PERMEABILITY OF THE APICAL ROOT FORAMEN OF HUMAN TEETH:

THE EFFECT OF APICAL BARRIERS

by

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DEDICATION

This work is dedicated to three young ladies:

Sara, Julie and Muffy

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ABSTRACT

The purpose of this work was to measure the hydraulic permeability of root canal apical barriers *in vitro*. These barriers were placed in 30 extracted human teeth after the pulp tissue was removed and the apical canals were enlarged in a standard way using endodontic files. Barriers one millimeter thick were placed just inside the apical opening using either autogenous dentin chips, calcium hydroxide powder, or durapatite particles. The prepared teeth were placed in a special chamber which permitted applying known water pressures to the barrier and measuring the resultant flow. In addition, permeability of apical barriers was measured in ten teeth in which the apical openings were not standardized. Scanning electron micrographs (S.E.M.) were made of selected barriers to evaluate consistency and density.

The standardized canals with the autogenous dentin chip barriers gave a permeability average of 0.0010 μl/second/psi at 20 lbs applied pressure. The permeability of calcium hydroxide barriers averaged 0.0012 μl/second/psi. Durapatite particle barrier permeability averaged 0.0220 μl/second/psi. The S.E.M. photographs showed densities consistent with the measured permeabilites.

It was concluded that autogenous dentin chips and calcium hydroxide barriers showed statistically significant lower permeability than did durapatite barriers ($p=0.5$) and that a useful technic had been developed for the measurement of hydraulic conductance across a barrier of this kind.

INTRODUCTION

A major objective of endodontic therapy as proposed by Kuttler (1958) is to completely obliterate and seal the root canal system. The process of instrumentation of the canal space frequently results in debris being forced apically. Brynholf (1967) showed histologically that this debris was dentin and that it was associated with successful cases at autopsy. The use of an apical barrier of autogenous dentin, whether inadvertantly or purposely placed, prevents extrusion of filling materials into periradicular tissues. Gollner (1937) and Pitts (1984) have shown histologically the formation of cementum apically after dentin chips were placed deliberately. This barrier resulted in a physiologic barrier at the apex. Although the usefulness of autogenous dentin chips as an apical barrier in endodontically treated human teeth has been demonstrated, an apical barrier of one millimeter of dentin chips was shown to be permeable to penetration by S^{35}, Pappin (1982). In an effort to study ways of enhancing this seal, a method has been devised to determine the permeability of various apical barriers in extracted, freshly frozen, single-rooted, human teeth.

The objectives of this study include the following:

1. To develop a method for measuring barrier hydraulic conductance *in vitro* in extracted human teeth.

2. To develop a reliable and reproducible, standardized method for barrier placement in human teeth.
3. To compare the results obtained using standardized preparations with a standardized apical opening to the results obtained using non-standardized apical openings but standard preparations.
4. To compare the relative effectiveness of autogenous dentin chips, calcium hydroxide powder, and granular durapatite particles in producing a barrier to fluid movement.
5. To use scanning electron micrographs to describe the microscopic structure of the barriers and to compare this structure to the fluid permeability of the three materials tested.

REVIEW OF THE LITERATURE

INTRODUCTORY REMARKS

Pappin (1982) proposed that blocking the apical foramen with a biologically acceptable material might prove to be very useful in endodontic therapy. Gottlieb et al. (1950) suggested that closure of the apical foramen by the apposition of cementum was the ultimate and perhaps the only physiologic seal. Presently in endodontics, the use of an apical barrier is being evaluated by research and clinical practice. The technique is being taught in undergraduate, preclinical, and clinical courses. Froese and Schechter (1981) presented the technique in the sophomore laboratory manual presently used at the Oregon Health Sciences University School of Dentistry. This review will present the literature pertinent to our current understanding and use of apical barriers in endodontics.

INADVERTENTLY PLACED DENTIN BARRIERS

Apical dentin barriers, inadvertently placed, have been reported by a number of investigators. The treatment in many of these cases was considered successful. Moodnick (1963) noted that true denticles and dentin chips played a role in endodontic therapy when they were forced apically during mechanical instrumentation. During preparation of the root canal, dentin chips may be inadvertently packed into the apical constriction. This often leads to situations, particularly in narrow canals, in which instruments cannot be advanced apically as desired. He reported that this condition is caused by packing hard tissue in the apical constriction, and he further speculated that this may be a method for biologically obturating the apex of the root canals. Brynholf (1967) reported on 292 endodontically treated teeth at autopsy. Histologic evidence of complete apical healing of the root filled teeth occurred in only seven percent of the cases, and a tendency for healing occurred in another 20 percent. She indicated that the prospects of healing were brighter if the root filling did not extend down to the foramen and if there were fragments of dentin superficially in the foreign material. Davis et al. (1971) found that in spite of careful instrumentation and frequent irrigation, dentin debris, along with other root canal contents, may not be removed completely but may be left in the root canal or forced into periapical tissues during reaming, filing, and filling of canals. He found that quantities of new bone and cementum tended to form adjacent to dentin filings (chips) which had not been removed from the apex. Seltzer et al. (1973) reported in a study of human teeth deliberately instrumented two to ten millimeters beyond the apex that dentin filings packed accidentally in the apical foramen seemed to minimize or prevent post-treatment periapical inflammation. They speculated that an apical plug of dentin filings possibly prevented or reduced chemical irritation of the periapical tissue from the cement ingredients or from the gutta percha itself. Tronstad (1978) purposely placed dentin chips in the apices of monkey teeth. Not only was this treatment successful, but so were some of the negative controls. In six of the ten controls, inadvertent dentin chip barriers were found in the canal and thought to be related to the success rate. Adams et al. (1979), in a filling permeability study using extracted teeth, tested leakage into the canal with radioisotope tracers. They prepared canals one millimeter short of the apex and sealed intentionally separated stainless steel files in the canal. They found that the least permeable fillings had a dentin chip plug at the apex. This plug was deemed unintentional but unavoidable in small canals with mature apices. Leonardo et al. (1984) histologically evaluated the effect of calcium hydroxide on the pulp stump and periapical connective tissue that remained after root canal treatment. They reported that the presence of dentin chips accidentally placed on pulp stump surfaces prevented an inflammatory reaction in all groups studied. Seven days after the pulpectomy, the pulp stump and periapical ligament were free of inflammatory cells. They suggested that the presence of dentin chips in the root canal treatment of teeth with pulpal vitality seemed to enhance periapical tissue repair. Yee et al. (1984) studied barriers inadvertently placed related to five different file sizes. They reported that leakage generally decreased with the increase in canal size as shown by Ca^{45} autoradiography and S.E.M. analysis. Patterson (1985), studying instrumentation of vital uninfected monkey teeth histologically, found that teeth with inadvertently placed dentin plugs had statistically less apical inflammation than those without plugs. He determined that preparation of canals frequently created a dentinal plug and that the filling material of plugged teeth was denser without apical extrusion. He also reported that the plug sometimes created a primary seal which supplemented the filling material seal.

