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A SCANNING ELECTRON MICROSCOPIC STUDY OF ORTHODONTIC ROOT RESORPTION IN HUMAN PREMOLAR TEETH

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TABLE OF CONTENTS

SYNOPSIS

It has been shown by Kvam (1972b) that when a human premolar tooth was tipped buccally by a continuous force of 50 grams, the tissue located near the cementoenamel junction was the first affected by pressure, followed by the mid-root area. Resorption started in the cementum after 10 days as small round cavities, approximately 6 micrometres in diameter. Kvam found that the resorption was characterised by extensive shallow resorptions composed of smaller round lacunae.

This project was undertaken to study the effects of the magnitude and duration of an intrusive force on the root surface topography of human premolar teeth. The material consisted of teeth from eleven patients, aged between 10 and 18 years who required the removal of first premolar teeth prior to orthodontic treatment. A metal ribbon arch bracket was directly bonded to the experimental premolar in each arch. The contralateral premolar of the same arch was used as a control, and a similar bracket was bonded to this tooth to rule out the effect of increased cheek pressure on the tooth due to the bracket thickness.

The experimental teeth were intruded with a light round archwire attached to the first molars, incisors and experimental premolar. Magnitudes of force used were 50 grams, 100 grams and 200 grams for durations of 14 days, 35 days and 70 days. The premolar teeth of two patients who had worn a fixed rapid palatal

expansion appliance were also examined for changes in root surface topography. These premolars were also extracted for orthodontic purposes. Following fixation and coating with carbon and gold, all teeth were examined in the scanning electron microscope.

Resorption was noted in all teeth that had been intruded with archwires for longer than 14 days, and was slightly more severe in teeth where heavy intrusive forces had been applied. Teeth that had been attached to the fixed rapid palatal expansion appliance showed severe resorption on the buccal surface of the premolars.

TABLE OF ILLUSTRATIONS

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SIGNED STATEMENT

This project report is submitted in partial fulfilment of the requirements of the Degree of Master of Dental Surgery in The University of Adelaide.

This report contains no material which has been accepted for the award of any degree or diploma in any University. To the best of my knowledge and belief, it contains no material previously published or written by another person except when due reference is made in the text of the report.

MICHAEL R. HARRY.

INTRODUCTION

Bone may not always be the only hard tissue resorbed during orthodontic tooth movement. Other tissues resorbed have often included cementum and dentine of the root, a phenomenon termed root resorption. Root resorption can be an unfavourable sequel to orthodontic tooth movement (Ketcham, 1929; Reitan, 1969; Newman, 1975; Goldson and Henrikson, 1975). Investigations on the occurrence of resorption in the roots of untreated permanent teeth have demonstrated sites of resorption, particularly the surface facing the direction of physiological movement (Henry and Weinmann, 1951). These authors found a high degree of bilateral similarity in the number of resorption areas per tooth.

The topography of tooth root surfaces has been examined using the light microscope (Reitan, 1974) and the scanning electron microscope (Lester and Boyde, 1970; Jones and Boyde, 1972; Kvam, 1972a). Only two studies (Kvam, 1973a and 1973b) are known in the literature describing a scanning electron microscopic study of changes on the cementum of human teeth following orthodontic tooth movement. Kvam only studied the effect of varying the duration of a fixed force of 50 grams. He found that the cementum located near the cemento-enamel junction was the first affected, followed by the cementum of the mid-root area. Resorption started after 10 days as small cavities in the cementum, and after 30 days extensive resorptions involving dentine had formed.

Many investigations have shown that when a force is applied to a tooth, areas of pressure and tension are created in the periodontium (Schwarz, 1932; Oppenheim, 1942; Moyers and Bower, 1950; Reitan, 1951 and Glickman et al, 1970). Reitan (1960) described the changes occurring in the periodontium during orthodontic tooth movement. He described the sites of pressure and bone resorption occurring in different types of tooth movement. Rygh (1977) showed that the elimination of hyalinized tissue removed the cementoid leaving a raw cementum surface. This raw surface was susceptible to attack by odontoclasts.

Massler and Malone (1954) suggested that there is an individual susceptibility to root resorption during tooth movement. It has also been claimed that there are differences in the susceptibility to root resorption due to local factors (Oppenheim, 1942), anatomical factors related to the maxilla or mandible (Ketcham, 1929; Hemley, 1941), tooth type (Massler and Malone, 1954) and also general causes such as metabolism or endocrine factors (Becks, 1936).

In an excellent study of apical root resorption under orthodontic therapy, Phillips (1955) found no correlation between the degree of resorption and such factors as sex, age at the onset of orthodontic treatment, length or method of orthodontic treatment, or the amount of orthodontic treatment involved. Newman (1975) used the records of forty seven patients, forty-one of whom had been treated orthodontically, in a radiographic investigation of possible aetiologic factors in root resorption. He found that the maxillary incisors and premolars, and the mandibular premolars showed the greatest incidence of apical shortness.

Kvam (1973b) only studied the effect of duration of applied force on the root surface. In view of the limited nature of Kvam's study, it is apparent that further investigations are required to broaden our knowledge in this field. Hence the present investigation was undertaken to provide additional clinical information on this subject.

AIMS OF THE PROJECT

The purpose of the present investigation was to study the effect of:

1. different magnitudes of intrusive forces on the root surface topography of human maxillary and mandibular premolar teeth
2. different durations of intrusive forces on the root surface topography of human premolar teeth
3. the root surface topography of teeth that have borne a fixed rapid palatal expansion appliance. To compare the topography of these root surfaces with the results of aims 1 and 2 above.

REVIEW OF THE LITERATURE

Some form of root resorption has been said to occur in almost every individual at one time or another (Gianelly and Goldman, 1971). In 1954, Massler and Malone in a radiographic study of 708 normal individuals aged between 12 and 49 years, found root resorption in every patient and 86.4 per cent of the teeth examined.

Gianelly and Goldman (1971) suggested that two types of root resorption needed to be distinguished; root resorption which was transitory and repaired by secondary (cellular) cementum, and root resorption which led to permanent loss of tooth structure. In orthodontics, the main concern has been the latter type of resorption which has led to shortening of the root and an increased crown/root ratio.

Sjolien and Zachrisson (1973) made a radiographic study of the periodontal bone support and tooth length in fifty nine orthodontically treated patients with Class II Division 1 malocclusions and sixty one untreated persons of both sexes. Long cone periapical radiographs were taken of all teeth except the first premolar and maxillary first molars approximately two years after removal of fixed edgewise appliances. The results showed that people who had received orthodontic treatment had significantly shorter teeth with less periodontal bone support than the control subjects, and that these findings were most evident in the closed extraction spaces and in the maxillary anterior region. Sjolien and Zachrisson also found that the distal roots of the mandibular first molars of orthodontically treated patients were more resorbed than the mesial roots. A similar finding has also been reported by Dougherty (1968) and it was suggested by Sjolien and Zachrisson (1973) that the tip-back bends in the arch wires may have been the causative factor.

Wainwright (1973) studied the effect of "third order" root movement on the histology of root and periodontium of premolar teeth in the Macaque speciosa monkey. He carried out four patterns of tooth movement. The first pattern (Stage A) consisted of moving the root apex buccally through the cortical plate. The second pattern (Stage B) carried out in different monkeys, consisted of Stage A movement followed by four months' retention in this position. In the third pattern (Stage C), Wainwright moved the root apex buccally as in the first stage and then back into cancellous bone. The fourth pattern (Stage D) consisted of the same movements as Stage C followed by three months' retention.

Wainwright found root resorptions of equal extent on the buccal and lingual surfaces of the teeth, with increasing severity towards the apical region. On the basis of these observations, Wainwright suggested that the density of bone through which the tooth was moved had no relation to the extent of the root resorption of the tooth. He considered that the stimulus for root resorption was more likely related to the stresses on the root and time involved.

Goldson and Henrikson (1975) studied root resorption resulting from treatment with the Begg Light wire technique. A longitudinal radiographic study was made of 42 consecutively treated patients, all of whom had had first premolars extracted. The radiographic examinations were made before treatment, during treatment (before uprighting of tipped teeth), after completion of treatment, and six months after completion of treatment. In all 42 cases, root resorption was noted in the final radiographic examination. Goldson and Henrikson constructed an index for quantitative radiographic assessment of root resorptions which scored resorptions in degrees of severity ranging from one to nine. Goldson and Henrikson found small resorptions in four per cent of the teeth examined before orthodontic treatment. At the completion of the treatment, resorption was recorded in 29 cases out of 42 and resorption of less than two millimetres (Score three) was the most common type comprising 48 per cent of all resorptions at the end of treatment. The incidence of resorption found six months after completion of treatment was highest in the lower central incisors, being 95 per cent. The upper central and lateral incisors showed signs of resorption in 90 and 87 per cent, respectively, of the teeth examined. The lower and upper canines had an incidence of 79 and 72 per cent, respectively. Lower premolars showed the lowest incidence of root resorption, comprising 53 per cent. The upper premolars similarly showed a low incidence of resorption of 56 per cent. Goldson and Henrikson also found that teeth which exhibited root resorption before treatment developed more resorption than the average during treatment.

Boyde and Lester (1967) studied the resorbing surface of dental hard tissue using the scanning electron microscope. In their study, the cementum surface of resorbing human deciduous molars was studied after extraction. The most outstanding feature of the resorption bays was the very sharp edges of each bay, a finding seen also by Jones and Boyde (1972) in the cementum of human premolar teeth that had recently come into occlusion.

Reitan (1972) discussed mechanisms of apical root resorption. He was particularly interested in the initial tissue reaction observed histologically in the apical portion of roots which had been subjected to movements of varying duration, direction and magnitude of force. Reitan investigated 72 human premolars obtained from 32 patients. He had subjected these teeth to various forms of orthodontic tooth movement. Eighteen teeth were intruded, 30 teeth were extruded, 24 tipped in a labial or lingual direction, and the forces applied ranged from 25 grams to 240 grams. The experimental period varied between 10 and 47 days. In the teeth that had been subjected to intrusion, he found varying degrees of root resorption which were generally of a very minor nature. Four teeth were intruded with forces ranging between 80 and 90 grams and four teeth with light forces not exceeding 30 grams. Reitan found that the phenomenon which he termed "apical side resorption" increased in cases in which strong forces had been applied. In five roots these resorbed areas were extensive. Apical side resorption was found in only one case following application of light forces, but there was a tendency for root resorption to occur in the middle portion of the root surface even with a force of 30 grams. Compression of pre-dentine and cementum was observed as hyalinization of tissue overlying the cementum. Reitan also found deposition of cementum on the opposite side in an area near the apex of the root. Stenvik and Mjor (1970) found similar root resorption in a histological study they made on 35 human premolar teeth intruded with forces ranging from 35 grams to 250 grams and for durations ranging from four to 35 days. They also reported that root development was affected in teeth that were intruded before root formation was completed. There was a deviation from the normal direction of root development and an abnormal matrix formed at right angles to the normal direction of root development.

Stenvik and Mjor (1970) found extreme difficulty in intruding teeth without some degree of buccal or lingual tipping movement. Reitan (1972) also investigated the effect of tipping teeth in a labial or lingual direction; he found that a tipping movement caused root resorption in the majority of teeth which he examined. The root resorption was obvious in experiments where a strong force had been applied for durations up to 47 days. Of the eight teeth Reitan moved with a 30 gram tipping force, none showed evidence of apical side resorption but Reitan stated that there may have been minor resorbed areas in the middle portion of the root. He also emphasised the individual patient susceptibility to root resorption, citing the case of one 16 year old patient in whom apical side resorption occurred in all four experimental teeth and another 15 year old patient in whom no apical side resorption occurred, even with a force of 100 grams.

Reitan's (1972) study of apical root resorption was based on observations with the light microscope. Scanning and transmission electron microscopic studies (Boyde and Jones, 1968; Furseth, 1974; Kvam, 1972b) have revealed minor resorption lacunae to be present in unmoved teeth but these changes cannot be readily seen by conventional microscopic methods. Reitan concluded that root resorption was a common occurrence in orthodontic treatment. He stated that root resorption increased with the duration of the experiment. In scanning electron microscopic studies of human premolar teeth Kvam (1972b) observed root resorption in all experiments of 25 days' duration. Reitan (1972) suggested that in young patients existing cementoid on the root surface could delay the onset of root resorption. Regarding the influence of the force magnitude, Reitan found this to be considerable in the experiments on intrusion, a movement which has been shown by Stenvik and Mjor (1970) to produce early root resorption. Deposition of cementum seen by Reitan on one side of the root indicated that a tilting of the root occurred during intrusion.

Stenvik and Mjor (1970) reported on their light microscope findings of root resorption, stating that resorption of cementum and dentine was found in 60 per cent of the experimental teeth. Relating the root resorption to the magnitude of intrusive force, these authors noted that in the group of teeth where less than 100 grams intrusive force was applied, 15 out of 18 teeth showed evidence of root resorption, and that where the force was above 100 grams, resorption was found in 6 out of 7 teeth. When considering the observation period, Stenvik and Mjor found increasing frequency of root resorption with increasing duration of force application.

The degree of root resorption was found to be more severe with longer force applications, and resorption lacunae often spread out into the dentine after penetrating the cementum. However, predentine was found to be more resistant and remained intact even when all the dentine overlying it had been resorbed by odontoclastic action. Stenvik and Mjor found evidence of deposition of cementum-like matrix in Howship's lacunae in eight of the 21 teeth showing resorption, and in some of these teeth resorption and apposition appeared to have occurred in close proximity.

The effects of rapid maxillary expansion on the teeth and periodontium have been investigated histologically by Timms and Moss (1971). They found that in all cases of rapid palatal expansion there was damage to the root surface. This was on the mesiobuccal and distobuccal aspects of the roots rather than directly on the buccal aspects. Two years after rapid expansion, there was histological evidence of recent root resorption and repair. They also observed changes in the pulp, where secondary dentine was laid down on the parts of the pulp nearest the trifurcation of molars. Pulp stones were also present in several cases. The resorption extended into dentine, and was mainly in the coronal one-third of the roots.

Electron microscopic studies of human cellular and acellular cementum have been reported by Awazawa (1963), Selvig (1965), Jones and Boyde (1972), Kvam (1972b) and Furseth (1974). Awazawa studied carbon-chrome replicas in the transmission electron microscope (TEM). However, this instrument and the light microscope proved to be of limited value in providing information concerning surface morphology. In the case of the light microscope, the resolution of approximately 200nm and poor depth of focus were limiting factors. With the transmission electron microscope the resolution was as high as 0.1nm, that is, 2000 times the resolution of the light microscope. However, the limitation was the small area of replica which could be recovered and kept intact as a self-supporting membrane on the electron microscope grid. The exact location of the replica in the original specimen was also difficult to ascertain in the TEM and further limited the value of this method.

The surface morphology of the root can be studied directly in the scanning electron microscope (SEM). Boyde and Jones (1968) rendered the root surface anorganic to reveal the mineral phase. The organic component of the periodontal ligament was removed by either distilling the tooth with hot 1,2 diaminoethane for 48 hours, or immersing the teeth in cold sodium hypochlorite for 25-48 hours. A third method described by these authors was freeze fracturing of the periodontal fibres close to the cementum surface. The mineralizing front was then observed directly in the SEM, unobscured by the periodontal ligament.

Swedlow, Frasca, Harper and Katz (1975) used hydrazine to deproteinize calcified tissue samples and claimed that its use revealed more information about the mineral phase of calcified tissue as it exists in situ, than the use of 1,2 diaminoethane. However, the great toxicity and the explosive nature of hydrazine required special care in its use.

Kvam (1971) described the preparation of human premolar roots for scanning electron microscopy. He evaluated the influence of the preparation procedures on the morphology of the tissues. He found the root surfaces of extracted teeth to be covered with fibrous tissue and nowhere was the cementum surface exposed. Kvam (1972a) used the morphology of the erythrocytes and the appearance of fibrous structures as criteria for the effects of various preparation procedures on the root surface morphology. Kvam found that both air drying and freeze drying produced no deleterious changes in fibrinous or collagenous elements, although the erythrocytes generally showed reduced size and some crenation.

Jones and Boyde (1972) found that in the untreated, postextraction condition the root surface was obscured by a dense covering of collagen fibre bundles. When the tooth was quenched in dichlorodifluoromethane, the adherent periodontal membrane often fractured away at the level of the mineralizing front of the cementum, leaving a surface which resembled that created by extracting the collagen. They suggested that this phenomenon was caused by a difference in thermal contraction between the mineralized and unmineralized collagen. Jones and Boyde also reported on areas of resorption identified by the characteristic excavated shape of the "Howship's lacunae". They frequently found areas of resorption on the root surfaces of young untreated teeth, especially near the root tip, and concluded that these areas resulted from the establishment of occlusal function for these teeth. These resorption areas were very small, approximately 15-20 micrometres wide and up to 10 micrometres deep, or about the size of a single Howship's lacuna in resorbing deciduous dentine. Jones and Boyde suggested that, on the basis of their small size, these lacunae may have been excavated by uninucleated osteoclasts. In general, resorption pits were seen to be areas where cellular cement deposition commenced. Larger areas of resorption were also noted, and the most outstanding feature of these areas was their very sharp edges.

