material. It has a relatively low tensile strength which is indicative of a brittle material (Tyldesley, 1959).

2.3.4 *The Dentino-Enamel Junction*

Multiple full thickness cracks that do not extend into the dentine are often found in enamel. It is believed that the presence of coarse, parallel collagen fibres that have a diameter of 1-5 μ m are responsible for preventing the extension of enamel cracks into dentine. The energy from crack propagation is thereby increasing the fracture resistance of teeth. When this area of plastic deformation is examined, it appeared that the functional width of the dentino-enamel junction is 50-100 μ m. Therefore, the dentino-enamel junction is not a simple interface of these two tissues, but a complex zone capable of plastic deformation, and having important physical and biomechanical properties as teeth respond to functional loading (Lin & Douglas, 1994).

2.3.5 *Enamel Permeability*

Enamel is composed of a series of micropores that act like a molecular sieve allowing the passage of water and small molecules (Darling et al., 1961; Poole et al., 1963). Enamel undergoes ultrastructural and chemical changes due to its exposure to the oral environment (Arends, 1983). Unerupted teeth exhibit greater permeability than erupted teeth (Silverstone & Johnson, 1971). Deciduous enamel is more permeable than the enamel from permanent teeth (Zahradnik & Moreno, 1975; Lindén, Björkman & Hattab, 1986). The transport of water is not a simple diffusion process as the microstructure of the pores results in significant energy barriers for water diffusion (Burke & Moreno, 1975).

The velocity of the spontaneous flow of fluid through enamel in vitro is approximately 0.1mm per hour (Bergman & Siljestrang, 1963). A similar flow rate was registered in vivo (Bergman & Lindén, 1965). The diffusion co-efficient for the

passage of tritiated water across enamel is $1 \times 10^{-10} \text{ cm}^2/\text{s}$ (Burke & Moreno, 1975). The diffusion rate for enamel is in the same range as that of the cemento-enamel junction. Water passage across cementum is approximately 100 times faster than enamel, while in dentine the rate is 1,000 times faster. Therefore, enamel and the cemento-enamel junction exhibit a rate-limiting barrier for the passage of water (Petelin et al., 1999). Enamel is rather impermeable, relative to dentine (Pashley, 1990).

Pre- and post- eruptive cracks exist in enamel. Pre-eruptive cracks are filled with the cytoplasmic process of the reduced enamel organ and can traverse the entire width of enamel. These cracks are commonly found on all surfaces of unerupted teeth (Schroeder, 1991). Post-eruptive enamel cracks complete to the dentino-enamel junction are a consequence of the forces of occlusion (Lin & Douglas, 1994). These cracks would be expected to increase the permeability of this tissue.

2.4 Cementum

2.4.1 *Introduction*

Cementum is a solid, heterogeneous connective tissue that is mineralized primarily by apatite crystals, that covers the root. From this tissue, the collagen fibre bundles of the periodontal ligament are anchored. Cementum also has an adaptive and reparative function as it is protective to root dentine (Schroeder, 1991).

2.4.2 *Composition*

Cementum is the least mineralized of the three dental hard tissues. It is approximately 50 to 60% mineral by weight, primarily hydroxyapatite crystals, 25%

organic matter, predominantly Type 1 collagen, and 15% water. Cementum has been described as 'bone-like'. It is a specialized connective tissue similar to bone, except that it is avascular (Ten Cate, 1998).

2.4.3 *Structure and Classification*

Cementum is a thin layer, approximately 20-50 μ m, at the cemento-enamel junction that widens to approximately 150-200 μ m at the apex of the tooth (Ten Cate, 1998). At the cemento-enamel junction, the cementum and enamel overlap in 60% of the cases, forms a butt joint in approximately 30% of cases, and in the remaining 10% of cases the cementum and enamel does not meet with a gap being present. It is possible for all cemento-enamel joints to be present at different sites around the same tooth (Schroeder, 1991).

Early classification of cementum recognized two basic types of cementum that were observed during the formation and eruption of the teeth, primary and secondary cementum. Cementum that is formed during the development and eruptive phase of the tooth was considered to be primary cementum (Thoma & Goldman, 1939). It does not have a cellular component, consisting essentially of hyaline, and covering almost the entire root surface. As the tooth erupts, cementum continues to be deposited and is referred to as secondary cementum. It is thicker than primary cementum and is more predominant on the apical aspect of the tooth. It contains cementocytes and lacunae in varying numbers, and its structure resembles that of bone (Held, 1951).

The cells associated with cementum are cementoblasts and cementocytes. Cementoblasts are responsible for the deposition of cementum and are found at the cementum/periodontal ligament interface. Bundles of periodontal fibres are present

between these cells. A primary layer of acellular cementum is present on all roots while the secondary layer of cementum will vary in thickness and distribution (Berkovitz, Moxham & Newman, 1982). During the formation of secondary cementum, cementoblasts become cementocytes as they are trapped in lacunae within their own matrix. They possess many long cytoplasmic processes up to 15 μ m in length. These fine channels, or canaliculi, project in all directions but are longer and more numerous approaching the surface of cementum (Ten Cate, 1998). These channels provide nutritive support for the lacunae and maintain contact with the surface cementoblasts (Schroeder, 1991). Cementocytes are vital cells that demonstrate variable metabolic activity. Cementocytes found deep in the cementum appear to decrease in size, though their lysosomal and autophagic vacuoles increase in number (Furseth, 1970).

Cementum is now classified according to its structure, which can be distinguished morphologically and functionally. This is dependent on the fibrillar type, and the presence or absence of collagen and cementocytes. As such, four types of cementum have been described (Jones, 1981):

1. *Acellular, afibrillar cementum (AAC)* contains neither cementocytes, nor collagen fibrils. It consists of mineralized ground substance, probably produced by the cementoblasts. It is present as coronal cementum but has no role in the attachment of the tooth to the periodontium. Its thickness ranges from 1-15 μ m (Schroeder, 1991)
2. *Acellular, extrinsic fibre cementum (AEFC)* consists almost exclusively of densely packed bundles of extrinsic collagen fibrils that originate from the periodontal ligament. AEFC was formerly termed primary cementum. It is predominantly found on the cervical and middle aspects of the root where it is the only type of

cementum formed. Its thickness ranges from 30-230 μ m and increases in thickness with age. When AEFC becomes exposed to the oral environment, its structure, mineral density, chemical composition and permeability is altered (Schroeder, 1991). The cemental surface exposed to saliva becomes hypermineralized with randomly arranged plate-shaped crystals (Selvig, 1969; Furseth, 1971; Selvig & Hals, 1977). Cementum from periodontal pockets has fewer, smaller apatite crystals and a changed collagen structure (Selvig, 1969). The roots of incisor teeth may be solely covered by this cementum though the percentage of root surface covered by AEFC decreases from the anterior to the posterior teeth (Schroeder, 1991).

3. *Cellular, mixed fibre cementum (CMFC)* contains both extrinsic Sharpey's fibres and intrinsic bundles of collagen fibres and are located entirely within the cementum. CMFC was formerly termed secondary cementum. The fibres and cells are uneven in their distribution and density. It is a co-product of cementoblasts and fibroblasts, and is mainly found in the apical and the furcations. Its thickness varies between 100-1,500 μ m. In older human teeth, CMFC has been found to contain isolated projections of soft tissue, blood vessels and nerve elements that are continuous with the periodontal ligament (Schroeder, 1991).
4. *Cellular, intrinsic fibre cementum (CIFC)* contains cementocytes and intrinsic bundles of collagen fibrils. This cementum is only found in the reparative phase. CIFC is believed to be identical in structure to the intrinsic component of CMFC. Its thickness varies with the depth of resorption (Schroeder, 1991). Root resorption occurs as single or grouped lacunal defects of varying size and depth, even in teeth that are caries free and periodontally sound (Massler & Malone, 1954; Harvay & Zander, 1959; Harry & Sims, 1982). These root resorptions are rare in the cervical

third of the root as approximately 75% are found in the apical third of the root. Most defects are limited to the cementum, though approximately 30% penetrate as far as the dentine (Henry & Weinmann, 1951).

In addition to the four major types of cementum is an ill-defined layer known as 'intermediate cementum'. The interface between CMFC and the underlying dentine, which includes intermediate cementum, is a mixture of outer root dentine and cementum that is ill-defined and not distinct (Schroeder, 1991). Tomes (1914) believed that cementum is connected to the dentine through the granular layer of dentine. This layer is external to the granular "layer of Tomes" and forms the apical part of the dentino-cemental junction. In the coronal aspect of the root this junction is formed by the homogeneous hyaline layer described by Hopewell-Smith (1920). Intermediate cementum describes a narrow layer of cementum found between dentine and root cementum. Both the layer of Hopewell-Smith and the intermediate cemental layer are ill-defined (Schroeder, 1991). Owens (1976) suggests that this homogeneous zone between cementum and the granular "layer of Tomes" represents the outer layer of dentine. Microradiographic studies show Tomes layer to consist of a narrow zone of hypomineralized-hyperorganic dentinal matrix that was subjacent to the cementum (Shackleford, 1971). The thickness of the cemento-dentinal junction is estimated to be $0.03 \pm 0.01\text{mm}$ (Petelin et al., 1999).

2.4.4 Permeability

The permeability of cementum was first investigated by a series of dye diffusion experiments (Stewart-Ross, 1933; Stones, 1934). These authors reported that only the

primary cementum of young animals is permeable, while the cementum of animals was found to be impermeable. Also, for the secondary cementum of the older animals the dye could only penetrate the outer layers. Stewart-Ross (1933) found the dentine-cementum border acted as a barrier for dye penetration. Penicillin placed into the pulp chamber has been found to penetrate dentine but did not penetrate into cementum (Wach, Hauptfuehrer & Kesel, 1958; Bennett & Miles, 1955). Lindén (1968) was able to observe that cementum was permeable to water and physiologic saline. The permeation of fluid was slower for older teeth. This was particularly noticeable in the apical third of the root and appeared dependent on changes in the dentine rather in the cementum. Fluid penetration of the acellular cementum exhibited a diffuse pattern and appeared to follow the Sharpey's fibres. Fluid flow through cellular cementum followed the lacunae and their canaliculi, and produced a less uniform pattern. Teeth with hypersensitive tooth necks that were devoid of cementum exhibited open dentinal tubules with a rapid rate of flow.

Tao et al. (1991) demonstrated that endodontic instrumentation did not significantly alter the permeability of root dentine if the cementum layer was intact. Cementum acts as an effective barrier because when the cementum was removed, there was a significant increase in root permeability.

Petelin et al. (1999) also report on the rate-limiting barrier that is present at the dentino-cemental junction. These authors investigated the transport of water soluble, spin-labelled molecules through cementum using electron paramagnetic resonance (EPR). A diffusion co-efficient was used to quantify molecular transport in cementum. The diffusion co-efficient for cementum is $1 \times 10^{-8} \text{ cm}^2/\text{sec}$, and at the cemento-dentinal junction it is $0.3 \times 10^{-10} \text{ cm}^2/\text{sec}$. These figures quantify the rate limiting barrier effect

that occurs at the dentino-cemental junction. The diffusion rate of the dentino-cemental junction is similar to enamel (Burke & Moreno, 1975; Petelin et al., 1999), and considerably slower than the flow of fluid in dentine.

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CHAPTER 3 AIMS AND OBJECTIVES

From the literature review it is apparent that dentine fracture is a significant clinical problem. Also, teeth that have been endodontically treated are more susceptible to fracture. There has been little consideration that dentine is a fluid filled composite material and how this dynamic aqueous environment would impact on the fracture process. The mechanism for fracture of dentine is also not clear. As dentine is considered a brittle material, a fracture mechanics approach is considered the best measure to quantify resistance to fracture. However, due to the complexity of the size and shape limitations of dentine samples only a few studies have examined fracture toughness of dentine.

The objectives of this study were to:

1. Assess the mechanisms of the fracture of teeth from the surfaces of fractured cusps which were examined by scanning electron microscopy to determine if the fracture propagated by cyclic fatigue, or fractured catastrophically as a single incident consistent with brittle behaviour. If crack propagation is progressive, re-initiation of the fracture would be required and SEM examination should reveal blunting of the crack tip or distortion at the position of crack re-initiation.
2. Quantify the difference in fracture toughness by measuring the work of fracture for hydrated, dehydrated and re-hydrated dentine samples.
3. Investigate differences in the mechanisms of fracture for the hydrated and dehydrated state for dentine by optical examination of the crack, which would be propagated utilizing a simple wedge-loaded double cantilever test.

CHAPTER 4 BACTERIAL CONTAMINATION OF CRACKS IN SYMPTOMATIC VITAL TEETH

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Bacterial Contamination of Cracks in Symptomatic Vital Teeth

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Key Words: Incomplete tooth fracture, dentinal crack, bacteria, microleakage.

Abstract

As part of an ongoing study on the initiation of cracks in teeth, twenty teeth exhibiting symptoms consistent with the presence of dentinal cracks were examined. The presence of a cracked cusp was confirmed by the selective application of pressure either with a mirror handle or Fracfinder*. Cracked cusps were fractured from the teeth after the removal of all existing restorations and were immediately placed into ten percent formalin. Subsequently specimens were dehydrated, sputter coated and examined under scanning electron microscopy. All the cracked cusps exhibited complete fracture of the dentine to the level of the dento-enamel junction. No partial fractures were seen. Numerous bacteria of many morphological forms were present on the dentinal surfaces, of all fractured cusps, in all teeth. Cocci, bacilli and filamentous forms were consistently found. Many bacteria were in the process of division. While bacterial contamination of dentinal cracks has been described in histological studies, the nature and distribution of these bacterial and fungal forms has not been shown previously in any detail. Prior Scanning Electron Microscopic studies investigating the nature and mechanisms of fracture have not revealed bacterial contamination of the fractured surface. This paper draws attention to the fact that all symptomatic cracks in teeth appear to (1) extend right through the dentine to the dentino-enamel junction, and (2) appear to be extensively contaminated by bacteria.

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Introduction

It is well documented that cusps of teeth can be incompletely fractured and, as a result, teeth may become symptomatic (1-11.) Classically, the symptoms related to these teeth are pain on biting and sensitivity to thermal changes, particularly to cold (2-11.), with pain on biting being the most consistent complaint (1-11.). Pain associated with the release of pressure, "rebound pain" (4,5,11.), is also a consistent finding. Occasionally, there is sensitivity to sweetness (3,10,12.). Patients often present with a protracted history of pain of varying intensity that may be difficult to locate (4.). Dentinal cracks are not generally evident radiographically (6,10.).

The recurring symptoms of pain in teeth with dentinal cracks are probably associated with a pulpal response to rapid movement of dental fluid within the tubules, due to an increase in hydrostatic pressure as masticatory forces cause flexure of the cusp (11,13.). Rebound pain can similarly be explained by fluid movement, as the pressure on the cusp is released and the crack rapidly closes together.

While the diagnosis and management of incomplete cuspal fracture have been the subject of a number of views (1-12, 14-16.), the mechanism responsible for cuspal fracture is not completely understood. Catastrophic and complete fracture of both dentine and enamel can of course occur from major trauma. However, incomplete fracture is not well documented. Incomplete fracture is primarily associated with restored teeth. The size of the restoration, cavity design, and the strength of the cavity surface tooth/restorative/adhesive interface all influence the strength of the remaining tooth structure (17). Wide and deep cavity proportions increase the stresses generated at the cavity floor during occlusal load (18). Clinically, there is often a period of some years between the placement of a restoration and the development of symptoms

associated with incomplete cuspal fracture. This observation suggests a failure mechanism where there is progressive failure of brittle tooth structure. That is, cracks propagate in response to repeated occlusal load until catastrophic failure occurs (7,8,15,17,19); a process known as cyclic fatigue.

In many substances the mechanism of fracture can be determined by scanning electron microscopic examination of the fractured surface. If any fracture process involves crack formation and propagation, it is often possible to determine by examining the fractured surface whether the fracture has occurred in a single incident or incrementally. A number of studies have examined fractured dentinal surfaces but have not shown conclusive results (20,21,22). The interwoven, collagenous structure of dentine is resistant to crack propagation, which provides an inherent strength to the tooth (23). Dentine is a resilient supporting tissue capable of resisting the energy of crack propagation as the collagenous structure allows the structure to undergo plastic deformation (24). If crack propagation is progressive, re-initiation of the fracture is required and scanning electron microscopic examination should reveal blunting of the cracked tip or distortion at the position of crack reinitiation. These observations have not been reported (20). The nature of crack propagation in dentine remains unclear. With the above observation in mind, it was considered that an examination of fractured surfaces of cracked cusps in symptomatic incompletely fractured teeth was warranted, as it could provide information on the precipitating factors, and the nature of crack propagation in these teeth. These studies are continuing. However, pilot studies also showed that the surface of the fractured cusps was almost entirely covered by bacteria. While the presence of bacteria has been demonstrated before as a result of microleakage (11,13), the authors were unaware of any publication that has described the extent of bacterial contamination of the dentinal surfaces of cracked cusps, or of the relationship

of bacterial contamination to the dentino-enamel junction. A detailed study of the extent of microbial contamination of cracks in teeth was therefore considered warranted.

Material and Methods

Twenty teeth from patients exhibiting symptoms of cracked teeth were identified by a thorough history of the patient's complaint. The identity of the crack was confirmed by the application of pressure, either with a mirror handle or Fracfinder. Teeth were isolated with rubber dam, and all restorations were removed. The presence of a cracked cusp was confirmed by the use of transillumination. Cusps were fractured from the remaining tooth structure by using an amalgam plugger to create a wedging effect. Once removed, cusps were immediately placed in 10% Formalin. The fractured cusps were dehydrated in an ascending series of ethanol, and placed into hexamethyldisilazane before air drying. Samples were mounted onto aluminium stubs and sputter-coated with gold prior to examination with a scanning electron microscope.** The surfaces of the fractured cusps were sequentially examined from the enamel across the dentine. Images of the fracture surfaces were recorded photographically.***

** JEOL JSM 35CF

*** Ilford FP 4 70mm

Results

Micro-organisms were found on the dentine surfaces of all fractured cusps. These micro-organisms were not evenly distributed across any of the fractured sample surfaces, but had a greater propensity to be located near the dentino-enamel junction (Figure 4.1). Bacterial numbers varied considerably. Some samples showed few micro-organisms on the fractured surface, while others appeared completely covered by bacteria. In all specimens, bacteria were found over the whole of the fractured surface, from the pulpo-axial line angle to the dentino-enamel junction; and in all specimens bacteria were present at the dentino-enamel junction. Micro-organisms were not found on the fractured enamel surface. Bacteria were noted protruding into the dentinal tubules in some samples (Figures 4.2 and 4.3). The bacteria were of many morphological forms: cocci occurred singly or in short chains (Figure 4.2). Straight bacilli of varying lengths, and curved bacilli were noted (Figure 4.3). Some organisms appeared to be covered by a mucus-like coating resembling glycocalyx (Figure 4.1). Bacteria of all morphologies were frequently seen in the process of division (Figure 4.3). Very elongated forms, which often were branched and were consistent with fungal morphology, were also noted on some fractured cusps (Figure 4.4). Bacterial sizes varied considerably. Most cocci were approximately $0.5\mu\text{m}$ diameter. The most prevalent bacillus form was approximately $0.5 \times 1.0\mu\text{m}$ in diameter. Filamentous forms were approximately $0.5\mu\text{m}$ in width and in excess of $10\mu\text{m}$ in length. On most samples, micro-organisms were aggregated in colonies. Generally, a number of morphologically distinct types of organisms were noted within each colony; rarely did a colony appear to consist of a single morphological form.

Discussion

This study demonstrates significant bacterial contamination of dentinal cracks in symptomatic cracked teeth. It must be emphasised that the only bacteria observed were those which remained attached to the one fractured surface examined. Many more bacteria are presumably present in the fracture space and the other fractured surface. The morphology of the bacteria was consistent with other studies examining caries in teeth and resembled normal oral flora (13,25).

The fact that bacteria were consistently found covering the entire cracked dentinal surface right to the dentino-enamel junction, confirmed that, in all twenty specimens from these symptomatic vital teeth, the fracture extended all the way through the dentine to the junction. The presence of bacteria may be an indication as to the nature of the fracture mechanism. Should dentinal fractures have been incomplete, the bacteria would not have covered the whole of the fractured surface right to the junction. Yet many reports in the literature describe the progressive nature of crack propagation where the failure mechanism can be attributed to cyclic fatigue growth as a consequence of occlusal load (7,8,15,17,19). If this is the mechanism of fracture, it would have been expected that partial fracture of the dentine would have been observed. Other reports have suggested that fracture of dentine can occur catastrophically (20,26). Interestingly, prior scanning electron microscopic studies that examined fractured dentinal surfaces to find evidence as to the nature of the fracture mechanism did not report evidence of bacterial contamination (20,21,22).

Dentine is permeable to bacteria and bacterial products due to its tubular structure. While bacteria and bacterial products are considered to be highly significant

in the development of pulpal inflammatory lesions under dental restorations (27) bacteria have seldom been found to penetrate vital dentine (28,29). The role of bacteria present on the fractured surface in the development of pulpal inflammation in cracked teeth is therefore speculative. Nevertheless, bacteria have to be implicated in the development of pulpitis in cracked teeth, and the presence of bacteria in the fracture site could itself be the precipitating cause of pulpitic pain in cracked teeth.

Treatment options for cracked teeth vary from complete removal of the cracked cusp to binding cusps together to prevent flexure. The latter treatment modality is not always successful, with endodontic intervention sometimes required (4,9,30). Bacteria trapped in the cracks under restorations could theoretically remain viable due to percolation of nutrients from open tubules. Viable bacteria have been cultured from teeth restored one year previously (31). Bacteria can also survive desiccation and depletion of nutrients and remain viable for many years (32). Quiescent bacteria could become active as a result of fluid derived from the oral environment as a result of the micro-leakage from poor marginal seals of the restoration. Bacteria trapped in cracks could be responsible for continued pulpal inflammation. Percolation of bacteria into cracks has been implicated in the development of infections in devitalised, traumatically injured teeth (33). Brännström and Nyborg (34) suggest that bacteria will survive and proliferate in a space that exists under a restoration and cause an associated injury to the pulp. However that pulpal injury associated with bacterial contamination of dentine has been shown to be self-limiting as healing is evident at 30 days despite the continued bacterial presence (35,36).

Further studies are required to investigate the fate of bacteria left in cracks and to determine whether these bacteria in teeth are partially or completely responsible for the development of pulpitis in teeth with cracked cusps.

Conclusion

The presence of cracks in restored teeth is a significant cause of restorative failure and tooth fracture. The propagation of the crack and the associated microleakage as a result of the bacterial contamination of dentinal cracks has important clinical considerations. Yet, the nature of crack propagation remains unclear. The findings in this study of bacterial contamination complete to the dentino-enamel junction further suggest that dentine may fracture catastrophically.

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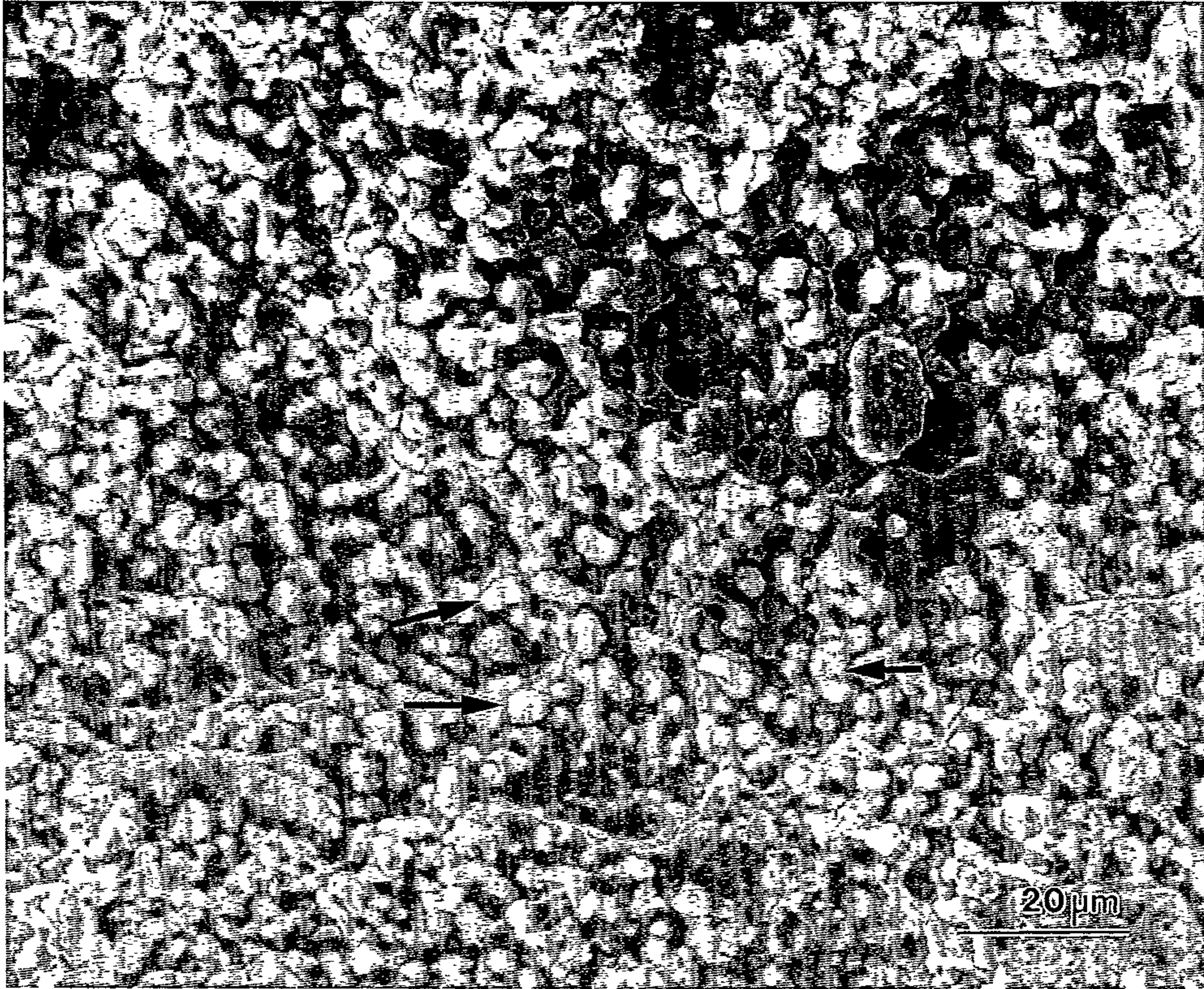


Figure 4. 1 Scanning electron micrograph of dentinal surface adjacent to the dentino-enamel junction in a fractured cusp showing predominantly coccal bacteria. Bacteria covered with glycocalyx or a mucus-like coating can be seen. x600.

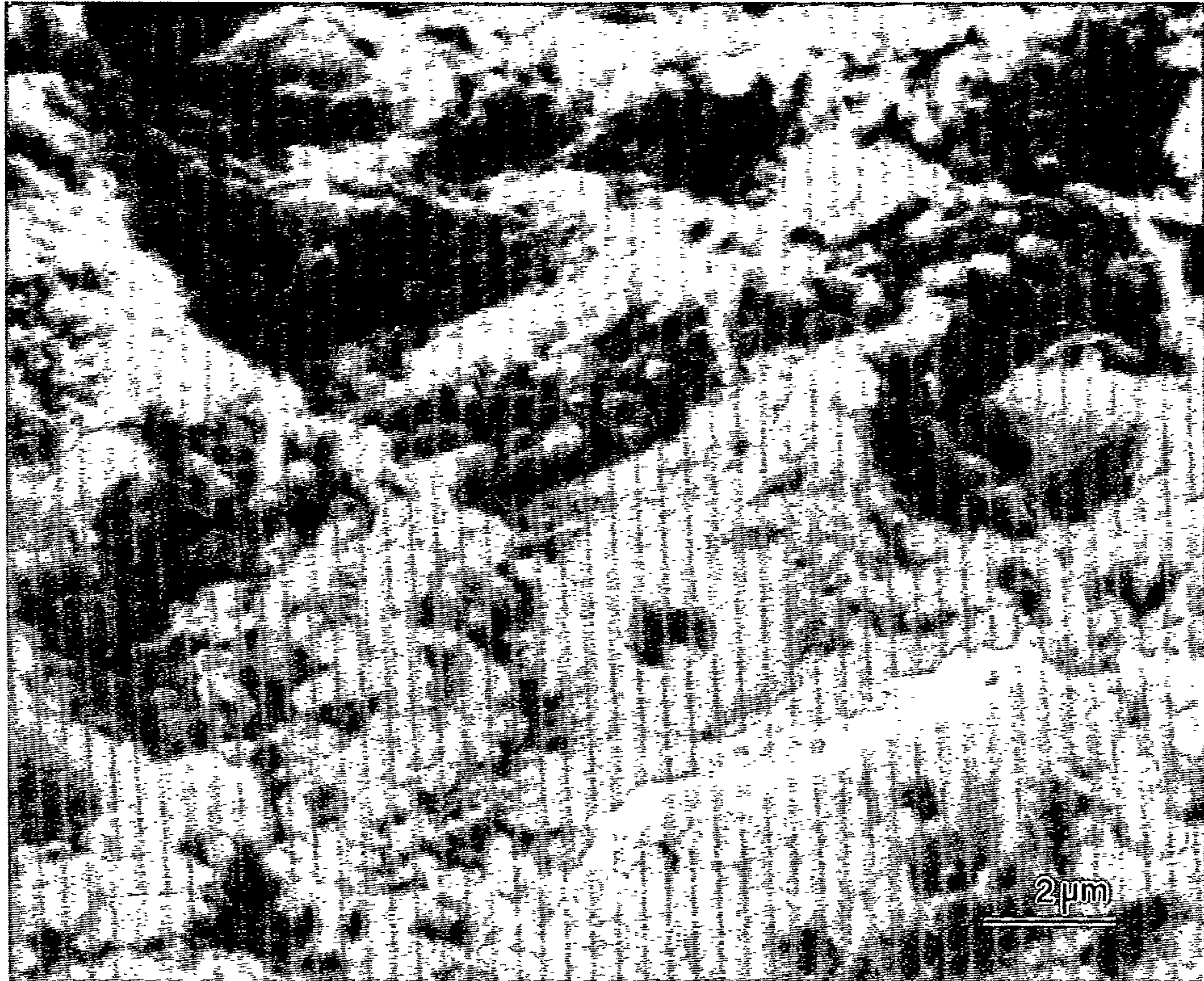


Figure 4. 2 Scanning electron micrograph of dentinal surface showing cocci, and baccilli. Note bacteria can be seen protruding from the dentinal tubules. The cracks at the tubular apertures are dehydration artefacts. x4800.