PURPOSELY PLACED APICAL DENTIN BARRIER

In other studies, investigators have purposely placed apical dentin barriers and shown the treatment to be successful. Gollner (1937) stated that the root should be filled with its own dentin and that this dentin exerted a stimulating influence upon cementum formation: "Whenever dentin surfaces were present, as occurs in tooth fractures, they were being covered by cementum.

The same will happen if the dental foramen is closed by dentin." Gottlieb et al. (1950) discussed the use of bone or ivory powder for the stimulation of hard tissue formation. They reported that a cement-dentin mixture, equal parts, stimulated connective tissue to form additional hard tissue. Kuttler (1958) stated that the ideal root canal filling was one which thoroughly filled the dentinal portion of the canal, sealed it at the cemento-dentinal junction, and stimulated the formation of cementum that obliterated the canal. He reported that such a filling would result in the formation of a healthy periapical condition, one in which the periodontal membrane and osseous tissue were normal and in which the lamina dura was continuous around the apex of the tooth. He stated that periapical regeneration and new cementum formation could be accelerated by the deposition of autogenous dentinal shavings at the cemento-dentinal junction or in the cemental portion of the canal. In addition, he recommended the use of autogenous dentinal filings at the cemento-dentinal termination of the root canal to isolate the filling material from the periodontal membrane and to stimulate the biologic closing of the cemental canal with new cementum. Baume et al. (1971) described a technique for a radicular pulpotomy in which a step was cut in the dentinal wall and a primary plug of dentin chips covered the amputated plug; the final dentin plug was in direct contact with living pulp tissue. Pappin (1982) described another technique that used a one-millimeter apical barrier of dentin chips deliberately placed one-and-one-half millimeters from the radiographic apex as part of his crown-down preparation of the root canal.

EVALUATION OF SUCCESS OF APICAL DENTIN BARRIERS

Evaluation of success of the apical dentin barrier has been demonstrated both clinically and histologically. Kuttler (1958) observed radiographically and clinically that dentinal shavings implanted in the terminal portion of the canal stimulated a more rapid periapical regeneration. Seidler (1976) reported a case of severe intractable pain that developed in a patient after conventional endodontic treatment. Removal of the root canal filling and sealing in various medicated dressings did not relieve pain; neither did leaving the tooth open for drainage. The pain disappeared when the apical foramen was intentionally blocked with dentinal filings. Petersson et al. (1982) assessed the clinical and radiological long-term success of dentin chips placed after pulpectomy one to three millimeters from the apex and one-half to one millimeter thick. Their results showed 92 percent clinical success when followed from three to six-and-one-half years. Brady et al. (1985), in a study of over-instrumented baboon teeth, showed radiographically that teeth with dentin plugs appeared abnormal while those without dentin plugs were generally normal. However, these dentin plugs were extruded two millimeters beyond the end of the root while those without dentin plugs were filled by lateral condensation of gutta percha and sealer confined to the root canal system.

Gollner (1937) demonstrated histologically in studies of the teeth of dogs that in most instances the dentin fragments were united with cementum. Gottlieb et al. (1950) reported from histologic evidence of treated dog teeth that calcified bridging of the apex occurred, even in teeth with necrotic pulps, when dentin powder was deliberately placed in the apical canal. Ketterl (1963) demonstrated in human teeth that cementum developed apically to a plug of dentin chips. He indicated that complete histologic healing was observed in 68 percent of the cases treated, even though complete cemental closure of the foramen was not seen. Baume et al. (1971), in an histologic study of 22 symptom-free, vital human teeth which were extracted three months after placement of dentin chip plugs, showed a complete seal at the apex with osteodentin deposition. He reported that calcific obliteration depended on the presence of a dentinal plug and its proximity, three to five millimeters, to the apex. Tronstad (1978), in a study of tissue reaction following apical plugging of the root canal with dentin chips in vital monkey teeth, showed that 22 of 24 teeth were successful at 95 days after pulpectomy. He demonstrated that a plug of dentin chips was well tolerated by the tissues and stated that the plug may be an effective barrier in the apical part of the root canal, facilitating the accomplishment of a well-condensed, tight-sealing root filling. Holland et al. (1980) reported an histologic study in dogs that used infected dentin chips (teeth left open for five days then closed with camphorated parachlorphenol for two days), half of the teeth were filled with zinc oxide and eugenol and half with zinc oxide, eugenol, and dentin chips. Unlike Gottlieb's findings, they reported that the use of dentin plugs from these contaminated cases was contraindicated. Oswald et al. (1980) studied histologically and radiographically apical dentin filings in the teeth of cats. The teeth were intentionally instrumented through the foramen. One tooth had dentin chips packed into the apical opening; the contra-lateral tooth served as a control. The results indicated quicker healing, characterized by cementum deposition and minimal inflammation, in the specimens with packed dentin filings. Pappin (1982) studied histologically 22 vital human teeth which were root filled with a plug of dentin chips and extracted after 46 or 98 days. He used tetracycline labelled, undecalcified sections to show that active calcification occurred in the apical canal adjacent to the dentin chip plug. No calcification occurred in controls in which no dentin chips were placed. Vogel (1984), in a study of 60 human teeth similar to Pappin's, examined tetracycline labelled, undecalcified sections and found that both calcium hydroxide powder and dentin chip barriers showed apical calcification. Controls again showed no labeling of calcification in the time periods studied. Matsumoto (1984), using dogs' teeth, examined the histologic character of the apical barrier produced by calcium hydroxide powder, dentin chips, or regular root canal fillings. The specimens were examined for the presence of a tetracycline tracer. It was shown that apical bone repair and calcification of the apical root canal resulted when calcium hydroxide powder or dentin chips were used. Regular fillings without dentin chips showed no dentin repair during the time studied. Holland (1984) directly compared the periapical response to dentin and calcium hydroxide powder in terms of cemental deposition, foramenal closure, and periapical inflammation. He found that the thickness of cementum deposited postoperatively was statistically significant in seven cases. In six of these cases a dentin plug had been placed. Pitts et al. (1984), similarly to Oswald et al. (1980), compared calcium hydroxide and dentin chip plugs histologically at one-, three- and nine-month intervals. They found that the plugs acted as efficient barriers, keeping the filling material out of the periapex in the intentionally over-instrumented canals. Significant washout of the calcium hydroxide plug occurred at one month, and by nine months essentially all of the plug disappeared from the apical portion of the root canal. The calcification associated with the dentin plug was more complete than those observed with the calcium hydroxide plug. The appearance of the newly calcified tissue was consistent with that of cellular cementum. Brandell et al. (1985) compared hydroxylapatite, demineralized dentin, and untreated dentin chips as barriers in an attempt to determine which component of the dentin chip stimulated hard tissue formation. They studied monkey teeth histologically at three- and six-month intervals and found that samples with apical plugs of hydroxylapatite (inorganic component) had more hard tissue formation and less inflammation than did the other specimens. Brady et al. (1985), in a study of over-instrumented baboon teeth, showed there was a statistically significant tendency for those roots with dentin plugs to show histologically a more severe periapical inflammatory response at six months than those roots without dentin plugs. As mentioned previously, roots in which dentin plugs were placed were packed with dentin chips two millimeters beyond the end of the root, while those without dentin plugs were filled by lateral condensation of gutta percha and sealer contained within the confines of the root canal system. They found no evidence that dentin chips induced hard tissue formation.