Kvam (1973a, 1973b), using the scanning electron microscope, studied the surface of human premolars following experimental tooth movement. His material consisted of 40 teeth from individuals aged between 10 and 12 years, none of whom had previously received orthodontic treatment. Twenty three of the teeth were moved buccally by means of a fixed appliance, 15 control teeth were fitted only with orthodontic bands and two teeth were left untreated. Kvam arranged his experiment so that one control tooth was available for comparison from each subject, and attempted to keep the observation periods of the experimental and control tooth similar. Kvam used a spring attached to the first molar to exert a buccally directed force of

50 grams on the experimental tooth, which was provided with a twin arch bracket. The force exerted by the spring was measured with a Correx gauge. The experimental periods were 5, 10, 15, 20, 25, 30, 35, 45 and 76 days. Kvam found that on the pressure side of the tooth root surface the organic tissue was considerably altered. The thin fibres of the principal fibre bundles were said to have lost their cross-striation and had fused into a homogeneous substance. Around this hyalinized tissue he observed disorganized fibre bundles which still exhibited periodic cross-striations. He also found areas where the hyalinized tissue was partly removed and resorbed areas of cementum were revealed. In order to record the incidence of resorption, Kvam removed the organic components from the root surface. He found the root surfaces of the untreated teeth had a smooth surface, and only two of these specimens had small resorption lacunae. After experimental buccal movement, the test teeth showed resorption which started at 14 days, appearing as small cavities approximately six micrometres in diameter. With increasing duration of force application extensive excavations consisting of small, round, thin-walled lacunae appeared on the pressure side of these teeth. Root resorption was noted in the coronal marginal area at 10 days and the number of small resorption lacunae increased and merged into extensive, shallow excavations. Kvam found the gingival portion of the root most affected initially, with the middle root portion subsequently showing resorption. He did not report on the apical area. All teeth which had been moved for longer than 20 days showed gingival marginal root resorption which

extended into the dentine in teeth which had been moved for longer than 25 days. The excavations were most extensive when they were located near hyalinized zones.

Kvam (1973b) further commented that in sites where active resorption had occurred, the resorption surface consisted of latticed fibres. He suggested that this feature indicated that the inorganic minerals were removed before the collagen component of dentine and cementum.

Boyde and Lester (1967) reported on scanning and transmission electron microscopic investigations of resorbing surfaces of dental hard tissues. Their findings also indicated that the inorganic minerals were removed before the collagen component during resorption. They investigated the surfaces of enamel and dentine in exfoliated human deciduous molars selected for obvious naked eye resorption of the cervical region. Cementum resorption was studied in the roots of extracted human deciduous molars in areas of obvious resorption bays. Boyde and Lester also studied bone resorption in a piece of inter-radicular bone attached to an exfoliated human deciduous molar. They found that on resorbing cementum and dentine surfaces, viewed indirectly by a single stage carbon replica technique for the transmission electron microscope, the typical crossbanding of collagen was obvious. They suggested that this finding indicated that demineralization was the first step in resorption, a finding which is in agreement with that of Kvam (1972b).

Boyde and Lester (1967) in their scanning electron microscope study found that the highly mineralized peritubular dentine remained above the resorbing surface and suggested that the mineral component of this dentine may have been selectively protected. Peritubular dentine has been shown to be more highly mineralized than intertubular dentine (Miller, 1954; Boyde, Switsur and Fearnhead, 1961).

MATERIALS AND METHODS

Clinical methods

The material consisted of 40 human premolar teeth. Eleven subjects aged between 11 and 18 years were selected from orthodontic patients who had been examined at the Dental Department, Royal Adelaide Hospital. Diagnosis and treatment planning confirmed that extractions were a necessary prerequisite to their orthodontic treatment. Long-cone periapical radiographs were taken of all the premolar teeth, both before bonding and immediately before extraction. The first permanent molars and central incisors were all banded and the paired experimental and control first premolars to be extracted were either both banded with a preformed band onto which a ribbon arch bracket had been prewelded, or both had a ribbon arch bracket directly bonded to the buccal enamel surface (Figs. 1, 2, 3).

Banding and bonding techniques were employed since these are routine methods for placing attachments on teeth. Banding was performed on the paired experimental and control premolars of three subjects. Direct bonding of attachments to enamel was used on the paired premolars of the remaining subjects to avoid the necessity for separation, and the possible effects the forces of separation may have on the root surface.

Ribbon arch brackets were selected because they are essential components in the Begg appliance which allows effective intrusion of teeth. The control tooth in each dental arch was the contralateral first premolar. The purpose of attaching a bracket to this tooth was to imitate all conditions existing in the experimental tooth, with the exception of the intrusive force which was applied by the archwire only to the experimental premolar.

A light round archwire was inserted in each arch and engaged in the central incisor brackets and ligated to the experimental premolar in each arch. The archwires were bent so as to deliver an estimated light, medium or heavy force (Table 1). Where necessary, especially if a heavy force was to be applied, offsets were bent in the wire to place the buccal span of wire more gingival opposite the first premolars (Figs. 2, 3). These offsets enabled a greater force to be delivered to the premolar because greater deflection of the archwire was necessary to approximate it to the brackets. A slight bend in the middle of each offset enabled more positive location of the ligature (Figs. 2, 3).

The force delivered by the archwire was measured with a Correx gauge (Haag-Streit, Bern, Switzerland).

Figs. 1, 2, 3. Frontal, right and left intra-oral views of archwires inserted to apply intrusive force on the lower right and upper left first premolars. Note gingival offset in wires to enable greater intrusive force to be applied to the experimental teeth.

Magnitude and duration of forces.

The experiment was designed to test variables of both magnitude and duration of force acting on the premolar tooth. The following combinations of force magnitude and duration times gave nine experimental combinations:-

TABLE 1

	3 variables		
Magnitude of force	Light 40-60g	Medium 90-110g	Heavy 180-220g
Duration	Short 2 weeks	Medium 5 weeks	Long 10 weeks

Combinations

Force	Duration	No. of experimental teeth	Control teeth
Heavy	Long	2	2
Heavy	Medium	2	2
Heavy	Short	2	2
Medium	Long	2	2
Medium	Medium	2	2
Medium	Short	2	2
Light	Long	2	2
Light	Medium	2	2
Light	Short	2	2
		18	18

A total of 36 teeth was obtained from 10 patients, eight of whom had extractions from both arches, and two of whom had extractions from one arch only. It proved impossible to deliver a constant, accurate force to any of the experimental premolar teeth, despite claims by a previous investigator (Kvam, 1972b). For the force to be constant, both the magnitude and direction of the force must be controllable. The magnitude of the force was impossible to keep constant, since the anchor teeth moved under the influence of the archwire, with the result that the intrusive force on the premolar decayed. The archwire was also subject to masticatory distortion.

With respect to the direction of the force, the attachment of the archwire to a bracket on the buccal surface of the crown of the premolar simulated routine orthodontic appliance therapy. The position of this attachment meant that there was a buccal component of the force acting on the test premolar tending to tip this tooth in a buccal direction, as well as intruding it.

The initial force was set at 10-15 per cent higher than the force desired to allow for stress relaxation in the appliance (Twelftree, 1974). It was found that, even following this precaution, the force had decayed to less than 50 per cent of the intended value seven days after insertion of archwires in most individuals. This force reduction necessitated the use of .018" and even .020" archwire in the cases where heavy forces were required such as 200 grams of intrusion. Stainless steel ligature wires of .010" diameter were used to ligate the bracket of the experimental tooth to the archwire. Thinner ligatures were subjected to stretching and consequent loss of intrusive force. The ligatures were shaped into elongated form before being adjusted to final tension.

Another problem encountered in the experiment concerned the design of the appliance. The long span of unsupported archwire on the control side resulted in breakages of upper and lower initial archwires after four weeks in the patient who had been scheduled for 10 weeks of intrusion. This problem also occurred later in another of the patients and was solved by protecting high-stress bends within stainless steel tubing.

All patients were carefully counselled on diet and care of the appliance, teeth and supporting tissues. In spite of this, breakages did occur in the two patients mentioned. It was difficult to determine whether the cause of the breakages in the long-term subject was patient neglect, resulting in breakages to both archwires and one loose band, or the design of the appliance as described above. The patient concerned was without an effective upper archwire for 20 days because the upper archwire fracture occurred while he was on vacation approximately 1,200km from Adelaide. A "reserve" patient was banded and the same experimental conditions were applied as had existed in the patient with the broken archwires.

The teeth were extracted under local anaesthesia by conventional forceps method. The distobuccal apex of one upper premolar was fractured at the time of extraction and discarded by the surgeon. All other extracted teeth were immediately placed in

10 per cent buffered neutral formosaline for fixation period of at least 48 hours. The first premolars of two patients aged 11 and 12 years, who had previously undergone three weeks' rapid palatal expansion followed by three months' retention were also included in the investigation. Rapid expansion premolars enabled a comparison to be made of the effects of different directions of tooth movement and magnitudes of force on the root surface topography.

The long cone periapical radiographs taken before tooth intrusion and immediately before extraction were masked and examined with a 10x magnifying glass on a tracing table with diffuse variable lighting.

Sectioning methods

The teeth were sectioned through the crown near the cemento-enamel junction (see Appendix 6.1). At the time of sectioning a groove 1mm. deep was made in the enamel adjacent to the mesial root to enable identification in the microscope chamber. All sectioning was done under water coolant, with a thin diamond wheel mounted on a hard tissue section cutting machine, running at 6,000 rpm, (W.E. Niclas, New York). The crowns of all sectioned teeth were retained and filed as a safeguard to enable confirmation of specimen identity. After sectioning, the specimens were thoroughly rinsed in distilled water and then taken to absolute alcohol and air dried for approximately six hours at room temperature.

After drying each specimen was mounted with Fast Set Araldite (Ciba-Geigy Ltd., Basle) onto an aluminium holder, and left for 30 minutes. The specimens were then placed in the vacuum chamber of the coating unit (Denton Vacuum DV502), Dental Vacuum Inc., Cherry Hill, New Jersey) and held under vacuum for 12 hours prior to coating to ensure complete moisture removal. The specimens were coated with a thin layer of carbon, followed by gold, evaporated during continuous tilting and rotation of the coating stage for one minute (Fig. 4).

Fig. 4. Coating Unit. Denton Vacuum DV502.

The specimens were examined in the scanning electron microscope (Siemens Autoscan, manufactured by ETEC Corporation, Hayward, California) operated at 5KV, 10KV and 20KV (Fig. 5).

Fig. 5. Siemens Autoscan scanning electron microscope. Specimen chamber is on a separate unit to the right of the main operating and viewing console.

It was intended to examine all four surfaces of each root (mesial, distal, buccal and lingual). This necessitated the machining of a special specimen holder to enable specimens to be rotated about the long axis of the root (Fig. 6).

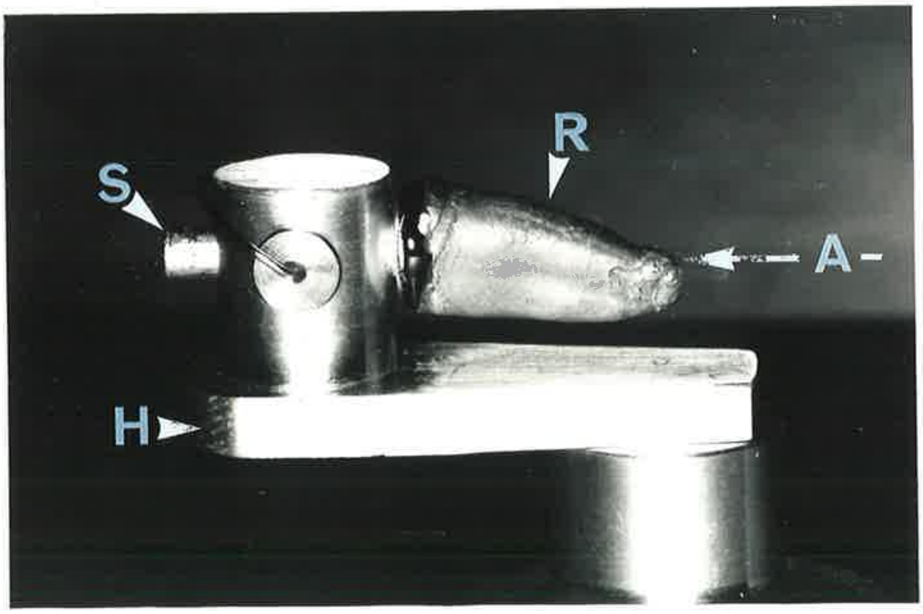


Fig. 6. Specimen holder, Note holder (H) has been machined to accept specimen stubs (S) at right angles to the plane normally used in the specimen chamber. This enables rotation of the tooth root (R) about the long axis (A).

The buccal, lingual, mesial and distal surfaces of the roots were examined in detail. Representative areas were photographed with a Singer Graflex camera attached to a separate photographic screen on the Autoscan. Films used were Kodak Verichrome Pan and Ilford FP4 in the 120 size and Polaroid type 105. The Kodak films were developed in D76 developer and the Ilford films in ID11. The Polaroid films yielded a print which required coating and a negative which required final treatment in sodium metabisulphate. Where possible, the working distance was kept short (11.0mm) to improve image detail. This was not always possible because the large size of the specimen required maximum working distance to include as much of the root surface as possible to enable comparisons between root surfaces. The maximum working distance also enabled greater depth of focus, an important factor in viewing a curved surface.

At the low magnification used when viewing large areas of the roots the S.E.M. presented a problem with respect to consistency of magnification. The machine indicated a magnification of ten times for all magnifications between six and 14 times. Several of the photographs were therefore taken at magnifications slightly over or under ten times, although the machine indicated a nominal ten times.

After being viewed in the organic state, all specimens were rendered anorganic, either by distillation with hot 1, 2 diaminoethane in a Soxhlet condenser for 48 hours (Appendix 6.5) after the method suggested by Boyde and Lester (1967) or by immersion in a cold 5 per cent solution of sodium hypochlorite for 24 hours. Both methods produced some separation of the cementum from the dentine. The specimens were rinsed in distilled water, taken to absolute alcohol, air dried, and remounted on the specimen stubs with "fast-set" Araldite. They were then recoated with carbon, and gold, and re-examined in the SEM as described above.

Specimens rendered anorganic

The specimens that had been rendered anorganic and recoated with carbon and gold initially showed severe charging. This problem was traced to insufficient time for equilibration in the solvents, and inadequate drying time. Vacuum drying was routinely used after the first two specimens were processed. A further problem occurred during the coating of the specimens. The length of the specimens and curvature of the roots caused some areas of the surface to be shielded from the coating source, and hence the charging tendency was accentuated in the uncoated regions.

The moisture problem was solved by air drying all the specimens for three days after immersion in alcohol. Mounted specimens were then held under vacuum in the coating unit for 16 hours to remove any remaining alcohol or moisture from the deeper dentine before coating with carbon and gold. To enable full coverage with the carbon and gold coating, no more than eight specimens were coated at a time, despite the capacity of the coater to handle twelve stubs simultaneously.

The scope of the investigation, in particular, the time available for the project, did not permit a detailed evaluation of all surfaces. All four surfaces of each root were examined on selected test teeth but no resorption was noted on the mesial or distal surfaces of the roots, except where these surfaces merged with buccal and lingual surfaces. Such resorptions were clearly visible from the buccal or lingual surface and separate examinations of the mesial and distal surfaces were therefore discontinued.

An estimation was made of the depth and area of the root resorptions (Table 2, Appendix 6.6). The depth was estimated by adjusting the scanning electron microscope to give a shallow depth of field and focusing on the floor of the resorption area. The vernier reading on the stage lowering micrometer was recorded, and the stage lowered until the edge of the resorption was in focus. The vernier reading was again noted, and the difference in the two readings gave an estimation of the depth of the resorption defect.

The area of the resorption was estimated by cutting the root outline from the Polaroid print of the buccal and lingual surfaces of one tooth in each force/duration combination. The polaroid prints were of a sufficiently large format to include the whole of the root length, whereas the 120 size film used for the majority of the project only enabled two-thirds of the root length to be included in one photograph. Each root outline paper was weighed, and the resorption areas then cut out of each outline. The resorption area pieces were then weighed and this weight expressed as a percentage of the root outline weight.

All units used in this report conformed to the International system of units (SI) (Standards Association of Australia, 1974).

FINDINGS

Radiographic findings

There was no detectable shortening of the tooth length in any of the intruded teeth. No evidence of resorption could be detected on the mesial or distal surfaces. Radiolucent areas that could be identified with the scanning electron microscope or macroscopically as resorptions on the buccal or lingual surfaces could not be detected on the x-rays.