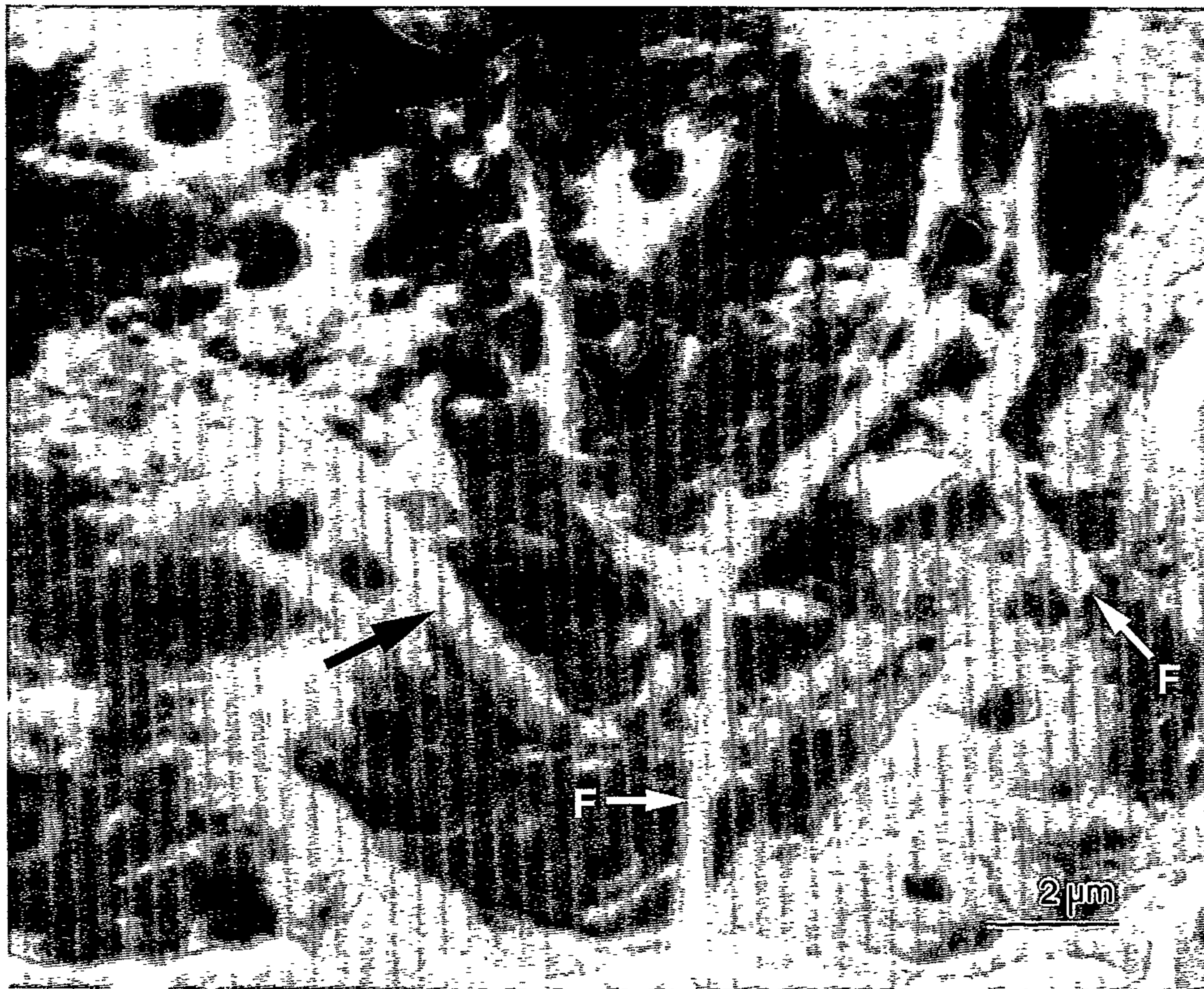


Figure 4. 3 Scanning electron micrograph of dentinal surface showing cocci, bacilli and rods. Morphologies consistent with fungus can also be seen. A bacillus in the process of division is evident. x4800.

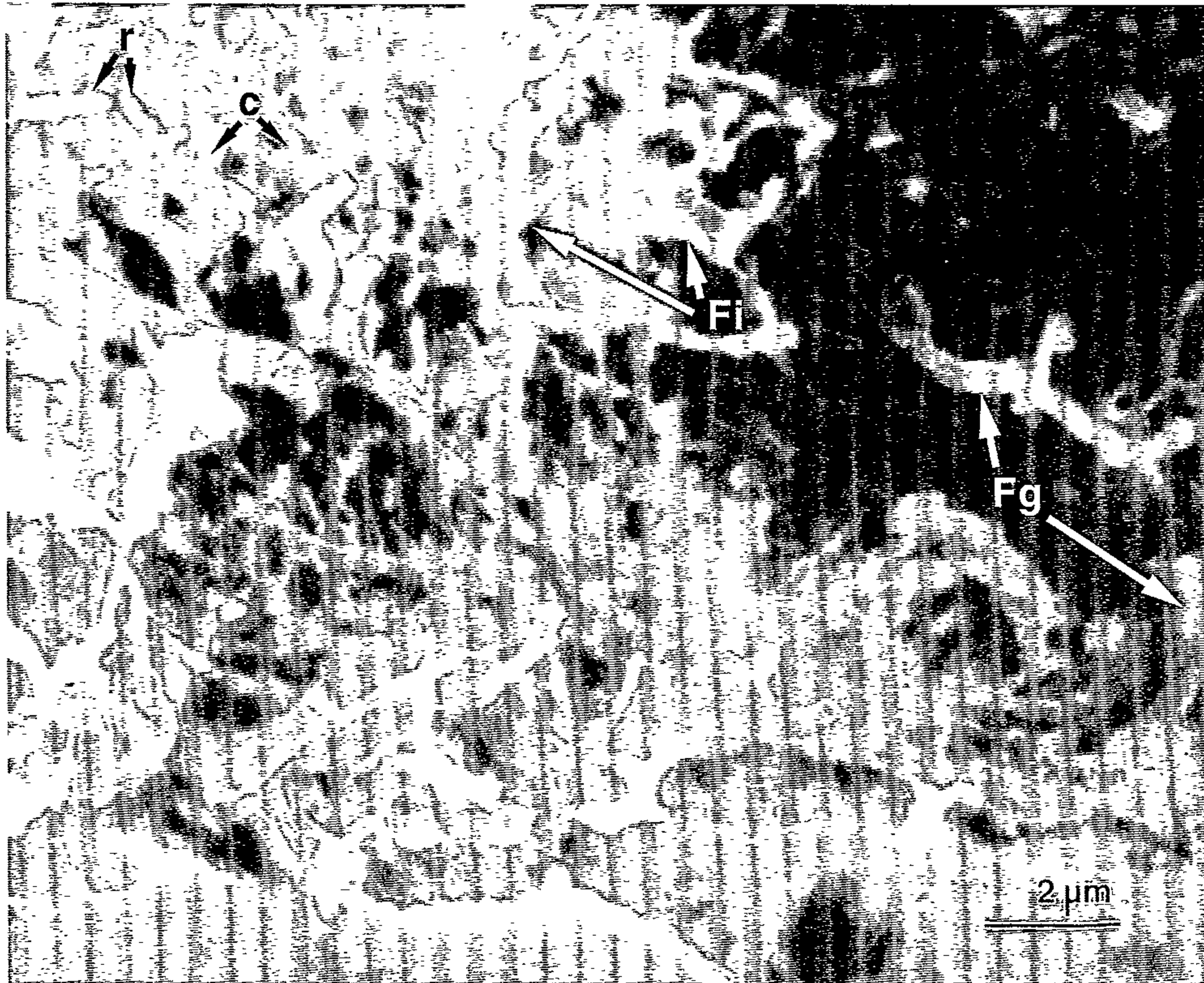


Figure 4. 4 Scanning electron micrograph of dentinal surface showing cocci rods, filaments and fungal forms. x4800.

**CHAPTER 5 FRACTURE TOUGHENING MECHANISMS
RESPONSIBLE FOR DIFFERENCES IN WORK
TO FRACTURE OF HYDRATED AND
DEHYDRATED DENTINE**

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Fracture Toughening Mechanisms Responsible for Differences in Work to Fracture of Hydrated and Dehydrated Dentine.

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Keywords: Dentine, bone, work to fracture, fracture toughening mechanisms,
micro-cracking.

Abstract

This study investigates the nature of deformation and differences in the mechanisms of fracture and properties of dentine where there has been a loss of moisture, as may occur with removal of the pulp in the endodontic treatment of teeth. Controlled fracture toughness testing was conducted on bovine teeth to determine the influence of hydration on the work of fracture of dentine. Significant differences ($p < 0.01$) were observed between the fracture toughness of hydrated ($554 \pm 27.7 \text{ J/m}^2$) and dehydrated ($113 \pm 17.8 \text{ J/m}^2$) dentine. Observations of the crack tip region during crack extension revealed extensive ligament formation occurred behind the crack tip. These ligaments provide considerable stability to the crack by significantly increasing the work of fracture, thereby acting as a fracture toughening mechanism. Micro-cracking, reported as a fracture toughening mechanism in bone, is also clearly seen. A zone of in-elastic deformation may occur as hydrated specimens revealed upon crack extension, a region about the tip that appeared to suck water into the structure and to exude water behind the crack tip. In dehydrated dentine, no in-elastic zone was observed. Micro-cracking is present though the cracks are smaller, straighter and with less opening than hydrated dentine. Only limited ligament formation just behind the crack tip was observed. These differences resulted in a significantly lower work of fracture with unstable brittle fracture characteristics. Based on these results, several fracture-toughening mechanisms were identified in dentine, with micro-cracking not considered the most important. These findings may be relevant for bone, a similar mineralised hydrated tissue.

Keywords: Dentine, bone, work to fracture, fracture toughening mechanisms, micro-cracking.

Introduction

Dentine is a highly mineralised tissue, which forms the bulk of the tooth. It is a hydrated compound that contains fluid filled tubules surrounded by highly mineralised peri- tubular dentine embedded in intratubular matrix. Hydroxyapatite crystals, the main inorganic material, provide strength, while collagen fibrils provide toughness (Marshall, 1993). Dentine is able to resist fracture as the orientation of collagen fibrils counter the directional effect of the dentinal tubules, thereby exhibiting crack stopping behaviour (Renson et al., 1974). Also, Pashley (1990) has suggested that the fluid filled dentinal tubules could function to hydraulically transfer and dissipate the occlusal forces applied to teeth. From the perspective of theoretical mechanics, the structural stability of dentine is a function of mineralization and of moisture content (Kinney et al., 1993; 1999).

Although significant differences in biomechanical properties of hydrated and dehydrated dentine have been reported, the influence that moisture itself plays in the biomechanical behaviour of teeth is still not well understood or fully investigated (Huang et al., 1992). From a clinical perspective it is well established that teeth are more susceptible to fracture if the pulps have been removed (Meister et al., 1980; Gher et al., 1987). Fractures occurring in these endodontically treated teeth present significant and ongoing clinical problems. The reason for the increased susceptibility to fracture has not been clearly established. However, perceptions that root filled teeth are more brittle than vital teeth has historically been attributed to their decreased moisture content (Helfer et al., 1972). Many studies have attempted to compare properties of untreated teeth directly with root filled teeth (Jameson et al., 1993, Huang et al., 1992). Loss of tooth structure associated with restorative procedures, has been proposed as a

primary reason for increased fracture susceptibility in some posterior teeth (Reeh et al., 1989; Hansen et al., 1990; Hood, 1991; Panitvisai and Messer, 1995). This does not fully explain why endodontically treated teeth are more susceptible to fracture particularly over time. There have been relatively few measurements of the fracture of dentine presumably because of the small sizes of specimens obtainable and the shape complexity of this tissue. A number of studies have suggested that there are no major differences in the dentine mechanical properties of vital and endodontically treated teeth (Sedgley and Messer, 1992; Huang et al., 1992). However, prior studies have not fully investigated the mechanisms of fracture for hydrated and dehydrated dentine. Toughness, defined as the energy required to induce fracture is significantly reduced by dehydration (Jameson, 1993). Dehydrated dentine loaded in tension or flexure exhibited a lack of plastic flow, demonstrated elastic-brittle behaviour, and required less energy to induce fracture than hydrated dentine. Changes in biomechanical properties as a result of dehydration could be reversed by re-hydration. Studies which have attempted to compare the moisture content of untreated and endodontically treated teeth have reported mixed results (Helfer et al., 1972; Papa et al., 1994). Dehydration results in 30% moisture loss from human dentine over seven days and 50% humidity (Jameson et al., 1993). Tubules contain 75% of the moisture content in dentine with the rest being contained in the mineralised matrix (van der Graaf and Ten Bosch, 1990). The influence that dehydration plays in the increased susceptibility of endodontically treated teeth to fracture is still not well understood.

Rasmussen et al. (1976), using the work of fracture (W_f) approach, provided a direct measurement of the fracture properties of human enamel and dentine. This approach has been used in controlled fracture studies on bone, ceramics and composites (Tattersall and Tappin, 1966; Zioupos, 1998). A notched specimen is subjected to

loading in flexure or tension using a constant deformation rate testing apparatus so that the crack stably extends from the notch. The (W_f) is determined from the area under the load versus extension curve, that is the work done, which is divided by the area of the two fractured surfaces. This is different from the fracture energy approach by Jameson et al. (1993) where small dentine bars were not notched and loaded by three point bending and tension until fracture, which was usually unstable. The fracture energy was determined from the area under the stress-strain curve.

The present study was designed to extend the work of Jameson et al. (1993) by investigating the mechanical testing and water content of dentine from the perspective of the mechanism of fracture. The hypothesis tested is whether partial dehydration of dentine, as may occur with removal of fluid from the pulp cavity, is a contributing factor in the higher reported incidence of fracture for endodontically treated teeth. The work of fracture approach was chosen because of the complexity of the shape and size limitation of the samples of dentine. In addition, this study investigates in-situ the nature of deformation about the crack tip microscopically to test for differences in the mechanism of fracture for hydrated and dehydrated dentine during crack extension.

Materials and Methods

Specimens were prepared from bovine incisor teeth. The teeth were manually extracted from the mandibles of cattle aged approximately eighteen months immediately after the death of the animals and placed into 10% neutral buffered formalin (Jameson et al., 1994; Goodis et al., 1991). Teeth with fractures or very thin root structure were rejected. The crowns were prepared in the form of hollow, tapered cylindrical double

cantilever beam specimens. This testing geometry leads to a more stable cracking specimen provided the testing machine is sufficiently rigid (Lawn, 1993). The crowns were sectioned 2mm above the cemento-enamel junction under constant irrigation (Figure 5.1). A box cavity preparation approximately 2mm square was cut separating the cemento-enamel junction to allow for mechanical gripping. A notch was cut a further 2mm through the entire root. An additional shallow notch to guide the crack was then extended through the cementum and dentine on both the mesial and distal root surfaces to the apex. A high strength multi-strand wire was used to load the teeth (Figure 5.1). Specimens were dehydrated at 22°C and 50% relative humidity for 7 days. Specimens to be re-hydrated had all dentinal surfaces coated with a thin layer of nail polish to render them impermeable and re-hydrated for 6 hours in water. Tests were conducted on 5 hydrated, 5 dehydrated and 5 re-hydrated dentine roots in a custom built assembly and a Shimadzu Autograph (Shimadzu AG-50kNE, Japan), a screw driven universal testing machine, with a 1kN load cell. Tests were conducted in a water bath at 37°C for hydrated and re-hydrated specimens. Specimens were loaded at a rate of 0.2mm/minute. Displacement of the crosshead was measured with a linear variable displacement device built into the testing machine.

Fracture energy was determined from the area under each force-displacement curve, which was divided by the area of crack surface generated. To avoid the error of enlargement from imaging, a scale was included in the digital image. Results from the tests were analysed using ANOVA and Scheffe multiple mean differences tests at $p=0.01$. After mechanical testing, the fractured roots were critical-point-dried and sputter coated with gold and examined with a scanning electron microscope (Phillips XL30, Japan).

Roots of a further five teeth were prepared to optically observe propagation of the crack. The crowns were sectioned 2mm above the cemento-enamel junction under constant irrigation (Figure 5.2a). The teeth were then bisected in a mesio-distal orientation from the crown to the apex. The buccal surface was polished with a descending order of grit to 6 microns to expose dentine along the entire root surface (Struers Roto-Force 4, Radiometer, Copenhagen) and was lightly etched with a mild phosphoric acid solution to expose dentinal tubules. A 2mm notch was placed at the coronal aspect of the tooth beyond the cemento-enamel junction. Initial attempts to apply a bending moment to the sample to achieve crack extension beneath the optical microscope were abandoned because of the difficulty of attaching external beams. Instead, a simple wedge loaded double cantilever type procedure was adopted which resulted in excellent fracture stability and identical stress state about the crack tip at the onset of fracture (Lawn, 1993). A thin scalpel blade was placed in the notch and the specimen inserted into a small engineer's vice (Figure 5.2b). Upon closing the vice jaws the blade was slowly driven into the notch resulting in stable crack extension from the notch tip. The scalpel wedged into the notch did not contact the crack tip. In this manner, repeatable small increments of crack extension, typically 20 to 50 microns, could be viewed with an optical microscope.

Results

Examination of the force displacement curves (Figure 5.3) reveal significant differences in the work to fracture for the hydrated and dehydrated samples. The method of testing allowed for excellent crack stability of samples differing in shape and size so that work to fracture could be measured. The dehydrated samples had a

maximum load and maximum crack opening displacement of less than half of the hydrated samples. The work to fracture for the different states of hydration were $554.4 \pm 27.7 \text{ J/m}^2$ for hydrated dentine, $113.5 \pm 17.8 \text{ J/m}^2$ for dehydrated dentine, and $505.2 \pm 27.3 \text{ J/m}^2$ for re-hydrated dentine. ANOVA analysis indicated a significant difference between at least one of the three treatment groups ($p=0.000$). Multiple comparisons using conservative Scheffe's test revealed significant differences between hydrated and dehydrated groups and the re-hydrated and dehydrated groups ($p<0.01$). There was a significant difference between hydrated and re-hydrated groups although the probability level was lower ($p<0.05$).

The wedge (scalpel) loaded fracture test (Figure 5.2a) of the tooth also led to very stable crack extension that allowed observation of the different fracture toughening mechanisms for hydrated and dehydrated specimens and account for the differences in the work to fracture values. Observations of the crack tip morphology of the hydrated dentine are shown in Figure 5.4. A high magnification image (Figure 5.4a) shows the discontinuous nature of the crack tip fracture processes. Small micro-cracks formed ahead of the main crack, and coalesced with other micro-cracks resulting eventually in a continuous crack. A noticeable feature of these observations was the width of the micro-cracks and the discontinuous nature of the linkage of the crack. Even at distances several hundred microns behind the crack tip (Figure 5.4b) the crack was not continuous but showed ligaments bridging the crack tip. In some instances major ligaments formed leading to large bridges across the extending crack. An additional feature evident during the testing of the hydrated samples was the development of droplets of water on the surface just behind the crack tip (Figure 5.5). These droplets formed within moments of the crack arresting following crack extension. It was also noted that, when

the surface ahead of the crack tip was covered with water just prior to crack extension, pressing the scalpel into the notch to re-initiate crack growth resulted in water being sucked into the tooth in a region about the crack tip. The extent of this region of water ingress was comparable to that of the water egress and over a region much larger than the zone of visible micro-cracking.

An explanation of the lower work to fracture values for dehydrated dentine was the reduced effect of the fracture toughening mechanisms. Observations of the dehydrated crack tip (Figure 5.6) show small micro-cracks developed ahead of the crack tip in much the same manner as seen in the hydrated dentine. The micro-cracks are much straighter with less crack opening than hydrated specimens. Linking of the micro-cracks resulted in small ligament development just behind the crack tip, but much less than hydrated specimens. There was no evidence of major ligament formation.

Prior studies that describe the appearance of scanning electron micrographs have described step-like and ridge patterns and crater-like pullout from the deeper layers of dentine (Renson et al., 1974; Jameson et al., 1993) can now be attributed to areas of major ligament formation. Scanning electron micrographs of the fracture surfaces of the hydrated and dehydrated specimens (Figures 5.7 and 5.8) show the predominant fracture surface parallel to the dentinal tubules. The tubule pattern, clearly seen on the dehydrated fracture surface in Figure 5.8, shows the highly planar nature and limited evidence of ligament formation between some of the tubules. The fracture surface of the hydrated dentine (Figure 5.7) showed a more complex structure. There was more evidence of cracking between the tubules and tearing ligaments. The surface was less planar and less continuous across the specimen that would correspond to areas of ligament formation.

Discussion

This study has demonstrated that water content has a profound effect in the fracture of dentine. The work of fracture values of hydrated ($554.4 \pm 27.7 \text{ J/m}^2$) and dehydrated ($113.5 \pm 17.8 \text{ J/m}^2$) dentine showed a very large difference. This result was statistically significant ($p < 0.01$). Re-hydration substantially restored these values ($505.2 \pm 27.3 \text{ J/m}^2$). These values are similar to human dentine (Rasmussen et al., 1976). Bovine incisor dentine and human radicular dentine have similar tubular diameter and density (Fogel et al., 1988). The results of this study may or may not have a direct correlation to the increased fracture susceptibility of endodontically treated teeth. It could be argued that endodontically treated teeth exist in a fluid filled environment (Huang et al., 1992). However, the removal of the pulp, pathological and iatrogenic changes to dentine, and the rate limiting barrier to fluid by enamel and cementum should logically effect the degree of hydration over time.

Fracture of dentine is a function of crack initiation and crack propagation (Arola et al., 1999). This study clearly demonstrates the presence of micro-cracking for the first time in dentine (Figures 5.4 – 5.7). Crack growth resistance of a material is a consequence of intrinsic micro-structural damage mechanisms operating ahead of the crack tip, and extrinsic crack tip shielding mechanisms that operate behind the crack tip. Intrinsic mechanisms are an inherent property of the material that control crack initiation. Extrinsic mechanisms, which include crack deflection, inelastic or dilated zones that surround the crack wake, and bridge formation (ligament toughening) between the crack surfaces acting in the crack wake, are responsible for resistance-curve behaviour (R-curve). They are the primary toughening mechanisms in brittle materials (Evans and Faber, 1984; Ritchie et al., 2000).

The optical and SEM observations reveal some similarities and differences in the fracture mechanisms of the hydrated and dehydrated dentine. The observations clearly show that a number of extrinsic toughening mechanisms, such as micro-cracking (Figures 5.4 and 5.4a), occur ahead of the crack tip and ligament development (Figures 5.4a and 5.4b) behind the tip in both conditions. In addition, with the hydrated sample, dilatancy about the crack tip was observed as indicated by the fluid ingress and egress (Figure 5.5). The present observations do not permit us to determine whether, or to what extent, a zone of plastic or visco-elastic deformation behaviour occurs about the tip although the known viscous behaviour of dentine (Marshall, 1993) coupled with the more open micro-cracks in the hydrated dentine suggest it occurs. The size of this zone appeared to be much larger than the narrow zone of micro-cracking about the crack tip. During loading, a region of hydrostatic tension and superimposed shear stresses develop about the crack tip. These stresses are able, in the case of the hydrated and porous dentine, to induce dilation of a region about the crack tip in a similar manner to the development of a plastic zone about the crack tip of a metal. The major difference being that dentine, particularly the more collagenous inter-tubular region, contains many fine tubules connected to the main tubules. Fluid is able to migrate into the structure to accommodate both the dilation ahead of the crack tip and the relaxation of this region behind the crack tip. Energy is consumed by both the inflow and egress of fluid from this region. The collagen within this region is also able to extend when moist to accommodate such dilation and shear strains. In the absence of fluid flowing into this region, the dilation would have to be solely accommodated by shear or cavitation of the existing fluid within this area. These observations of fluid flow about the tip of a crack on loading and unloading support the hydrodynamic theory of dentinal sensitivity (Brännström, 1982).

The micro-cracks appear to initiate from the stress concentration associated with the dentine tubules ahead of the crack tip and which form in the more highly mineralised peri-tubular region. In all instances, the individual micro-cracks do not readily link up but appear more to join in a shearing fashion as expected (Swain and Hagan, 1978). Micro-cracking has been one of the major mechanisms proposed for the toughening of bone, a similarly mineralised tissue to dentine (Zioupou, 1998; Vashishth et al. 1997). However, despite the similarity of micro-cracking in both the hydrated and dehydrated dentine, a four-fold difference in the work to fracture is measured in the present work.

The major differences between the hydrated and dehydrated behaviour are in the development of extensive crack bridging ligaments behind the crack tip and also the evidence of the more planar nature of the fracture surface of the dehydrated dentine. The dehydrated fracture surface is almost entirely coincident with the dentine tubules whereas in the hydrated tissue the fracture path often passes around the peri-tubular region and through the more collagenous inter-tubular material. This apparent minor difference in crack path and the greater influence of more highly deformable collagenous component of the intertubular region, when hydrated, is considered to result in a greater range and propensity of localised ligament bridging. These ligaments across the crack tip greatly contribute to the greater toughness of the hydrated tissue as the closure forces generated reduce the magnitude of the stress at the crack tip. This mechanism is primarily responsible for the high toughness of fibre-reinforced materials.

Figures 5.9a and 5.9b are schematic diagrams summarising the toughening mechanisms considered to be operating during the fracture of hydrated and dehydrated dentine. The similarity of mineralised tissues, bone and dentine, the latter a more

regular organised structure than bone (Weiner and Wagner, 1998), lead us to compare the toughening mechanisms. For bone they include the formation of an in-elastic zone about the crack tip, as bone does exhibit non-linear stress-strain behaviour (Zioupus, 1998) and micro-cracking about the crack leading to a stress shielding mechanism similar to a plastic zone (Vashishth et al., 1997; 2000). Braidotti et al. (1997; 2000) claim that collagen fibre bridging occurs behind the crack tip, and that this is more evident for fracture of hydrated, rather than dehydrated, bone. All of these mechanisms are potentially possible during fracture of dentine as it has similar components. Recently, there has been considerable attention given to micro-cracking as the major toughening contribution (Vashishth et al., 1997; 2000). Previous measurements of the toughening contribution resulting from micro-cracking by Evans and Faber (1984) and Hutchinson (1987) indicate only a modest toughening increment. However, if micro-cracking becomes significant and leads to crack branching, then a major toughening effect can occur (Lutz et al., 1991). On the basis of the current observations we would contend that micro-cracking is but one of a number of toughening mechanisms operating in the case of dentine, and also by association in bone, and that it is by far not the most effective one.