PREVENTION OF APICAL IRRITATION - PRESENCE OF PHYSICAL DENTIN BARRIER

Langeland (1974) stated that "all sealers are irritants in the freshly mixed state." The barrier at the apex does prevent filling materials from being expressed into the surrounding tissues. Safavi et al. (1982) utilized ten teeth in two baboons in an histologic study and found that when the dentin plug was complete it prevented the extrusion of filling materials into the apical tissues. Holland et al. (1983), using monkey teeth, examined histologically the effect of the filling material on tissue reactions following apical plugging of the root canal. They found no differences in the results with the different filling materials. They attempted to place the barrier one millimeter short of the apical foramen, but this was not done in all specimens. The level of the barrier did not seem to influence the results. *The majority of the specimens showed deposition of cementum directly over the barrier*, including some cases in which the barrier reached the periodontal ligament. In other specimens, the dentin chips had also blocked the accessory canals. In most, cementum deposition completely walled off the root canal and no periapical inflammation was evident. Results of the study suggest that the filling material does not influence the healing process when the barrier is present. El Deeb et al. (1983) examined and treated extracted teeth, some with a dentin barrier and apical constriction intact, some with apical constriction intact but no apical barrier, and others with no barrier and no constriction. They found that when dentinal debris was packed at the end of the canal, irrigation solution could not be forced through the apical foramen, even under considerable pressure. They also found that over filling was prevented completely when the apical constriction was preserved together with the presence of the dentinal plug.

DECALCIFIED DENTIN USED AS APICAL BARRIERS

Many studies have shown that decalcified dentin has osteogenic potential. Yeomens et al. (1967) studied allogenic decalcified cortical bone, decalcified dentin, and undecalcified dentin implanted in mucosal, osseous, and muscle tissue of rabbits for four, eight, and 12 weeks. Autoradiographically they found that decalcified bone and dentin induced osteogenesis in all three locations, while the decalcified dentin only induced bone in 75 percent of the implants and then only after a latent period. Nordenram et al. (1975), in a clinical and radiographic study of human jaw cysts treated with allogenic, demineralized dentin for six months to 66 months, found that the dentin group had less incidence of operational defects and a higher incidence of complete healing of the cyst cavity on radiographic examination. Silston et al. (1979)

found that grafts of decalcified dentin from humans or rats brought about repair of deliberately resected bone in rats. They found that allogenic and xenogenic dentin matrix stimulated sufficient new bone formation to bridge the gap between cut ends of a bone. Rossmeisl et al. (1982) utilized lyophilized dentin from other donor monkeys, placed a two- to five-millimeter barrier in both anterior and posterior teeth, and then filled the canals with gutta percha softened in chloroform. Control teeth treated identically but without the dentin barrier showed no mineralization at the apex in 23 weeks. Duncan (1984) evaluated the osteogenic potential of three forms of processed dentin particles implanted in the calvaria of dogs. Organic dentin was demineralized, lyophilized, and sterilized. Inorganic dentin was produced by oven ashing. Physically altered dentin was produced by grinding with dental burs. The materials were inserted into defects created in calvaria of four dogs. Eight preparations in each animal were made. Six were filled with materials, and two were left unfilled. Tetracycline HCl was administered to label the healing for histologic examinations and to measure the amount of new bone that developed after 42 days. ANOVA analysis confirmed that all defects in all dogs filled with new bone at the same rate. Brandell et al. (1985) found histologically at six-month intervals that demineralized dentin used in monkey teeth as apical barriers produced less hard tissue formation and more inflammation than did hydroxylapatite and dentin chip barriers.

OTHER MATERIALS USED AS APICAL BARRIERS

Materials other than dentin have been used as an apical barrier. Gottleib (1950) reported the use of bone and ivory powder. Narange and Wells (1973) used decalcified, allogenic, bone matrix grafts and found clinically, radiographically, and histologically that they were not rejected within 12 weeks and that they were capable of enhancing new bone formation in periapical areas. Rossmeisl et al. (1982) obtained lyophilized cortical bone from other donor monkeys by biopsy. This material was placed as an apical barrier two- to five-millimeters thick in the canals of completely formed teeth instrumented two millimeters beyond the apex. They found that control teeth treated identically but without the cortical bone showed no mineralization at the apex. The experimental teeth showed mineralization at the apical barrier in 24 weeks. Eleazer et al. (1984), in a histologic study of monkey teeth, found that Proplast, a felt-like implant of polytetrafluorethylene (Teflon), and carbon offered no advantage as an apical barrier over gutta percha and zinc oxide root canal sealer in reducing inflammation in the periapical tissue in teeth that were overinstrumented and overfilled. Zakariasen et al. (1985) completed an _in vitro_ study on extracted molars to ascertain whether a dentin filing plug could be fused by a Nd-YAG laser beam to adjacent canal dentin. Prepared canals were packed with dentin to within one millimeter of the orifice. The canals were lased for 0.5 seconds or less at power levels of 25, 37, and 50 watts. The laser beam was carried through a 600-micron-diameter optical fiber wand held three millimeters from the dentin plug surface. It was found that the dentin filing plug and the surrounding dentin fused and recrystallized into a continuous mass that varied in its degree of fusion from minimal to essentially complete. McMurray et al. (1986) compared carbon dioxide laser-fused dentin and enamel root canal plugs and showed that enamel particle plugs could be laser-fused with greater consistency than dentin particle plugs. These findings suggest that lased enamel plugs may be used more effectively in apical sealing than lased dentin plugs.