Clinical findings

There was some extrusion of incisors, especially the lower central incisors, due to a reciprocal force to the intrusive force on the premolars. The extrusive force was minimised by increasing the anchorage bends mesial to the molar tubes. There was clinically detectable intrusion of premolars only in cases where force had been applied for at least five weeks.

Scanning electron microscopic findings

These findings confirm the value of the preparation methods suggested by Jones and Boyde (1972) and Kvam (1971). The carbon coating prior to the gold coating reduced the tendency of specimen charging. Charging is a phenomenon whereby peaks on the specimen surface become charged and appear bright, with a dark surrounding surface on the viewing screen and in photographs (Fig. 7).

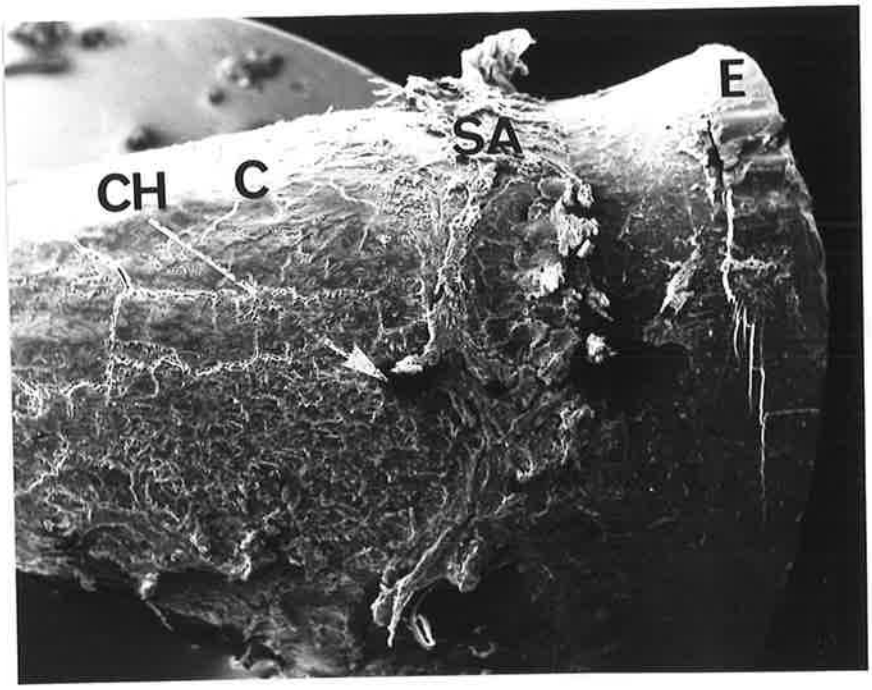


Fig. 7. Charging (CH) occurring at sharp peaks on the root surface; abundant organic tissue covers the root particularly in supra-alveolar area. Mandibular premolar, coronal half of the buccal root surface. E: enamel, C: cementum, SA: supra-alveolar tissue. Carbon and gold coating.
X10, enlarged 50%.

Normal surface topography:

Viewed without removal of organic components

The root surfaces of the extracted teeth were covered by organic tissue which was particularly abundant in the supra-alveolar region (Fig. 7). Fibre bundles, which were widest adjacent to the root surface, were also observed. These bundles approximated 50 micrometres in width and tapered towards the alveolar side (Fig. 8). At higher magnification, entangled tissue elements such as collagen fibres, erythrocytes, blood vessels and nerves were identified (Figs. 9, 10, 11, 12 and 13). The erythrocytes were generally not distorted but were reduced in size to approximately 5 micrometres in diameter compared to a normal size of 7 micrometres. Only occasionally were crenated erythrocytes observed (Fig. 9). Some bone was also observed (Fig. 14), which was presumably alveolar bone detached at the time of extraction of the tooth. The collagen fibre bundles were made up of smaller fibres with a diameter of 4-5 micrometres. These smaller collagen bundles exhibited a fibrillar appearance (Fig. 9).

In no case was it possible to detect periodic cross-striation, even in the thinnest fibrils. However, magnifications above 8000 times were not used because of loss of definition due to charging. Usually a pattern of collagen fibre bundles was not evident, but in one specimen (Fig. 10) a definite pattern of the collagen bundles of the periodontal ligament could be discerned. Principal fibre bundles running approximately parallel to each other were seen together with smaller fibrils which appeared to cross-link the principal fibre bundles.

What was thought to be fibrin was seen overlying the erythrocytes and was partly associated with aggregations of thrombocytes. The reasons for assuming these structures to be fibrin were firstly, it was overlying erythrocytes, secondly, it was composed of long straight strands and, thirdly, that it differed markedly in appearance to the background structures (Fig. 11). This "fibrin" appeared as long strands with few branches superficially located on various organic structures, including collagen bundles (Fig. 11).

Vessels of varying size were regularly observed. These vessels were longer than the collagen fibre bundles, had a larger, uniform diameter, and occasionally branched at narrow angles (Fig. 12). The vessels were often twisted and invariably collapsed which prevented exploration of their inner surface at the ends. Large nerve fibres were occasionally observed. These structures were of a uniform width and longer than connective tissue fibres. They ranged in diameter from 2 micrometres to 16 micrometres. At high magnification the surface of the nerves exhibited a pattern resembling fish scales (Fig. 13).

Viewed after specimens rendered anorganic.

Initially, the specimens treated in 1, 2 diaminoethane showed cracking and flaking of the cementum (Fig. 15).

The position of the Sharpey's fibres in the specimens was obvious, and they generally presented in one of two ways. They either showed as projections above the plane of the mineralized front (Fig. 16), or as depressions in this front (Fig. 17).

In high magnification, images of the mineral skeleton of Sharpey's fibres exhibited a granular appearance which was thought to represent the mineralization of the individual collagen fibres (Fig. 18). Components the same size as the individual fibrils could be distinguished but could not be traced very far.

In the coronal two thirds of the root surface, the Sharpey fibre insertions showed as mounds or projections above the surrounding acellular cementum surface (Fig. 16). The apical portion of the root surface was covered in cellular cementum which showed the appearance of depressions in the plane of the mineralized front (Fig. 17).

The cross-sectional shape of the Sharpey's fibre projections could be described as a three-dimensional arrangement based on hexagonal packing (Figs. 16 & 18).

Where the fibres were closely packed together, each fibre appeared as a low mound in profile when the specimen was tilted through 45 degrees. If the fibres were less densely packed, the middle of the mound often had a lesser elevation than its periphery, leading to a concave surface (Fig. 17). The depths of the depressions in the mineralized remnants of the fibre insertions was approximately 1-5 micrometres.

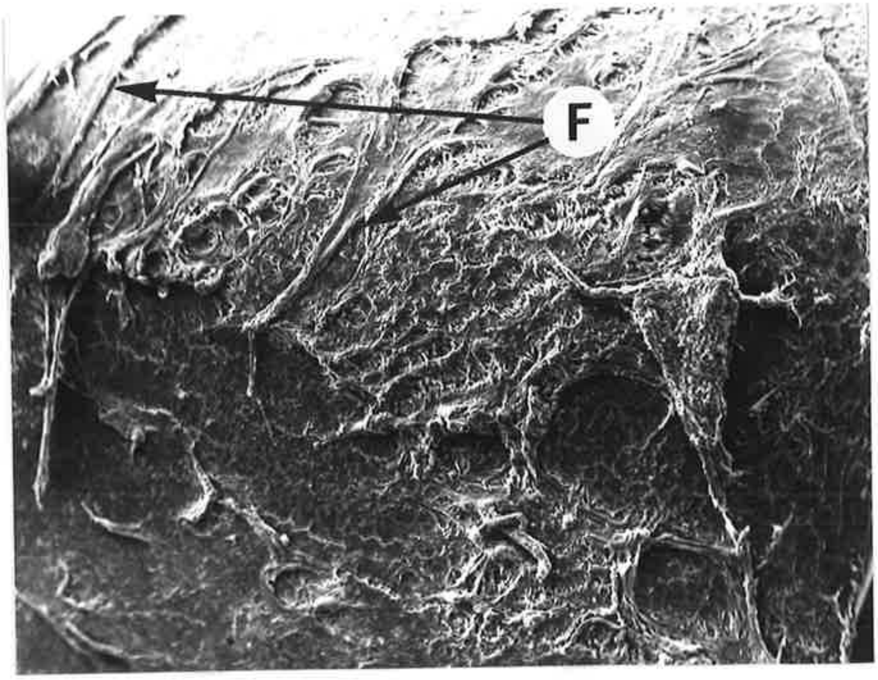


Fig. 8. Mesial root surface of maxillary premolar, showing the tapered fibres (F) of the periodontal ligament widest near the root surface and thinner on the alveolar side.
X120, enlarged 50%.

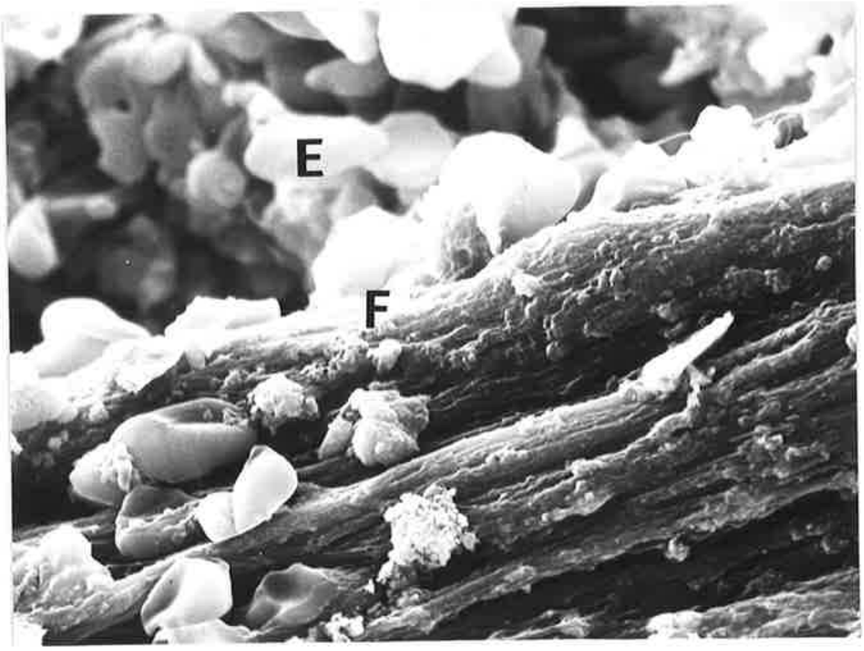


Fig. 9. A collagen fibre (F) of the periodontal ligament and erythrocytes (E) some of which are distorted in shape. Buccal surface of the buccal root of a maxillary premolar.
X1500, enlarged 50%.

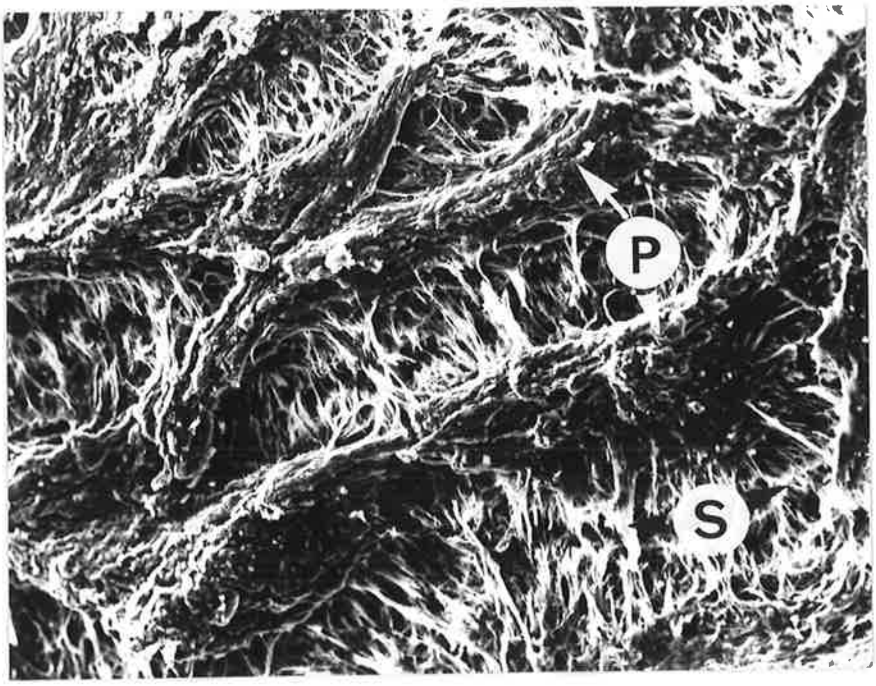


Fig. 10. Periodontal ligament on the mesial root of a mandibular first premolar. The principal fibres (P) appear to be cross-linked by smaller fibrils (S) running at approximately right angles to the principal fibres. Carbon and gold coating.
X150, enlarged 50%.

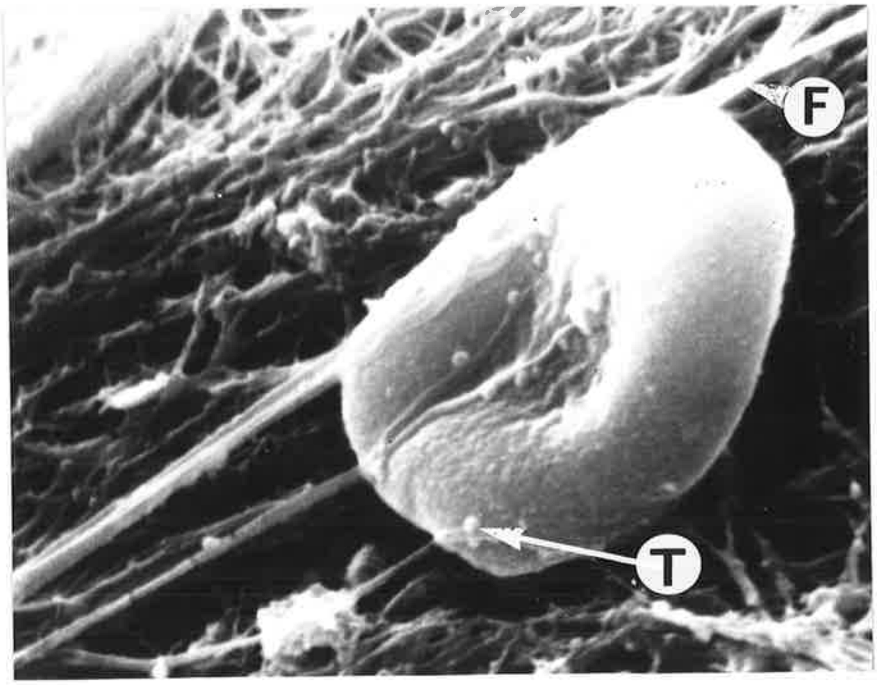


Fig. 11. Tissues covering the buccal surface of the buccal root of a human maxillary premolar. Fibrin (F) overlies the erythrocyte and is closely associated with thrombocytes (T).
X8000, enlarged 50%.

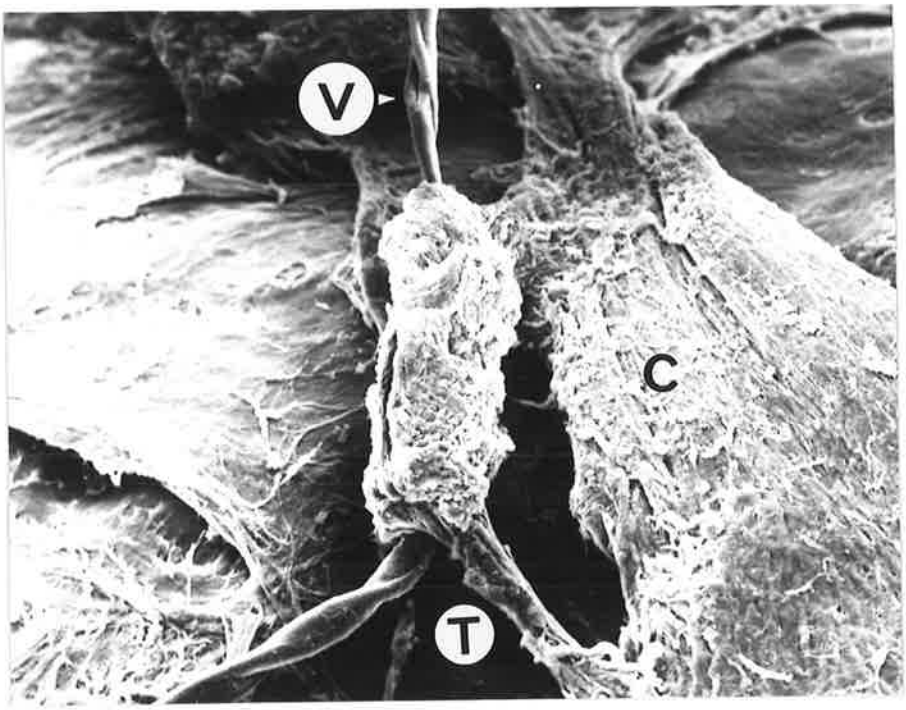


Fig. 12. A collapsed, twisted blood vessel (V), passing through a tunnel (T) formed by part of a collagen bundle (C). Lower premolar, mesial aspect of apical portion of root.
X150, enlarged 30%.