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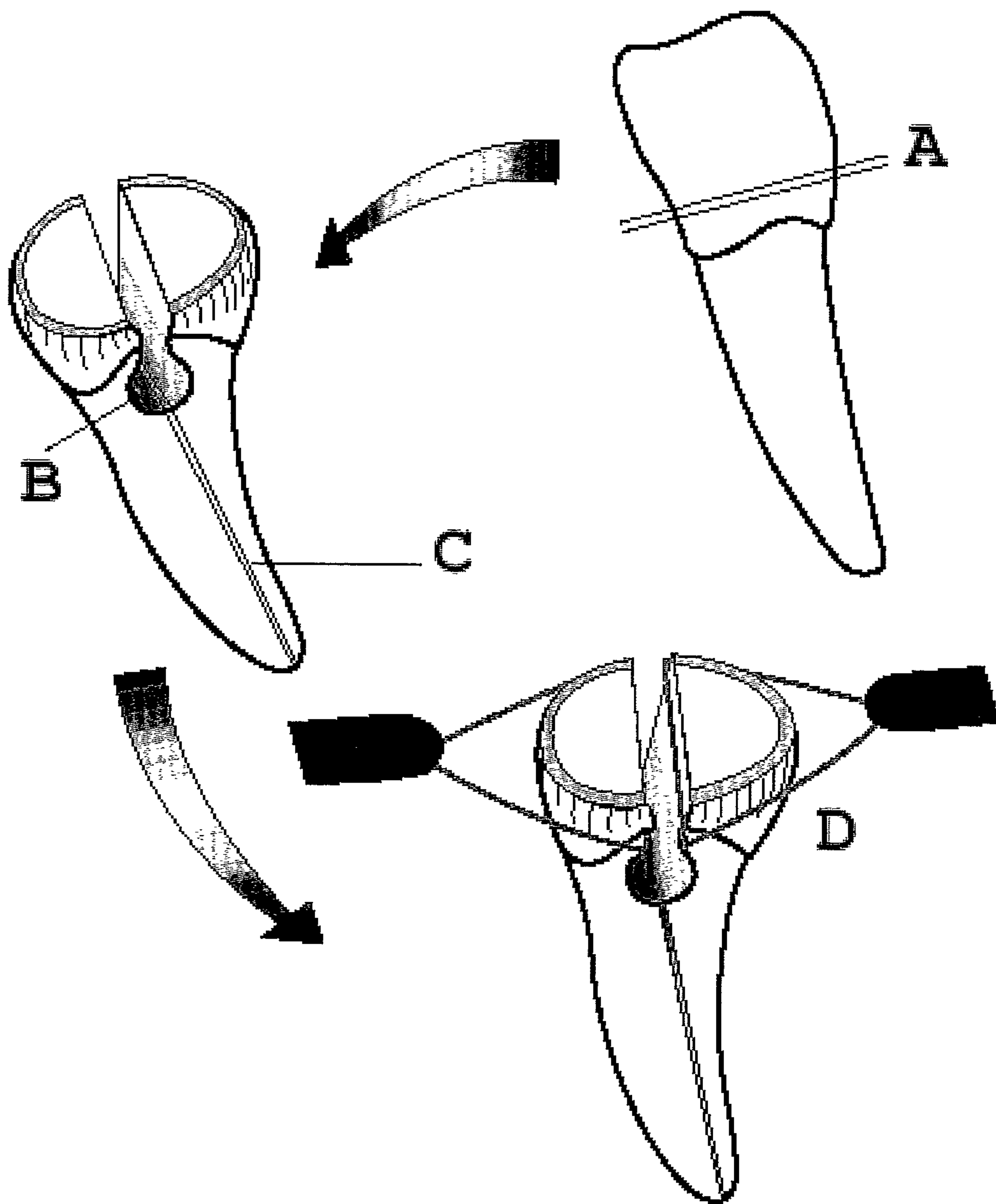


Figure 5.1 Schematic illustration of bovine incisor teeth prepared for hollow, cylindrical double cantilever bend tests. The crowns were sectioned 2mm above the cemento-enamel junction (A), a 2mm square box form cavity prepared both mesially and distally (B), and a shallow guide notch placed through the cementum along the entire root surface to the apex (C). Fracture tests were conducted (D).

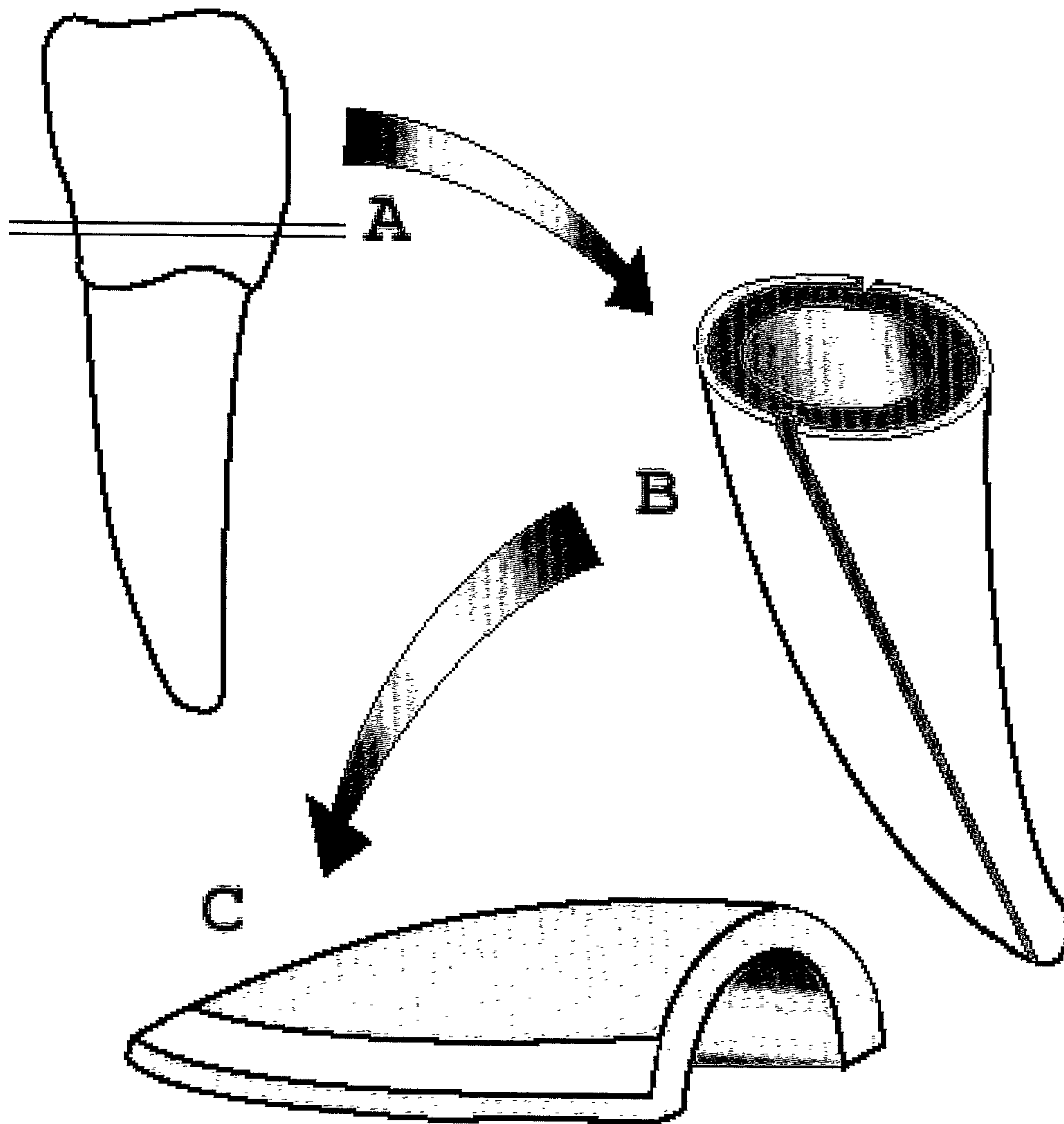


Figure 5.2a Schematic illustration of bovine incisor teeth prepared for wedge loaded double cantilever tests. The crowns were sectioned as in Figure 5.1 (A). The tooth roots were then sectioned in half in a mesio-distal orientation with a 2mm notch placed in the middle of the coronal aspect of the root (B). The cementum was then removed to expose the dentine, which was then polished and lightly etched with mild phosphoric acid (C).

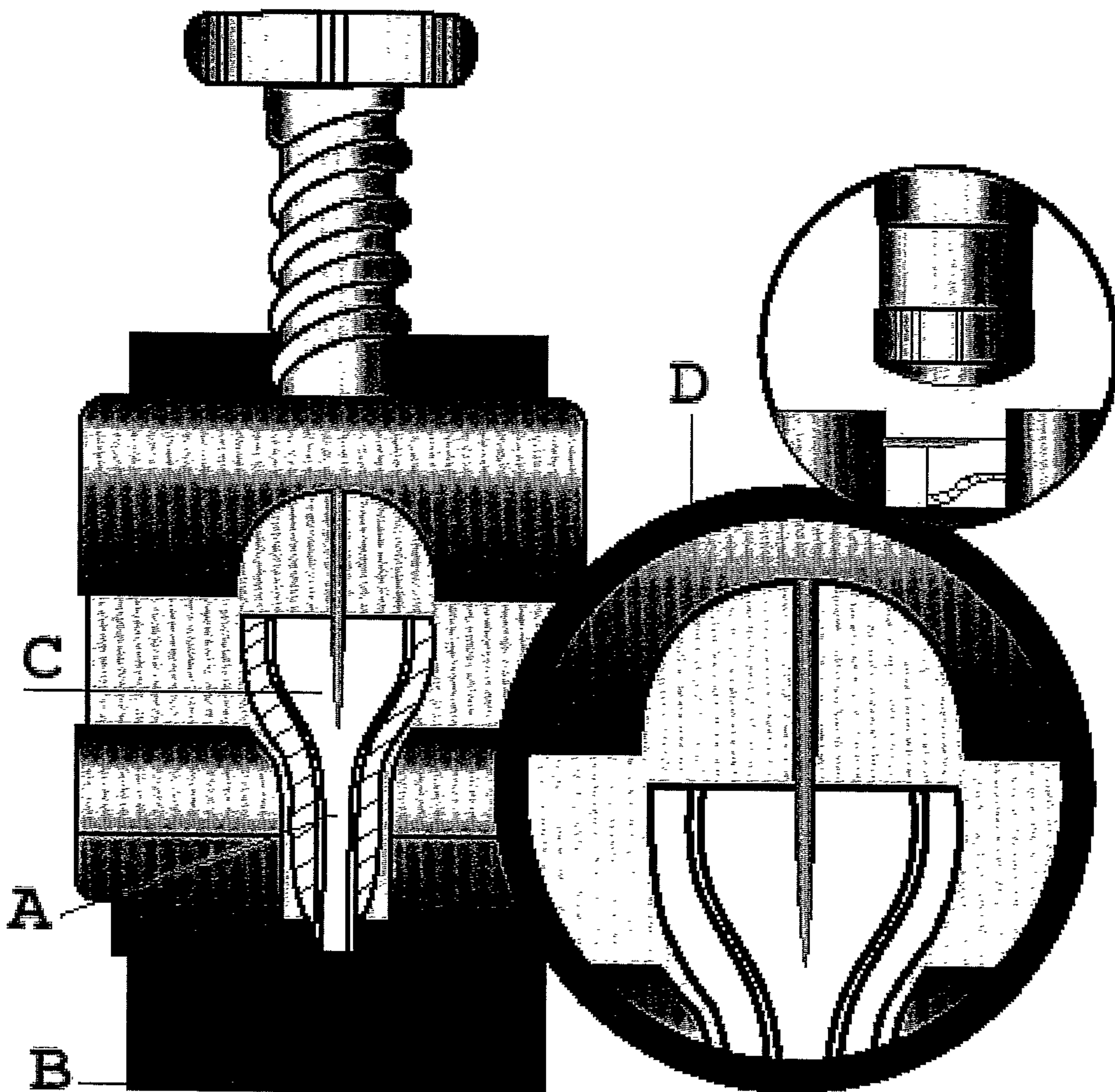


Figure 5.2b Schematic illustration of a tooth root (A) placed in a small engineer's vice (B). A scalpel blade was placed in the notch (C). Stable crack extensions by small increments were achieved, which were viewed with an optical microscope (D).

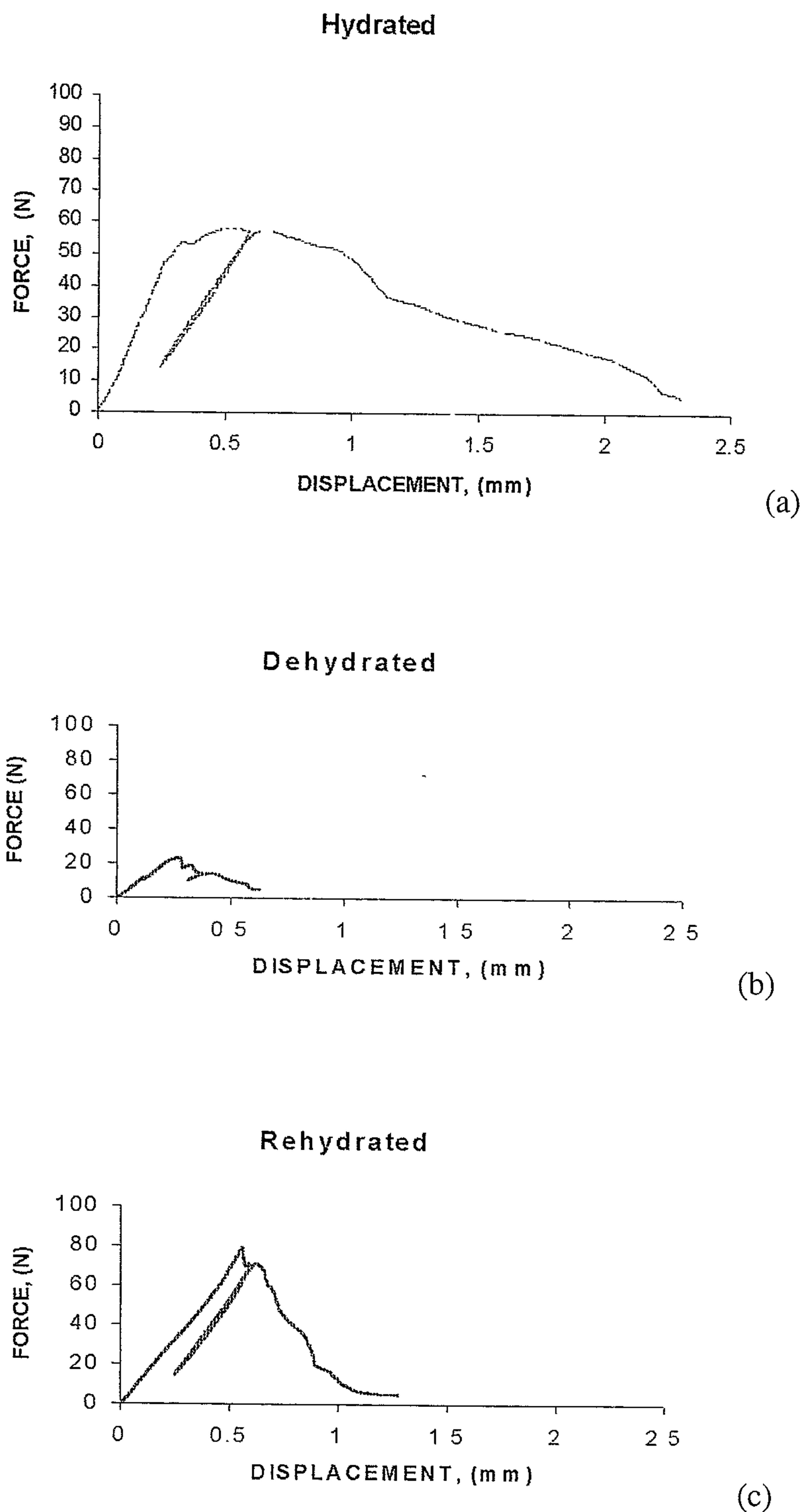


Figure 5.3 Typical force-displacement curves for stable crack extension through (a) hydrated, (b) dehydrated, and (c) re-hydrated specimens. Tests were interrupted after initial crack opening displacement, and the displacement reversed prior to reloading to complete fracture. All unloading curves were less steep, indicative of crack extension. From these plots, the peak force and the total work done (the area under the force-displacement curve) were recorded.

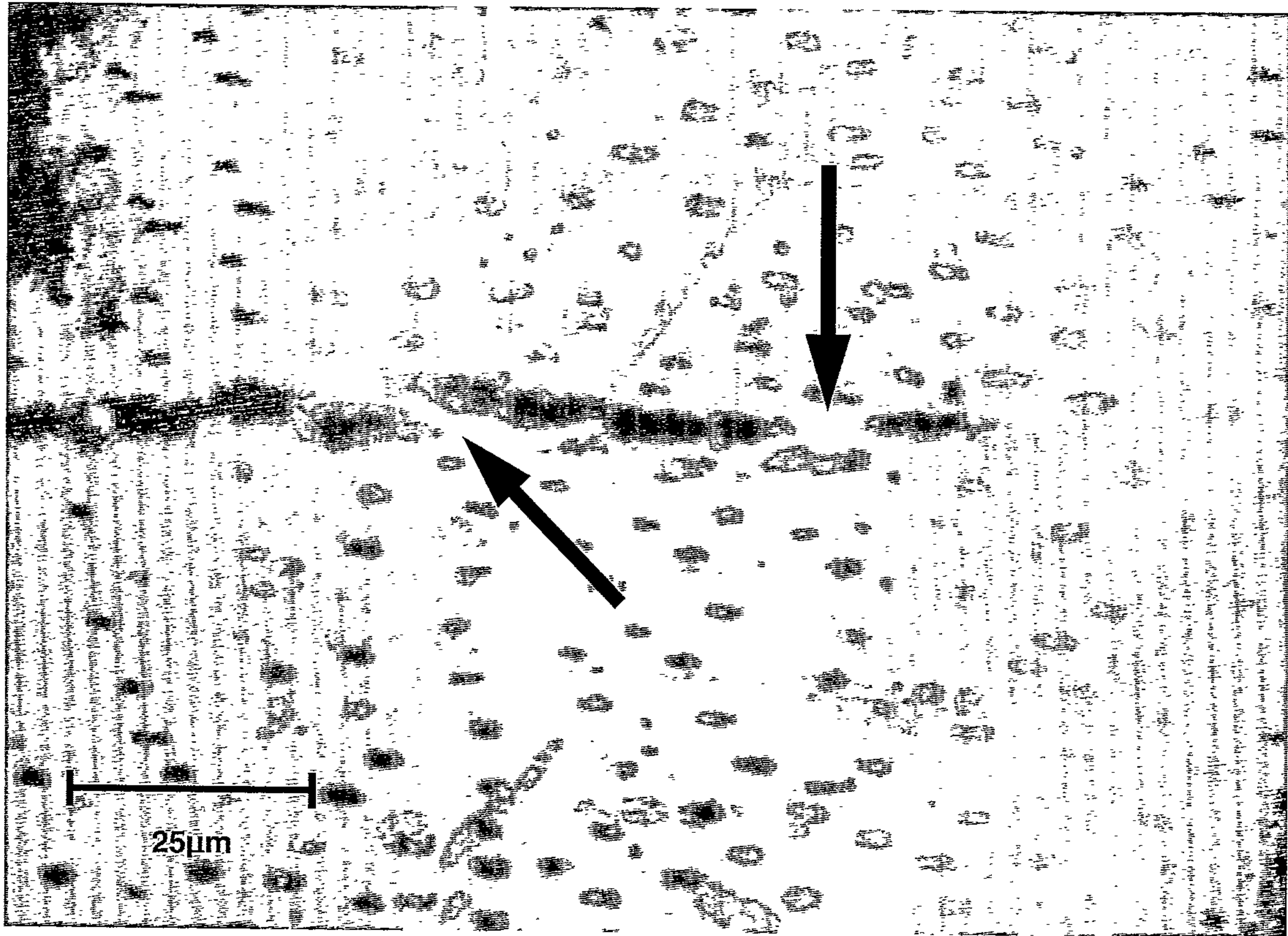


Figure 5.4 Optical micrograph of the crack tip illustrating its discontinuous nature (arrows). Many small micro-cracks coalesce resulting in a continuous crack.

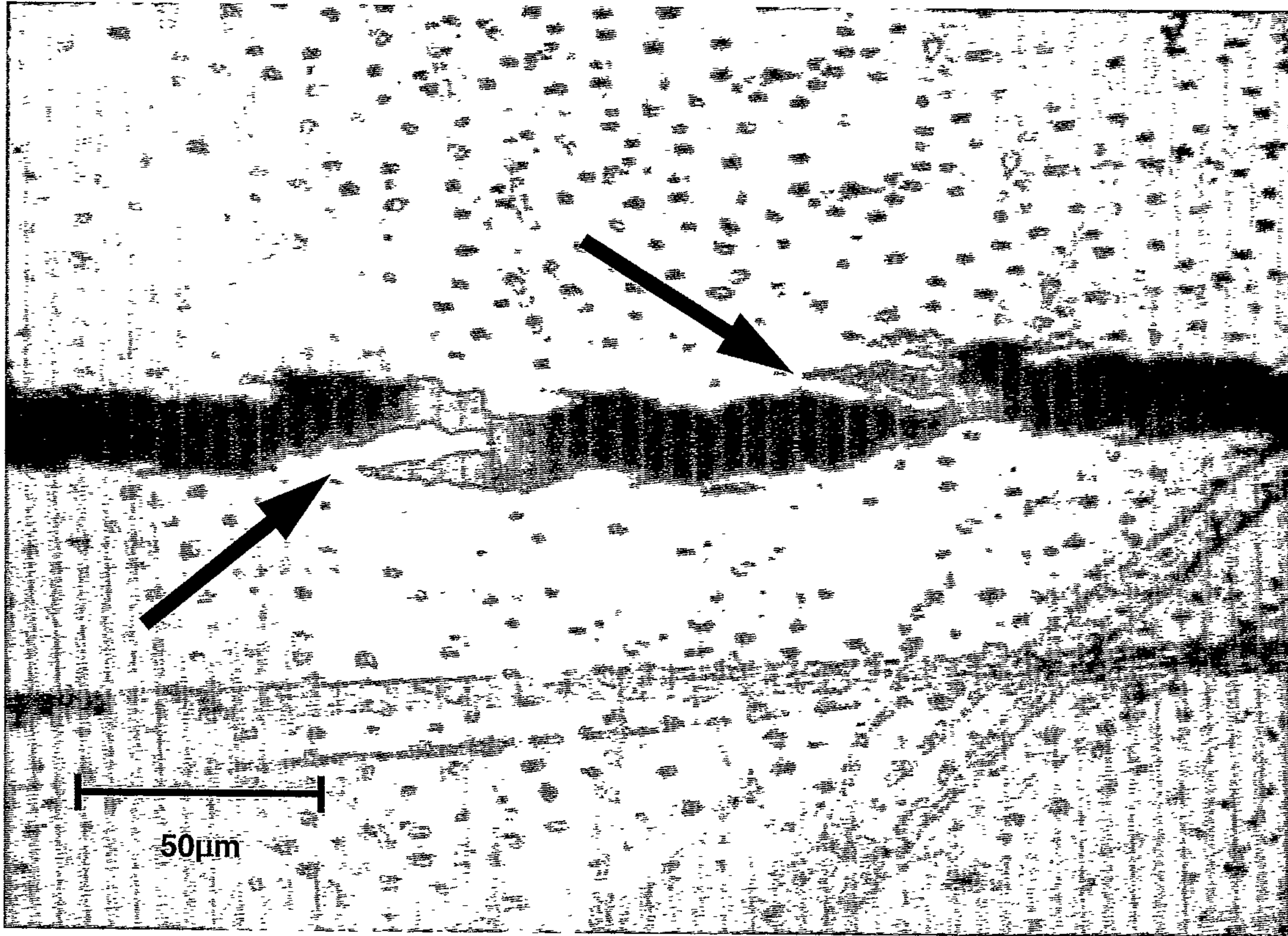


Figure 5.4a Optical micrograph illustrating the discontinuous nature of the crack tip with the formation of ligaments that bridge across it (arrows). Many of these ligaments formed as a result of the micro-cracks that developed parallel to the main crack.

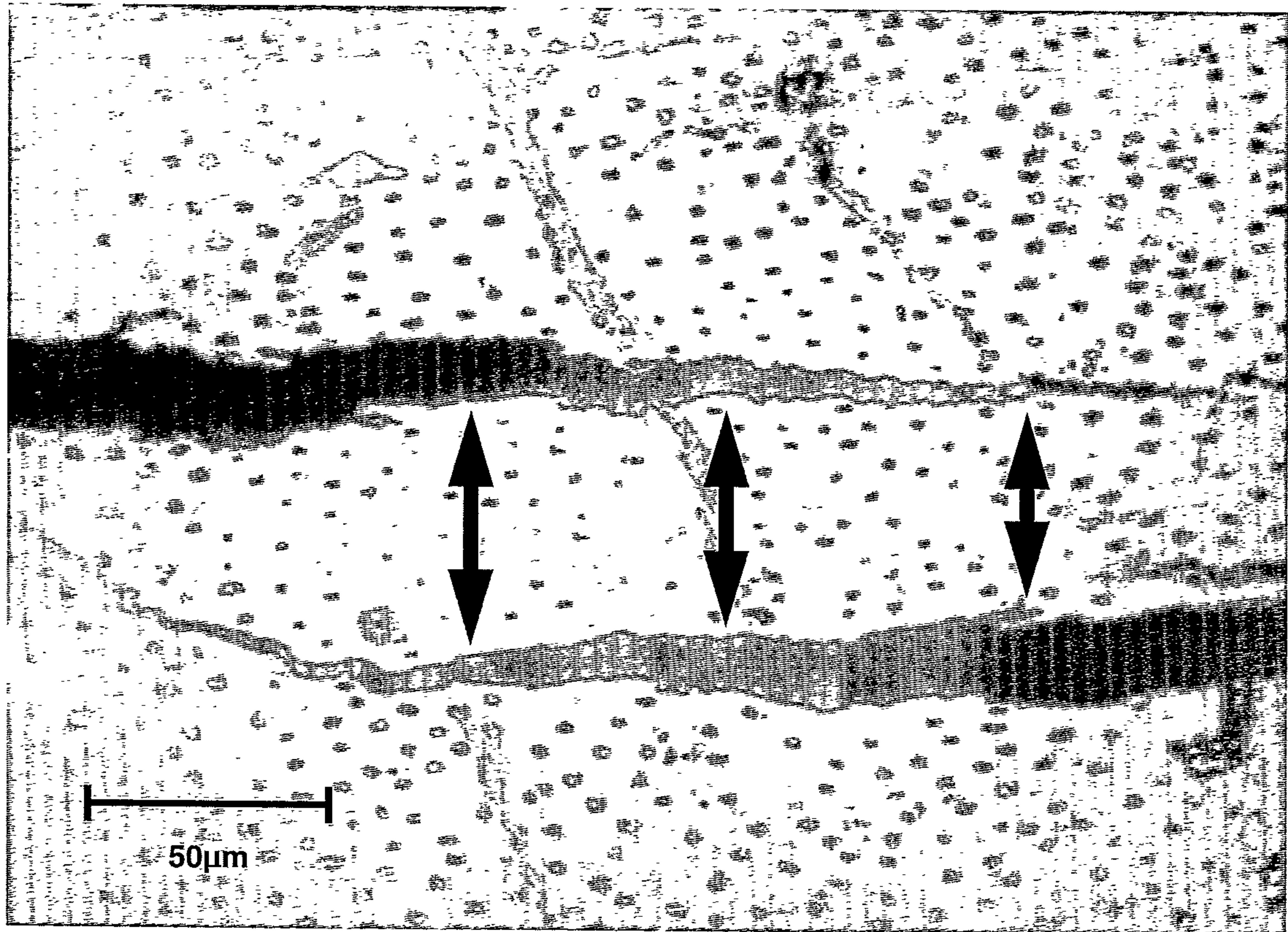


Figure 5.4b Optical micrograph illustrating the formation of major ligaments bridging across the crack tip (arrows).



Figure 5.5 Optical micrograph illustrating the development of water droplets just behind the crack tip formed moments after the crack arrested following crack extension.