Tricalcium phosphate ceramic has been evaluated clinically, radiographically, and histologically as an apical barrier and as an osteogenic potentiator in advanced periodontitis. Bhaskar et al. (1971) used tricalcium phosphate in periodontal defects as an implant that could be replaced by bone or act as a matrix for bone formation. The ceramic was found to be well tolerated by tissues, resorbable, and able to stimulate bone formation. Bone was seen forming directly on the ceramic at two weeks along with a progressive decrease in the amount of ceramic. Getter et al. (1972) compared the effect of three types of biodegradable calcium phosphate ceramics and blood clots in similar bony defects. Using electronmicroscopic studies, they found that bone healing occurred almost as rapidly with tricalcium phosphate and calcium phosphate as it did with a blood clot. Tricalcium phosphate degraded somewhat more slowly than the calcium phosphate. Hydrated tricalcium phosphate was the slowest to resorb. Defects containing this material showed the least bone repair. Cutright et al. (1972) indicated that tricalcium phosphate was well accepted by the tissues. They found that it may actually contribute mineral salts for the formation of bone at the site as the ceramic was broken down into granules. The previous three studies were all done on rats. Levin et al. (1974), using dogs and monkeys to show the response of periodontal tissues to biodegradable tricalcium phosphate, created periodontal defects and filled them with this ceramic. Specimens were examined from one to 22 weeks after placement of the materials. Results indicated excellent tissue tolerance and regeneration of lost periodontium. Nery et al. (1975), in an histologic study of dogs, showed that the ceramic was also well tolerated by the tissues and gave no toxic reactions. They found bone ingrowth into the pores of the material and repair of the periodontium. Koenigs et al. (1975) induced apical closure of permanent teeth in adult primates using a resorbable form of tricalcium phosphate ceramic. Twenty-four fully developed anterior teeth were filed through the apex with a size 80 file. Twenty were filled with tricalcium phosphate followed by gutta percha. Four were filled only with gutta percha. All samples were evaluated histologically at two weeks, four months, and six months. Bridging of the open apices by mineralized tissue was shown at six months, although histologically the apical bridge was not complete. Regeneration of the periodontal ligament about the apices occurred and a minimal inflammatory response, consistent with healing, was associated with the ceramic. Roberts and Brilliant (1975) used tricalcium phosphate and calcium hydroxide powder clinically in 16 pulpless human teeth to stimulate closure of the apex. Half were treated with calcium hydroxide, pH 11.8, and half with tricalcium phosphate, pH 8.6, and studied over a one-year period of time. They found that apical closure occurred clinically following treatment with either material but did not occur in every case. They stated that the use of a very alkaline material may not be necessary to induce apical closure. Howden (1977) placed tricalcium phosphate in apical lesions following endodontic surgery of human teeth and evaluated the results radiographically. He reported that the material was incompatible with bone and biodegradable. It appeared that with time (nine months) the tricalcium phosphate (TCP) particles became smaller, more radiolucent and that trabeculated bone appeared to cover it. Coviello and Brilliant (1979) used tricalcium phosphate and calcium hydroxide as an apical barrier in pulpless, necrotic human teeth with open apices to determine if a one-appointment apexification technique was better than multiple appointments. The results indicated that the one-appointment technique was as effective as the multiple-appointment technique.

They found that tricalcium phosphate and calcium hydroxide could act as a substitute apical barrier against which gutta percha could be condensed in teeth with necrotic pulps and open apices. Based on the number of clinical trials, there was no substantial difference between the healing with either technique in cases using tricalcium phosphate or calcium hydroxide.