Fig. 13. Tissue attached to the lingual surface of the root apex of a mandibular premolar showing a large nerve (N), approximately 16 micrometres in diameter, curved back on itself.
X400, enlarged 50%.

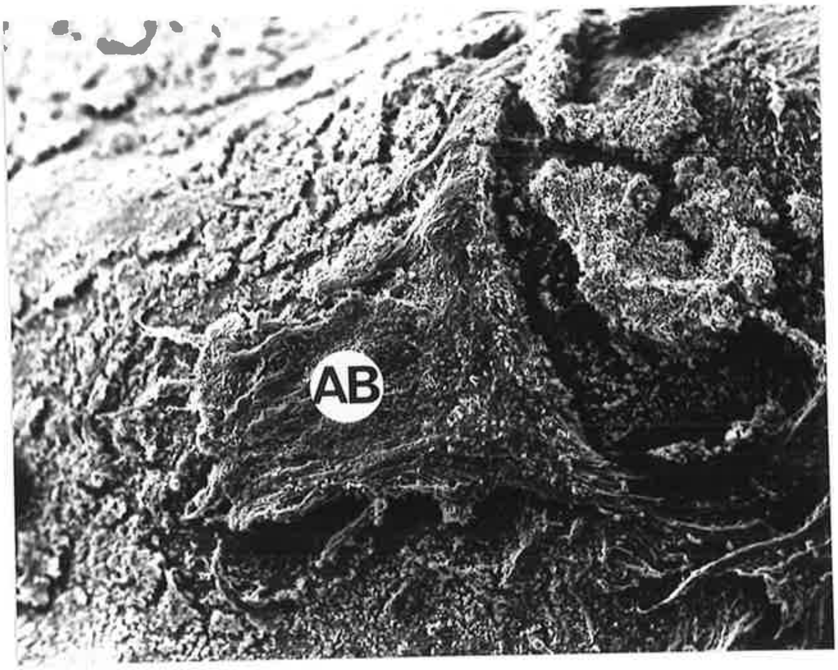


Fig. 14. Fragment of alveolar bone (AB) detached during extraction of a maxillary premolar. Buccal surface of the buccal root. X40, enlarged 50%.

Fig. 15. Human mandibular premolar. Buccal surface showing cracked, flaking cementum resulting from processing with 1, 2 diaminoethane. X40, enlarged 50%.

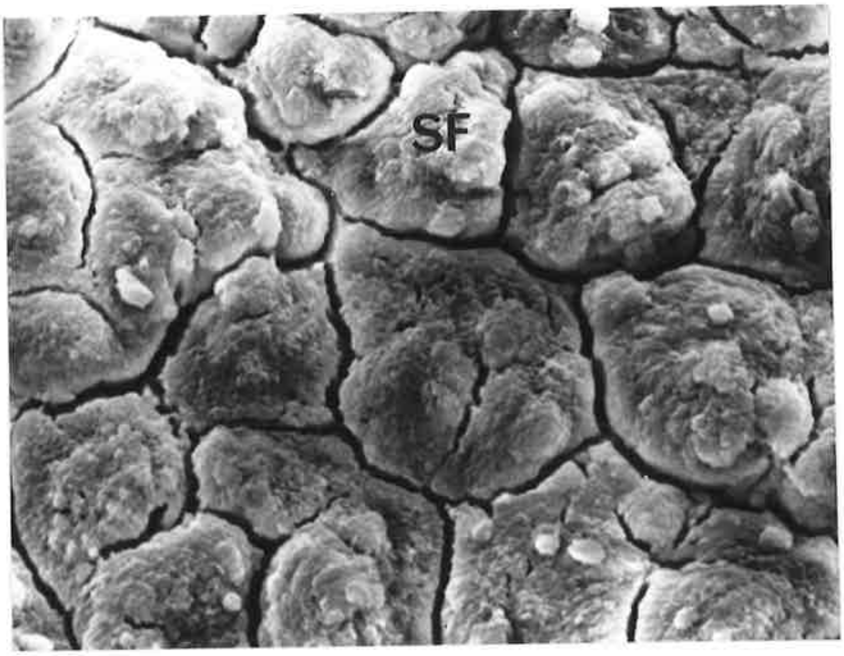


Fig. 16. Sharpey's fibre insertions (SF) presenting as projections in the plane of mineralization. Buccal surface, coronal two thirds of maxillary premolar root. Prepared by distillation in hot 1, 2 diaminoethane for 48 hours. X1900, enlarged 50%.

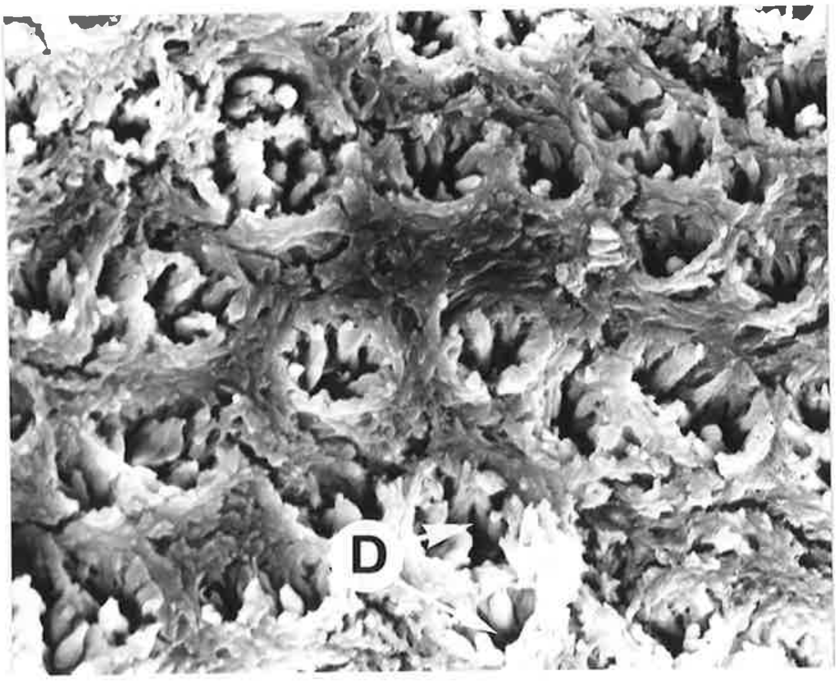


Fig. 17. Cellular cementum on the apical one third of the buccal surface showing insertion sites of the Sharpey's fibres as depressions (D) in the plane of mineralized front. Mandibular premolar, Prepared for 24 hours in cold sodium hypochlorite to render surface anorganic. X1200, enlarged 50%.

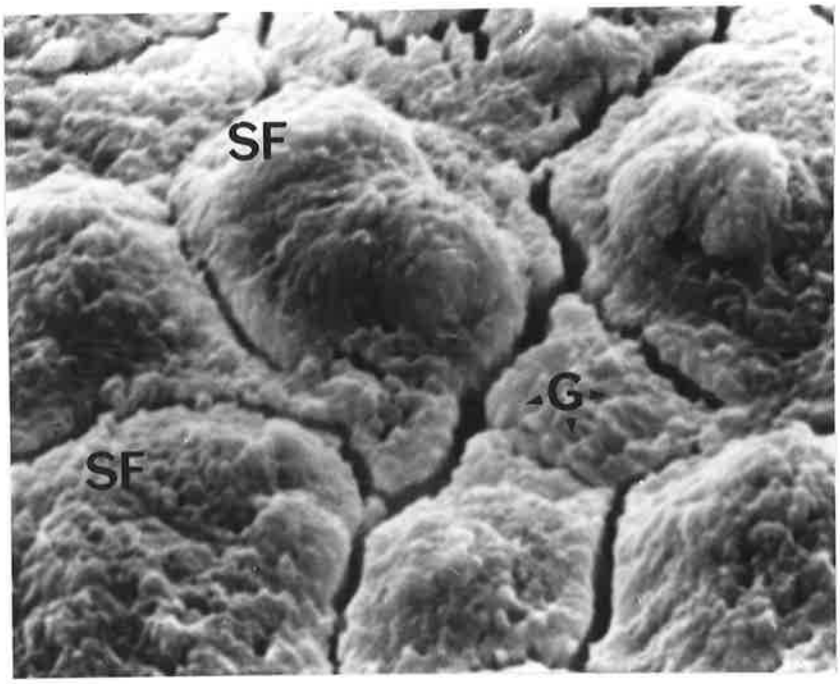


Fig. 18. Hexagonal packing of Sharpey's fibres (SF) and granular pattern (G) which may represent the appearance of the mineralizing front. Mandibular premolar. Buccal surface of coronal one third of root. Anorganic preparation.
X4000, enlarged 50%.

Effect of intrusive force on root surface topography

Viewed without removal of organic components

The periodontal ligament obscured the cementum surface and made assessment of changes in the surface topography difficult (Fig. 19). Most photomicrographs describing the root resorption were therefore presented in the anorganic state (Fig. 20).

Viewed in the anorganic state

Effect of light forces (50 grams)

These produced minimal resorption areas when applied for durations of 14 days (Fig. 21). However, when these light forces were applied for long durations of 35 and 70 days, many deep resorption areas were produced (Figs. 23 & 25). Insignificant resorption was observed in the control teeth (Figs. 24 & 26). A characteristic feature of resorption areas was the sharp edges. These areas will be described in detail on p.3.27 in the section reporting observations with high power photomicrographs.

Effect of medium forces (100 grams)

These produced numerous shallow resorption lacunae after 14 days (Fig. 27). The teeth that were intruded for longer durations (70 days) showed deeper, more severe resorptions (Figs. 29, 31 & 33).

Effect of heavy forces (200 grams)

After 14 days, minimal resorption had been produced (Fig. 35). However, after durations of 70 and 35 days, more severe resorption was produced (Figs. 37 & 40). The resorption was more extensive on roots that had been intruded for 70 days (Fig. 39) than on roots that had been intruded for 35 days (Fig. 40).

These results are summarized in Table 2 (Appendix 6.6). There was no difference noted in the amount of resorption on the surfaces of control teeth which had been banded and those to which had been bonded a bracket.

Fig. 19. Resorption area (R) on the buccal surface of the mid-root area of a lower first premolar tooth intruded for 70 days by a force of 200 g. Organic preparation.
X40, enlarged 30%.

Fig. 20. Same area as Fig. 1 - anorganic preparation showing increased detail and revealing base of resorption area (R).
X40, enlarged 30%.

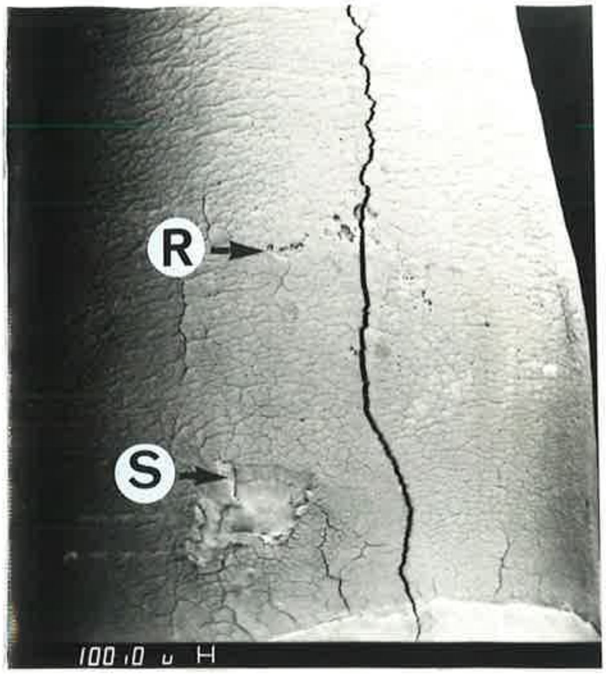


Fig. 21. Early minimal resorption (R) caused by 14 days intrusion by a force of 50g. Forceps scrape (S) is distinguishable from resorption area by one straight edge and torn edges. Coronal third of buccal root surface of upper right premolar. Anorganic preparation. X40, enlarged 30%.

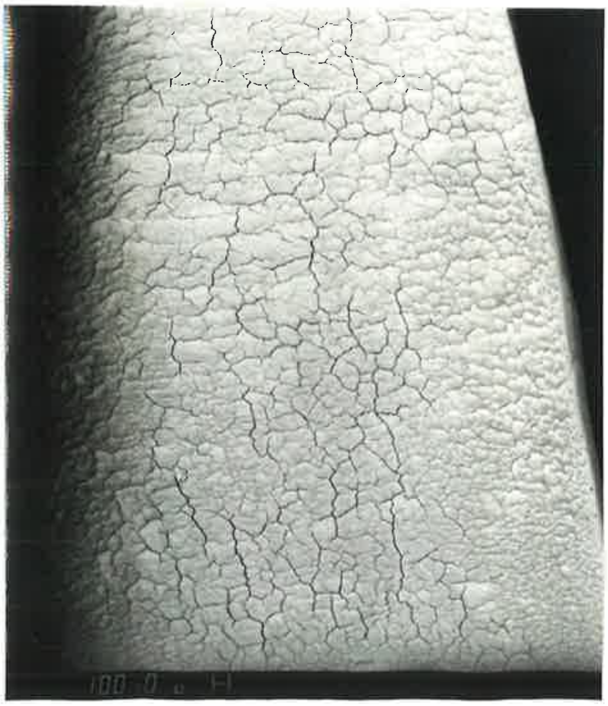


Fig. 22. Lack of resorption on buccal surface of upper left control premolar. Anorganic preparation. X10, enlarged 30%.

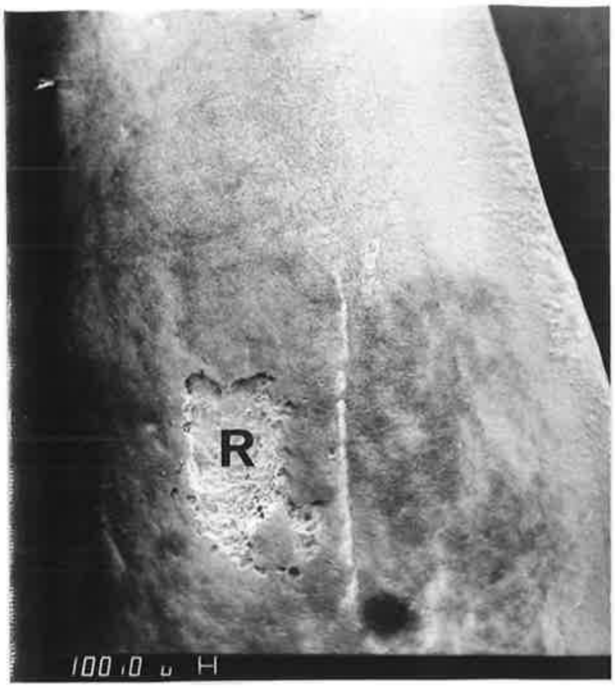


Fig. 23. Resorption area (R) after 35 days intrusion by force of 50g. Buccal surface of middle third of root of upper left premolar. Anorganic preparation. X10, enlarged 30%.

Fig. 24. No evidence of root resorption in control upper right premolar. Cracking of cementum surface has occurred. Middle third of buccal root surface. X10, enlarged 30%.

Fig. 25. Deep resorption (R) caused by 70 days intrusion by a force of 50g. Anorganic preparation. X10, enlarged 30%.

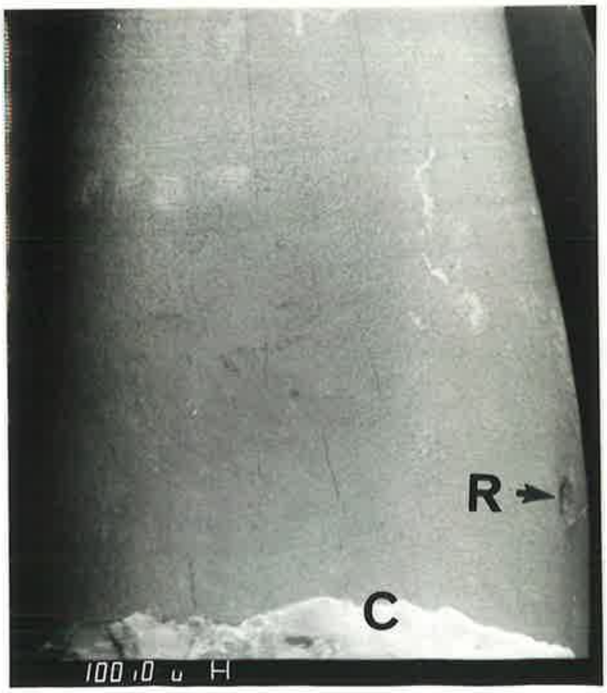


Fig. 26. Absence of resorption apart from one small resorption area (R) on distobuccal aspect of cemento-enamel junction (C). Upper left control premolar to Fig. [illegible]. Anorganic preparation. X10, enlarged 30%.