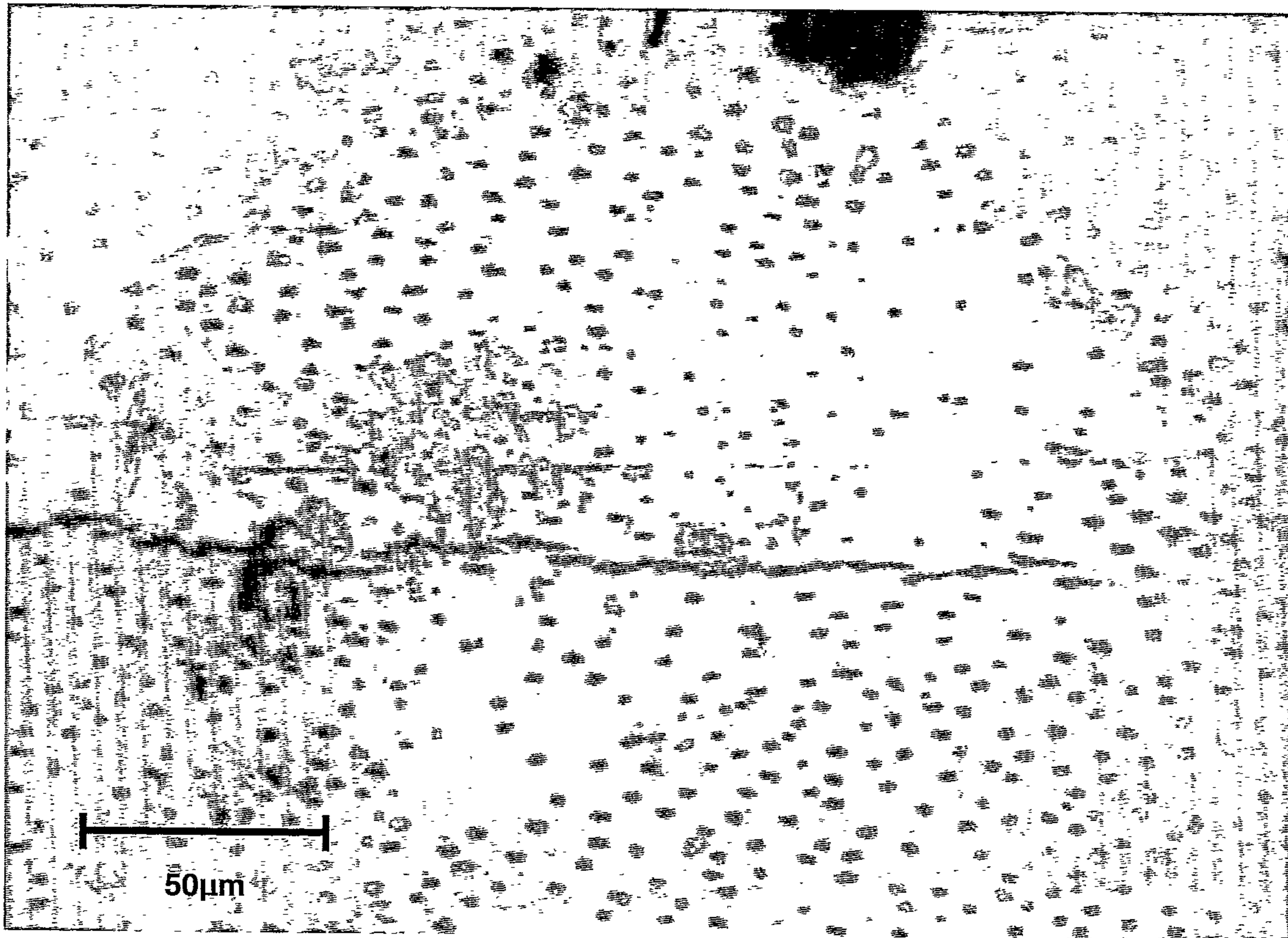


Figure 5.6 Optical micrograph of a dehydrated specimen illustrating that the micro-cracks are much straighter and with far less crack opening. Only limited ligament development just behind the crack tip occurred. There was no evidence of major ligament formation.

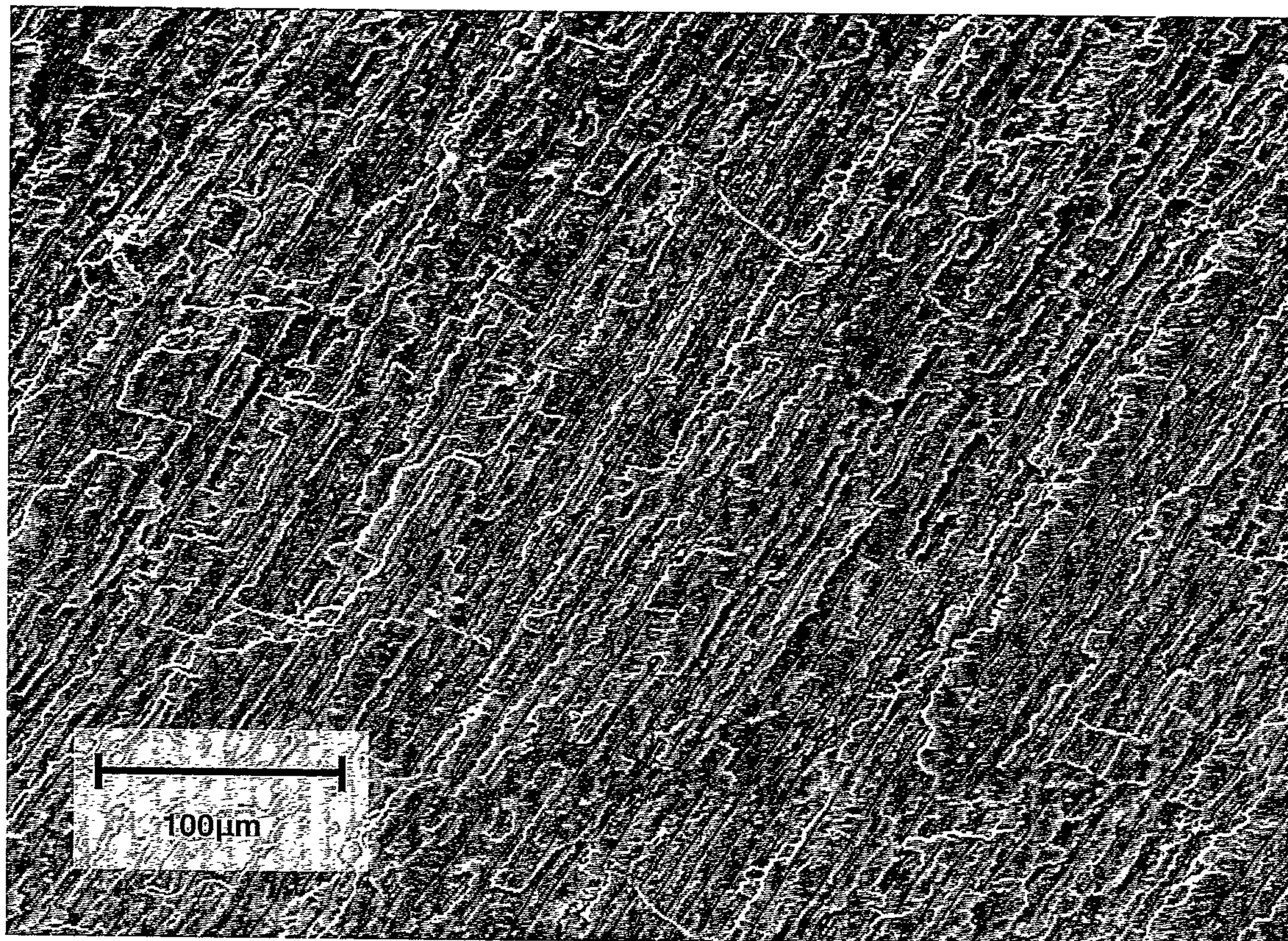


Figure 5.7 Scanning electron micrograph of a dehydrated specimen illustrating the highly planar nature of the fractured surface, with only limited ligament formation between some of the tubules. The fracture runs left to right.

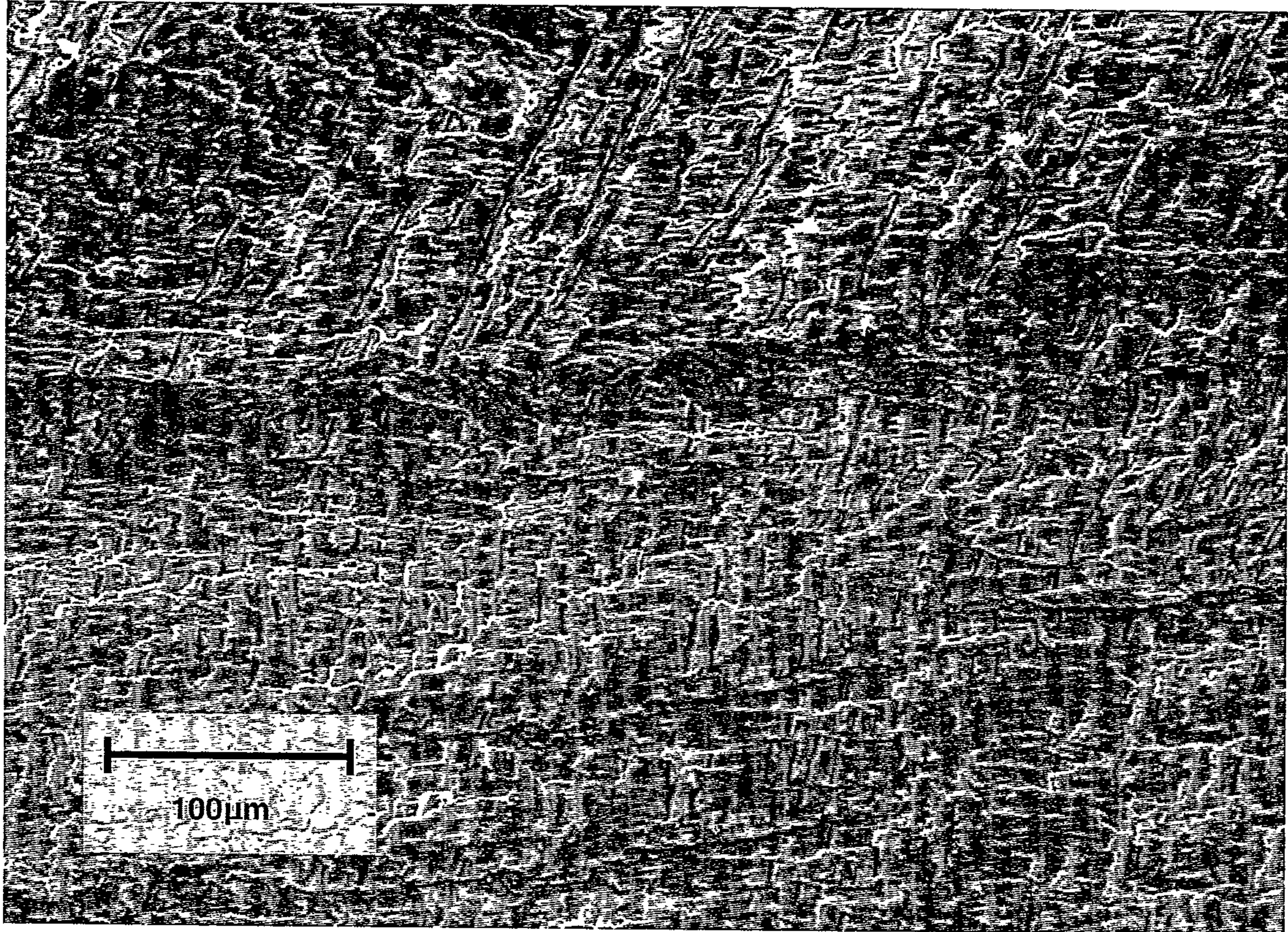


Figure 5.8 Scanning electron micrograph of a hydrated specimen illustrating a less planar fractured surface with evidence of cracking between the tubules and tearing ligaments.

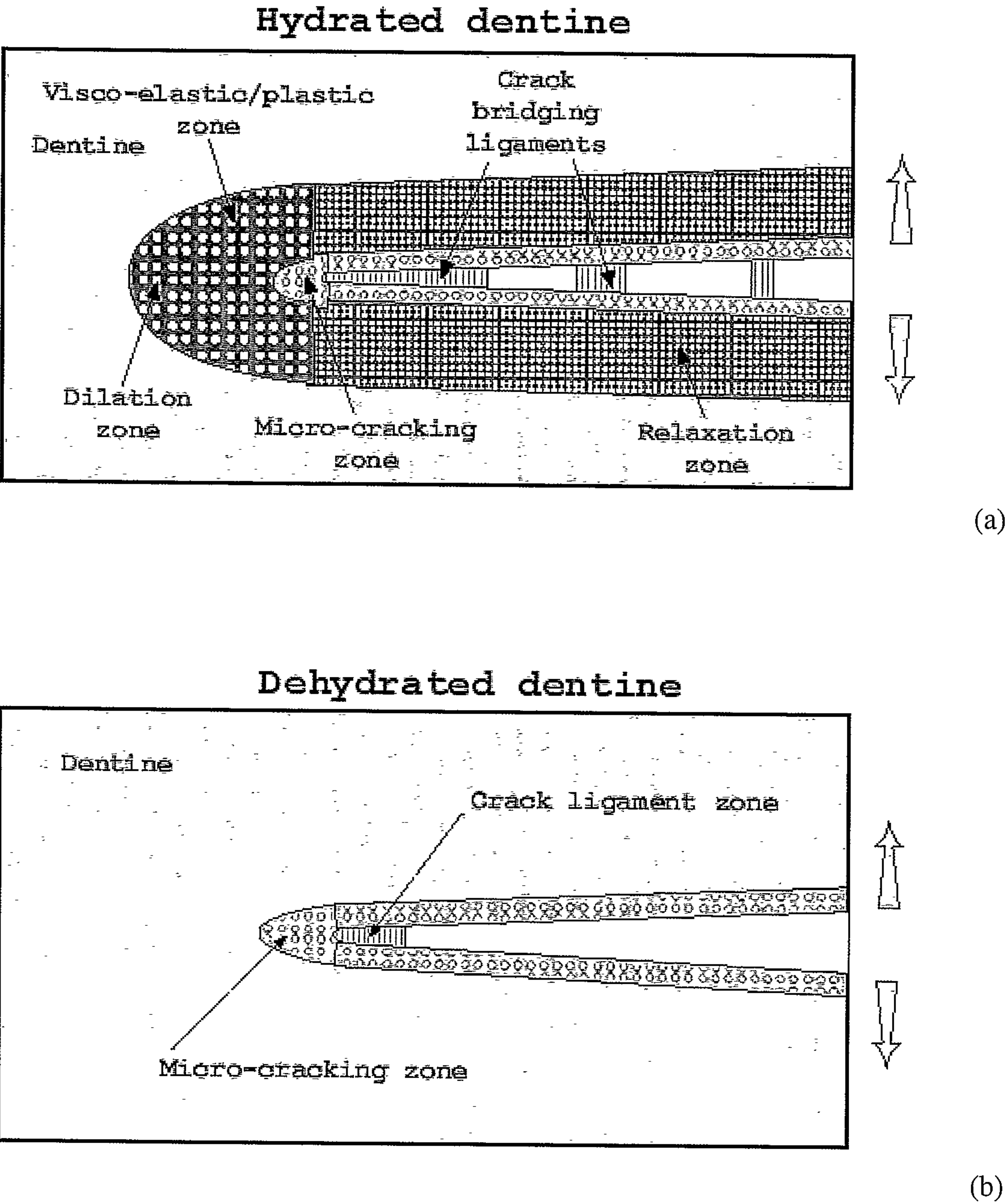


Figure 5.9 Schematic illustration of the toughening mechanisms operating during the fracture of (a) hydrated, and (b) dehydrated, dentine. The major difference is the extensive ligament formation bridging the crack and the visco-elastic/plastic energy dissipation zone about the crack tip with the hydrated dentine specimens.

CHAPTER 6 SUMMARY AND CONCLUSIONS

Tooth fracture is a common presentation that often poses significant clinical difficulties. It is well established that teeth are particularly susceptible to fracture if the pulp has been removed. The diagnosis and management of teeth with vertical root fractures was reviewed so the clinical significance of tooth fracture would be a major focus of this thesis. Prior studies have primarily been in vitro experiments which examined particular mechanical properties, or attempted to compare untreated teeth directly with endodontically treated teeth. There are many difficulties in establishing similar controls and test procedures with this approach. There has been little consideration that dentine is a fluid filled composite material and how this dynamic aqueous environment would impact on the fracture process.

This thesis examined the nature and mechanism for fracture of dentine. As the thesis was intended to have a clinical focus, the surfaces of incompletely fractured cusps from symptomatic vital teeth were fractured and then examined by scanning electron microscopy to determine the nature of the fracture. From an engineering perspective, an SEM examination may determine if the fracture process has been rapid or progressed incrementally. Cyclic fatigue has been proposed as a mechanism of fracture for dentine as there is often a period of some years between the placement of a restoration and the development of symptoms associated with incomplete cuspal fracture. If crack propagation is progressive and incremental, as would be expected by the mechanism of cyclic fatigue, re-initiation of the fracture is required and the SEM examination should reveal blunting of the crack tip or distortion at the position of crack re-initiation. As reported in Chapter 4, the surface of the fractured cusps were almost entirely covered

with bacteria. Numerous bacteria of many morphological forms were present on the dentinal surfaces of all fractured cusps for all teeth. The bacterial contamination extended right through the dentine to the dentin-enamel junction. No partial fractures were observed and bacteria were not present on the enamel surfaces. The findings of this study of bacterial contamination complete to the dentino-enamel junction suggest that dentine fractures catastrophically as a consequence of a single traumatic incident.

In Chapter 5, the influence of hydration on the fracture of bovine dentine was investigated. Specifically, hydrated, dehydrated, and re-hydrated dentine specimens were compared. A measure of fracture toughness, the work of fracture was used. This study investigated the nature of deformation and differences in the mechanisms of fracture, and properties of dentine where there has been a loss of moisture, as may occur with removal of the pulp in the endodontic treatment of teeth. Controlled fracture toughness testing was conducted on bovine teeth to determine the influence of hydration on the work of fracture of dentine. Significant differences ($p < 0.01$) were observed between the fracture toughness of hydrated ($554 \pm 27.7 \text{ J/m}^2$) and dehydrated ($113 \pm 17.8 \text{ J/m}^2$) dentine. Observations of the crack tip region during crack extension revealed that extensive ligament formation occurred behind the crack tip. These ligaments provide considerable stability to the crack by significantly increasing the work of fracture, thereby acting as a fracture toughening mechanism. Micro-cracking, reported as a fracture toughening mechanism in bone, is also clearly seen. A zone of in-elastic deformation may occur as hydrated specimens revealed, upon crack extension, a region about the tip that appeared to suck water into the structure and to exude water behind the crack tip. In dehydrated dentine, no in-elastic zone was observed. Micro-cracking is present though the cracks are smaller, straighter and with less opening than hydrated dentine. Only limited ligament formation just behind the crack

tip was observed. These differences resulted in a significantly lower work of fracture with unstable brittle fracture characteristics. Based on these results, several fracture-toughening mechanisms were identified in dentine, with micro-cracking not considered the most important. These findings may also be relevant for bone, a similar mineralised hydrated tissue.

The mechanism for fracture of dentine remains unclear. However, the presence of fracture toughening mechanisms identified in bone and composite materials have now been identified for dentine. Different fracture toughening mechanisms were identified for hydrated and dehydrated dentine, and these differences resulted in a significantly lower work of fracture for dehydrated dentine. The demonstration of these differences may have no relevance to the greater incidence of fracture of endodontically treated teeth. Further studies could assess the degree of dehydration, and mechanical properties of aged and sclerotic dentine. The contribution of fluid movement in the fracture process should be further explored. Slow loading rates utilised in this study do not simulate the clinical situation, though it was not possible to obtain stable crack extension with faster loading rates. Further investigations are warranted.

APPENDIX A

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Diagnosis and management of teeth with vertical root fractures

Diagnosis and management of teeth with vertical root fractures

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Bill Kahler†

Abstract

Vertical fractures in teeth can present difficulties in diagnosis. There are, however, many specific clinical and radiographical signs which, when present, can alert clinicians to the existence of a fracture. In this review, the diagnosis of vertical root fractures is discussed in detail, and examples are presented of clinical and radiographic signs associated with these fractured teeth. Treatment alternatives are discussed for both posterior and anterior teeth.

Key words: Endodontics, diagnosis, vertical fractures.

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Introduction

Vertical root fractures have been described as longitudinally oriented fractures of the root, extending from the root canal to the periodontium.¹ They usually occur in endodontically treated teeth, although occurrence in non-restored teeth has been described.²⁻⁴ The vertical fracture may involve the whole length of the root or only a section of it. It may involve only one or both sides of the root.⁵⁻⁷ In molar teeth, the fracture is most commonly bucco-lingual in orientation in individual roots. Mesio-distal fractures are less common. In anterior teeth, the fractures are most commonly in a bucco-lingual direction.⁵ Vertical root fractures can be initiated from coronal tooth structure (Fig. 1) or at the apex (Fig. 2). Incomplete and complete root fractures have been described.^{8,9} Most vertical root fractures are complete.⁶ The radiographic and clinical signs of vertical root fractures were extensively reviewed by Pitts and Natkin in 1983.¹ A number of other diagnostic reviews have been published.^{7,10-13} Numerous case reports also appear in the literature describing single or multiple cases of vertical root fractures.¹⁴⁻²⁸

If unrecognized, vertical root fractures can lead to frustration and inappropriate endodontic treatment. Diagnosis is sometimes difficult as there is often no

single clinical feature which indicates that root fracture is present¹¹ and signs and symptoms are often delayed. Indeed, average time between root filling and the appearance of a vertical root fracture has been estimated to be between 39 months²³ and 52.5 months²⁹ with a range of three days to 14 years. In general, however, all vertically fractured teeth exhibit specific clinical and radiographic signs which should alert the practitioner to the possibility of a root fracture being present. This paper reviews these diagnostic features, presenting examples of each. Treatment alternatives are discussed but causes of vertical root fractures are not addressed. They will be the subject of a further review.

Clinical presentation

The clinical presentation of a vertical root fracture is extremely variable. The clinical signs and symptoms vary according to the position of the fracture, tooth type, time after fracture, the periodontal condition of the tooth and the architecture of the bone adjacent to the fracture. Teeth with vertical root fractures often present with a long history of variable discomfort or soreness, usually associated with local chronic infection. The pain is usually mild to moderate in intensity.²³ Rarely is severe pain associated with these teeth. Vertically fractured teeth can also present with a history of pain on biting.

Vertical root fractures should be considered if an apparently well root filled tooth does not settle after the root filling is completed.¹⁶ Where a root filled tooth is associated with 'pain on biting' and is also accompanied by a 'bad taste', a vertical root fracture is most likely present. Occasionally, the patient can be aware of a sharp cracking sound at the time of condensation of gutta percha,^{1,2,23} or the cementation of a post.²¹ Bleeding during condensation of a root filling material and an apparent lack of resistance within the canal during condensation, leading to an almost unlimited ability to condense gutta percha into the canal,¹¹ are also signs that a vertical root fracture is present.

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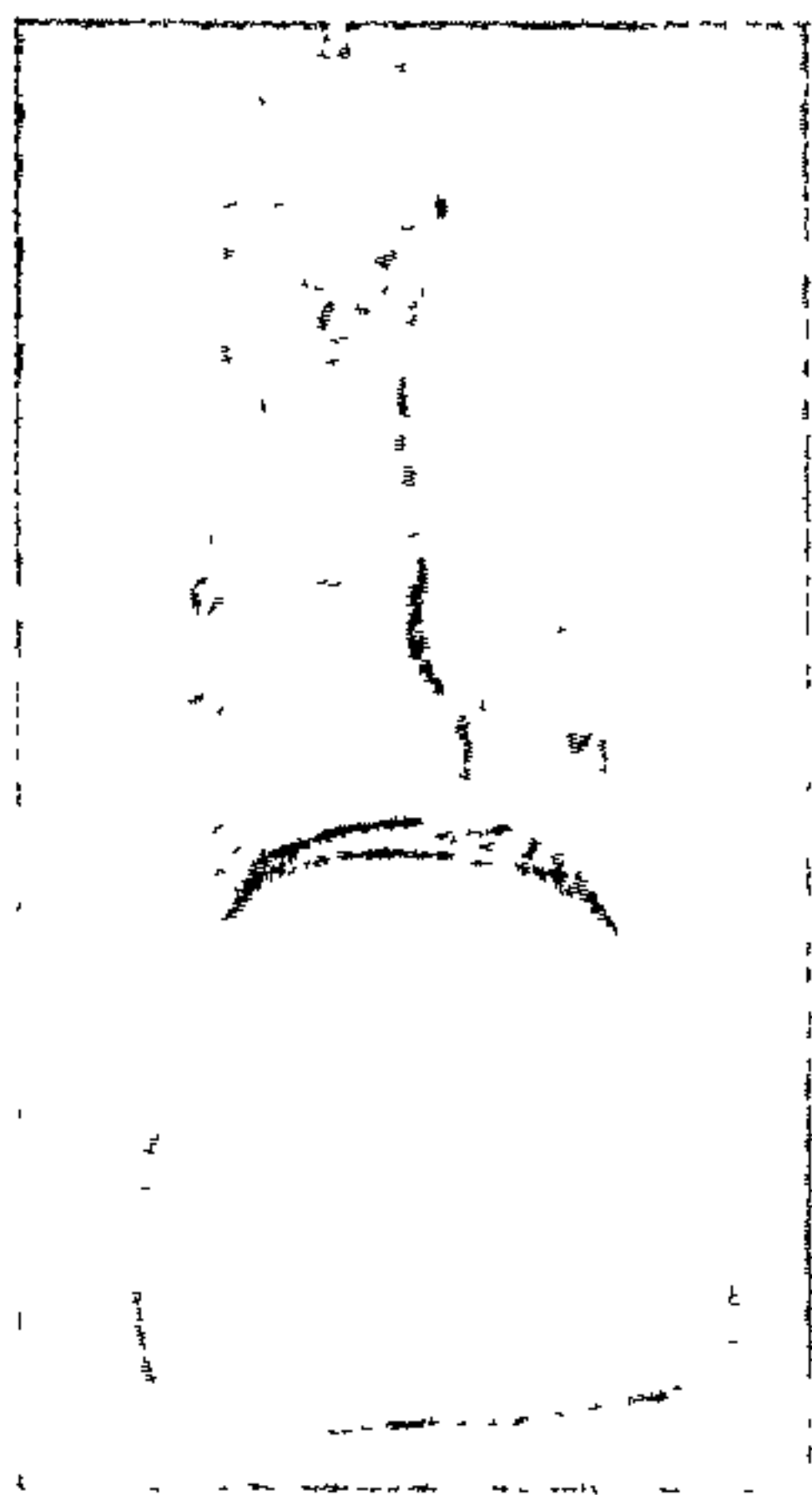


Fig. 1. – Upper central incisor showing complete crown-down vertical root fracture.

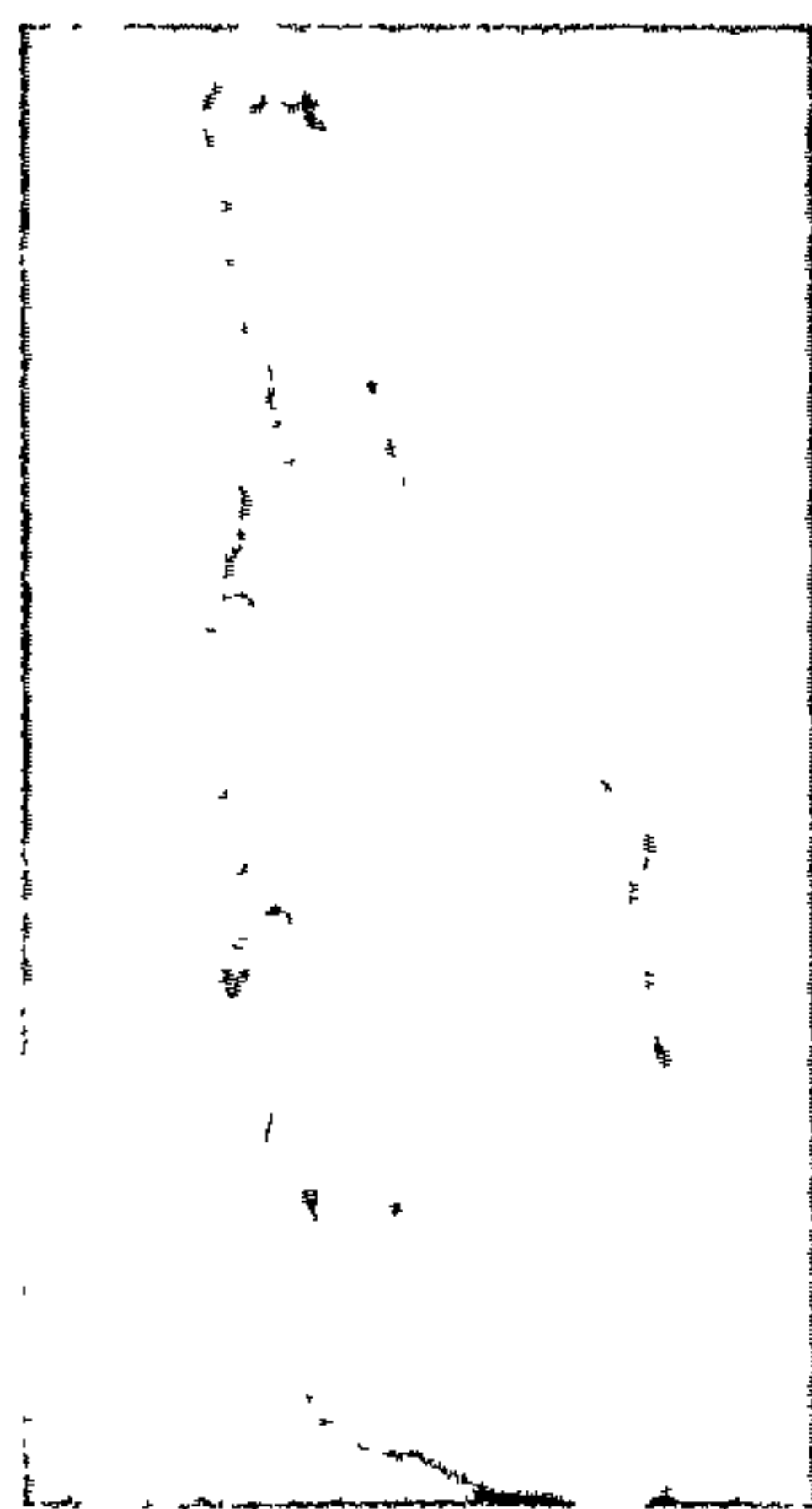


Fig. 2. – Maxillary second premolar shows an incomplete bucco-lingual vertical root fracture which has been initiated in the apex. Note the V-shaped resorptive defect which has occurred apically.