Calcium hydroxide has been recommended repeatedly for induction of calcified repair tissue and as an apical barrier. Matsumiya and Kitamura (1960), using calcium hydroxide in the infected canals of dogs, found histologically that after 25 days a number of cases began to show healing and fewer bacteria in the canal. At 50 days, further healing was noticed, and many canals were bacteria free. They reported that calcium hydroxide was an excellent filling material and had the effect of accelerating the natural healing in periapical tissues. Laws (1962), studying the effects of calcium hydroxide, found that the bactericidal effect due to pH was limited. Using tissue implants in rats and partial pulp extirpation, he found no induction of calcified tissue. Moodnick (1963) reported that calcium hydroxide was the agent of choice in pulpotomy procedures on immature, adult human teeth. He showed that the effect of this drug on vital human pulp tissue was a rapid elaboration of reparative dentin, whereas zinc oxide and eugenol used in the same manner caused abscessing of pulpal tissues. He found that the effect of calcium hydroxide on pulpal tissue was uncontrollable in that the root canal continued to calcify and that complete calcification and obliteration of the root canal might occur. He reported that it was necessary to remove this pulp tissue after apical development to prevent future pulp necrosis and periapical breakdown. Pulpectomy following root closure minimized the necessity for surgical treatment. Frank (1966) also stressed that, once apical formation became complete in immature, adult pulpless teeth treated with calcium hydroxide, root canal treatment was required. His technique used a paste that consisted of calcium hydroxide and camphorated monochlorophenol. Michanowicz and Michanowicz (1967) used a technique in which calcium hydroxide was placed at the open apex after treatment of the canal space with camphorated parachlorophenol. Continued root formation was shown following filling with gutta percha and sealer with lateral condensation. Frank (1967) reported that an antiseptic paste, antibiotic paste, or calcium hydroxide paste could be used instead of surgery for treatment of non-vital, immature teeth with open apices and apical pathosis. He made the point that it was not the paste that determined the success of treatment, but the reduction of the canal contaminants by biomechanical instrumentation. He recommended calcium hydroxide because it was easy to remove and because it was resorbable. Steiner and Van Hassel (1968) histologically showed apical closure in monkey teeth with deliberately produced apical pathosis and apical perforations. The teeth were cleaned and medicated with calcium hydroxide and camphorated monochlorophenol. Nine out of ten teeth showed apical closure at nine months. Dylewski (1971) using immature monkey teeth purposefully filed through the apex, treated them with calcium hydroxide and camphorated parachlorophenol paste, and then filled them with gutta percha four millimeters short of the apex. He found histological repair of apices in 71 days but could not demonstrate complete closure. Laws (1971), in an histologic and clinical study of human teeth, removed the dental pulp from the root canal by reaming with larger to smaller reamers until the middle or apical third of the root canal was reached. This was followed by heavy condensation of a calcium hydroxide paste that appeared to prevent resorption of the filling material and possibly promoted the formation of a mineralized bridge. Fourteen teeth were followed for three years or more and none showed adverse clinical or radiographic signs. Ham et al. (1972), in an histologic study of monkey teeth with induced pulpal necrosis, compared calcium hydroxide and apically induced blood clots and showed no complete calcification, only partial bridging. Cvek (1972), in a clinical and radiographic study of traumatized, immature, permanent, anterior teeth with pulpal necrosis and large periapical lesions, showed that when calcium hydroxide was condensed into the canal, 50 out of 55 had apical closure (apexification). The size of the apical lesion had no effect on the time of apical closure. In cases where calcium hydroxide was pushed into the periapical area, no clinical symptoms developed and the material was resorbed. Binnie and Rowe (1973), in an histologic study of closure of immature, pulpless dog teeth, compared calcium hydroxide paste with Calyxl, Grossman's sealer, and controls. Fifty-four percent of the calcium hydroxide-treated teeth showed an absence of inflammation and continued root formation. They also showed a complete absence of adverse reaction when the calcium hydroxide was in direct contact with the periapical tissues. Torneck et al. (1973) histologically compared the effects of debridement alone with debridement and camphorated parachlorophenol calcium hydroxide paste in the closure of immature teeth in which pulpal and periapical disease had been induced. The results indicated that more advanced apexification occurred when the treatment paste was used than when camphorated parachlorphenol (CPC) alone was used. They reported that the use of calcium hydroxide increased the amount of hard tissue formation. Cvek and Sundstrom (1974) histologically examined extracted teeth with immature apices that had been treated for trauma with calcium hydroxide. The teeth showed periapical healing and radiographically complete apical closure. The tissues associated with apical closure showed minimal inflammation. The apical barrier consisted of a cementum-like tissue as well as calcified areas which contained vital loose connective tissue that was non-inflamed. The apical closure had established a barrier which appeared to have withstood condensation of the gutta percha filling. Leonardo and Holland (1974) evaluated clinically and histologically the effect of a calcium hydroxide plug combined with a gutta percha and Richert's cement filling in the one-appointment treatment of vital human teeth. Biological closure of the apical foramen occurred when a barrier separated the filling material from the pulp stump. When Richert's cement accidentally contacted the pulp stump, an inflammatory reaction occurred. When the barriers of either calcium hydroxide or dentin chips were present, they prevented inflammation and post-operative pain. Heithersay (1975) outlined 11 treatment uses for calcium hydroxide. He discussed the possible modes of action, and described a technique for the use of a commercially prepared calcium hydroxide called Pulpdent. Krakow et al. (1977) used Pulpdent (calcium hydroxide with methyl cellulose) to maintain pulp vitality and to achieve complete root formation. They reported that root canal treatment was not needed after completion of root formation. Holland et al. (1977) investigated the histologic characteristics of human apical tissues after vital pulp extirpation and immediate root canal filling with calcium hydroxide. Results indicated that the healing process of the apical tissues was similar to the healing process of pulp exposures coronally when the same materials were used. They also found that calcium hydroxide as a root canal filling material maintained the pulp stump vitality and induced apical closure by hard tissue deposition. Weinstein and Goldman (1977) found no apical bridging histologically in adult monkey teeth with vital or necrotic pulps in which calcium hydroxide was placed in the apical third for nine to 11 months. Citrome et al. (1979) compared calcium hydroxide, calcium phosphate gel, and induced blood clots in an histologic study of necrotic dog teeth. All samples with calcium hydroxide showed apexification and cementogenesis, while none of the calcium phosphate gel samples showed any, and the blood clot produced only one sample that showed cementogenesis. Goldberg and Gurfinkl (1979) used Dycal-coated gutta percha points and found that Dycal, used as a sealer, allowed adequate filling of the root canal and that its alkalinity persisted up to eight months after mixing. This persistence of alkalinity had a definite antimicrobial effect and stimulated the formation of the apical hard tissue. Holland et al. (1979), in a series of articles, evaluated histologically the effect of overinstrumentation, overfilling, and replacement of calcium hydroxide at thirty days. They reported that replacement assured an increase in favorable results, that closure of the apical foramen could occur in cases where the pulp stump was destroyed by instrumentation, and that overfilling with calcium hydroxide elicited resorption. They also showed that results were more favorable when no material was forced out the apex in canals instrumented to a size 80 file. They also found more favorable results when the calcium hydroxide was packed into canals that were cleaned extensively. Tronstad et al. (1981) used pH indicators on sections of monkey teeth after intracanal treatment with calcium hydroxide. They found that the pH was highest in the dentin closest to the root canal: circumpulpal dentin was pH 8.4 to 11.1, and peripheral dentin was pH 7.4 to 9.6. The periodontal membrane and cementum were unaffected. Non-treated teeth had a pH throughout of 6.4 to 7.0. Leonardo et al. (1984), in an histologic study of vital dog teeth, used calcium hydroxide to cover the pulp stump following pulpectomy and before immediate filling with gutta percha. They found that calcium hydroxide improved the condition of apical and periapical tissues. Smith et al. (1984) histologically examined monkey teeth to compare calcium hydroxide and barium hydroxide used as root canal fillings. Barium hydroxide was chosen because it had a similar pH to calcium hydroxide, and it also possessed a divalant cation. Sixteen teeth were intentionally instrumented beyond the apex and innoculated with s. faecalis for three months. Half of the experimental teeth were filled with calcium hydroxide and half with barium hydroxide. The teeth were histologically evaluated nine months after filling with calcium and barium respectively. All teeth treated with calcium hydroxide produced apexification and either dentin or cementum bridging. The barium hydroxide-treated teeth displayed no evidence of vital pulp tissue or bridging. The predominant features were multinucleated giant cells and foreign body reactions accompanied by acute and chronic inflammation periapically. Holland (1984) compared the periapical responses to apical barriers of dentin chips and calcium hydroxide histologically in ferret teeth. Teeth were prepared to size 80 file, one millimeter short of the radiographic apex. In half of the cases, dentin chips were generated with the final file in a rasping motion counter-clockwise on the canal wall and vertically condensed, producing a two- to three-millimeter plug. In the other half of the cases, calcium hydroxide was introduced into the canal and condensed with the final file. The teeth were then evaluated histologically at 84 days. The results suggest that there is little difference in response of the periapical tissues to calcium hydroxide or dentin chip plugs. Kline et al. (1985) completed a study of calcium hydroxide plugs in single-rooted, extracted human teeth to determine pH and calcium ion concentration change apically using ion specific microelectrodes. They found that calcium hydroxide increases the pH but does not seem to influence the calcium ion concentration. The fact that pH rises in the presence of calcium hydroxide apical plugs could indicate that the plug is dissolving and that over time their seal could be suspect. Javelet et al. (1985) completed an histologic study of immature monkey teeth innoculated with staphylococcus aureaus that compared the effects of high and low pH levels on the induction of calcific barriers. They used calcium hydroxide, pH 11.8, and calcium chloride, pH 4.4, and observed at three and six months periapical repair and formation of calcified apical tissue in pulpless, infected, immature teeth occurred more readily with calcium hydroxide than with calcium chloride or empty canals. The fact that complete apical closure was not observed in teeth filled with calcium chloride suggests that the high pH of calcium hydroxide may play a more significant role than the presence of exogenous calcium in the induction of root closure.