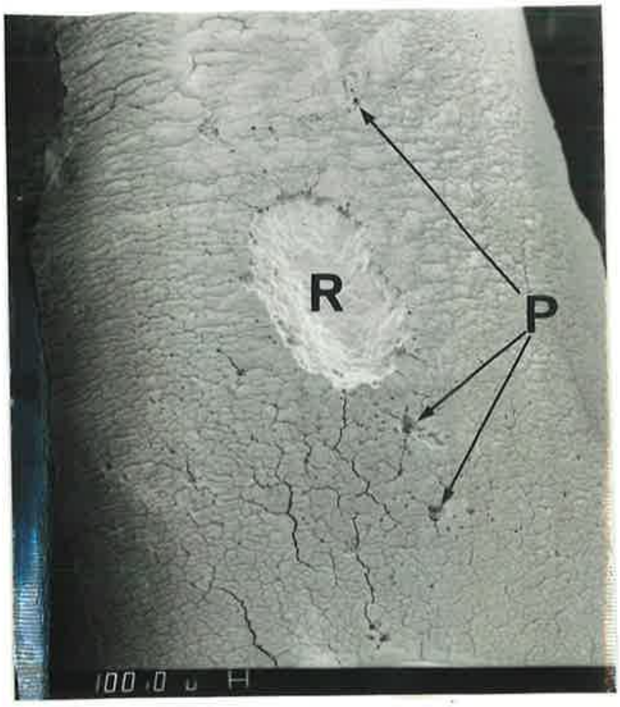


Fig. 27. Shallow resorption area (R) and many pits (P) on buccal root surface after 14 days application of medium intrusive force of 100g. Lower right premolar. Coronal third of buccal root surface. Anorganic preparation.
X10, enlarged 30%.

Fig. 28. Lower left premolar. Control tooth to Fig. 27. Coronal third of buccal root surface showing no resorption. Anorganic preparation.
X10, enlarged 30%.

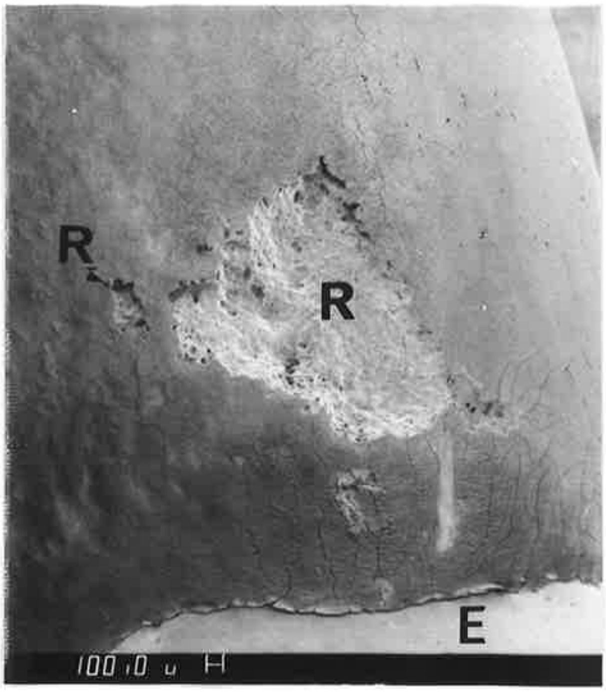


Fig. 29. Extensive sharp-edged resorption areas (R) after 35 days intrusion by medium force of 100g. Coronal third of buccal surface of lower right premolar. Enamel (E). Anorganic preparation.
X10, enlarged 30%.

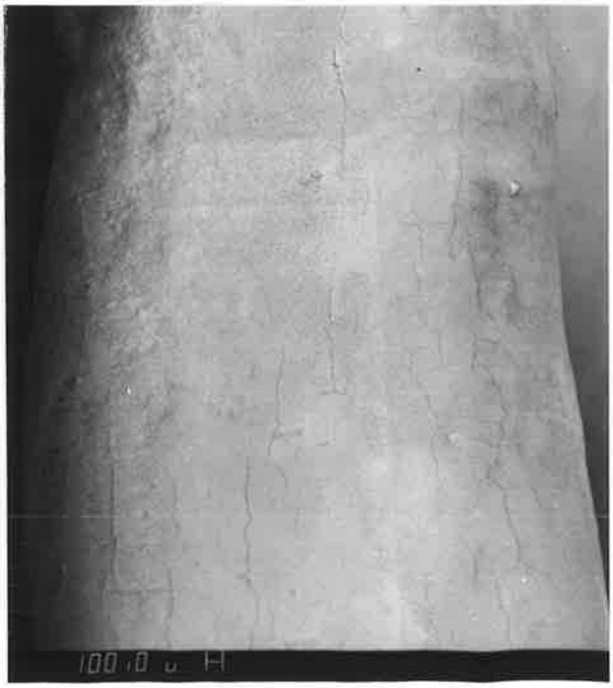


Fig. 30. No resorption is evident in the control premolar. Coronal third of buccal surface. Anorganic preparation.
X10, enlarged 30%.

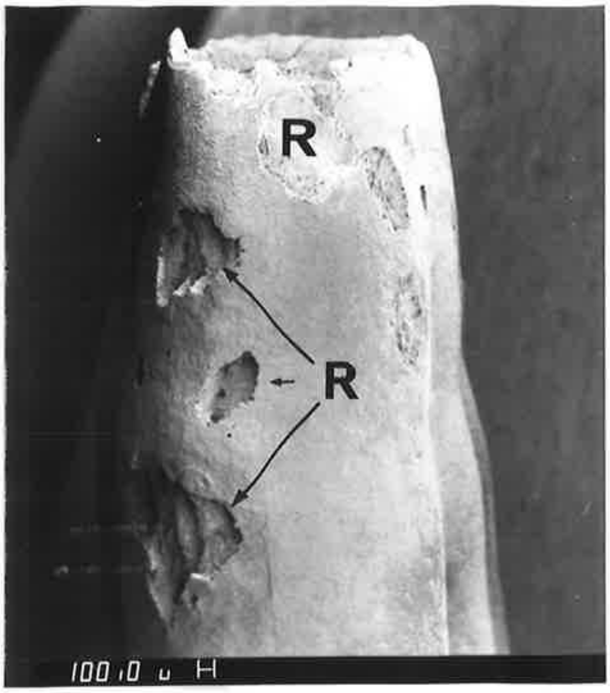


Fig. 31. Many severe resorption areas (R) after 70 days intrusion by medium force of 100g. Narrow apical portion of lingual root surface. Developing apex is to top of picture. Lower left premolar. Anorganic preparation. X10, enlarged 30%.

Fig. 32. Developing apex (A) of lower right control premolar from same patient as Fig. 31. Apical area of lingual surface showing no resorption. Anorganic preparation.
X10, enlarged 30%.

Fig. 33. Severe resorption (R) present after 70 days intrusion by a force of 100g. Developing apex (A). Accessory canal (C). Apical third of mesiolingual surface of lower right premolar. Anorganic preparation.
X10, enlarged 30%.

Fig. 34. Lower left control premolar. Apical third of mesiolingual surface of root showing no resorption. Anorganic preparation.
X10, enlarged 30%.

Fig. 35. Minimal resorption (R) caused by 14 days intrusion by force of 200g. Coronal third of buccal root surface of upper right premolar. Anorganic preparation.
X10, enlarged 30%.

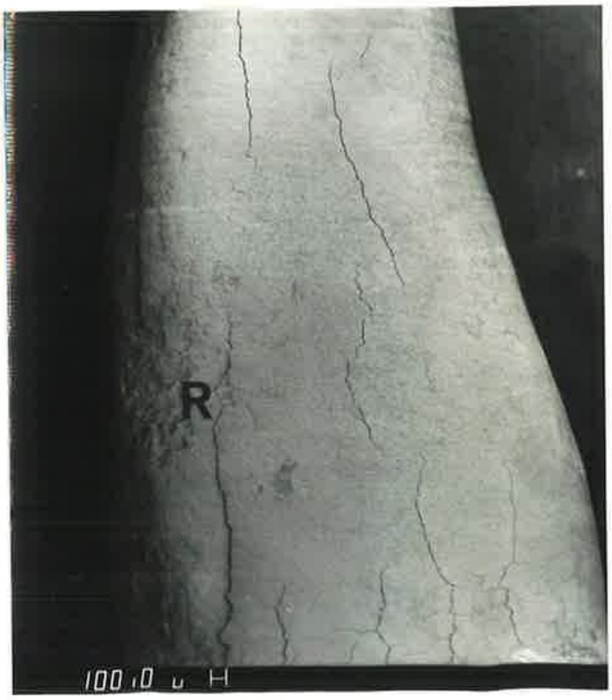


Fig. 36. Early root resorption (R) on control premolar. Anorganic preparation.
X10, enlarged 30%.

Fig. 37. Many extensive severe resorption areas (R) after 70 days intrusion by force of 200g. Accessory canal (C). Lower premolar. Coronal third of buccal surface. Anorganic preparation. X10, enlarged 30%.

Fig. 38. Early resorption area (R) on control tooth to Fig. 37. Coronal third of buccal root surface. Lower left premolar. Anorganic preparation. X10, enlarged 30%.

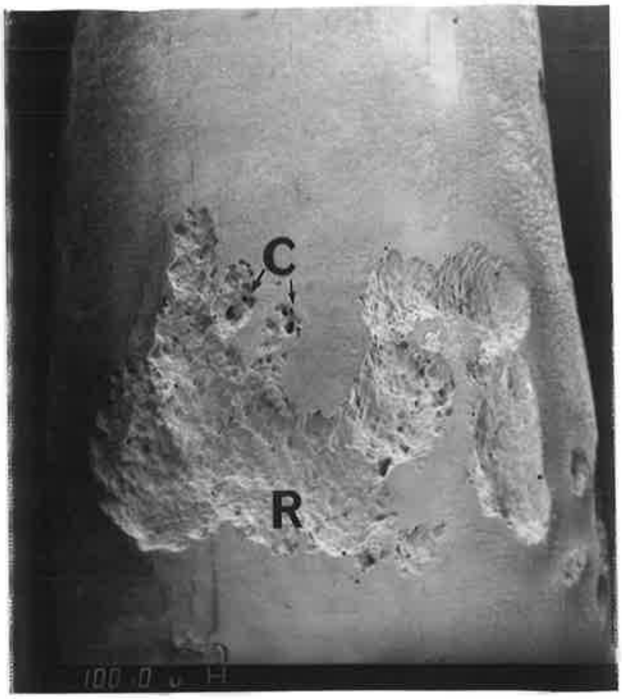


Fig. 39. Resorption (R) caused by 70 days intrusion by force of 200g. The resorption area (R) is closely related to accessory canals (C). Buccal root surface of lower right premolar. Anorganic preparation. X10, enlarged 30%.

Fig. 40. Resorption (R) caused by 35 days intrusion with force of 200g. Resorption is less extensive than Fig. 39. Buccal root surface of upper left premolar. Anorganic preparation. X10, enlarged 30%.

Effects of same force in different patients

When the same force (50 grams) was applied for the same period (70 days) to a similar tooth (upper first premolar) but in different patients, a similar amount of moderate root resorption was produced in each subject (Figs. 41 & 42).

The sample was small, and therefore the findings must be interpreted with caution. However, a comparison of the experimental and control teeth reveals resorption areas caused by the intrusive force.

Site of resorption areas

In most cases the resorption areas were on the coronal third of the buccal root surface and on the apical third of the lingual root surface (Figs. 29 & 31). In two cases the resorption area was on the mesiolingual aspect and the distobuccal (Fig. 33). In these cases the premolars were rotated distobuccally before intrusion and the resorption areas represented the same sites of resorption, namely the buccal, as in the non-rotated teeth. An interesting finding seen in many of the resorption areas was their close proximity to accessory canal openings (Figs. 33, 37 & 39).

Fig. 41. Resorption (R) caused by 70 days intrusion by force of 50g. Note cemento-enamel junction (C). Upper left premolar. Buccal root surface. Anorganic preparation.
X10, enlarged 30%.

Fig. 42. Similar amount of resorption (R) as in Fig. 41 caused by 70 days intrusion by force of 50g, in a different patient to Fig. 41. Buccal root surface of upper right premolar. Anorganic preparation.
X10, enlarged 30%.

Observations at high magnification of individual resorption areas.

organic preparation

Resorption areas were observed as crater-like defects on the root surfaces that had been subjected to pressure. The fibrous elements of the organic coating appeared to pass in parallel over a sharp underlying edge, and then merge into a hyalinized coating where the orientation of the fibres was lost (Fig. 43). The organic covering of the floor of the resorption lacunae exhibited an interlacing network (Fig. 44) of fibrous elements. In most cases, the pattern of the thicker, collagenous fibre bundles was lost, but the smaller, fibrous pattern was retained in the floor of resorption lacunae (Fig. 45).

anorganic preparation

Greater detail of the resorption areas was observed after removal of the organic covering (Fig. 46). The edges of the resorption lacunae were extremely sharp. Small lacunae were observed in the cementum adjacent to the main resorption areas. In some areas the edges were undermined, in others the sharp edge sloped towards the centre of the lacunae.

The edges of the lacunae were observed to pass through, rather than around Sharpey fibre bundles (Fig. 47). The floor of the resorption areas contained smaller lacunae, some with the openings of dentinal tubules in the depths of the lacunae. The edges of the dentinal tubules were raised above the floor of the lacunae (Fig. 48).

The lacunae floor of the teeth that had been attached to the broken archwire (p 2.6) exhibited a different surface. The resorption lacuna had occurred in, and was surrounded by, acellular cementum. However, the floor was composed of cellular cementum which appeared to be filling in the smaller lacunae (Fig. 49).

Fig. 43. The fibrous periodontal covering passes over a sharp edge (E) and some fibres can be traced to the edge of the resorption floor (R). Buccal root surface of lower right premolar after intrusion by a force of 100g for 14 days. Organic preparation. X300, enlarged 30%.

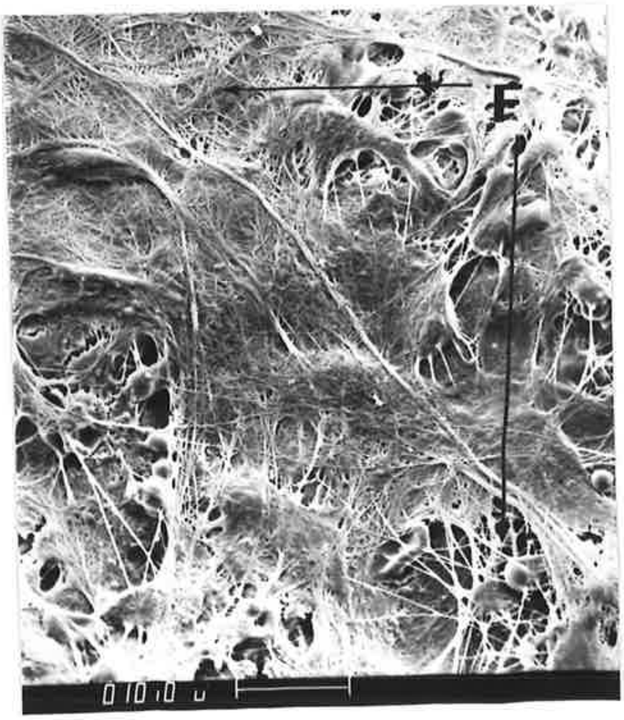


Fig. 44. Floor of resorption area showing fibrous structures covering floor of resorption area (F) as interlacing network. Buccal root surface of lower right premolar after intrusion by a force of 100g for 14 days. Organic preparation. X1000, enlarged 30%.