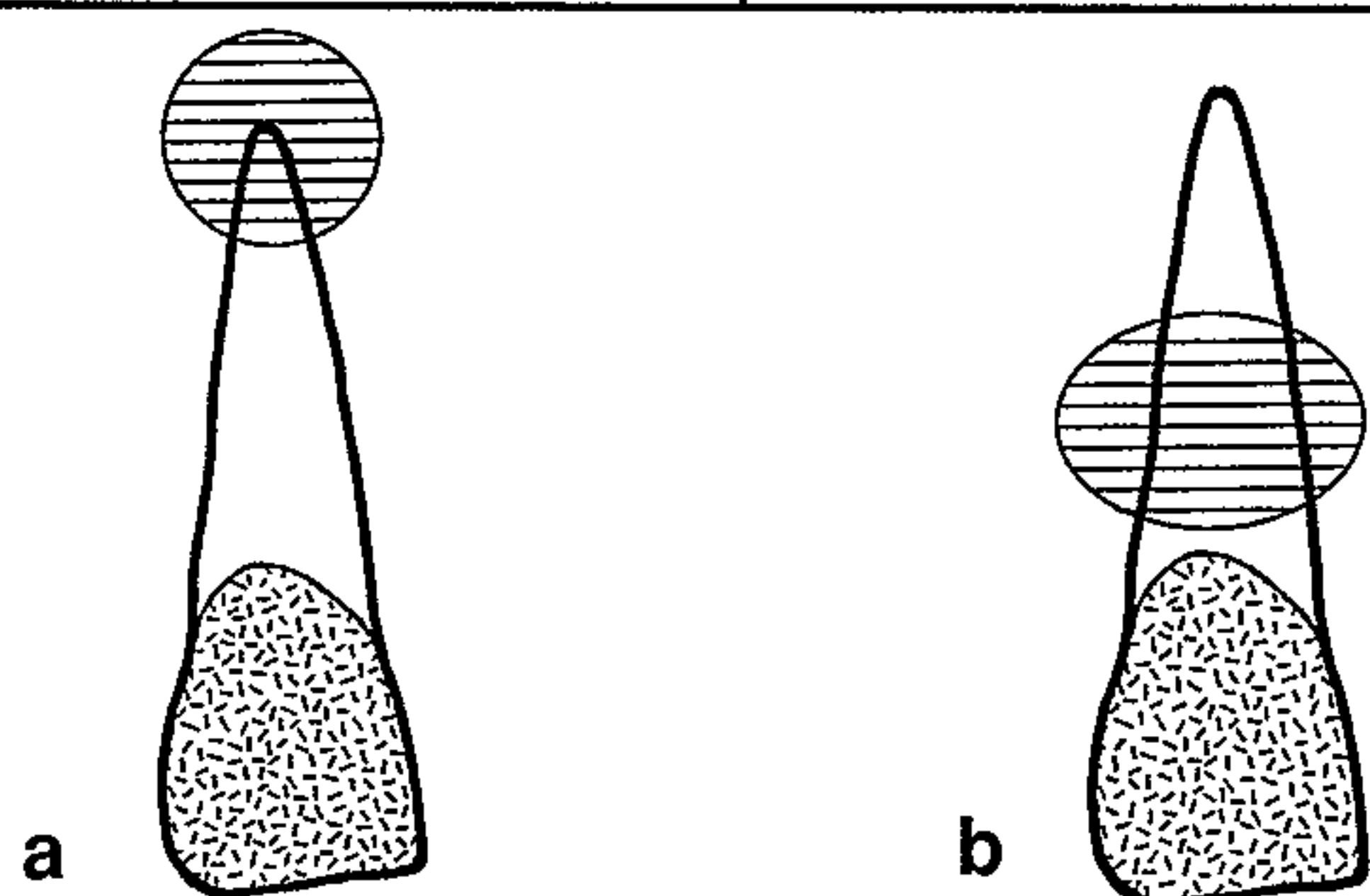


Fig. 3. – Diagrammatic representation of the position of soft tissue swelling (a) in a tooth with a periapical abscess, and (b) in a tooth with a vertical root fracture.



Fig. 4. – A broad-based swelling over the mesio-buccal root of this mandibular first molar is typical of that associated with a vertical root fracture.



Fig. 5. – Double or multiple sinus tracts are a feature of vertically fractured teeth.

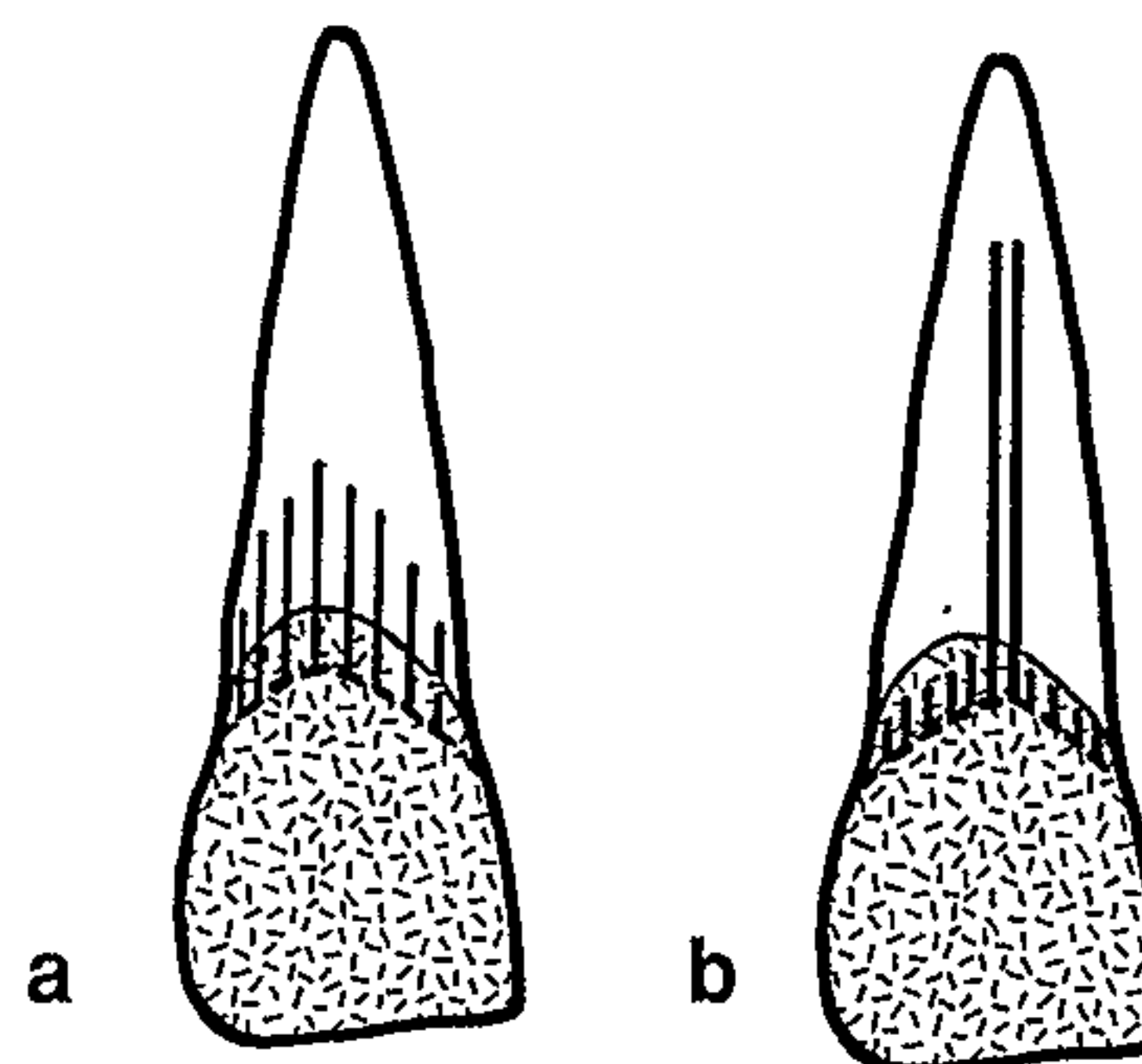


Fig. 6. – Diagrammatic representation of a probing pattern seen in (a) periodontal disease and (b) vertical root fracture. A deep narrow pocket in one position around the circumference of the tooth and the presence of otherwise normal attachment is a feature of vertically fractured teeth. When similar pocketing occurs in two points around the circumference of the tooth, a vertical root fracture is inevitably present.

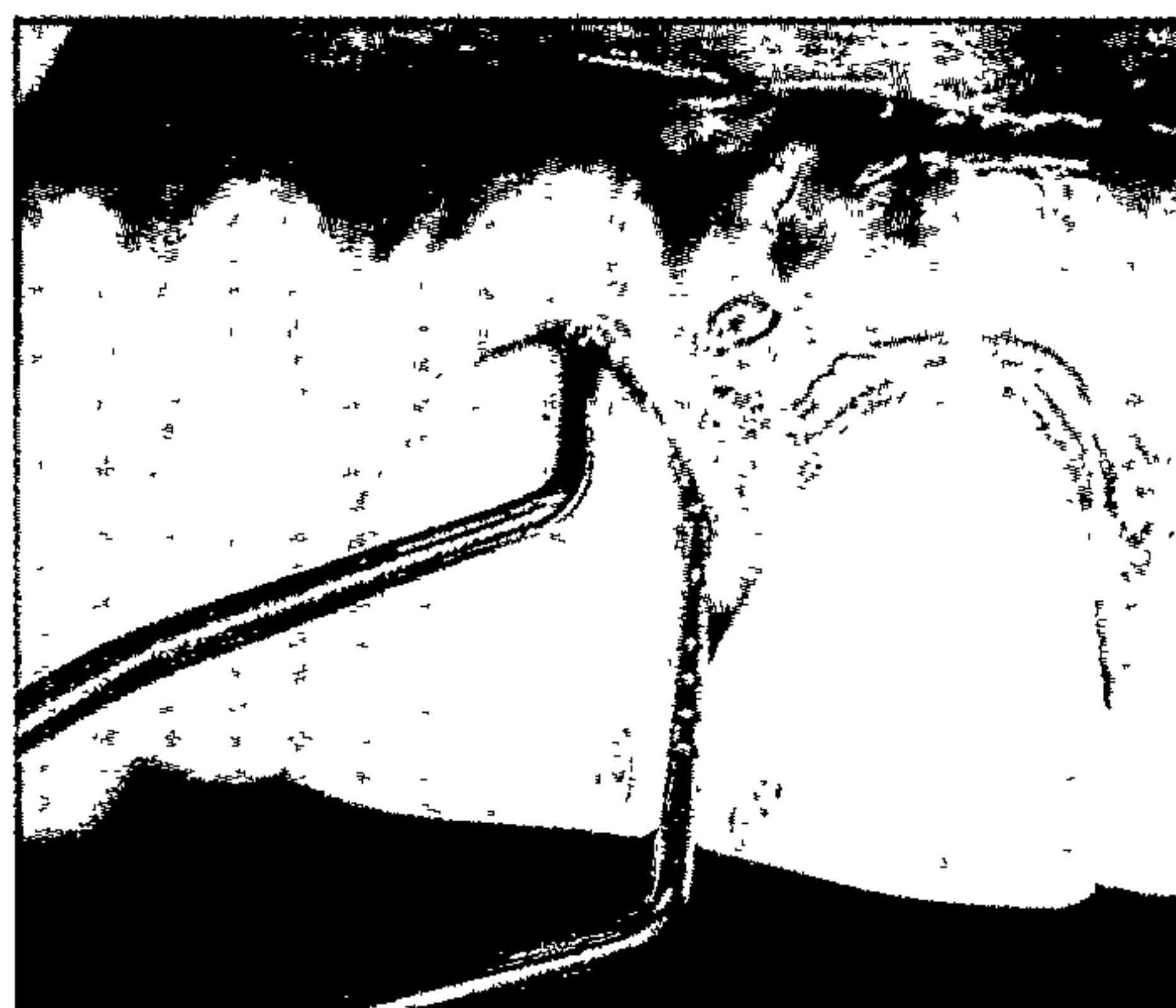


Fig. 7. – Maxillary central incisor tooth exhibiting a deep narrow pocket on the labial surface of the tooth with normal attachment in the interproximal area. The presence of a bucco-lingual vertical root fracture was confirmed by surgery.

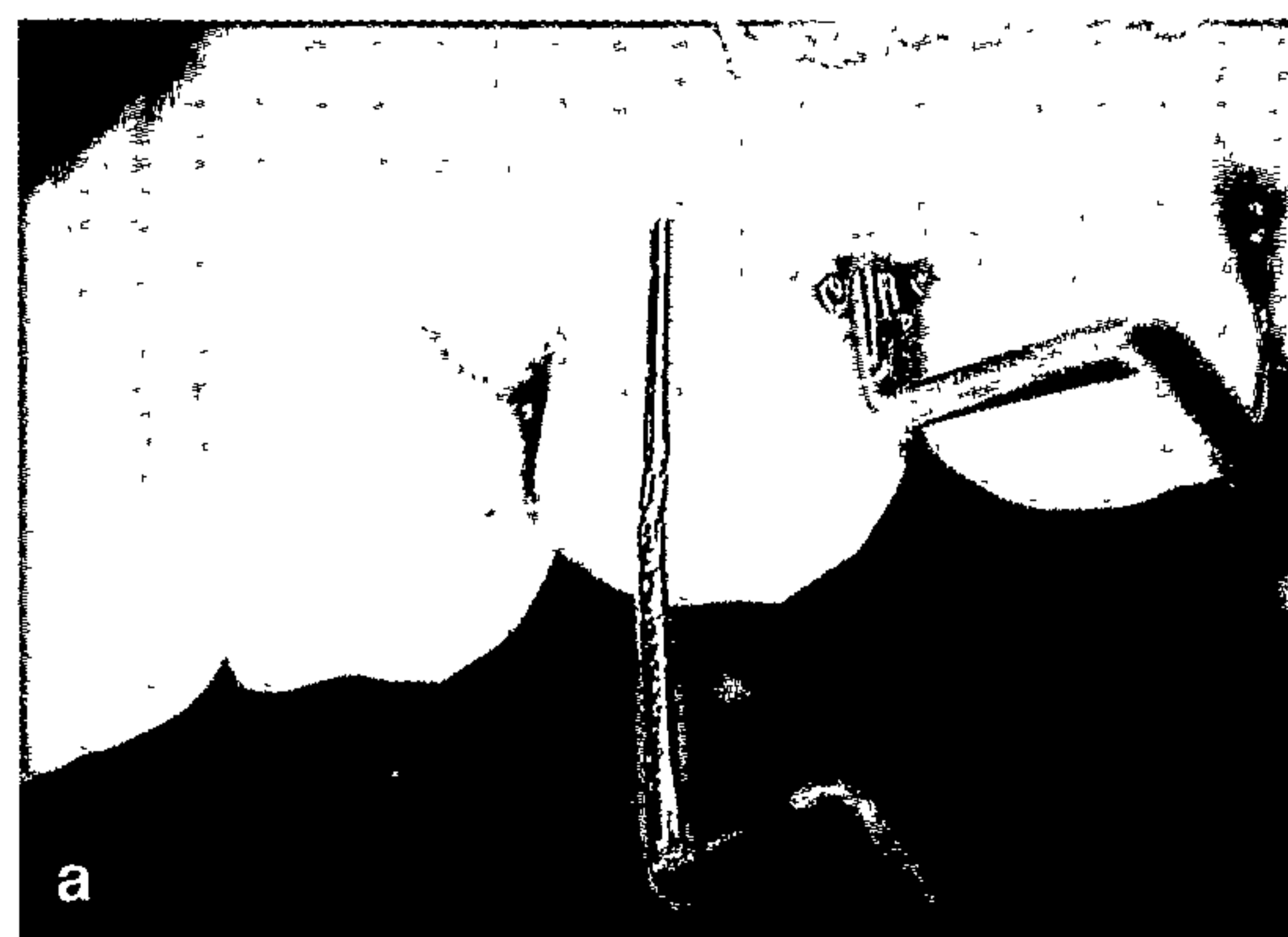


Fig. 8. – (a) Maxillary right first premolar with a mesio-distal fracture. Deep probing is evident mesially and distally but attachment is normal on the buccal and lingual aspect. (b) Radiograph of same tooth. Note the extensive bone loss mesially and distally but little evidence of bone loss apically.

Some swelling of soft tissues is usually present. The swelling is usually broad-based, and mid-root in position. Palpation will often show swelling and tenderness over the root itself, but little swelling in the periapical region (Fig. 3, 4). When a sinus tract is present, it may be situated in or close to attached gingiva rather than in the apical region. Double or multiple sinus tracts are common.¹ Where multiple sinus tracts are present one or more of these tracts may be located some distance from the involved tooth. The insertion of a gutta percha point into each sinus tract can assist with diagnosis. An example of a vertically root fractured tooth exhibiting multiple sinus tracts is shown in Fig. 5.

A common feature of vertically root fractured teeth is the development of deep, narrow, isolated periodontal pockets. Pocketing is usually situated adjacent to the fracture site. When the fracture extends right through the root, probing patterns may be bilateral. The probing pattern for a tooth with a vertical root fracture is different from that seen in teeth with periodontal disease, where the pocketing is fairly consistent in depth around a large part of the tooth (Fig. 6). Deep probing in one position around the circumference of the tooth in the presence of otherwise normal attachment usually indicates that the tooth is fractured (Fig. 7, 8). Deep probing in two positions on opposite sides of the infection is almost pathognomonic for the presence of a fracture. It may be necessary to remove the restoration before deep pocketing can be probed in the interproximal region of molar teeth with mesio-distal fractures.¹

A common presenting feature is the dislodgement of a post or post crown. A root fracture should be suspected if an apparently well-fitting post or post core becomes dislodged. A typical case is illustrated in Fig. 9. The presence of a vertical root fracture should be strongly suspected in teeth where there has been a history of repeated dislodgement of a post or post crown. Because of problems with diagnosis, it is not uncommon for teeth with vertical root fractures to have been treated repeatedly by surgery before the presence of a fracture is suspected. When surgery fails for no obvious reasons, a vertical fracture should be considered a possibility before the periapical area is re-entered surgically.

Radiographic signs

While the clinical presentation of a vertical root fracture can be variable, radiographic signs are, at times, quite specific. These signs can vary considerably from case to case, depending on the angle of the X-ray beam in relation to the plane of fracture, the time after fracture and the degree of separation of the fragments. Radiographic changes seen in vertical root fractures are summarized below.

Separation of root fragments (Fig. 10-13)

When separation of root fragments occurs, the root fracture is clearly visible. Once separation of fragments has occurred, proliferation of granulation tissue²² often results in the rapid movement of the fragment away from the remaining root, in many cases until the fragment comes into contact with an adjacent tooth. Wide separation of fragments can occur very rapidly, sometimes occurring in a matter of weeks.

Fracture lines along the root or root fillings (Fig. 14-19)

On occasions, direct evidence of a fracture can be seen as a vertical radiolucent line running across the root or the root filling. Direct evidence of a vertical root fracture line is often difficult to visualize. For the fracture to be seen the X-ray beam must pass almost directly down the fracture line. Small changes in horizontal angulation may render the fracture undetectable. A four degree variation in the horizontal angulation of the film can prevent visualization of the fracture.³⁰ Pitts and Natkin¹ suggest that a fracture line that deviates from the long axis of the canal may be radiographically more obvious, whereas a fracture line running parallel and adjacent to a root filling may be less easy to see. While it is sometimes possible to see fracture images clearly on a radiograph, care should be taken when attempting to identify vertical lines as fracture lines, as anatomical features, palatal grooves, artefacts and scratches can mimic the appearance of a fracture.

Space beside a root filling (Fig. 20)

Minor separation of fragments can result in the radiographic appearance of a vertical space adjacent to the root filling material in an otherwise well-obtimated canal. Vertical root fractures should be suspected if the root filling appears well condensed but is in close contact with only one wall of the root canal.

Space beside a post (Fig. 21)

In general, posts are constructed so that they fit the canal. When a post is present in a vertically root fractured tooth, slight separation of the fractured fragments can result in the appearance of a space between the edge of a root canal, which may be coated with cement, and the post itself.

Double images (Fig. 22)

When separation of fragments occurs in a direction other than parallel to the X-ray beam, overlapping of fragments may result in double images of the external root surface. While this effect is sometimes seen in normal teeth, for example, in the mesial concavity of maxillary premolar teeth, step-like double images on the external outline of a

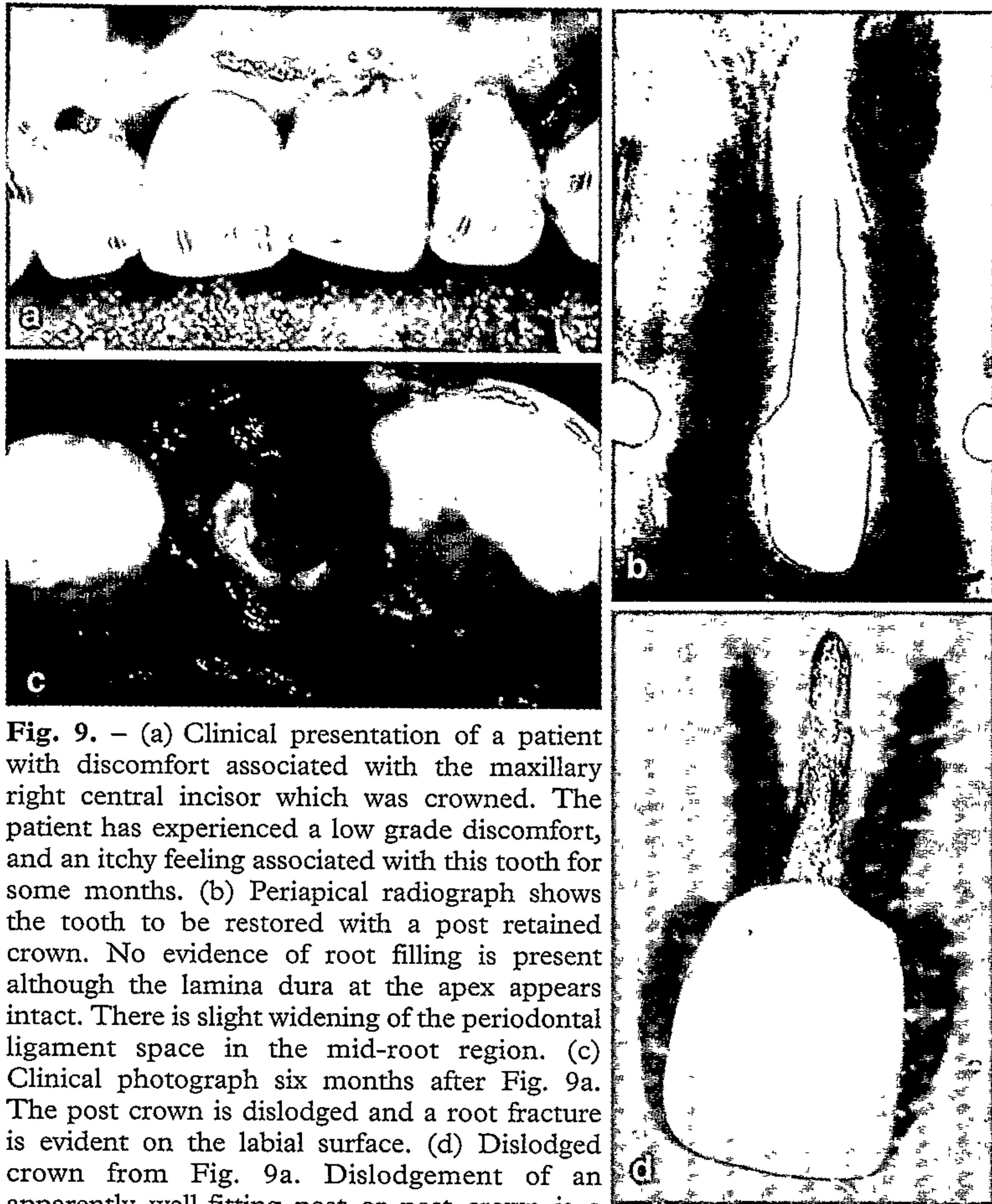


Fig. 9. – (a) Clinical presentation of a patient with discomfort associated with the maxillary right central incisor which was crowned. The patient has experienced a low grade discomfort, and an itchy feeling associated with this tooth for some months. (b) Periapical radiograph shows the tooth to be restored with a post retained crown. No evidence of root filling is present although the lamina dura at the apex appears intact. There is slight widening of the periodontal ligament space in the mid-root region. (c) Clinical photograph six months after Fig. 9a. The post crown is dislodged and a root fracture is evident on the labial surface. (d) Dislodged crown from Fig. 9a. Dislodgement of an apparently well-fitting post or post crown is a sign that the root may be fractured.

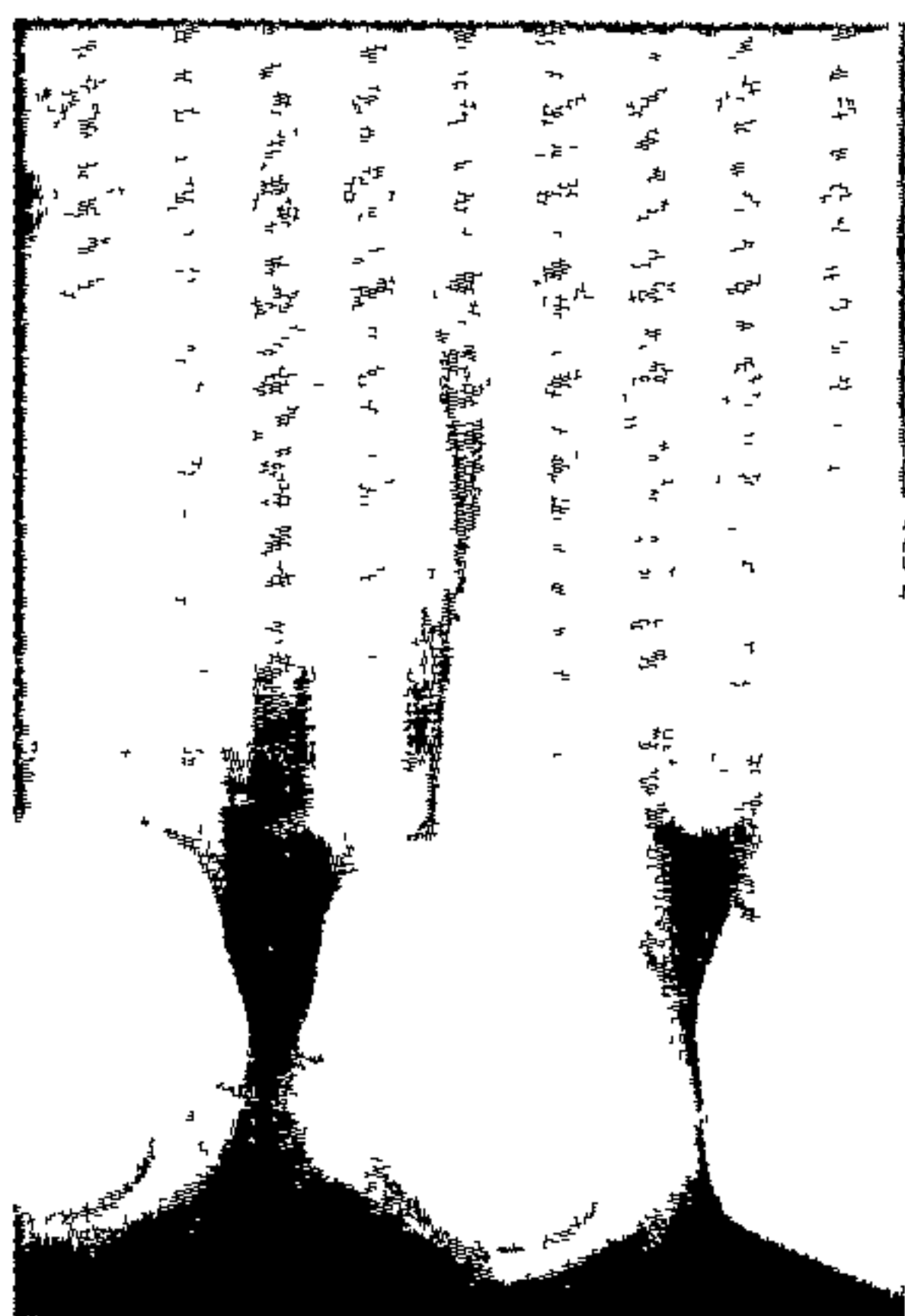


Fig. 10. – Separation of the fragments is clearly visible in this vertically fractured maxillary left first premolar.