PERMEABILITY OF APICAL BARRIER

Permeability of the apical barrier placed in endodontic procedures has been examined. Douglas and Zakariasen (1981) reported a volumetric assessment of apical leakage utilizing a spectrophotometric dye recovery technique. They immersed obturated teeth in an aqueous solution of two-percent methylene blue dye for an appropriate dye exposure. The stained teeth were then dissolved in nitric acid to return the dye back to solution. The method was found to be easy to utilize, was subject to minimal error, and provided determination of volumes of leakage rather than linear measurements. Pappin (1982) used 60 single-rooted teeth that contained pulp tissue following extraction and filled them with a one-millimeter apical dentin chip barrier plus a gutta percha and zinc oxide and eugenol filling. The apical canals in these teeth were permeable to 1.5 mm when immersed in S^{35}. Zakariasen and Fuller (1982) investigated in vitro the effects that a dentin plug or a calcium hydroxide plug had on the apical seal. Extracted teeth were divided into three groups: no plug, dentin plug, and calcium hydroxide plug. The barriers were placed, the teeth obturated with gutta percha and sealer, and placed in two-percent methylene blue for two weeks. Analysis was completed with linear and volumetric measurements. They found that the calcium hydroxide plug may significantly decrease the apical leakage. The no plug and dentin plug techniques did not decrease the leakage significantly. Zakariasen (1982) compared barriers of calcium hydroxide and autogenous dentin chips by measuring leakage using volumetric assessment with spectrophotometric analysis. It appeared that the calcium hydroxide apical plug leaked significantly less than did the dentinal plug. Although leakage around the different plugs varied considerably, he reported that this was the result of the inadequacies of the spectrophotometric technique and that a vacuum system could resolve the problem. Secrist et al. (1982) studied the seal of thermo-mechanical condensation of gutta percha with and without apical plugs. They indicated that thermo-mechanical condensation with Grossman's sealer and an apical calcium hydroxide plug provided a significantly better seal than did lateral condensation with no apical plug. The teeth were immersed in two-percent methylene blue dye for one week to provide a linear measurement for assessment of leakage. El Deeb et al. (1983), using extracted teeth, some with a dentin barrier and an apical constriction in place, some with an apical constriction intact but no dentinal barrier, and others with no barrier and no constriction, found no significant difference in leakage among the three samples using methylene blue. Zakariasen et al. (1984) completed a linear dye study using two-percent methylene blue on four apical barriers. They compared refined dentin filings (high speed bur-cut and NaOCl-treated), zinc oxide powder, calcium hydroxide powder, and regular dentin filings. They determined that the calcium hydroxide plug leaked significantly less than did the refined dentin filings and zinc oxide plugs and was comparable to the regular dentin filings. Yee et al. (1984) used Ca^{45} in an autoradiographic study to determine leakage of canals inadvertently plugged with dentin and pulpal remnants. The plugs that showed no leakage to Ca^{45} ion were less fibrous in nature, with particles more tightly packed together, thus giving the plug an extremely homogenous surface. Zakariasen et al. (1985), in another linear dye study, showed that extending the apical dentin plug length back from the apex may result in increased leakage in obturated root canals. Jacobsen et al. (1985) conducted an S.E.M. analysis and a linear dye study of apical plugs. They found that teeth with apical plugs of dentinal filings showed a statistically significant larger amount of leakage than did teeth with no plugs (all teeth were obturated with lateral condensation of gutta percha and sealer). Zakariasen et al. (1986) used two-percent methylene blue in a linear dye study to compare the seal of laser-fused enamel plugs and unlased enamel plugs. They showed that carbon dioxide laser fusion of enamel-particle apical plugs significantly reduced apical canal leakage when compared to leakage which occurred through unlased enamel plugs. Wesienseel et al. (1987) evaluated dye leakage in teeth with open apices and prepared root canals. The study compared leakage found in teeth with a two-millimeter apical plug of calcium hydroxide powder to those without the apical plug. The teeth with apical plugs of calcium hydroxide demonstrated significantly less leakage than teeth without the apical plugs.

SCANNING ELECTRON MICROGRAPH APPEARANCE OF BARRIER

Scanning electron micrograph (S.E.M) analysis of apical barriers has been completed previously. Zakariasen (1982) showed the particle size of dentin chip barrier to be larger and less consistent in shape than calcium hydroxide particles. The dentin chips were produced with hand files while the calcium hydroxide powder was machined. Fuller and Zakariasen (1982) reported that a dentin plug did not improve the apical seal in comparison to conventional gutta percha and sealer obturation in which no plug was present. However, a similar plug of calcium hydroxide powder did significantly improve the apical seal. The calcium hydroxide plug was more uniform in consistency, denser, and more closely conformed to irregularities of the canal wall than the dentin plug. They stated that particle size and uniformity may explain why calcium hydroxide is less susceptible to moisture penetration. Morela et al. (1984) split teeth longitudinally that had apical barriers of dentin filings, refined dentin filings (high speed bur and NaOCl treated), calcium hydroxide, or zinc oxide. These root sections were analyzed by S.E.M. They compared particle size, uniformity, porosity, adaptation to the canal walls, and consistency from plug to plug. Zinc oxide showed the smallest and most uniform particle size, the least porosity, and the best adaptation to the canal walls. Calcium hydroxide ranked second in these qualities followed by the dentin filings and the refined dentin filings. However, the zinc oxide group exhibited zinc oxide particles adhering to the canal walls coronal to the plugs which might interfere with the sealer/dentin interface and affect canal sealability. Yee et al. (1984) determined the amount of leakage using Ca^{45} autoradiography and S.E.M. analysis of inadvertently formed apical dentin plugs. The scanning electron microscope study showed that the process of dentin plug formation was a gradual packing of particles of dentin into the apical region of the canal, usually over residual pulp tissue. As packing continued, a greater amount of hard tissue particles in proportion to soft tissue resulted. The plugs that did not leak were less fibrous in nature, with particles more tightly packed together, with a surface that appeared extremely homogenous and canals that leaked did so because no plug was formed or because the one that did form was of insufficient density to stop the ingress of Ca^{45}. Jacobsen et al. (1985), in an S.E.M. analysis of the penetration of two-percent methylene blue dye, showed numerous empty spaces both at the interface between the plugs and the dentin walls and in the core of the plugs.