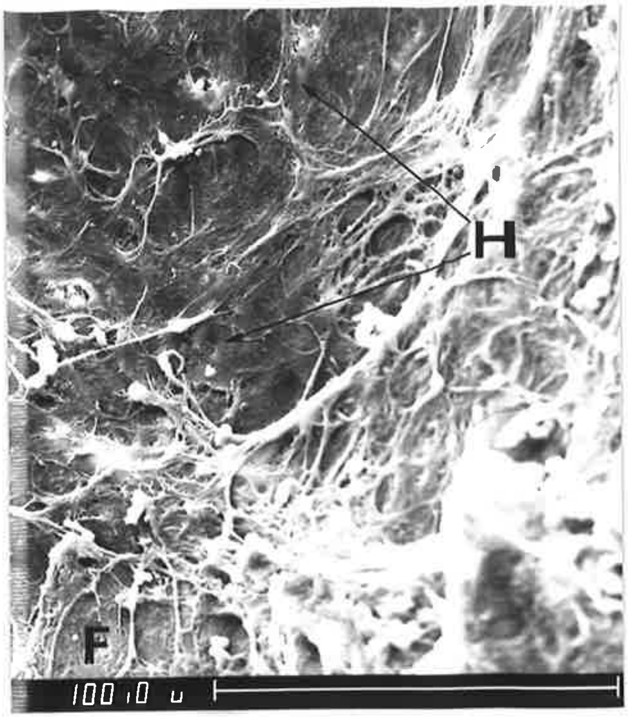


Fig. 45. Buccal root surface after 70 days intrusion by force of 200g. The floor (F) of resorption area in a compression region is shown with structureless regions (H) which may represent hyalinization as described in histological photomicrographs. Although the magnification is similar to Fig. 43, the fibres seem thicker than those in Fig. 43, possibly an illusion created by the perspective introduced by the shorter working distance of 11mm. Lower left premolar. Organic preparation. X360, enlarged 30%.

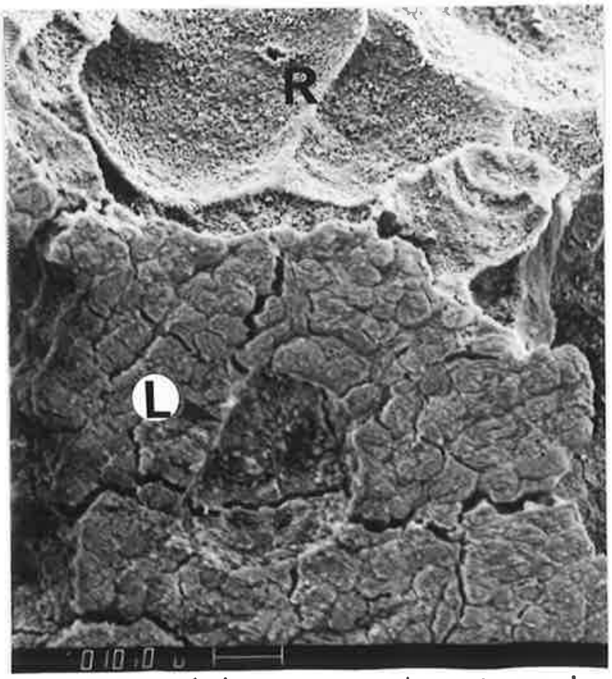


Fig. 46. Buccal surface of lower premolar shown in Figs. 19 & 20, showing edge of resorption (R). Greater detail is observed after removal of organic covering. Developing lacunae (L). Anorganic preparation. X600, enlarged 30%.

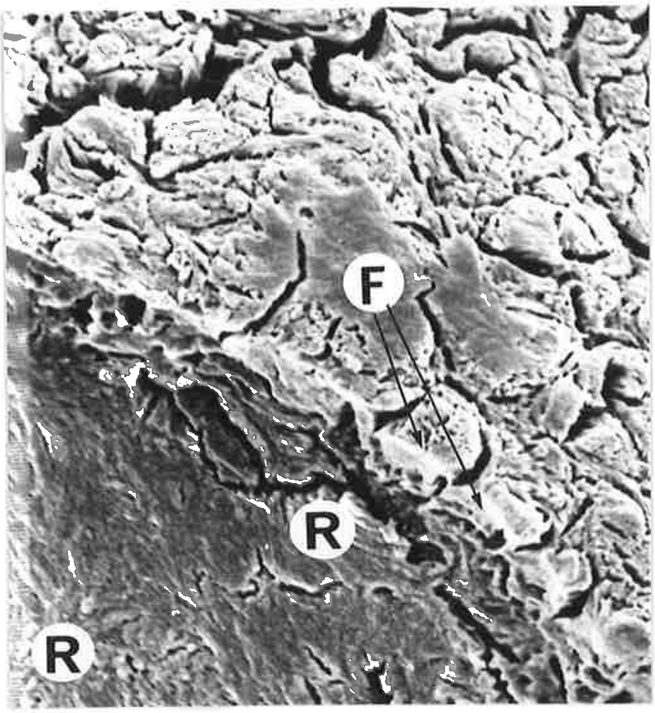


Fig. 47. Edge of resorption (R) passing through Sharpey fibres (F). Buccal surface of lower premolar in Figs. 19 & 20, intruded for 70 days by a force of 200g. Anorganic preparation.
X1300, enlarged 30%.

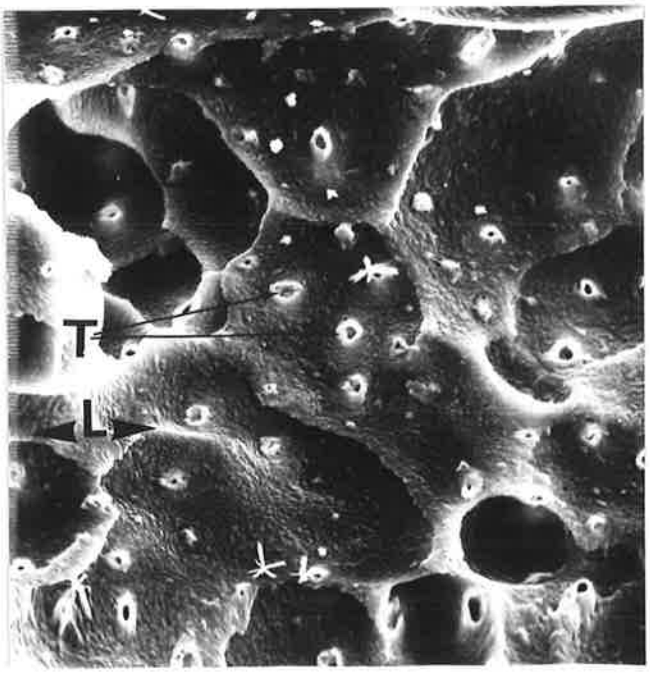


Fig. 48. Dentinal tubules (T) surrounded by peritubular dentine in the floor of resorption lacuna.
Some charging is evident as horizontal distortion lines (L). Buccal root surface of upper first premolar after 70 days intrusion by force of 200g.
X1100, enlarged 30%.

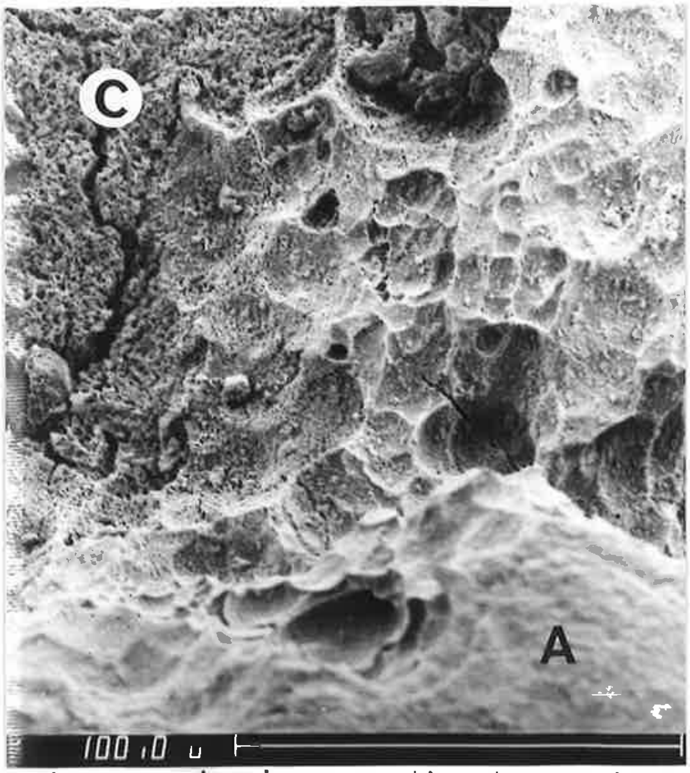


Fig. 49. Repair occurring in resorption lacuna in upper premolar attached to broken archwire. Resorption has occurred in acellular cementum (A) and the floor of the lacuna is being filled in by cellular cementum (C). Anorganic preparation. X35, enlarged 30%.

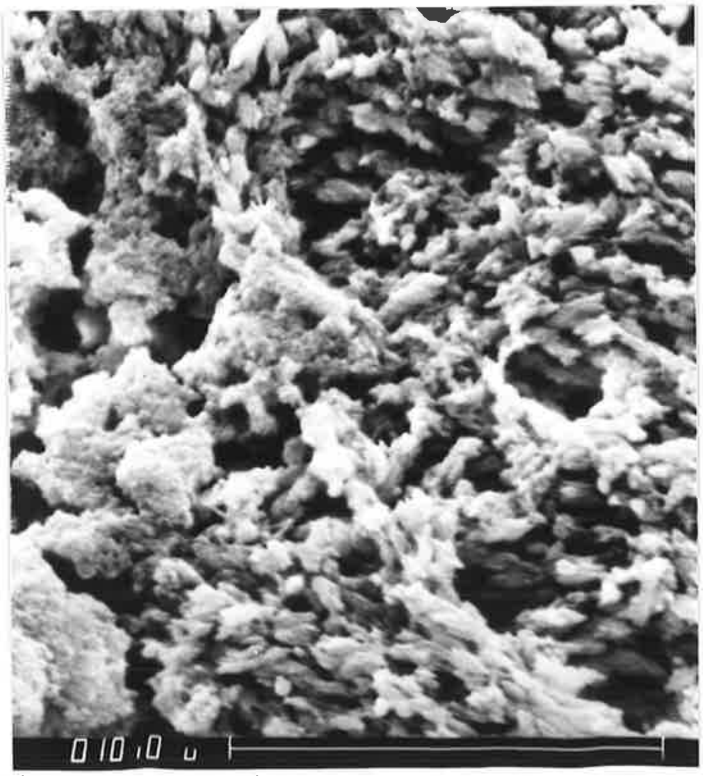


Fig. 50. High power view of cementum C in Fig. 49, showing cellular cementum pattern, similar to that described by Jones and Boyde (1972) in Fig. 61. X3400, enlarged 30%.

Rapid maxillary expansion results.

Severe resorption was observed on the buccal root surface of premolars which had been attached to the expansion appliance (Fig. 57). The resorption extended into dentine, where the openings of dentinal tubules were frequently observed (Fig. 54).

Figures 51-56 show views of a maxillary first premolar, extracted from an eleven year old female patient (Patient 1) whose palate had been rapidly expanded by means of a fixed palatal expander which was tooth borne. The expansion was obtained over two weeks, and retained by the same appliance for three months, when the four first premolars were extracted prior to full banding treatment. The premolars of this patient were triple rooted. Extensive resorption extending into dentine was noted on the buccal surface.

Figures 57 and 58 show views of a maxillary first premolar extracted from another patient, aged 14 years, whose palate had been rapidly expanded by means of a similar fixed palatal expander which was also tooth borne. In this case, the palate did not appear to widen as readily as in the above case and the orthodontist was of the opinion that the arch expansion was of dental origin only. Extensive resorption was noted, even more severe than in patient 1, covering one third of the buccal surface and extending into dentine. However, no root resorption was detected in the long cone periapical radiographs of this patient (Fig. 59).

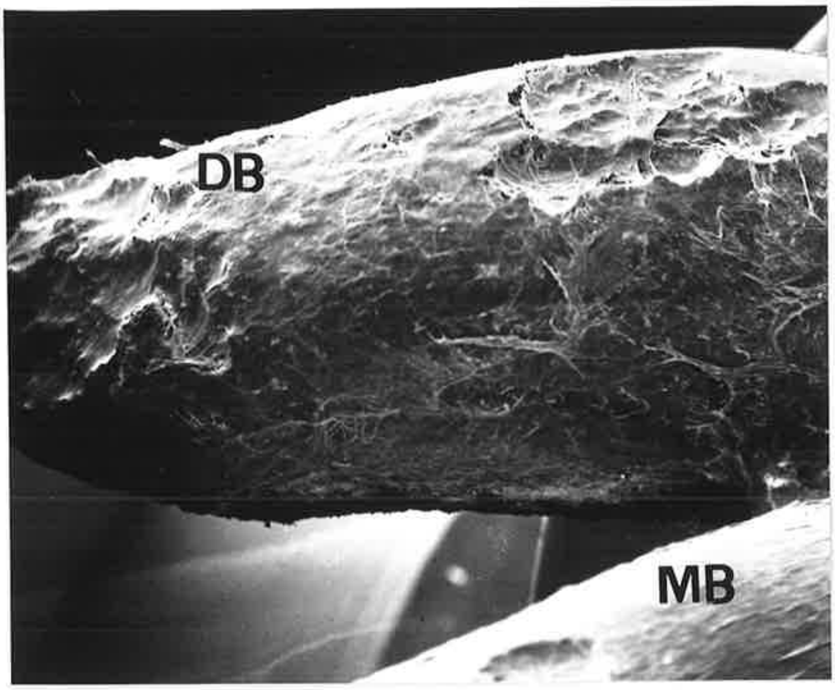


Fig. 51. Organic preparation. Root resorption at the apical and mid root surfaces. Buccal aspect of distobuccal root (DB) and mesiobuccal root (MB) of a premolar to which had been attached a rapid maxillary expansion appliance. Coated with carbon and gold.
X15, enlarged 50%.

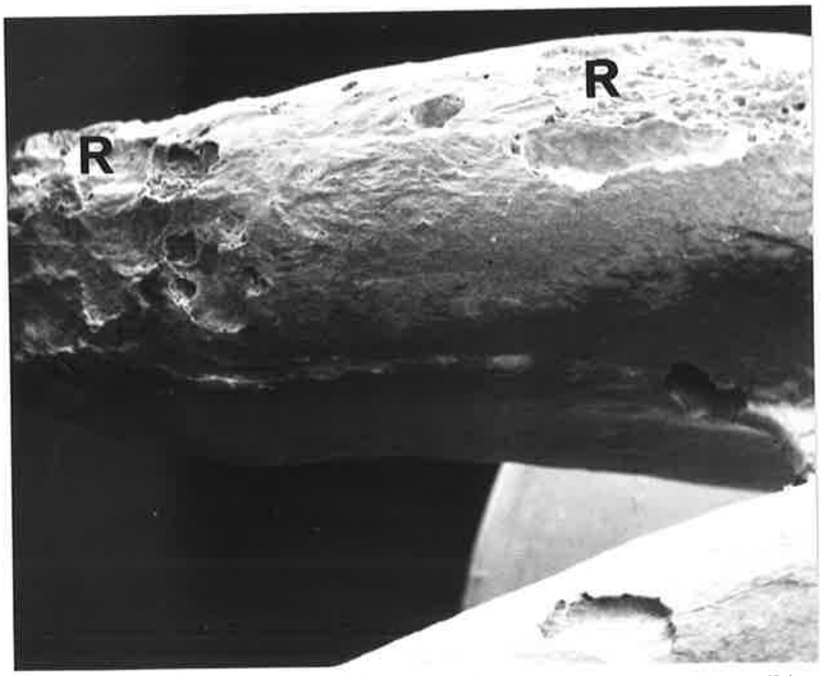


Fig. 52. Anorganic preparation. Same area as Fig. 51 but after removing carbon gold coating and rendering tooth anorganic in hot 1, 2 diaminoethane. Note resorption areas (R) with sharp edges which were previously obscured by the organic coating in Fig. 51.
X15, enlarged 50%.

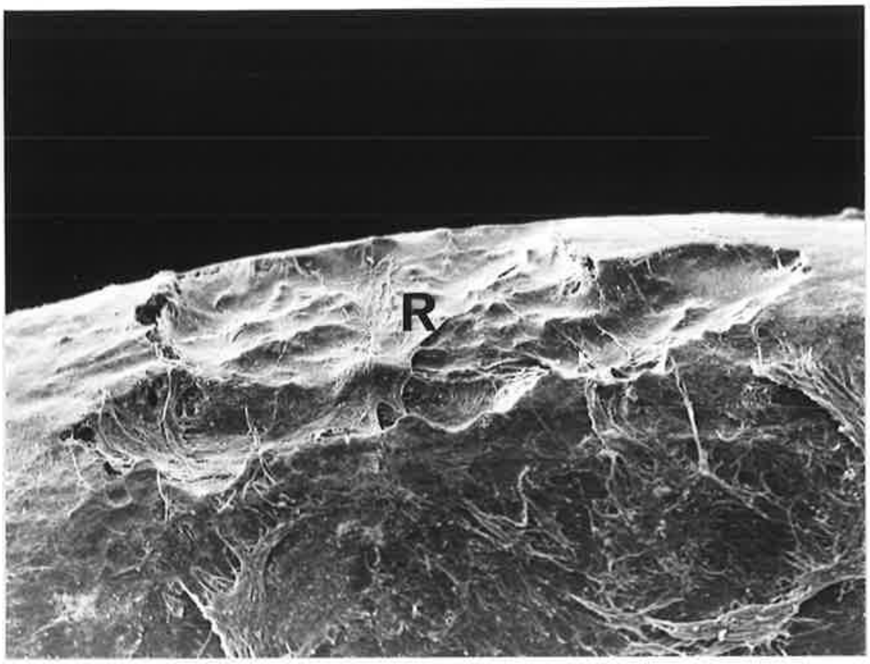


Fig. 53. Organic preparation. Midroot surface of specimen shown in Fig. 51. Organic state showing resorption (R).
X30, enlarged 50%.