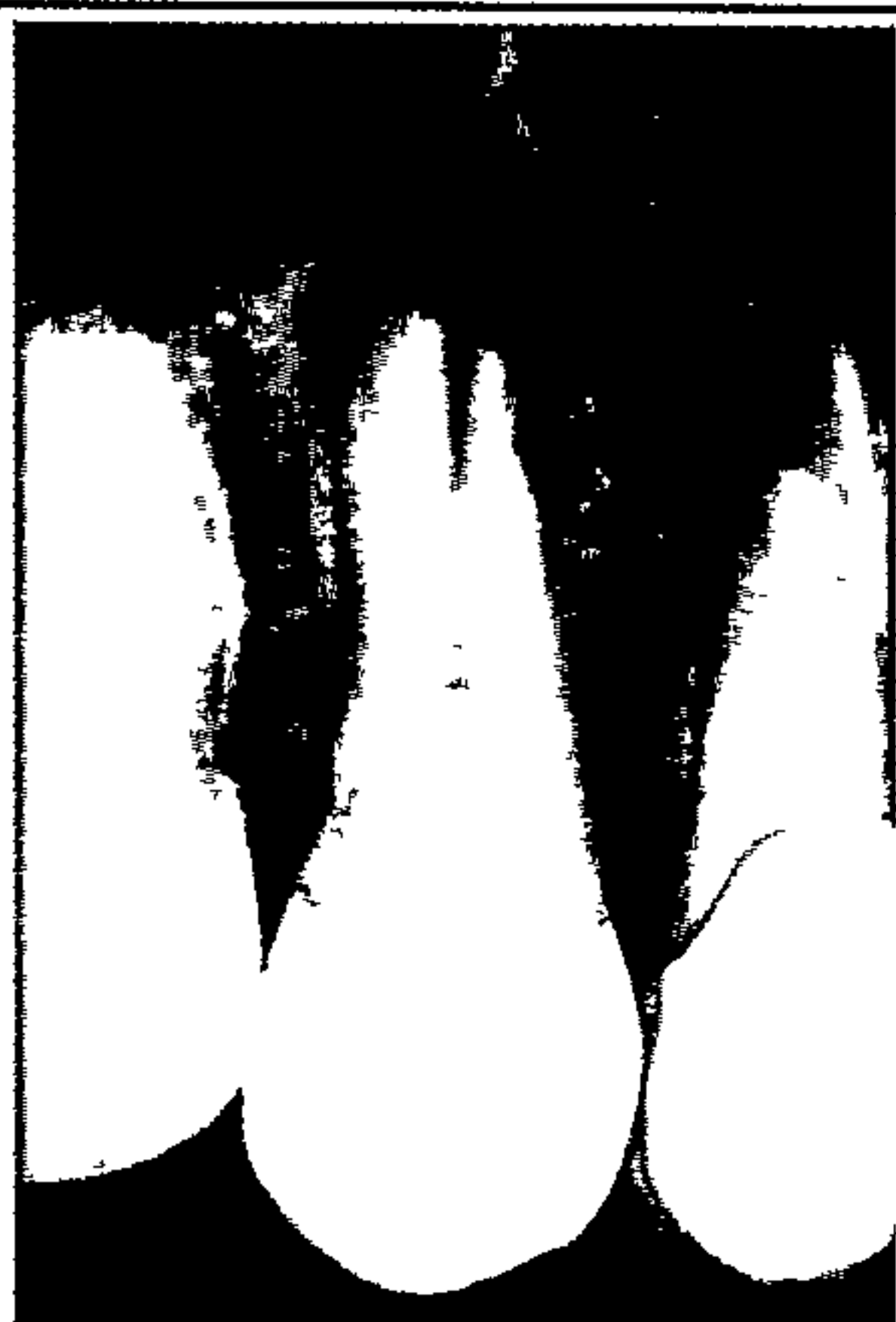


Fig. 11. – Vertically fractured mandibular lateral incisor showing wide separation of the fragments. The distal fragment is completely separate from the tooth and has moved distally to be in contact with the canine. Granulation tissue separates the gutta percha fill from both fragments.

Fig. 12. – Maxillary canine showing a vertical root fracture in the apical portion and wide separation of the fragments.

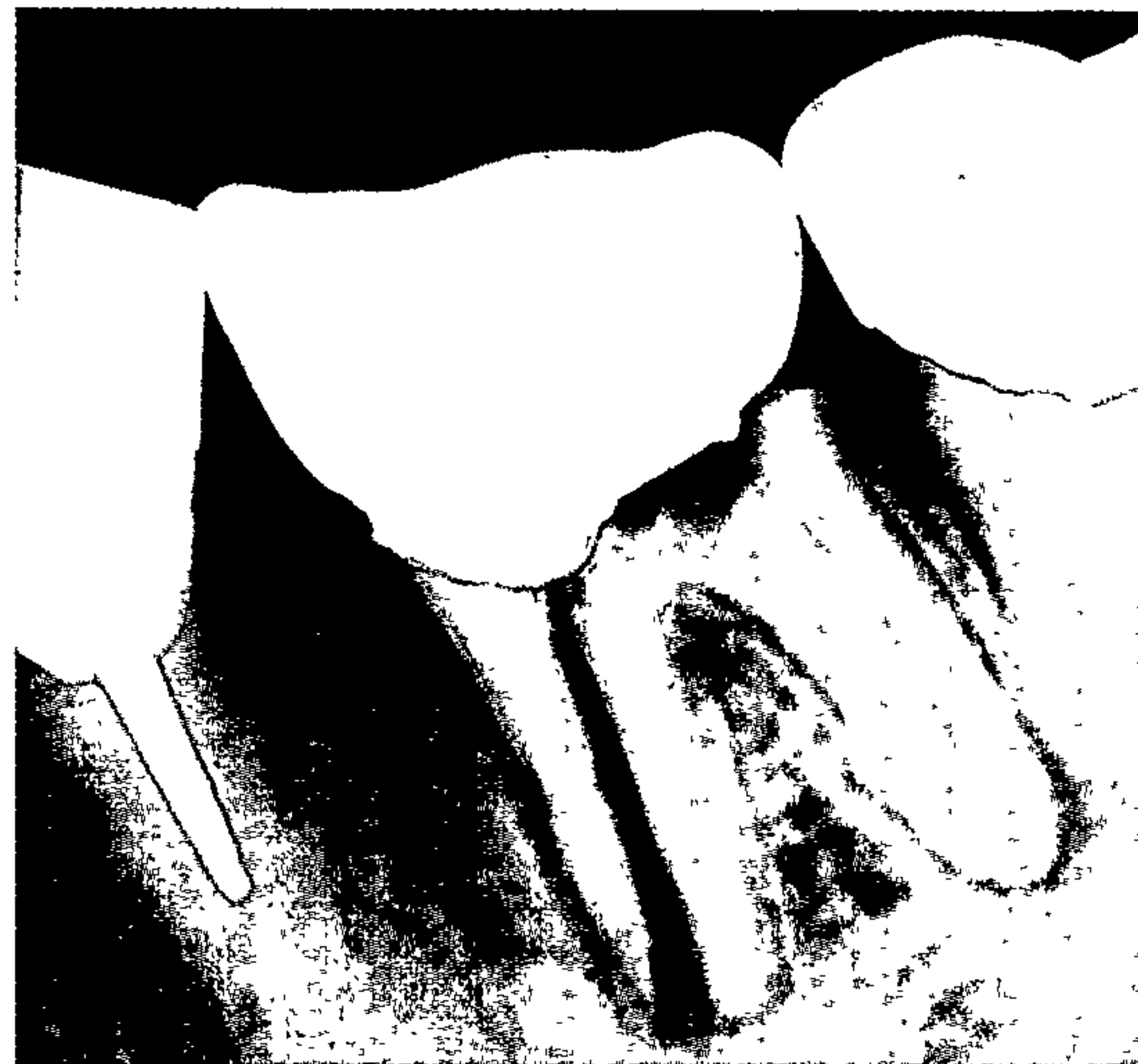


Fig. 13. – Separation of the fragments in the mesial root of this mandibular right molar can be clearly seen. The mesial fragment has remained attached to the large restoration.

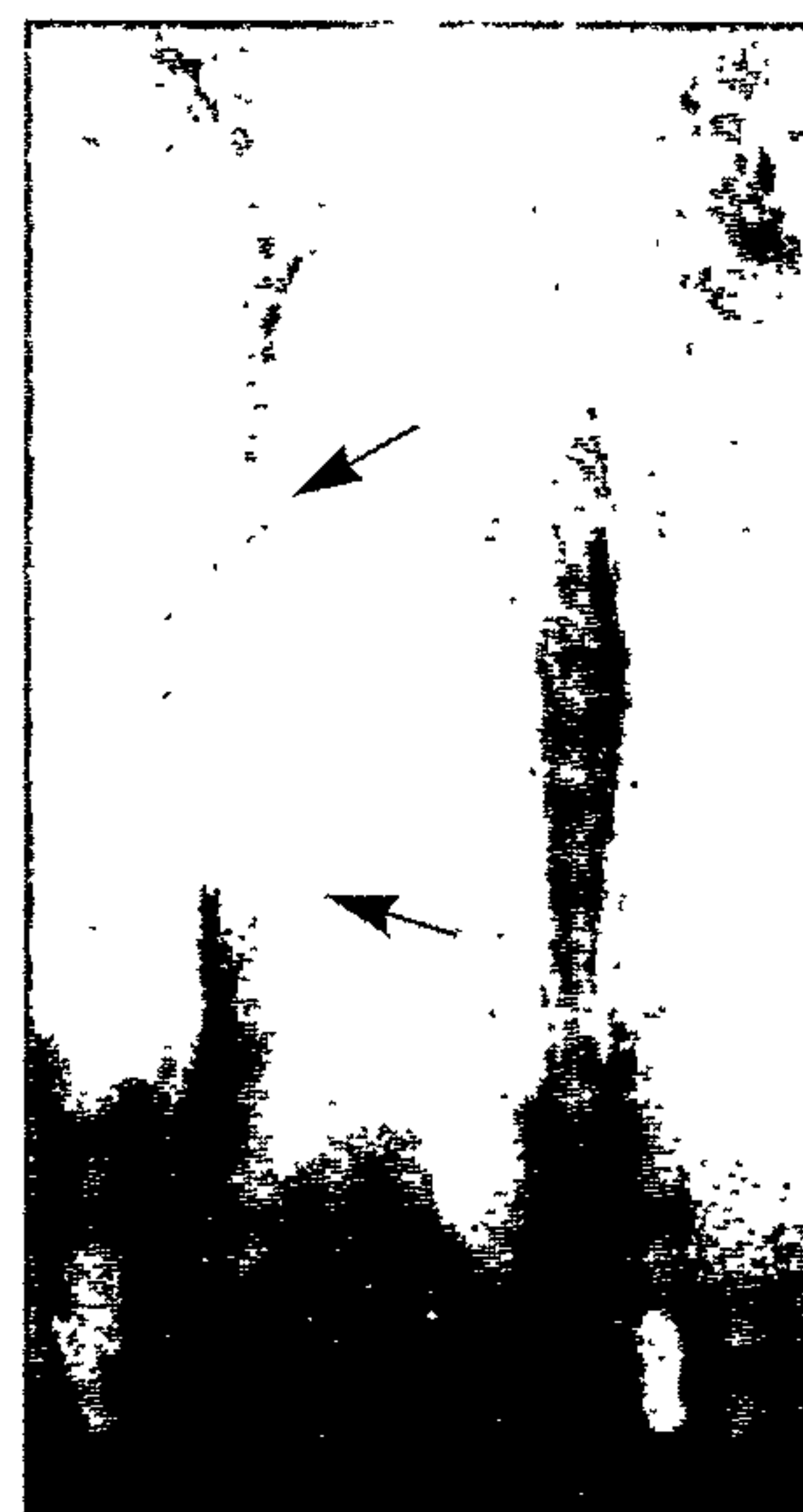


Fig. 14. – A fracture line (arrows) can be seen running parallel to the root canal and then exiting distally in the apical third in this maxillary left central incisor tooth.

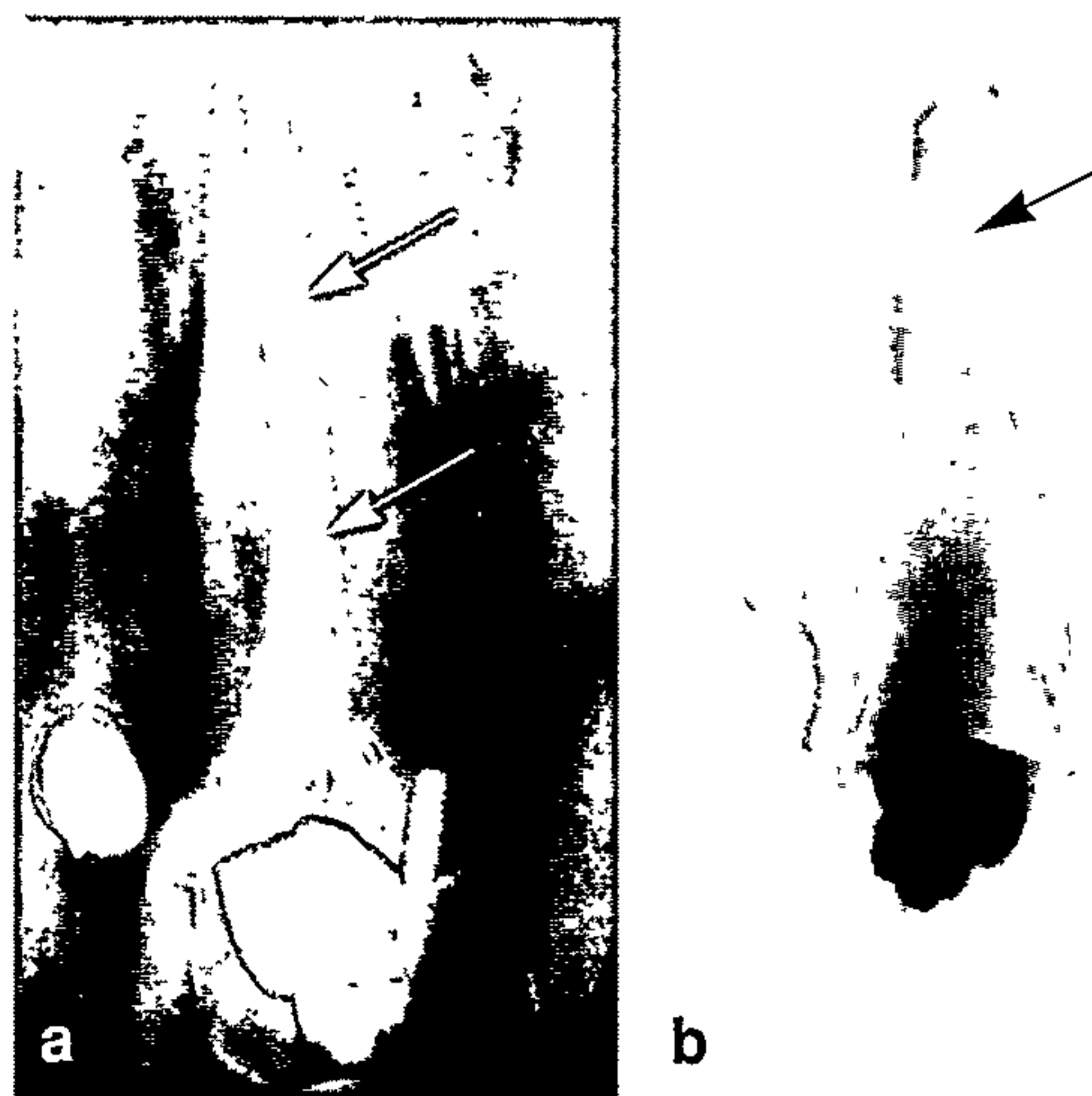


Fig. 15. – (a) A vertical fracture (arrows) radiographically superimposed over the root filling is present in this maxillary left central incisor tooth. (b) Clinical photograph of a tooth from Fig. 15a showing the fracture (arrow). Note the amount of fibrous tissue which is attached to this tooth once it has been extracted. This is a feature of teeth that are vertically root fractured.

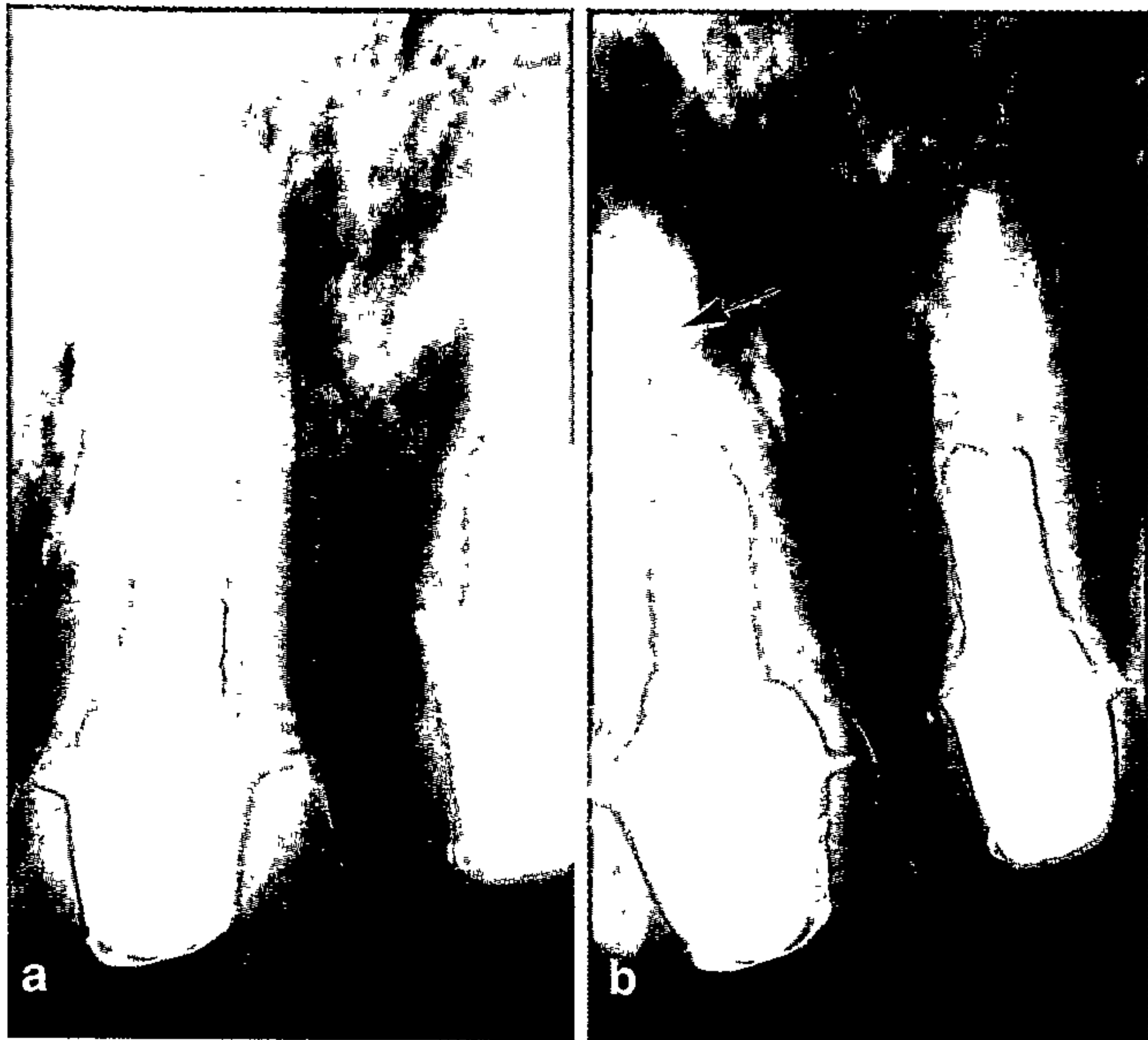


Fig. 16. – Two periapical radiographs taken at the same consultation showing the effects of angulation changes on the visibility of the root fracture on the right maxillary central incisor tooth. (a) The fracture is difficult to see. (b) The fracture is easy to see (arrow) where the X ray beam passes down in the plane of the fracture.

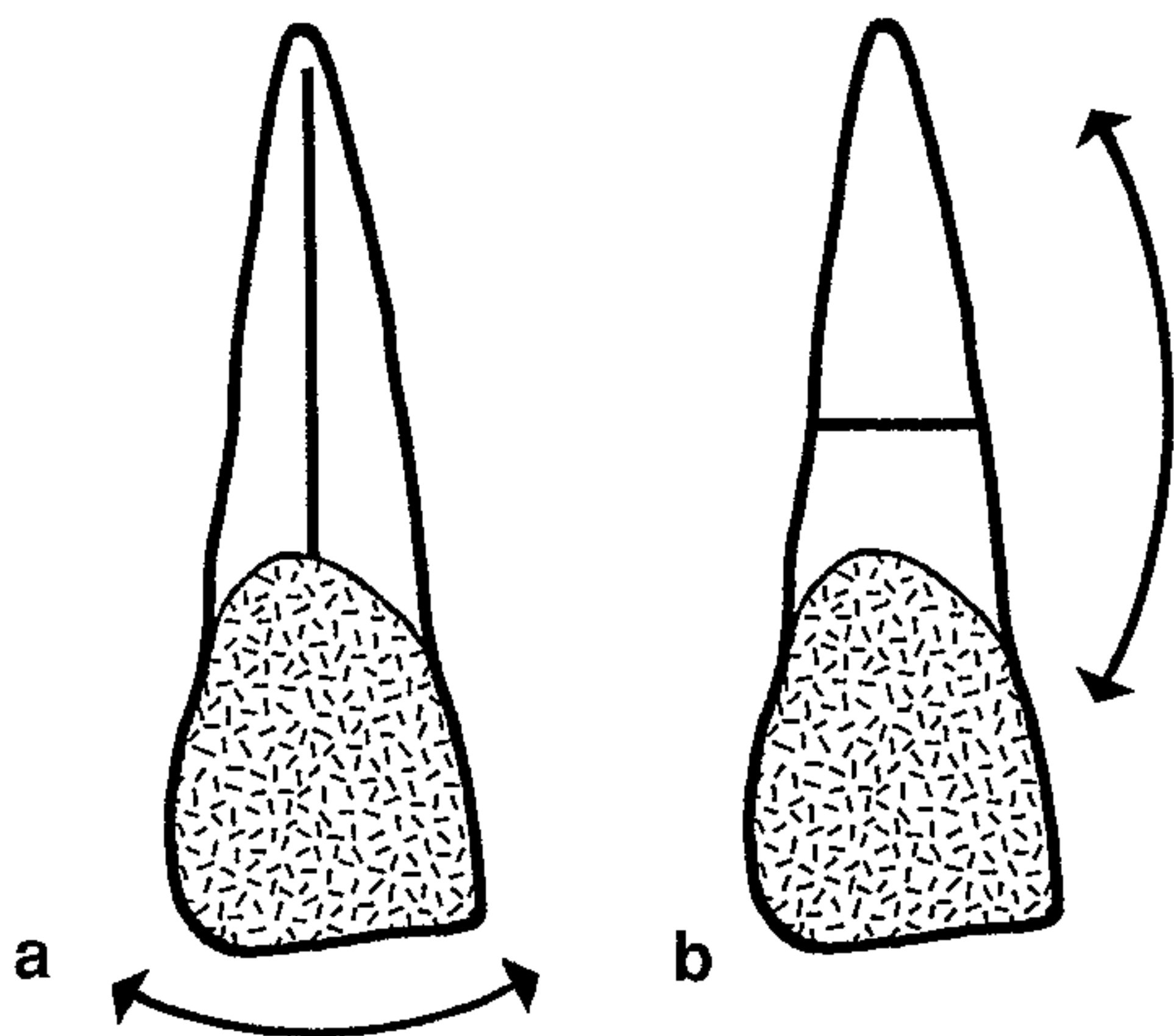


Fig. 17. – Diagrammatic representation of the changes in horizontal angulation of the X-ray beam that are necessary to detect a vertical root fracture (a). For better visualization of a transverse root fracture, the angulation is changed vertically rather than horizontally (b).



Fig. 18. – Periapical radiograph of maxillary right central incisor with a deep palatal groove, the radiographic picture of which mimics a vertical root fracture.

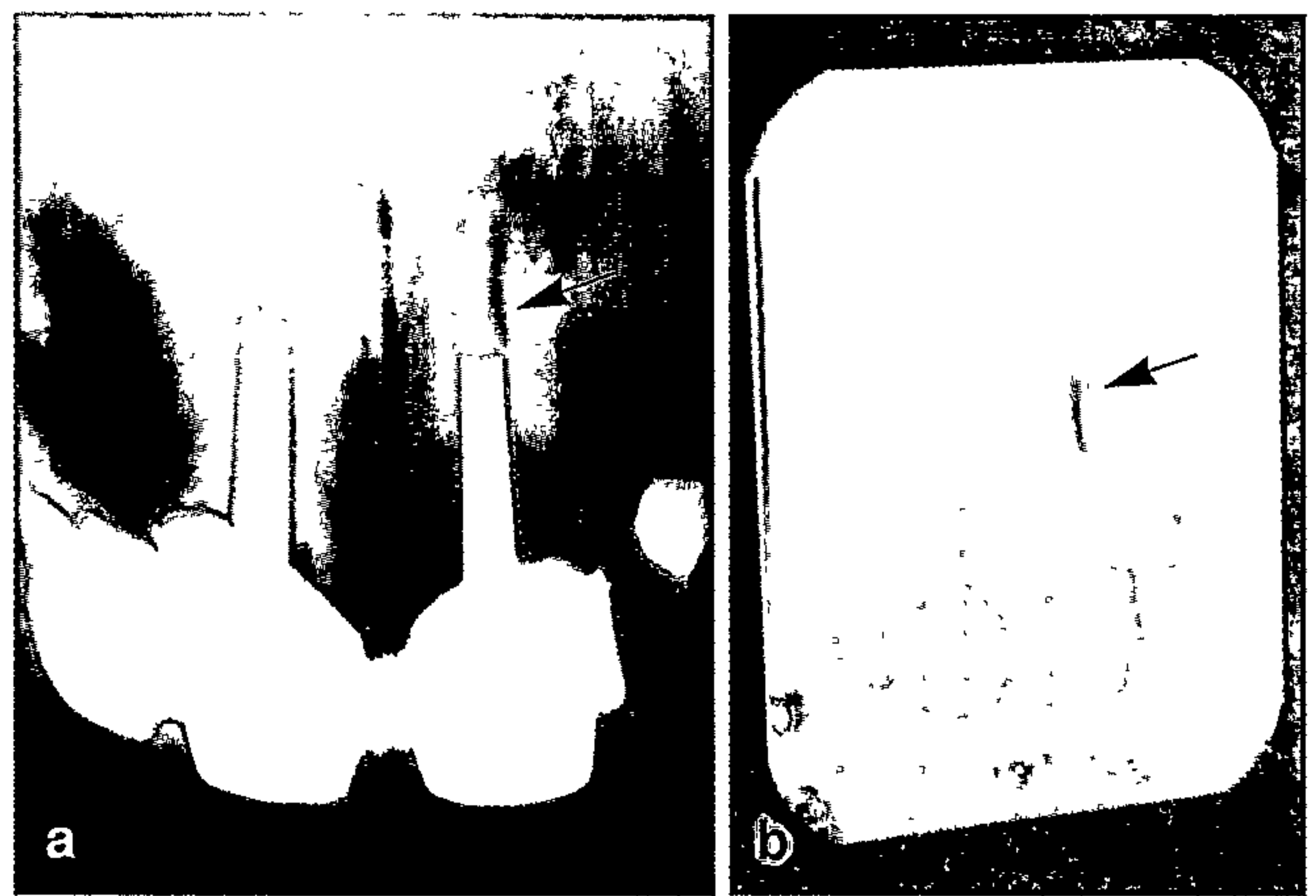


Fig. 19. – (a) Periapical radiograph of a failed anterior bridge. A dark line extending from the bottom of the post in the maxillary right central incisor to the apex (arrow) gives the appearance of a vertical root fracture being present. (b) Clinical photograph of the radiograph showing a mark (arrow) responsible for the radiographic image. In interpreting radiographic lines on radiographs consideration must be given for the presence of artefacts and scratches.