CHAMBER DEVICE

A chamber device to measure the permeability of dentin and hydrostatic pressure of fluids passing through dentin, *in vitro*, has been developed. Outhwaite et al. (1974) described the use of the split chamber device to measure dentin permeability. It was a closed system designed to minimize the evaporation of solutions and to allow for continuous perfusion of both sides of the dentin sample. Merchant et al. (1977) used a split chamber device to quantitatively compare the rates of Krebs-Ringer phosphate buffer with radioactive sodium iodide permeation through dentin by diffusion and filtration. They stated that filtration through dentin might offer some significant therapeutic advantages over diffusion. They used a known and constant hydrostatic pressure for filtration and showed that filtration doubled the rate of permeation of dentin before acid etching when compared with diffusion after acid etching. A 32-fold increase in permeation occurred by filtration. Pashley et al. (1978) used a split chamber device to calculate resistance to fluid flow through dentin. Resistance was found to be a result of surface resistance and varied due to the presence of debris occluding dentinal tubules, mineralized nodules, internal irregularities within the tubules, or odontoblastic processes and cell bodies within the tubules. They speculated that a fourth resistance was offered by the intact pulp chamber and root canal with its constricted apex and peripheral tissues. They showed that the first three surface resistances accounted for 86 percent of the total resistance. Pashley et al. (1978), using the split chamber device, compared the permeability of four types of dentin surface: a highly polished surface cut with a diamond saw, a bur-roughened surface, a surface etched using 50-percent citric acid, and a surface occluded by the precipitate of three-percent monopotassium monohydrogen oxalate. Using permeability coefficients and measuring surface area by two different techniques, they reported that the increase in tubular surface area available for diffusion after acid etching could be reversed by treating the surface with oxalate. Greenhill and Pashley (1981) used the split chamber device to determine the rate at which buffered solutions could filter across dentin under a known constant hydrostatic pressure. The discs of dentin were treated with agents thought to desensitize (occlude) dentin to determine if these agents reduced fluid flow. The treated discs showed more than 50 percent reduction in the flow rate and were examined by scanning electron micrography (S.E.M.) for occluded tubular orifices. Pashley et al. (1981) used the split chamber to measure dentin permeability and examined dentin discs with the S.E.M. to determine the effect of sequentially removing the smear layer, due to instrumentation, with applications of dilute citric acid and correlated the treatment with dentin permeabilty. Pashley and Galloway (1985) used a split chamber device to measure dentin permeability and hydraulic conductance in a study in which dentin was subjected to topical treatment with solutions of potassium chloride, neutral potassium oxalate, as well as neutral and acid oxalates. Frydenlund and Krell (1986) used a modified split chamber device to measure dentin permeability and hydraulic conductance in a study of scaling root surfaces, using sharp and dull instruments. The use of the sharp scalers on root surfaces significantly increased hydraulic conductance which may be reversed by burnishing with dull instruments. Krell and Frydenlund (1986) also used a modified split chamber device to study the effect of citric acid on hydraulic conductance when the citric acid was applied externally to root surfaces. They found that citric acid did not significantly increase hydraulic conductance, and they suggested that the smear layer found on root surfaces due to scaling was not easily removed by etching. Pashley et al. (1986) used a split chamber device to quantitate the fluid filtration rate through dentinal tubules (hydraulic conductance) when root surfaces were burnished with a paste of NaF, kaolin, and glycerin. The results indicated that burnishing reduced permeability more effectively than any of the other pastes used.

It is the purpose of this study to utilize the split chamber device to determine if the density of an apical barrier is the primary factor in prevention of the movement of fluid across it.

METHODS AND MATERIALS

Forty freshly extracted single-rooted human teeth were randomly selected for the study. Thirty teeth were utilized in Part One of the study, and ten teeth were utilized in Part Two. The clinical data regarding the reason for extraction, age and sex of the patient, and tooth number are presented in Table I and Table IV. After extraction, the teeth were fresh frozen and stored at -11°C until needed for processing. During the time they were used for experimental measurements, they were held at 100 percent humidity and 22° to 26°C.

Part One: Experimental Sample with Standardized Apex:

A. Preparation of Teeth:

Crowns of the teeth were removed at the cemento-enamel junction with a circular carborundum saw using coolant irrigation. This provided a flat root surface and access to the root canal system. The flat surface of the root was glued with cyanoacrylate cement[1] to a delrin washer for placement in the chamber device. To prevent possible leakage through lateral canals, the root surface was painted with three coats of methylcellulose fingernail polish[2] and was allowed to bench dry (Figure 1).

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[1] Krazy Glue manufactured by Krazy Glue, Inc., Itasca, Illinois.

[2] Quencher Nail Glaze, Clear: 701, Clearwater Natural, manufactured for Millet-Morton Co., Richmond, VA.

B. Standardization of the Apex:

The apex of the root was reduced with a 1558 high-speed carbide bur to allow the insertion of a #25 file 1-2 millimeters into the apical opening (Figure 2).

C. Preparation of the Canal:

Canal preparation was consistent for all samples. Once the crown was removed and the apical opening standardized, the canals were examined for pulp tissue. Teeth with empty canals were discarded. The root segments were irrigated with water using a syringe and a 25-gauge needle. It was noted if the root segment was completely blocked, freely irrigated, or partially blocked (only a drop of water expressed at the apex).

Root length was determined by placing a #25 file in the root segment flush with the reduced apex. A rubber stop was placed on the file and was set at the surface of the delrin washer as a reference point. Canal preparation length was measured one millimeter less than the root. The canals were prepared (See Pappin, 1982) to a file size two times the size of the first size to bind. The canals were irrigated and filed so that the apex was patent. Water could be passed through the apical end of the root segment, and paper points could be seen through the apex (Figure 3).

D. Placement of the Apical Barrier

After the canals were dried, either autogenous dentin chips, dry calcium hydroxide powder[3], or durapatite[4] was placed as an apical barrier in

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[3] Lilly USP Calcium Hydroxide Powder No. 40 manufactured by Eli Lilly and Company, Indianapolis, IN.

[4] Periograf periodontal bone-grafting implant material, durapatite (40-60 mesh) manufactured for Cook-Waite Laboratories, Inc., New York, NY.

the 30 root segments of Part One. All barriers were terminated one millimeter from the end of the root and were one millimeter in thickness.