Fig. 54. Anorganic preparation. Same area of specimen as Fig. 53 after tooth had been rendered anorganic. Resorption has exposed dentinal tubules (T). Good correlation is shown between organic and anorganic states.
X30, enlarged 50%.

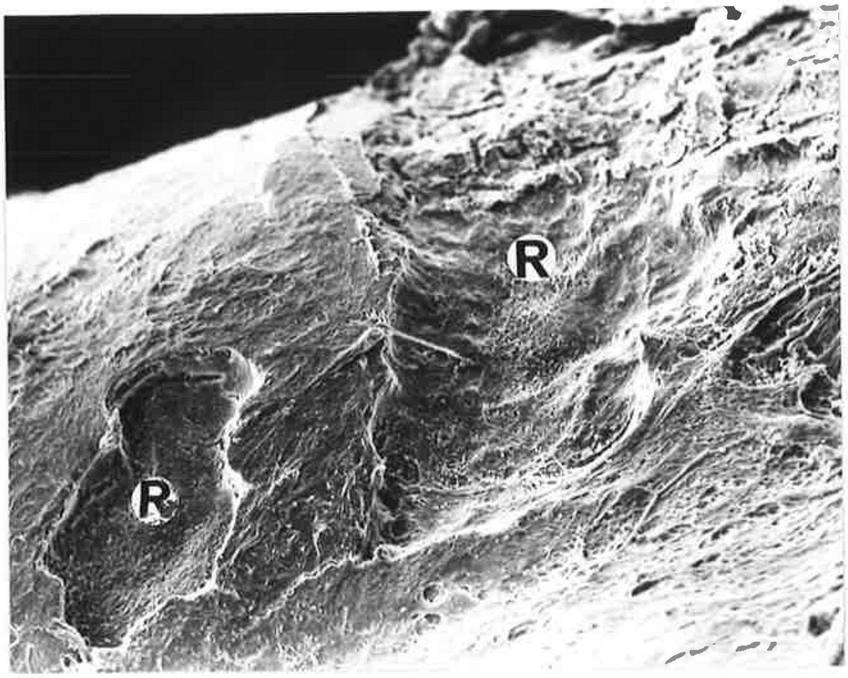


Fig. 55. Organic preparation. Coronal area of root surface shown in Fig. 51. Organic state, tooth coated with carbon and gold, showing resorption (R). X30, enlarged 50%.

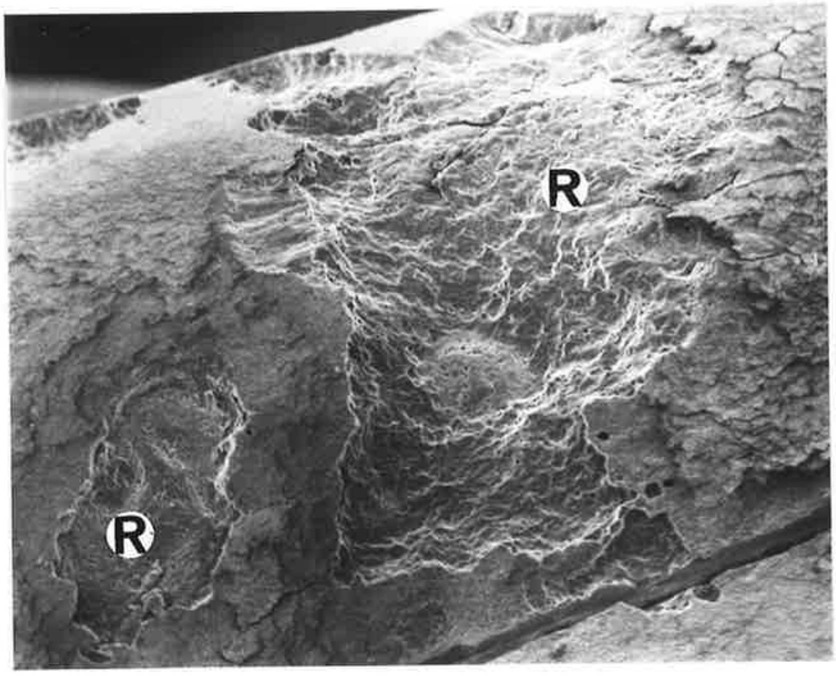


Fig. 56. Anorganic preparation. Same area as Fig. 55 after rendering tooth anorganic. X30, enlarged 50%.

Fig. 57. Extensive resorption (R) on buccal root surface of upper first premolar which had been attached to rapid fixed palatal expansion appliance during 10 days activation and 90 days retention.
Anorganic preparation.
X10, enlarged 30%.

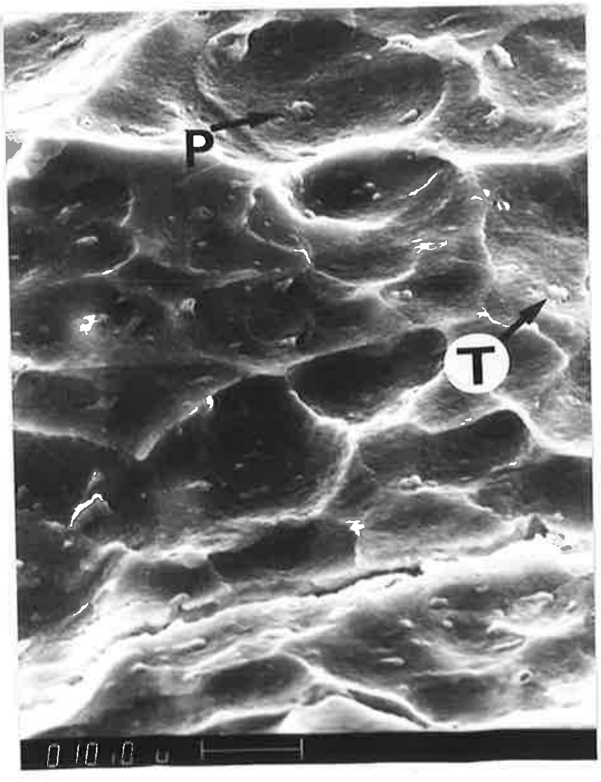


Fig. 58. Dentinal tubules (T) exposed in floor of resorption area on buccal root surface of upper premolar seen in Fig. 57. The peritubular dentine (P) is above the floor of the lacunae and appears to have resisted resorption more than the other dentine. Anorganic preparation.
X900, enlarged 50%.

Fig. 59. Long cone periapical radiograph of first premolar in Fig. 57 to which has been attached a rapid maxillary expansion appliance. No resorption can be detected radiographically. Enlarged 3X.

DISCUSSION

The findings of the present investigation indicated that intrusive forces of at least 50 grams applied to human premolar teeth were capable of causing resorption of cementum and dentine if permitted to act for a minimum duration of 14 days. These findings agree with those of Kvam (1973b), who stated that all teeth moved for longer than 20 days showed root resorption and that the amount of resorption increased with increased duration of force.

In the present study, tooth movement for 14 days produced minimal resorption with light forces of 50 grams and only slightly more resorption with heavier force. On the basis of the root resorption observed, the scanning electron microscope results can be correlated with the histological results of Stenvik and Mjor (1970) and Reitan (1972) who found increasing severity of root resorption with increasing duration of force application. Serial sectioning is necessary in histological investigations to enable determination of the number, size and shape of resorption areas. Stenvik and Mjor serial sectioned their specimens at 5 microns.

The advantage of the scanning electron microscope over the light microscope is its ease of specimen preparation and greater depth of focus which enables the observer to record a three dimensional view, indicating the number, size and shape of the resorption areas. However, a disadvantage is the necessity to identify structures by morphology alone. Histological sections enable identification of different tissue structures by differential staining, a method which cannot be used with scanning electron microscopy. Limited literature has been written concerning the morphology of structures on the root surface (Jones and Boyde, 1972; Kvam, 1972a). Therefore, the present study has attempted to describe structures both on the root surface and in resorption lacunae.

A problem with all experiments using human or animal material is the extent to which results are influenced by biological variability between patients and animal species. It has been suggested by Massler and Malone (1954) that there is an individual susceptibility to root resorption during tooth movement. This factor was considered in this experiment by comparing intra-patient test teeth in all except two patients. These two patients had extractions in one arch only. Where inter-patient test teeth were compared, it was demonstrated that a comparable intrusive force acting for a similar duration in different patients resulted in an equivalent amount of root resorption. On the basis of the size of the sample it is concluded that there is little evidence of biological variability in the patients examined in this investigation.

The findings of moderately severe resorption areas on the roots of teeth that had been intruded for 10 weeks with a light force of 50 grams suggests that the lightest value of force selected was not small enough to prevent resorption. In clinical practice, the 50 grams intrusive force on each side of the archwire would be applied over six anterior teeth and hence would be distributed over a larger total root area. This would reduce the pressure on individual root surfaces.

The general location of the resorption areas seen on the intruded teeth, namely the coronal half of the buccal root surface and the apical third of the lingual root surface, suggests that the teeth were tipped buccally as well as intruded. This type of movement would be expected with an archwire acting on an attachment to the buccal surface of the crowns. This finding of buccal tipping is in agreement with that of Stenvik and Mjor (1970), who commented that a certain tipping movement occurred in the intrusion of premolar teeth in their experiment using a buccally attached spring. With axial intrusion of the tooth it would be expected that a more even distribution of periodontal ligament compression areas would occur. The resorption lacunae would therefore be more evenly distributed over the root surface.

Reitan (1972) has suggested that uncalcified predentine is not readily resorbed, and that cementoid may also delay the onset of root resorption. Where a thick layer of predentine existed over a tooth apex, Reitan claimed that apical resorption did not occur. This suggestion implied that permanent loss of the apical part of the root may be prevented by moving teeth before the apex is fully developed. This concept is interesting theoretically, but unrealistic in terms of orthodontic treatment because the roots of different teeth develop at different times.

According to Gianelly and Goldman (1971) the roots of permanent teeth under physiological conditions are resistant to severe resorption. The fact that bone resorbs more readily than cementum enables orthodontic tooth movement to be carried out. However, some form of minor root resorption has been said to occur in nearly all people at some time during their lifetime. Massler and Malone (1954) found root resorption in all the people they examined radiographically, and an increased frequency and severity of root resorption in those patients who had received orthodontic treatment. The present study has indicated that intrusion and buccal tipping movement of premolars increased the frequency and degree of root resorption observed with the scanning electron microscope.

Henry and Weinmann (1951) in a histological study of the dentitions of 15 autopsy cadavers, reported root resorption in 90 per cent of the teeth they examined. They concluded that this high incidence may have been even higher had serial sectioning techniques been used. The majority (77 per cent) of the resorbed areas were found in the apical third of the root. These authors stated that the resorptions included both deep irreparable resorption, and shallow reparable resorption areas. The findings of Henry and Weinman (1951), together with those of Massler and Malone (1954) suggested that some degree of root resorption is a normal occurrence. Although the root did not have the rapid remodelling ability of bone, some repair of resorption defects by secondary cementum was observed by Henry and Weinmann. The appearance of cellular cementum in the resorption lacunae of the patient with the broken archwire in this investigation suggested that repair had occurred after the initiating force was removed.

In the present study, small resorption defects were seen in many of the control teeth. There appeared to be little relationship between the amount of resorption found in the control teeth and the resorption observed in the experimental teeth of different patients subjected to the same intrusive forces for the same duration. This finding contrasted with the radiographic findings of Massler and Malone (1954) who found a high correlation between the amount of root resorption prior to orthodontic treatment and the severity of root resorption after orthodontic treatment.

Many authors have stated that the pathogenesis of root resorption remains in doubt, and that excessive pressure applied for an excessive time will cause root resorption (Schwarz 1932, Orban 1936, Oppenheim 1942 and Stuteville 1937). Henry and Weinmann (1951) found that active resorption was almost invariably associated with traumatic changes in the periodontal ligament. However, the amount of resorption was not necessarily related to the severity of the ligament changes.

Reitan (1969) in a histologic study described a form of human root resorption, which he termed "physiologic" and considered to be preceded by hyalinization. He stated that these lacunae, which are formed as a result of occlusal pressures, are quickly repaired by cementoblasts. Henry and Weinmann (1951) found similar areas of resorption on the surface of roots facing the normal direction of migration of the tooth. The findings of these authors suggest that root resorption is a dynamic process and that under physiologic conditions resorption and repair occur continuously.

Infection has been suggested as a causative factor in root resorption (Becks, 1936). However, infection does not seem to be an important factor because the gingival portions of the root which are subjected to infectious agents are the least affected by root resorption in this investigation. No clinical evidence of infection was observed in the present study.

The sharp edges of the resorption lacunae in the present investigation and their irregular floors, together with the finding of increased depth of resorption in the centre of the lacunae suggested that resorption occurred in an expanding pattern. Enlargement of the resorption area appeared to occur by continual erosion at the edges as with caries. The observation that the edge of the resorption area passed through the Sharpey fibres, rather than around them (Fig. 47) suggested that the extrinsic fibre cement had similar resorption resistance to the Sharpey fibre.

Bien (1966) suggested that on the pressure side of the tooth root, compression of the periodontal ligament and blood vessels caused decreased blood pressure in the areas past the obstructed portion of the vessel. Bien hypothesized that oxygen came out of solution from the plasma, diffused through the vessel wall, and that bubbles lodged at sharp points, such as bone spicules, and caused their chemical erosion. Perhaps cementum is susceptible to resorption in pressure areas because of a localized surface "rough spot" or altered oxygen tension of interstitial fluid. In the present investigation, however, the magnification used would not have been sufficient to reveal irregular areas of cementum of the molecular magnitude hypothesized by Bien.

The movement of intrusion is resisted by the orientation of the oblique fibres, and viscoelastic fluid systems (Melcher and Walker, 1975). Gianelly and Goldman (1971) have said that orthodontic tooth intrusion occurs only when bone resorption in the apical area has occurred. However, Picton (1969) has shown that bone elasticity allows some intrusion before bone resorption occurs. Gianelly and Goldman have stated that the intrusive movement of a tooth is somewhat unique in certain respects, because the total area of the apical portion of the ligament is under pressure. However, this concept assumes an equal width of periodontal ligament in all areas of the apical portion and equal perforations of the ligament. If one or two points of the root surface contact the alveolus prematurely then intrusion would cease until these points are resorbed or deformed.

As recently as 1966, Graber suggested that intrusion only occurred after the root had been shortened by root resorption, a suggestion which has been disproved by the present investigation and by clinical results of the Begg technique. Reitan (1969) stated that root resorption occurred frequently during intrusion. Resorption areas seen with the SEM in the present study may be related to histological assessments of compression and resorption regions described in the human periodontal ligament by Reitan. Heavy orthodontic forces have been shown by Reitan to be capable of readily producing hyalinization of the ligament with subsequent resorption of the root, and therefore extensive root resorption is possible during orthodontic tooth movement. Schwarz (1932) similarly had found that heavy forces can result in root resorption. In support of Reitan's (1969) views, Gianelly and Goldman (1971) have suggested that the amount of hyalinization might determine the extent of root resorption.

With the use of constant intrusive forces of less than 50 grams, Dellinger (1967) found slight apical premolar root resorption in monkeys. Forces of 15 to 50 grams were sufficient to intrude teeth in dogs but forces between 100 grams and 200 grams produced significant apical root resorption. Thus the tissue reactions varied according to the magnitude of the applied force. However, care is needed in interpreting such results in different species because of unique characteristics of a particular species.

Regarding the magnitude of the applied force, Reitan (1969) has suggested that this is the single most important factor in root resorption. The present investigation relates to human teeth which demonstrated similar resorption patterns to that reported in various animal experiments. The resorption resistant property of cementum has been related to its "metabolic activity and architectural design" by Gianelly and Goldman (1971). Cementum, which is constantly laid down, is usually covered by a resorption-resistant layer of cementoid. The techniques used in the present investigation did not enable differentiation of cementoid from cementum. Where orthodontic force was applied for a long duration, however, the resorptive process could enlarge and include cementum as well as bone. In support of this view, Reitan (1969) observed histologically that no root resorption occurred adjacent to the hyalinized zone in short term experiments. Kvam (1972b), using the scanning electron microscope, found that root resorption only occurred after 14 days of applied pressure in human premolars. Sims (1976) has shown histological evidence of root resorption after 25 days of continual tooth movement in humans.