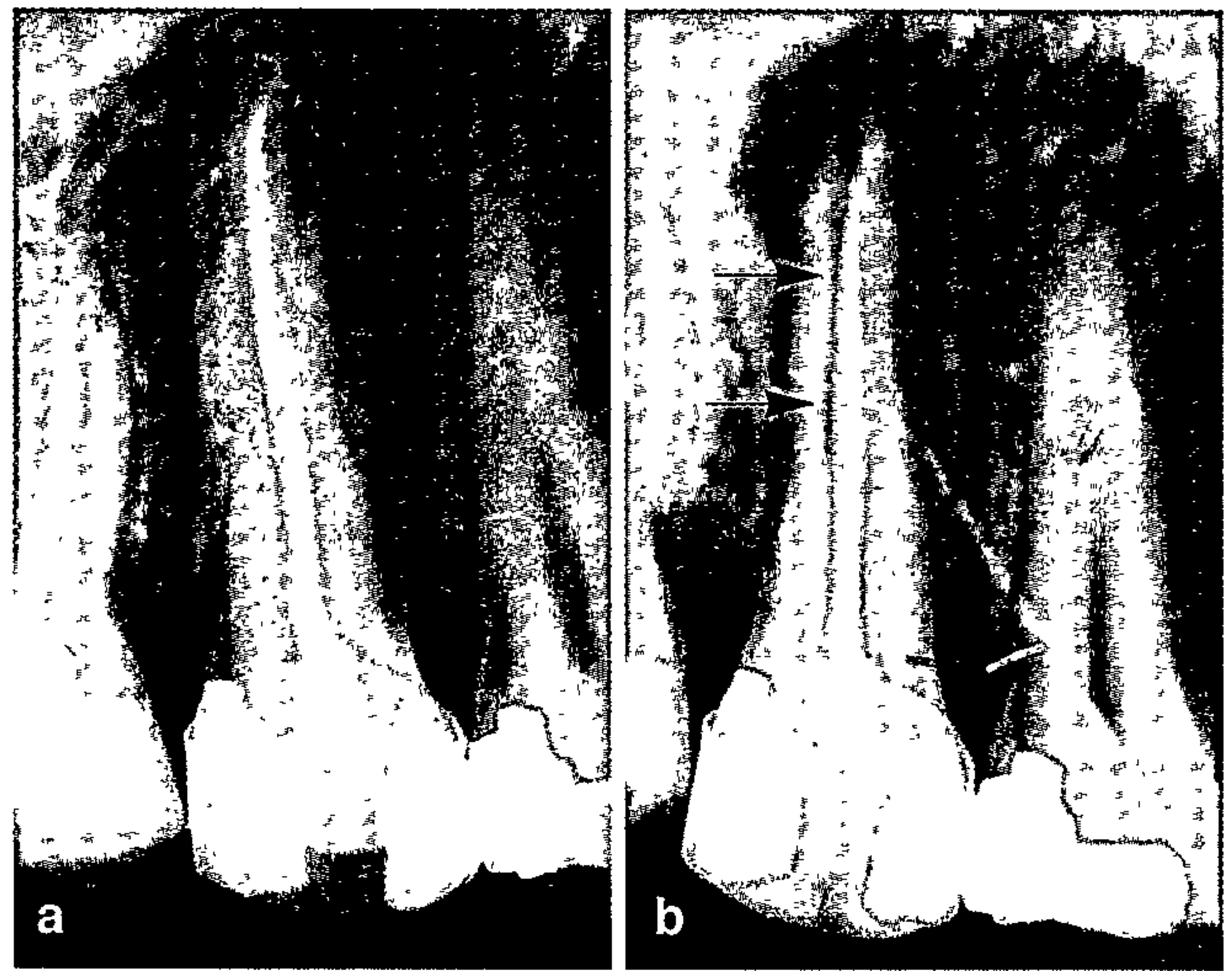


Fig. 20. – Periapical radiographs of a root filled premolar tooth. (a) At one year recall, there is no evidence of any radiographic changes which are suggestive of a problem. (b) Two years later there is widening of the periodontal ligament space and the appearance of a large periapical lesion. The fracture is seen as a space (arrows) which has developed on the distal side of the root filling due to slight separation of the fragments.



Fig. 21. – Maxillary right first premolar restored with a post/crown restoration. A space is present between the post and the root which is covered with a layer of cement. The space can be traced past the post beyond where the fracture line is clearly shown (arrow).

tooth are often an indication that a fracture is present.

Radiopaque signs (Fig. 23-25)

Where a vertical root fracture is present prior to root filling, or occurs during the root filling procedure, extrusion of cement or root filling material can occur into the fracture site or apically. When the plane of the fracture is predominantly in a bucco-lingual direction, the excess cement material can be seen as a more intensely radiopaque line superimposed over the root filling.¹ In some instances, this can give the appearance of a second canal or an irregularly obturated root canal. Where the plane of the fracture is mesio-distal, the cement excess can sometimes be seen as a thin film extending proximally from the root canal filling to the root surface. Where separation of the fracture occurs during root filling, extension of root filling material through the apex can result in a tangle of accessory points at the apex ('apical spaghetti').

Patterns of bone loss

Vertical fractures allow the ingress of bacteria and associated irritants which cause localized periodontal destruction and bone loss adjacent to the fracture site.⁶ The amount of bone loss is dependent on the nature of the fracture and the time the fracture has been present. Radiographically, there are certain specific patterns of bone loss which are found to be associated with vertically fractured teeth. The radiographic appearance of the bone loss is dependent on the extent of destruction, the plane of fracture and the architecture of the bone adjacent to the fracture. Thus, the appearance of bone destruction seen when the fracture plane is bucco-lingual will be different from that seen when the plane of the fracture is mesio-distal. Bone destruction associated with anterior teeth will be easier to see than that associated with lower molars, where changes are masked by a thick buccal plate of bone.

Widening of periodontal ligament space (Fig. 26)

Wide enlargement of the periodontal ligament around the whole length of the root is an indication that the tooth is vertically fractured. The radiographic appearance of bone loss is quite different from that seen in a periapical lesion where apical bone loss can occur but without destruction of the lamina dura along the root surface. When the fracture is in a bucco-lingual direction and involves the apical portion, there is loss of bone on the buccal and lingual surfaces of the tooth. Radiographically, the tooth root can be seen more clearly (or appears more 'in focus') than adjacent teeth. Widening of the periodontal ligament space around the whole length of the root is a classic sign that a vertical root fracture is present.

Radiolucent halos (Fig. 27)

When the plane of fracture is at right angles to the X-ray beam, the pattern of bone loss appears wider and more diffuse than that seen in bucco-lingual fractures. Pitts and Natkin¹ have described this appearance as a 'halo-like' radiolucency running around the whole of the tooth. While the width of the diffuse bone loss may vary, a radiolucent halo which runs around the whole of the root surface is a classic sign of a vertical root fracture.

Step-like bone defects (Fig. 28)

When the fracture runs obliquely across the root, or where the fracture does not extend into the apical portion, a characteristic step-like bone defect develops.^{1,31} The width of the bone loss can vary. However, the depth of the step is governed by the apical extent of the fracture. The appearance of a step-like bone defect on a particular tooth is subject to the angulation of the X-ray beam. Additional radiographic examination with the X-ray beam angled 15 degrees to the mesial or distal may provide a better view of the defect. It must be remembered that step-like bone defects can mimic simple endodontic lesions resulting from other causes, for example, post perforations and vertical grooves. Similar defects can also be associated with non-vital teeth that have not been root filled but such defects will include the apex. Step-like bone defects are only a sign that a fracture may be present. The presence of the fracture needs to be confirmed by other means. Pitts and Natkin¹ have suggested that the possibility of a fracture is increased if the pocket extends to the mid-root level rather than to the apex, as this eliminates apical pathology from consideration.

Isolated horizontal bone loss in posterior teeth (Fig. 29)

It is unusual for one tooth in a dentition to be severely involved with periodontal disease without involvement of other teeth. When only an isolated tooth shows bilateral horizontal bone loss the presence of a mesio-distal root fracture should be expected, particularly in the presence of apparently successful endodontic therapy, and where the overall periodontal situation is stable. Occasionally, the same radiographic appearance can be seen where there is a foreign body wedged in the periodontium.

Unexplained bifurcation bone loss (Fig. 30, 31)

Bone loss in the bifurcation region of molars can occur in patients without overt periodontal disease in situations where there is ingress of bacteria through defects in the bifurcation, for example, perforations and other defects in the pulpal floor. Bifurcation bone loss is also seen in lower molars with non-vital pulps but this is usually in association with periapical bone loss. Where bifurcation bone



Fig. 22. – Wide separation of the fragments has occurred in this vertically fractured maxillary right canine which is fractured mesio-distally. Double images of the distal root surface (arrows) are caused by overlapping of the fragments.



Fig. 26. – Periapical radiograph of maxillary left lateral incisor showing widening of the periodontal ligament space around the whole of the root. This is a classic sign that a root fracture is present.

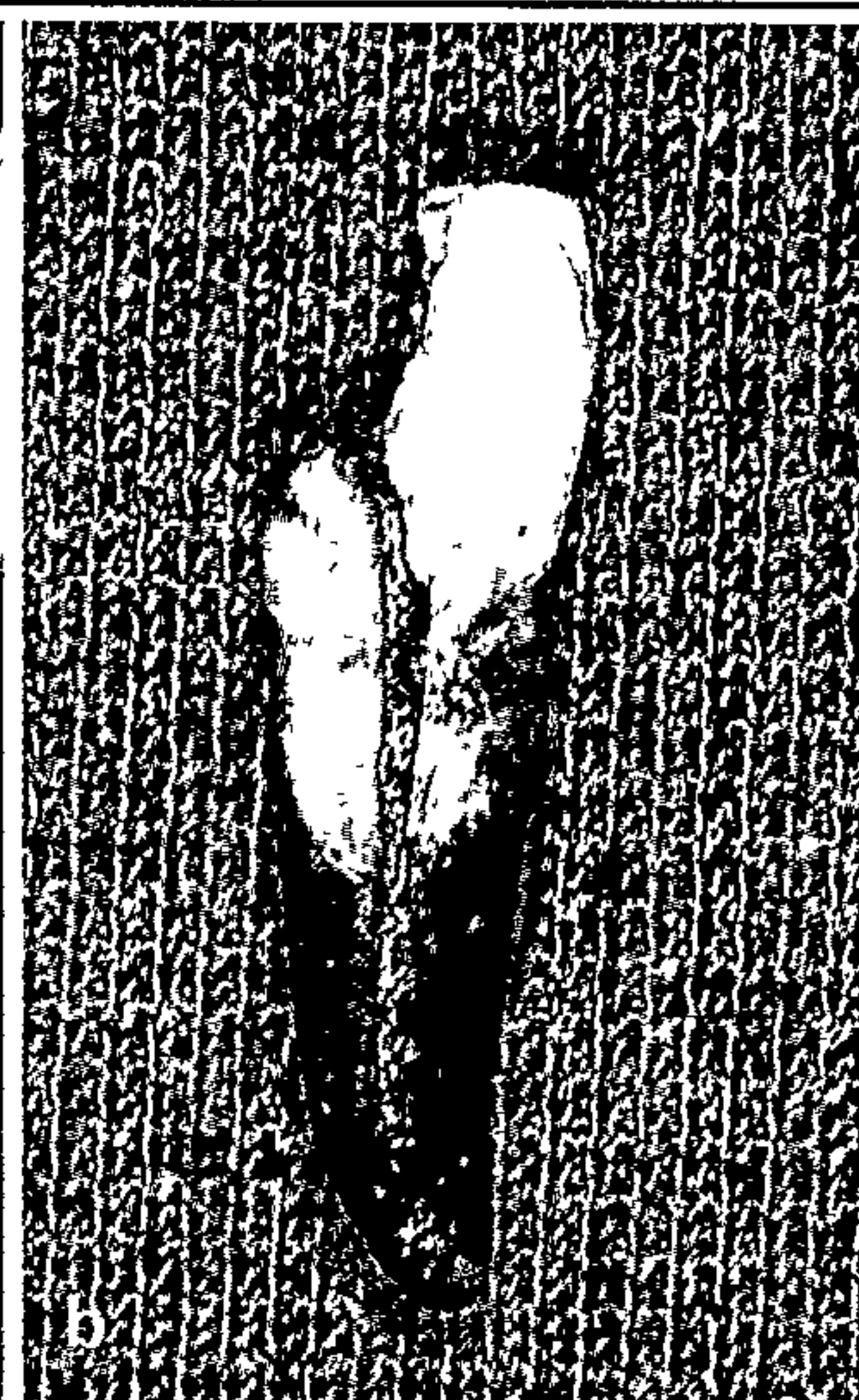


Fig. 23. – (a) Periapical radiograph of a recently root filled maxillary right canine showing a well condensed root filling with an irregular outline. (b) Extracted tooth showing vertically fractured root.



Fig. 24. – Periapical radiograph of a root filled maxillary right first molar which suffered a vertical root fracture. A thin film of cement (arrows) is evident in the buccal root extending from the root filling to the root surface.

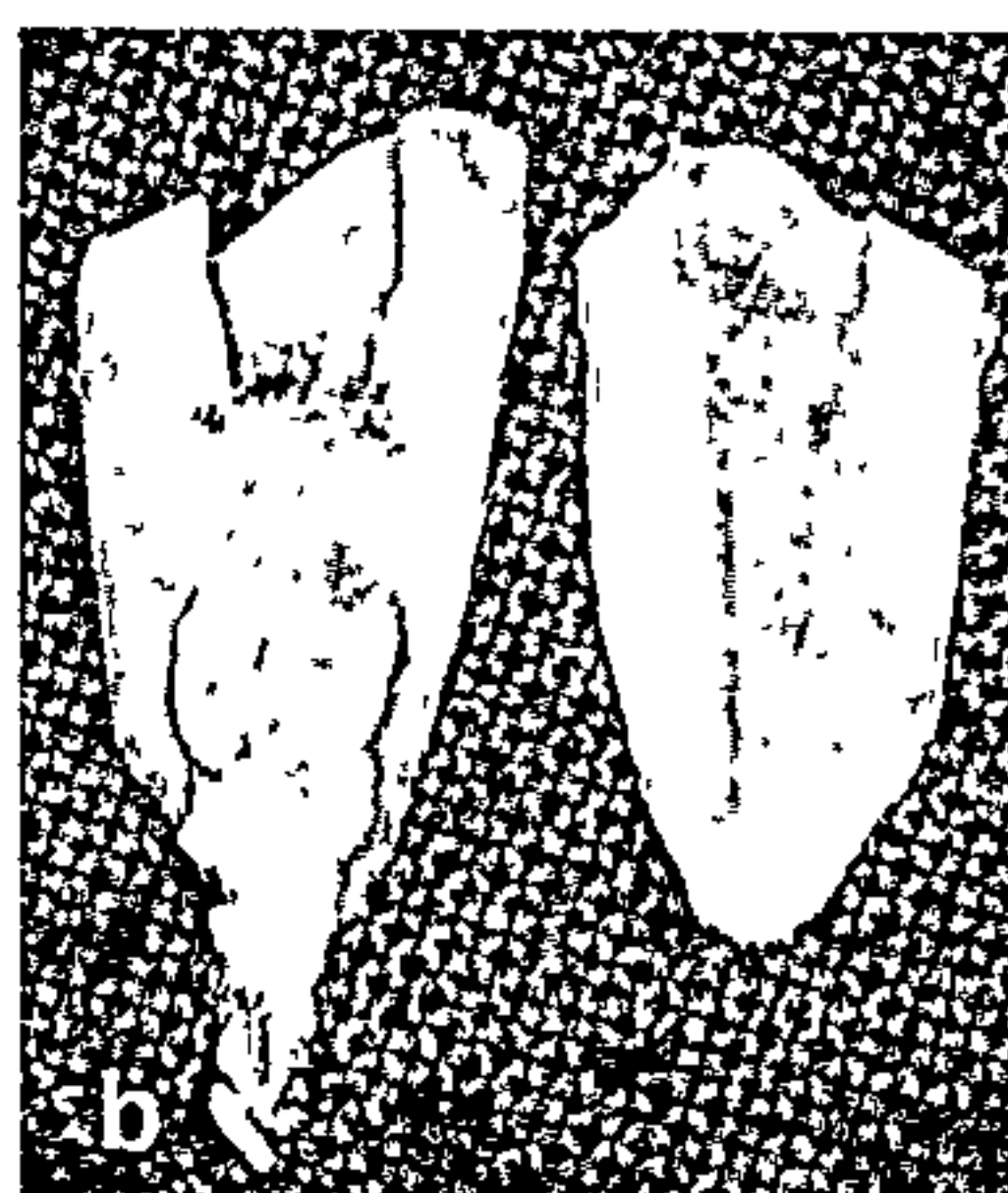


Fig. 25. – (a) Periapical radiograph of root filled mandibular left lateral incisor showing a tangle of accessory points in the apical portion (arrow). (b) Extracted tooth showing the fractured root and the tangled array of accessory points through the apex.



Fig. 27. – Periapical radiograph of mandibular left first molar showing a wide diffuse radiolucent 'halo' around both roots. The tooth was fractured mesio-distally. Radiolucent halos of this type are a classic sign that a vertical root fracture is present.

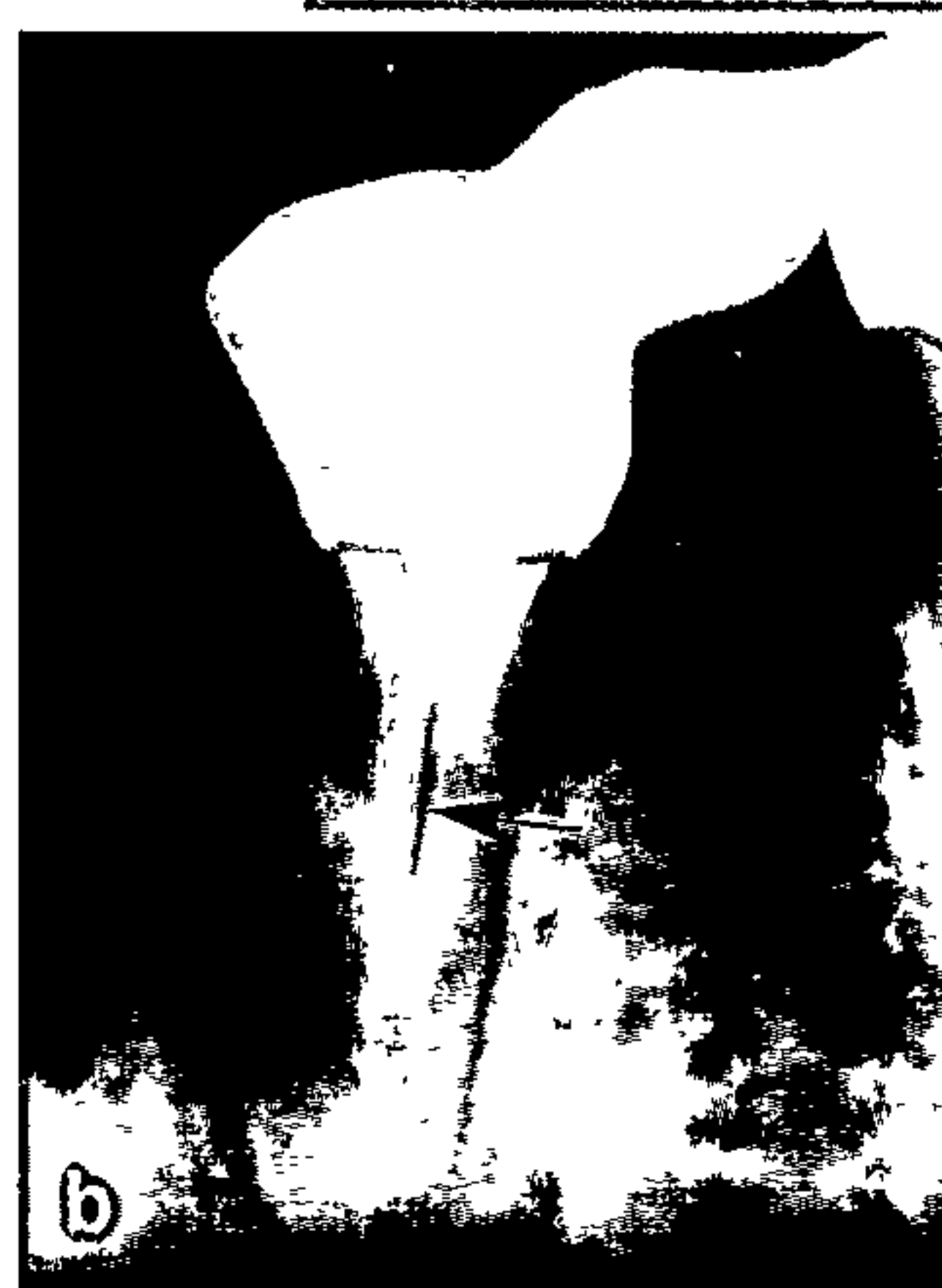


Fig. 28. – (a) Periapical radiograph of hemisected lower molar showing good bone adaptation to the distal surface. (b) A step-like bone defect has developed on the distal in association with a vertical fracture in the root. (c) A periapical radiograph taken at a slightly different angle reveals that the step-like bone defect finishes at the level of the fracture.



Fig. 29. – Isolated horizontal bone loss occurring in association with a single isolated tooth, in an otherwise periodontally stable mouth, is an indication that a vertical root fracture is present.



Fig. 32. – (a) Mandibular right first molar which has been root filled and restored with a large amalgam restoration. Note the diffuse V-shaped bone loss (arrows) around the mesial root which is a classic sign that a root fracture is present. (b) Periapical radiograph taken four months later clearly shows a major fracture with wide separation of fragments.

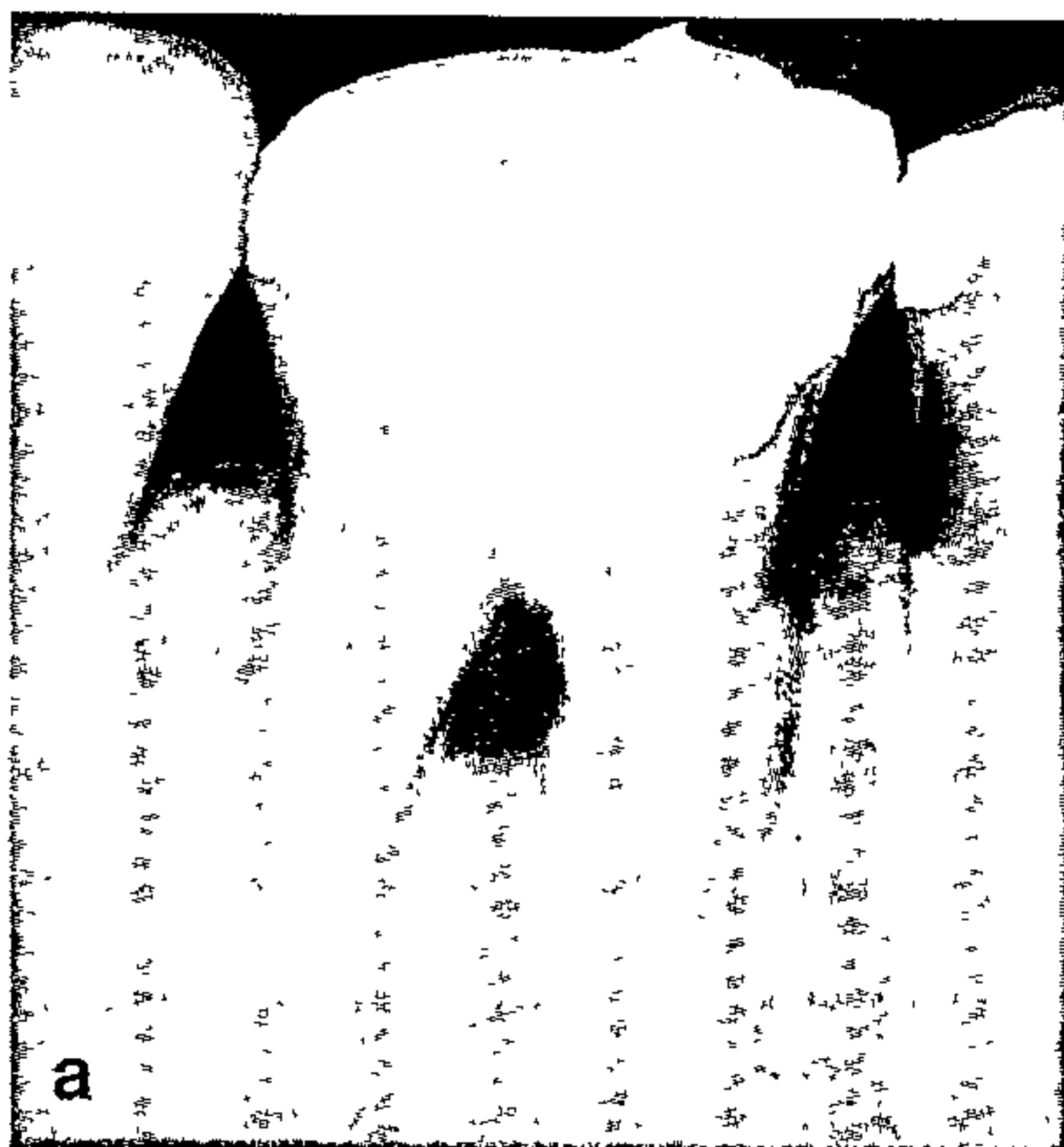


Fig. 30. – (a) Periapical radiograph of mandibular right first molar tooth showing unexplained bone loss in the bifurcation region. The lamina dura is intact apically and there is normal attachment buccally and lingually. (b) Clinical photograph of the tooth showing the mesio-distal fracture running across the pulp chamber. A vertical fracture should be suspected if there is unexplained bone loss in the bifurcation region of the molar teeth.



Fig. 33. – Vertically fractured second premolar tooth showing a V-shaped resorptive defect at the apex. The periodontal ligament space is widened around the whole root.



Fig. 31. – (a) Periapical radiograph of vertically fractured maxillary left first molar shows bone loss in the bifurcation region of this molar. (b) In a straight on view of the same tooth, the lesion in the bifurcation is masked by the palatal root. There is widening of the periodontal ligament space around the mesio-buccal root. The lamina dura appears to be intact around the tooth. This tooth was fractured mesio-distally.