The findings of Reitan (1972) and Kvam (1973b) indicated that root resorption was initiated only after approximately 14 days of force application, and these findings could explain the absence of root resorption in the banded control teeth of the present experiment because the separation force acted only for seven days. The results of the present author's experiments suggest that the duration of the applied force is more important than the magnitude of the force in producing root resorption. The present findings agreed with those of Stenvik and Mjor (1970), who found a significant relationship between duration of intrusive force and the severity of root resorption. However, the lightest value selected in the present investigation, namely 50 grams may not have been light enough to produce a different effect to the 200 gram force. Schwarz (1932) suggests that the optimum force to orthodontically move a tooth is the capillary blood pressure of 20-26 grams per square centimetre. He believes that forces above this level could cause root resorption. Halderson (1957) advocates the routine use of minute forces of less than 25 grams in orthodontic practice.

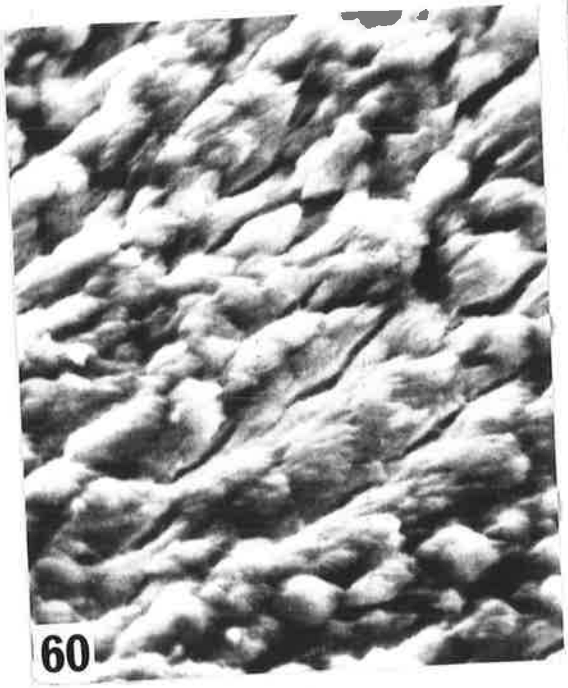
The effect of root resorption on the longevity of the teeth remains in doubt. Henry and Weinmann (1951) and Massler and Malone (1954) have suggested that most root resorption lacunae that occur during orthodontic tooth movement are small and will be repaired by cellular cementum. Superficial root resorption in the middle and coronal one third of the root has been stated by Gianelly and Goldman (1971) to have little, if any, long term effect on the teeth although they make no mention of subsequent repair. Gianelly and Goldman suggest that moderate root shortening due to root resorption will probably be "harmless" unless later periodontal disease should destroy crestal alveolar bone and further reduce tooth support when the stability of the tooth may be considerably reduced. Zachrisson (1975) completed a clinical and radiographic study of 110 Class II Division I patients who had been orthodontically treated by the edgewise appliance. He concluded that 2 mm reductions in tooth length due to root resorption were not detrimental to the lifespan and function of the dentition. He emphasised that the retention apparatus of the tooth is largely restricted to the coronal two thirds of the root. Phillips (1955) demonstrated that 2 mm loss of apical root reduced the total attachment area by only five to ten per cent, due to the conical shape of the root.

Vonder Ahe (1973) studied treatment records of 57 patients treated by private Californian orthodontists and known to have maxillary incisor root resorption. All cases were out of retention for at least three years, with the average post-retention period being six and one half years. Root resorption of maxillary incisors was assessed radiographically into three groups ranging in severity from slight blunting of the apex to loss of over one quarter of the root length. Vonder Ahe concluded that root resorption which was initiated by orthodontic treatment did not continue when the appliance was removed. He also found no excess mobility of the affected teeth.

Toda et al (1974) state that no scanning electron microscope studies of cementum lacunae have been carried out. On the contrary, Jones and Boyde (1972) exhaustively studied cementum lacunae with the SEM. Jones and Boyde (1972) commented that areas of resorption could easily be identified in the anorganic state on the basis of the characteristic excavated shape of the Howship's lacunae. They stated that at the edge of resorption bays, it appeared that the intrinsic matrix was removed preferentially to the Sharpey fibres themselves, because the Sharpey fibres appeared to be "eaten around". This appearance is contraty to the findings of the present investigation, in which the edge of resorption bays was routinely observed to pass through, rather than around, Sharpey fibres (Fig. 47).

Jones and Boyde (1972) were surprised at the high frequency of occurrence of small areas of resorption, particularly near the root apices of newly erupted teeth. They concluded that these resorption areas were related to the establishment of occlusal function of these teeth. In the present study, resorption areas in the control teeth were often located near openings which appeared to be accessory root canals (Fig. 39) at various locations on the root surface. This finding suggests that the resorption areas may be in some way associated with tissue components passing through these openings (for example, blood vessels or nerves). Boyde and Jones also commented on the size of these resorption lacunae located on the root apices of newly erupted teeth. The small lacuna size of 15-20 micrometres in diameter and 10 micrometres in depth corresponded to a single locus within Howship's lacunae as Jones and Boyde found in resorbing deciduous dentine. On the basis of size, Jones and Boyde suggested that these isolated resorption pits may have been excavated by uninucleated "osteoclasts". However, Hancox (1972) does not specify the size of the osteoclast cell, but talks in terms of a multinucleated cell. Resorption areas were located on the pressure side of the experimental tooth roots, a finding that agrees with the scanning electron microscope studies of Kvam (1972b) and the histological studies of Reitan (1969).

Jones and Boyde (1972) observed that large resorption bays may be surrounded by a raised rim or series of nodules formed of new cellular cementum. They believed this feature to indicate that compensatory hyperplasia of the cementum occurs where it is subjected to locally increased function. Temporary loss of collagen attachment function of the cementum occurs in resorbed areas. These authors reported that the appearance of repairing areas of resorption could easily be distinguished in the SEM from the appearance of actively resorbing areas by the relative smoothness of the latter and the spherical clusters of mineral particles in the repairing areas (Fig. 61). Jones and Boyde noticed a similarity in the appearance of repairing cementum and the clusters found by Boyde and Hobdell (1969) in mineralizing primary bone. Jones and Boyde suggested that the first stages of mineralization in repair of cementum seemed similar to the first stages of mineralization in repairing resorption bays in adult lamellar bone, because they both showed an identical picture to the primary bone (Figs. 60 & 61). They found that new cementum formation was rarely limited to the resorption areas, but rather that the mineralizing front filled up the resorption lacunae. Small clusters of mineral particles were said to flow over onto the surrounding unresorbed cementum area.



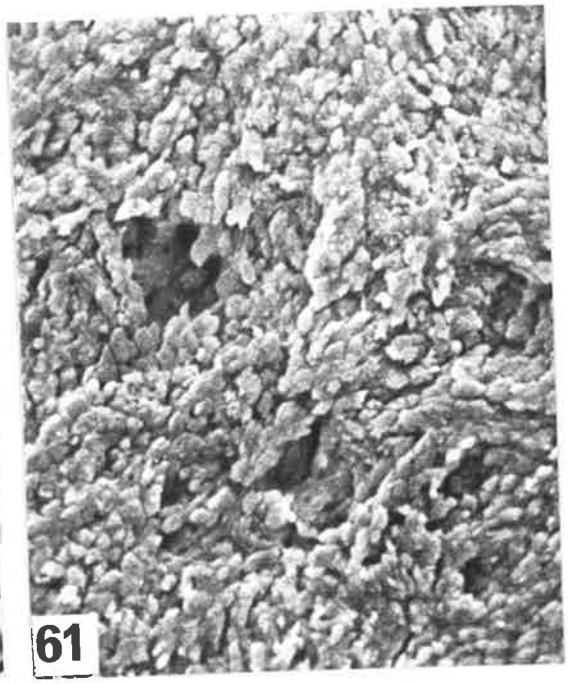


Fig. 60. Human primary bone showing similar appearance to repairing cementum in resorption lacunae. Anorganic preparation.
X3000, enlarged 40%.
From Boyde and Hobdell.

Fig. 61. Human premolar after movement by an orthodontic appliance. Mid-root surface. The appearance is similar to the mineralizing front of forming primary bone. Anorganic preparation.
X330, enlarged 40%.
From Jones and Boyde (1972).

In the present investigation the presence of raised peritubular dentine in the areas of resorbed dentine agrees with the findings of Jones and Boyde (1972). Peritubular dentine appears more resistant to osteoclastic resorption than the surrounding intertubular dentine because it is the last component resorbed. Peritubular dentine has been shown to be more highly mineralized (Miller 1954, Boyde, Switsur and Fearnhead 1961). Perhaps the resistance to resorption of the peritubular dentine is due to its greater density.

An important finding to emerge from this study was that intrusive forces applied to a tooth were generally capable of producing increased amounts of root resorption compared with the control tooth. The amount of resorption increased markedly with the duration of the force, and, to a lesser degree, with the magnitude of the force.

While the results of the present investigation provided no evidence relating to the prevention of root resorption, Reitan (1972) states that root resorption may be prevented by moving teeth with intermittent application of force with intervening periods of recovery. A wise precaution to take would appear to be radiographic assessment of root resorption before and at regular intervals during treatment. However, this project demonstrates that considerable resorption can occur before it is likely to be detected in radiographs (Fig. 59).

The extensive resorption seen on the buccal and to a lesser degree the lingual surfaces of the premolar teeth that had borne the rapid palatal expansion appliances suggested that more research is necessary into the effects of this appliance on the dentition. Rapid palatal expansion is frequently employed as a clinical procedure, and often the teeth used to expand the palate are not extracted (this applied particularly to first permanent molars). Buccal root resorption would not necessarily be observed in a normal periapical radiograph, because the bulk of the root would obscure the outline of the shallow resorption areas. Further research is already being undertaken to determine the observability of these areas on radiographs, and the effect of different methods of palatal expansion on root resorption.

Timms and Moss (1971) found evidence of active resorption and repair occurring on the root surface of teeth that had two years previously borne a rapid fixed maxillary expansion appliance. It appears that resorption may continue after the removal of the force that initiated it. Reitan's suggestion of rest periods during tooth movement to minimize root resorption therefore seems invalid, as well as being clinically impractical.

As a future extension of this project the effects of the following factors are currently being investigated:-

1. Light forces below 50 grams.
2. Resorption regions produced by bodily tooth movement compared with tipping movements.
3. Repair of resorption defects, which will involve discontinuing the force on the tooth and delaying extraction for varying periods.
4. Different diameters of archwire, e.g. .020 archwire would presumably apply heavier force over a shorter distance.
5. Cementum repair following rapid maxillary expansion.

CONCLUSIONS

The following conclusions were derived from the present investigation:-

1. The longer the application of force up to 70 days, the more severe the amount of root resorption.
2. The heavier the force within the range of 50 to 200 grams the more severe the amount of root resorption. However, variations in duration had a greater effect than variations in magnitude of force.
3. Rapid palatal expansion by means of fixed, toothborne appliances, produced severe root resorption on the pressure side, and minor resorption on the tension side of attached premolar teeth.
4. There was little variation in the susceptibility of different patients to root resorption in the experimental teeth. The same intrusive force applied for the same duration to similar teeth produced a similar amount of root resorption in different patients.
5. When intrusive force was applied to a premolar by means of a buccally attached bracket a tipping force was also applied. This tipping movement created pressure on the cervical one-third of the buccal root surface and on the apical portion of the lingual root surface.

APPENDIX

Planes of sectioning teeth

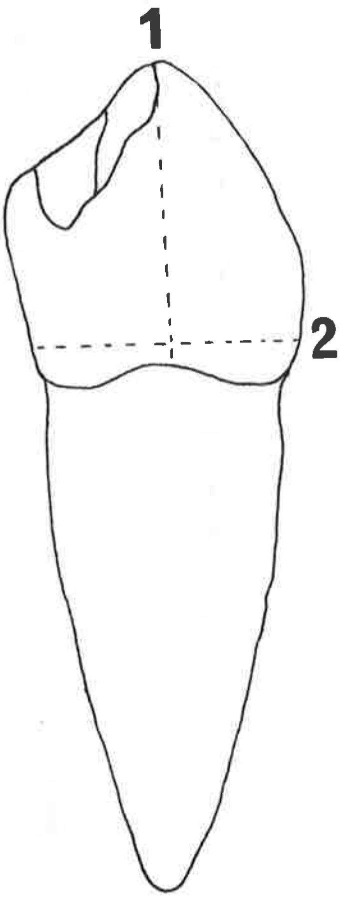


Fig. 62. Mandibular right first premolar.

1 first section - to produce groove on mesial surface of crown

2 second section - to separate crown from root.

The broken lines represent the planes of section.

SCANNING ELECTRON MICROSCOPE

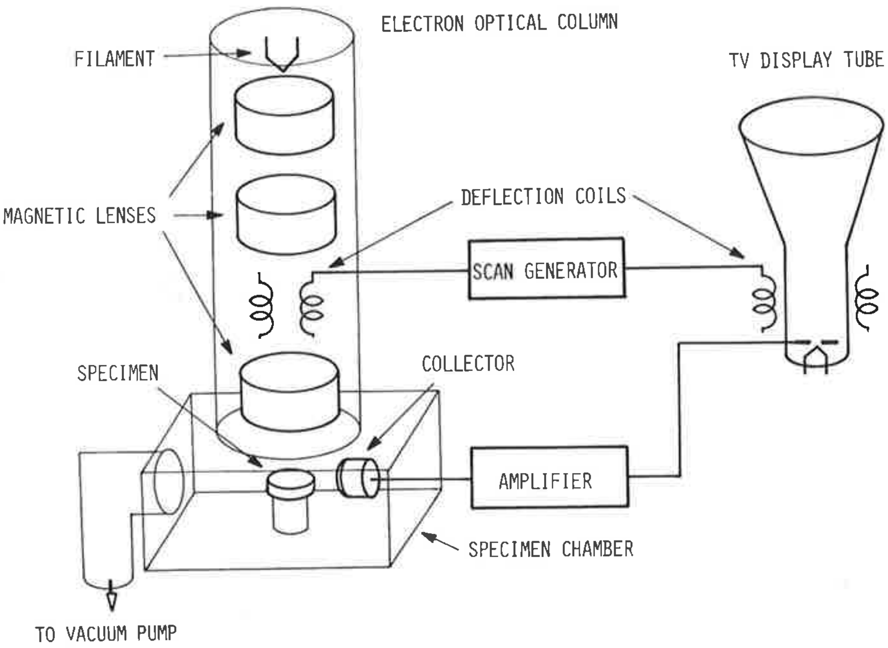


Fig. 63

The principle of operation of the SEM is based upon electrons emitted from a heated tungsten filament being accelerated by a high voltage, and formed into a narrow beam by a series of magnetic lenses inside the electron optical column. Deflection coils driven by a scan generator cause the electron beams to be deflected back and forth in a regular raster pattern across the specimen in the evacuated specimen chamber. The same scan generator is used to deflect the electron beam inside a TV display tube causing a similar but highly magnified raster pattern to be reproduced on the face of the TV tube.

The electron beam hitting the surface of the specimen causes secondary electrons to be emitted from the specimen, at a rate dependent on the specimen material and surface topography. The secondary electrons travel to the collector, the resultant current is amplified, and used to control the intensity of the beam inside the TV display tube. A magnified "picturé" of the specimen surface is thus produced on the TV tube screen.

FIXATIVE

Buffered neutral formalin solution (Lillie 1965)

40% Formalin	100.00 ml
Distilled water	900.00 ml
Disodium hydrogen orthophosphate (anhydrous)	6.50 g
Dihydrogen sodium phosphate	4.00 g

Soxhlet Extractor

Fig. 64 From Jena Schott (1966)

1 Liebig condenser

2 Adaptor

3 Specimen holder containing tooth

4 Soxhlet condenser

5 Round flask containing 1,2 diaminoethane

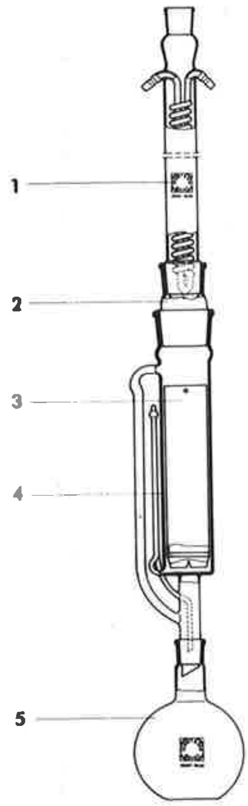


TABLE 2:

Duration of force	Magnitude of force	Average resorbed area. Buccal and Lingual Surfaces	Estimated maximum depth of resorptions (microns)
short	light	1%	75µ
short	heavy	3%	100µ
long	light	12%	250µ
long	heavy	16%	300µ
Rapid fixed maxillary expansion		35%	10,000µ

Table showing area and depth of resorption on test teeth

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