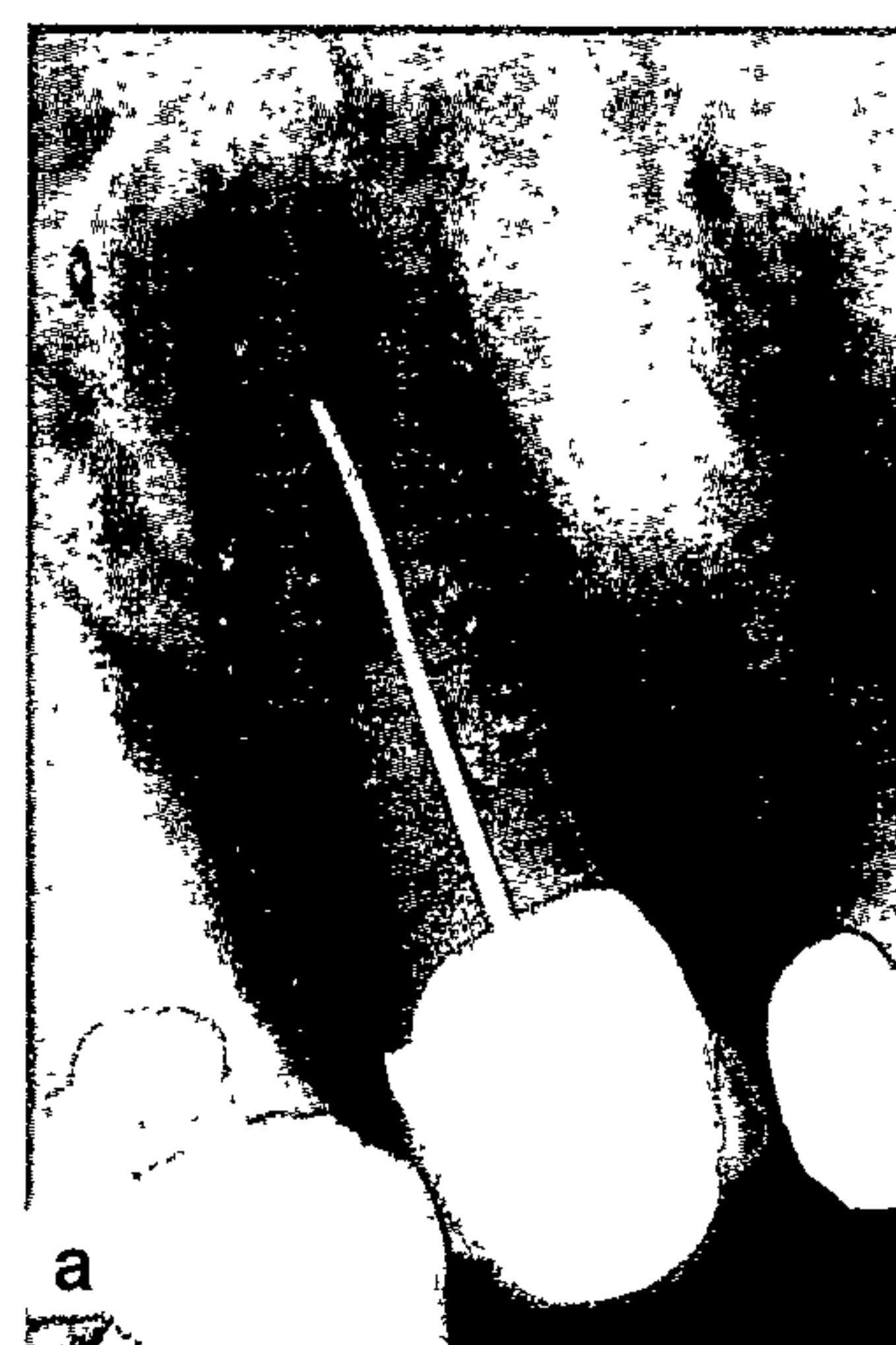
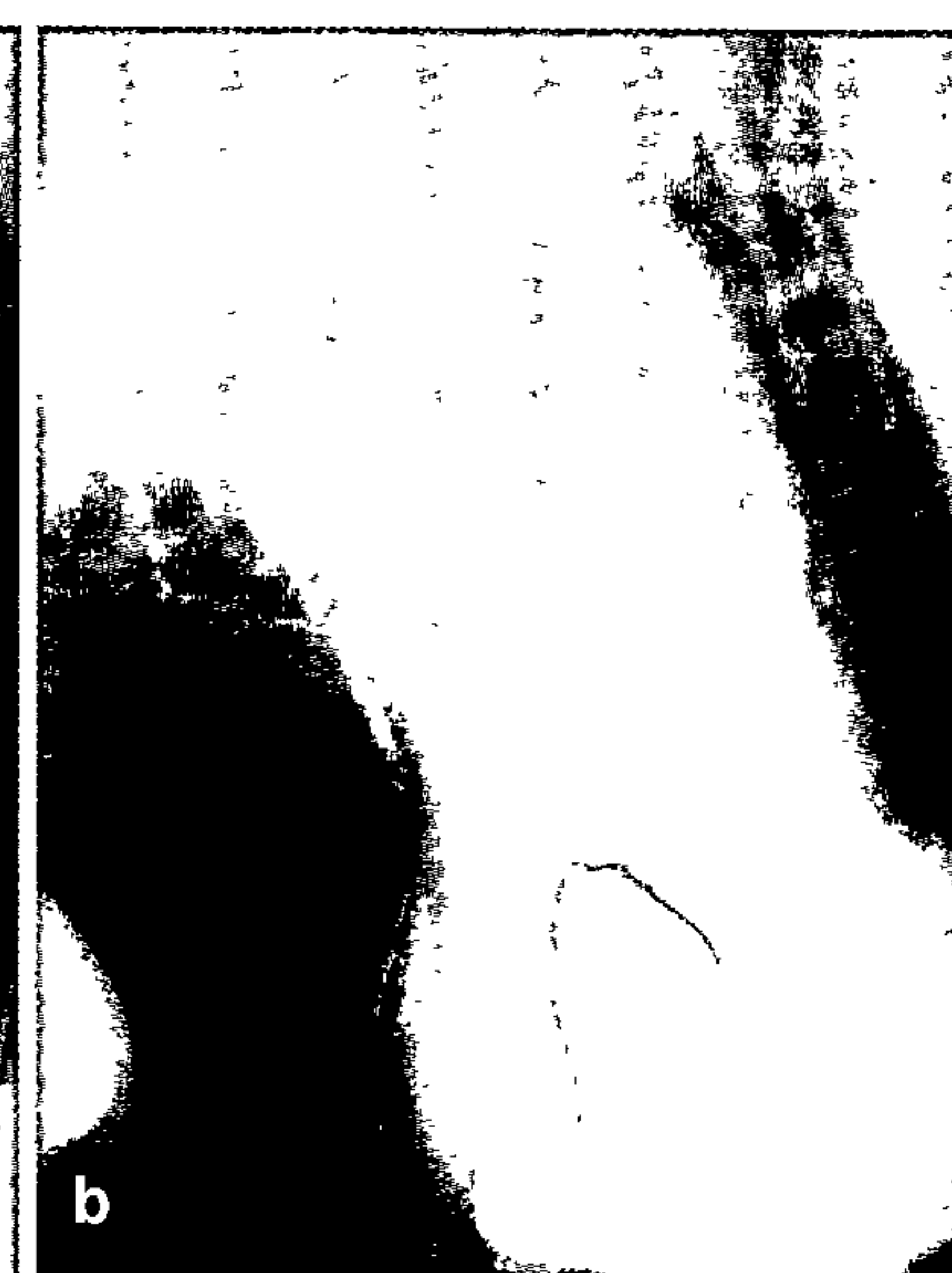


Fig. 34. – Dislodgement of a retrofilling material is a sign that a root fracture may be present. This premolar was treated surgically and a retrofilling material was placed at the apex. (a) A periapical radiograph taken prior to extraction shows the retrofilling material is no longer in place. (b) This patient returned with the amalgam restoration which had been dislodged through the soft tissues. The existence of a vertical root fracture is clearly evident.

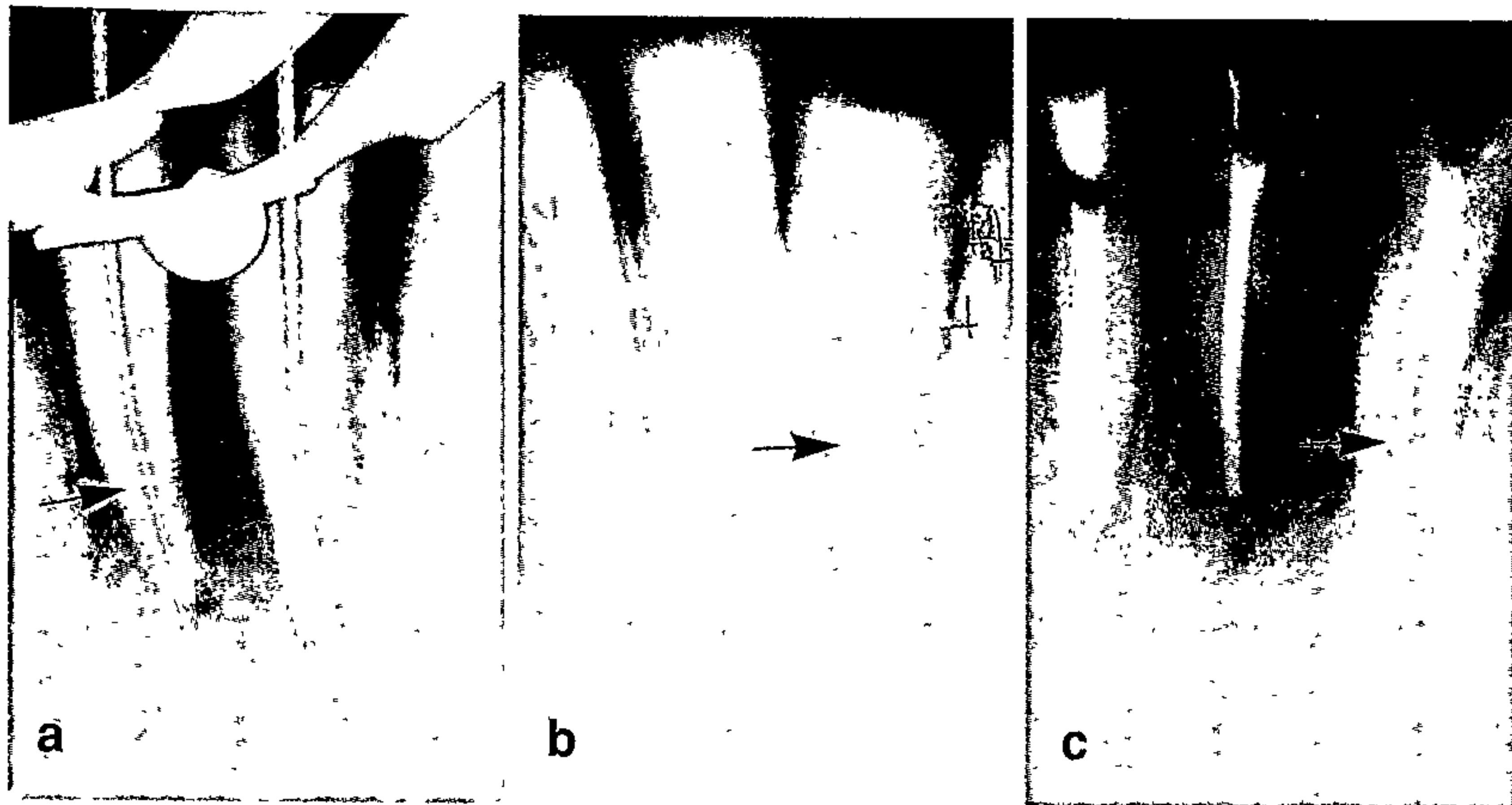


Fig. 35. – A vertical fracture should be suspected if there is breakdown of bony architecture which occurs subsequent to the complete resolution of an endodontic lesion. (a) At the time of initial endodontic treatment the mandibular left central incisor (arrows) is associated with a periapical lesion. (b) On review there has been complete healing. (c) Six years later a lesion has developed. This tooth is obviously vertically fractured. Note the resorption along the fracture line.



Fig. 39. – Where it is important to determine the type and extent of the fracture, a full thickness periodontal flap is recommended. Often a single vertical incision one tooth distal or mesial to the suspect tooth is all that is required to expose sufficient root surface to visualize the fracture (arrow).



Fig. 36. – The presence of a vertical root fracture is clearly visible on the root face. The post crown has been dislodged.



Fig. 37. – Gentle reflection of soft tissues under local anaesthesia is often all that is required to confirm the presence of a vertical root fracture.



Fig. 40. – Loss of bone and deposition of soft tissue adjacent to the tooth root is usually found in the presence of a root fracture. On this occasion, the fracture can be seen as a linear yellowish line in the mid-root region, running vertically from crown to apex (arrow).



Fig. 38. – A triangular 'miniflap' involving a single vertical incision (a) in the attached gingiva on the side of the tooth away from the probing defect or suspected fracture is a relatively atraumatic way of exposing the coronal root surface and (b) of confirming the presence of a suspected vertical root fracture.

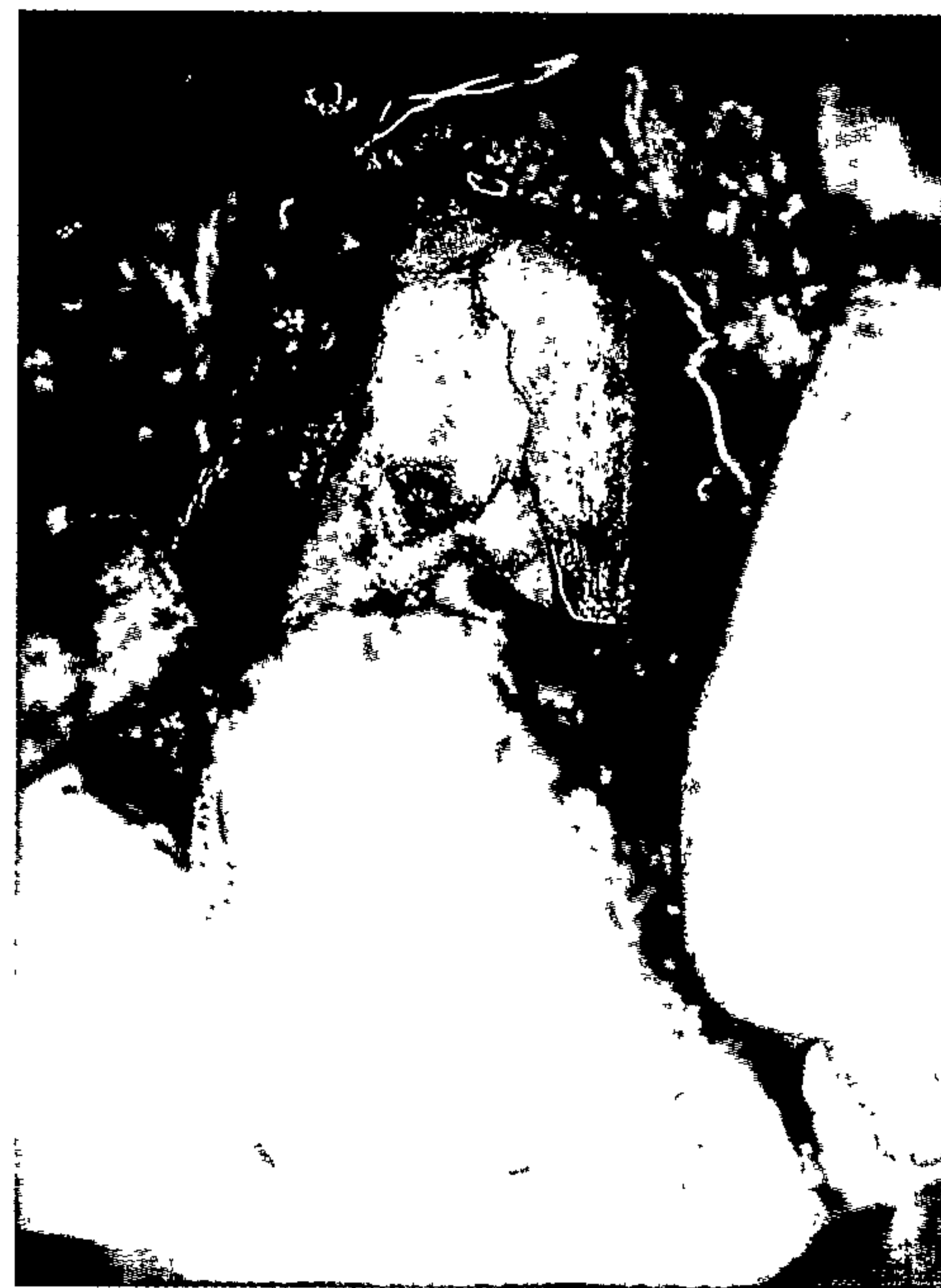


Fig. 41. – Reflection of a full thickness flap reveals the full extent and complexity of the root fracture in this central incisor tooth. Flap reflection is recommended to confirm the presence of a vertical root fracture.

loss occurs for no apparent reason, and without any obvious sign of apical pathosis, the presence of a vertical fracture through the bifurcation needs to be considered. In mandibular teeth, bifurcation bone loss is usually fairly easy to see. In maxillary molar teeth, however, it is usually masked by the position of the palatal root. An oblique angle on the radiograph is necessary to bring the bone loss into view.

V-shaped diffuse bone loss on roots of posterior teeth (Fig. 32)

Where the buccal roots of maxillary molars or the roots of lower molars are vertically fractured, the characteristic radiographic image of bone loss is a diffuse V-shaped radiolucency, widest at the crestal bone, narrowing towards the apex.¹ The shape and diffuse radiographic evidence of the bone loss is due to the fact that much of the bone lost is lingual to the buccal plate of bone, which to some extent masks its presence. Diffuse bone loss of this type, when confined to a single root or a single tooth in the mouth, is almost pathognomonic of a vertical root fracture.

Resorption along the fracture line (Fig. 33)

One of the presenting signs of a vertical root fracture is resorption along the fracture line.^{1,15} This resorption may occur apically where it causes a V-shaped notch in the apical region, or longitudinally along the whole length of the fracture, giving the appearance of an irregular long resorptive defect running along the gutta percha root filling. Disintegration of root canal sealer, silver points and gutta percha in association with extensive resorption of the root has been reported as being a feature of vertically root fractured teeth.¹⁵

Dislodgement of retrograde filling material (Fig. 34)

Dislodgement of retrograde filling material in association with vertical root fractures has been described previously.^{1,32,33} Dislodgement of retrograde root fillings can occur due to inadequate retention.³³ However, for the retrograde root filling to be displaced, some force usually has to be applied to move it away from the root apex. Should a retrograde root filling become dislodged, a likely cause is a vertical root fracture. In some cases the dislodged retrograde root filling material can be expelled through soft tissues.³²

Endodontic failure after healing has occurred (Fig. 35)

Endodontic failure can occur many years after the tooth is root filled for a large number of reasons.³⁴ Coronal leakage³⁵ is considered to be one major cause of long-term failure of endodontic procedures. However, when the endodontic status of a tooth

deteriorates rapidly after a long time without symptoms, or where radiolucencies reappear after healing has previously taken place, a vertical root fracture should be considered as a cause and further investigations of the tooth should be undertaken with this possibility in mind.

Direct visualization of the fracture

While clinical and radiographic signs give a reasonably accurate indication that a root fracture is present, direct observation of the fracture is the only sure way to confirm the presence of the fracture in many cases. Where sufficient coronal structure has been lost, or where a crown restoration has become dislodged, it may be possible to view the fracture directly by examining remaining tooth structure (Fig. 36). Where separation of fragments has occurred, the fracture space is clearly evident. Where separation has not occurred, a sharp probe can be used to identify the fracture. Should this not be possible, then gentle retraction of the soft tissues in the region of the suspected fracture line with a flat plastic or other instrument (under anaesthetic if required) may be sufficient to view the fracture on the root surface (Fig. 37). Once the soft tissues are displaced, the fracture often can be clearly seen. Location of the fracture can be assisted by passing a sharp probe lightly over the tooth surface. A 'clicking' sound can be heard as the probe is passed over the fracture line.¹ Where this is not possible, reflection of a small flap is recommended in order to view the root and confirm the presence of a fracture. The simplest way to do this is with a triangular 'miniflap'. A single vertical incision can be made in the attached gingiva on the side of the tooth away from the probing defect or suspected position of the root fracture and around the offending tooth only. This conservative flap usually allows sufficient reflection of soft tissues to confirm the presence of most vertical root fractures (Fig. 38). Where the extent of the root fracture is important to determine, or where it is considered that a miniflap will not expose sufficient tooth structure, a full thickness periodontal flap can be used. In general, a vertical root fracture is easy to see once the flap is retracted, particularly if there is some separation of the fragments (Fig. 39). Its presence is always accompanied by loss of bone and the deposition of soft tissue adjacent to the fracture. At the time of surgery, the appearance of the fracture can vary. Where the fracture is stained, visualization is easy. On many occasions, however, subtle linear colour change (Fig. 40) is all that is apparent. Change in the angle of lighting or the position of viewing is sometimes necessary to confirm the presence of the fracture. It is sometimes necessary to remove the soft tissue over the portion of the root being examined so the fracture can be visualized. A fibre-optic light is a useful diagnostic tool, particularly where the fracture

is not stained, or where separation of fragments has not occurred. It is proposed by these authors that, where possible, a small flap should be raised routinely to confirm the presence of a fracture, rather than just to suspect that one is present (Fig. 41).

Treatment alternatives

Once the presence of a vertical root fracture is confirmed, the decision needs to be made regarding the future treatment of the tooth. The discomfort associated with these fractures is often not acute, and often patients have put up with discomfort for many years. Some are reluctant to have the tooth removed, and this is understandable from a symptomatic point of view. However, it should be remembered that while the fracture is present, bone loss continues and should the fractured tooth be left in place indefinitely, the amount of bone loss that occurs may severely compromise the success of future restorative procedures and may result in the need for complex periodontal surgery or ridge augmentation. It is, therefore, recommended that root fractured teeth be removed as soon as practical. A number of complications have been reported where vertical root fractures have been left in place for some length of time.^{36,37}

Treatment of vertically fractured teeth is difficult and is dependent on the tooth type as well as on the extent, duration and location of the fracture. The majority of vertical fractures involve the gingival sulcus and result in destruction of the periodontium to the apical extent of the fracture, due to ingress of bacteria and other irritants,⁶ resulting in alveolar bone loss in almost all teeth.³⁰ Repair of the periodontium and the bone cannot occur in the presence of the bacterial infection.¹ The aim of treatment is therefore to eliminate the fracture or the leakage of bacteria along the fracture plane.¹ From a treatment planning point of view, a distinction must be made between a tooth that is cracked and a tooth that is fractured. Where there is separation of fragments and/or radiographic changes and/or bone loss associated with the root defect, a vertical fracture can be assumed to be present and elimination of the crack is a treatment priority. Where the tooth is cracked or crazed without bone loss or attachment loss the root is cracked. Conservative management of these cracked root filled teeth is sometimes possible.

Multirrooted teeth can often be successfully treated by resecting the fractured root, either by root amputation or hemisection.^{1,38} Prognosis for posterior teeth is good, provided the fracture can be removed in its entirety. Studies of root resected teeth have reported five year retention rates of 94 per cent³⁹ and ten year retention rates of 68 per cent.⁴⁰ A series of treatment options for posterior teeth involving hemisection and root amputation has been described in the literature.^{1,7}

In general, prognosis for single rooted teeth is poor and extraction is often the treatment of choice. However, many case reports are described in the literature where innovative attempts to treat and retain anterior teeth have been attempted with varying success. Clinicians have either removed the fractured segment or attempted to bond the root using a biocompatible material.

Cyanoacrylate has been used in an attempt to bond the fragments of anterior teeth.⁴¹ While the treated teeth were comfortable at a 16 month follow-up, long-term prognosis was considered poor due to deep pocketing and resorption. An *in vitro* study⁴² assessing the resistance to fracture of root segments bonded with glass ionomer cement, composite resin, and cyanoacrylate concluded that the bond strengths of composite resin and cyanoacrylate were superior to glass ionomer cement. A number of case reports appear in the literature suggesting the use of glass ionomer cement in vertically root fractured teeth. It has been proposed that glass ionomer cement may bond around the fracture line, preventing propagation of the fracture.⁴³ Glass ionomer and amalgam condensed into the coronal half to two-thirds of the root canal in teeth with incomplete vertical root fractures has been reported successful at eight month follow-ups⁴⁴ but long-term follow-ups have not been recorded in the literature.

Calcium hydroxide has been used to promote tissue repair and resolve osseous defects before the roots were restored. Teeth treated with calcium hydroxide, then 'reinforced' with glass ionomer cement, have shown healing at six month follow-up appointments.¹⁴ Studies using an expanded polytetrafluoroethylene Gore-Tex membrane to establish a new periodontal attachment after the fragments have been bonded with glass ionomer cement have reported differing results; six teeth failed in a twelve month period.⁴⁵ Only one study has reported success with this method of treatment. Trope and Rosenberg⁴⁶ extracted both segments of a maxillary second molar and protected the periodontal ligament by soaking it with Hanks balanced salt solution, while bonding the segment with glass ionomer and subsequently replanting the tooth using Gore-Tex membrane to establish a new periodontal attachment. After six months, they reported a reduction in pocket depth from 10 mm to 2-3 mm. A crown was placed after one year as the tooth was functioning normally.

It can be concluded from these results that the use of glass ionomer cement in teeth with incomplete vertical root fractures may be an effective way of treating the teeth on a short-term basis. Long-term follow-ups have yet to be reported on these teeth and this treatment can only be regarded as experimental. Also, on balance, the use of Gore-Tex membrane in association with glass ionomer bonding of the fragments can only be regarded as experimental. It

may be appreciated that there is no point in attempting such treatment in anterior teeth if there is not sufficient coronal tooth structure to allow for an adequate ferrule to hold the coronal tooth structure together.⁴⁷

Regeneration of bone has been shown to occur after surgical removal of the fractured segment from an anterior tooth, but long-term follow-up was shown to be unfavourable due to deep pocketing and mobility.⁴⁸ Successful three year follow-up has been reported where the fractured fragment was removed in a tooth without periodontal disease and the remaining root filling covered by an amalgam restoration.⁴⁹

Though the majority of vertical root fractures are complete, fracture of only one side may occur.⁶ In these instances, complete removal of the fracture has been proposed.¹ It has been suggested that in instances where the gingival sulcus is intact, the root can be sectioned, maintaining a long bevel and eliminating the entire fractured segment. A fibre-optic light source or the use of a dye are valuable aids in assessing the fracture lines.³¹ Despite considerable loss of root length, provided plaque control is adequate and the entire fracture is eliminated, these teeth with a reduced periodontium can still have a good long-term prognosis.^{1,50} Claims have also been made for the successful conservative treatment of vertical root fractures which originate apically but which do not involve the gingival sulcus. Root extrusion⁵¹ or intentional replantation in an extruded and/or rotated position are possible. It has also been suggested that if the fracture only involves the facial wall, and does not involve the gingival sulcus, the fracture may be eliminated with the preparation of a long amalgam restoration.^{1,18,52} Vertucci⁴⁹ treated a single tooth with an incomplete bucco-lingual vertical fracture by removal of the buccal segment, covering of the root canal filling with an amalgam restoration and treating the remaining root surfaces with 20 per cent citric acid solution for five minutes. The tooth was considered functional with no probable periodontal defects or radiographic evidence of disease at a three year review. The advantage in these procedures is that the original root length is maintained. It may be reasonable to expect that the fracture could still propagate to the lingual wall. The placement of a long buccal restoration may be indicated if resection of the tooth root in a coronal dimension would not leave the tooth with adequate root support. Obviously, any detection of a lingual fracture would require beveling of the root as described earlier. None of the above procedures would be effective in the long term in the presence of a contaminated root filling. Thus, if such treatment is considered, re-root filling is indicated wherever possible.

A number of other case reports discussing treatment alternatives have been published. Takatsu *et al.*⁵³ used orthodontic elastics to join the buccal and palatal segments of a vertically fractured maxillary second molar which were then sealed with a photocured resin liner to allow the tooth to be endodontically treated and restored with a cast crown. The tooth remained in function for more than three and a half years with a reduction in pocket depth. Sinai and Kratz⁴⁸ demonstrated regeneration of bone and healing when the detached root segment, root canal filling and soft tissues were surgically removed. However, long-term follow-up was unfavourable due to deep pocketing and mobility.

An *in vitro* study⁵⁴ proved CO₂ and Nd:YAG laser to be an ineffective way to fuse fractured tooth roots. Scanning electron microscopy revealed heat-induced fissures and cracks, areas of cementum breakdown and separation of cementum from underlying dentine. Energy densities required to induce melting were considered excessive and damaging to pulp tissue. At the present time, there does not seem to be any justification for the use of a laser to fuse fractured portions of tooth together.

Conclusion

Many of the treatment options reported in this review have involved extensive procedures on small numbers of teeth, often with poor outcomes. Where successful outcomes have been claimed, the long-term prognosis has yet to be proven. All case reports published so far which describe a treatment rationale, do not include enough teeth to ascertain the efficacy of any procedure. There is room for further clinical research on the treatment of teeth that are vertically root fractured. While there is no doubt that, with some posterior teeth, treatment procedures which successfully remove the fractured fragments completely (either by hemisection or root amputation) can result in a long-term successful result, treatment of anterior teeth can at best be regarded as experimental. While it must be acknowledged that attempts to treat strategic teeth in an effort to defer complicated or extensive restructure treatment¹ may be warranted, before any complex experimental treatment procedures are considered, the desirability for retention of the tooth root should be carefully weighed up against extraction and replacement with a denture, bridge or implant.

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APPENDIX B

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Abstract

AN INVESTIGATION INTO THE VERTICAL ROOT FRACTURE OF TEETH USING SCANNING ELECTRON MICROSCOPY AND THE FINITE ELEMENT METHOD

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Introduction

This study investigates the longitudinal vertical root fracture (VRF) of teeth. VRFs occur suddenly, often appear to be associated with dental repairs, and can result in the loss of the tooth. SEM was used to investigate the nature of the VRF surfaces and cracks. SEM images were then compared to models of tooth fracture developed by the finite element method (FEM). The FEM simulated the effects of the anisotropic properties of teeth on possible fracture behaviour.

Methods

A JEOL 35CF was used to study the fractured surfaces of several mandibular first molars. ANSYS 5.5 FE software running on a Sun workstation, was used to develop and analyse a model of a mandibular first molar. Tooth geometry was derived from diagrams and data reported by Ruben et al. (1983). The FE study required precise element orientation to simulate the effects of the anisotropic (material) properties of dentine. The FEM used a linear elastic stress analysis consisting of a 20-node 3D model as this model has been found to tolerate irregular shaped elements and allow modelling of curved boundaries. 5.37 MPa was applied to part of the occlusal surface to represent biting forces, and the entire root was restrained in all degrees of freedom to simulate the bone support.

Results and Discussion

SEM fractographic analysis indicates that VRFs are probably initiated internally. Zig-zag crack paths were associated with the direction of dentine tubules. On several fracture surfaces large numbers of bacteria were also noted. When mastication loads

(300-1500 N) were applied to the FE model, stress levels were found to be independent of the location of the applied force, but were sensitive to the magnitude of the force and sensitive to the model restraints. The 3D FE modelling also indicated that large lateral strains developed in the dentine in the lower 1/3 of the tooth. The regions of high anisotropic strain appear to coincide with the regions of crack nucleation and growth observed from the SEM studies. The effects of bacteria on VRF are part of a separate on-going study (Kahler et al. 2000).

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