Autogenous dentin chip barriers were placed in ten root segments. The dentin chips were generated using a #4 Gates-Glidden drill on the dry walls of the coronal one-third of the prepared root canal. These chips were swept apically using extra coarse and medium-sized paper points and lodged in the apex. A file, one size larger than the final file size used in preparation, was used to start packing the chips to form a barrier. Then consecutively smaller files were used. All files were rotated counter-clockwise and up and down at the same time. The barrier was tested for mechanical resistance with the use of a #10 file. If resistance was not met, the process was repeated beginning with the generation of more chips with Gates-Glidden drill followed by repacking with the series of files. Resistance was judged to be adequate when the #10 file felt as though it were striking a formica countertop (Figure 4).

Small increments of dry calcium hydroxide powder were placed in ten root segments with an endodontic Messing Gun[5]. The powder was then swept apically as above using extra coarse and medium-sized paper points. A large file was used as above for packing the calcium hydroxide powder until the same resistance was met with the #10 file. This procedure of placing and packing powder was repeated until the resistance was adequate.

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[5] Union Broach Messing Root Canal Gun #23500.

Durapatite, 40-60 mesh, a particulate ceramic used in bone grafting and as an implant material, was ground to an appropriate size in a mortar and pestle. A vibrating column containing layers of monofilament nylon mesh screens of decreasing mesh size, 500 microns, 350 microns, 250 microns, and finally 210 microns, was used to collect particles that passed through the 250-micron screen but not through the 210-micron screen. These particles were carried into the canal using a Messing Gun[5] and packed in the same manner as above, sweeping with paper points, packing with a file rotated counter-clockwise, up-and-down motion until the same resistance was felt with a #10 file.

The thickness of each barrier was tested by placing a #10 file from both ends into the canal until resistance was felt. Measurements were made to ensure that all barriers were one millimeter plus or minus one-half millimeter thick.

E. Experimental Apparatus

The apparatus was designed to measure water flow through the canal at a constant pressure. Each tooth acted as its own control, with a pretreatment and post-treatment pressure/flow measurement. Pressure could be varied for individual teeth depending upon flow resistance. The apparatus was capable of establishing a range of pressures from 10 mm Hg (0.19 psi) to 1396.31 mm Hg (27 psi). Flow in the order of milliliters-per-second to microliters-per-minute could be determined by measuring the rate of liquid displacement in either a graduated six-milliliter syringe barrel or a 50-microliter pipette.

Root segments were placed in a chamber device designed by Outhwaite et al. (1974) and modified by Pashley et al. (1978) (Figure 5). Hydrostatic pressure applied to one side of the chamber induced fluid movement through the unfilled or filled root segment and into the other side of the chamber. The rate of fluid movement was then measured by timing the fluid displaced in either the micropipette or a graduated six-milliliter syringe barrel connected to the other side of the chamber (Figure 6).

Typical samples were tested for leakage at the tooth-disc interface and the coated root surface by sealing the apical opening with glue and placing it under pressure. No measurable conductance occurred at 27 psi developed by the apparatus.

Before placement of the barrier, flow was measured at low pressure (because of the low resistance) using the six-milliliter syringe barrel (because of the relatively high flow). This system utilized the bulb from a blood pressure sphygmomanometer to develop pressures of 20 mm Hg. The air pressure was transferred to a liquid column by utilizing a reservoir of distilled water in a 250-milliliter flask. The liquid column was in turn applied to the root segment in the chamber device (Figure 6).

A selector valve was utilized to convert the apparatus to a system for developing high hydrostatic pressures and measuring small amounts of flow. This system, using filtered and regulated compressed air, developed pressure of 20 pounds per square inch. Pressure was transferred to a liquid column via the same reservoir of distilled water in a 250-milliliter flask. The column was applied to root segments via the chamber device after the apical barrier was placed. The flow as a result of this pressure was measured by liquid displacement in a 50-microliter pipette and expressed in units of microliters-per-second (Figure 6).

F. Recording of the Measurements

First, the hydraulic resistance of the chamber and associated tubing was determined by measuring the time required for four milliliters to flow into a graduated six-milliliter syringe barrel at 20 mm Hg (0.386736 psi). Next, filtration of the root segments, mounted in the chamber, without barriers but with a standardized apex, was determined by taking four replicate flow rate measurements at 20 mm Hg. Then filtration time was determined in ten root segments with a dentin chip barrier, ten root segments with a calcium hydroxide barrier, and ten root segments with a durapatite barrier. The pressure used with the barrier in place was 20 psi (1034.30 mm Hg), and the volume displaced was measured with a 50-microliter pipette. The 50-microliter pipette was placed over a millimeter rule, and the meniscus movement was viewed and measured with use of an Ednalite macroscope(TM)[6]. If the fluid movement in ten minutes was less than 0.5 μl (one millimeter in the 50-microliter pipette), flow was recorded as zero. The results were calculated and expressed as the hydraulic conductance in microliters per second per psi.

G. Scanning Electron Microscopy

Scanning electron micrographs[7] (S.E.M.) were made of ground cross-sections of selected barriers to show the consistency and density of the barrier at the canal wall interface. A representative sample of each barrier was imbedded using the Buehler(TM)[8] expoxide resin system: 35 grams of resin and

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[6] Ednalite Macroscope, Model 150A, Ednalite Research Corporation, Peeko Kill, New York.

[7] Scanning Electronmicroprobe Model EMXSM, Applied Research labs, Sunland, CA.

[8] Buehler Expoxide Resin, Buehler, Ltd., Evanston, Illinois.

seven grams of hardener. One-inch plastic rings were placed over root samples which had been glued to mylar sheets. The Buehler(TM)[8] resin was poured over the root end and filled the ring. Then the sample was left to bench set for 24 hours.

The dentin chip and durapatite samples were wet ground on a 120-grit Leco(TM)[9] belt sander until the sample was exposed. The specimens were then hand sanded wet with 320-, 400-, and 600-grit paper. The calcium hydroxide sample was dry sanded using a 120-grit belt sander. It was then hand sanded dry using 320-, 400- and 600-grit paper. After grinding, the samples were observed with a 60-power microscope and checked with a #15 file to insure that the barrier was still intact.

The samples were further polished using Polimet Polisher(TM)[10] and Metal Graphic Polishing Wheels(TM)[11] utilizing a nylon cloth stretched over an eight-inch brass wheel with Metadi II(TM)[12] diamond compound of 15, nine, and three microns. The three-micron polishing required changing cloths to a Microcloth(TM)[13] to complete the polishing phase. The dentin chip and the durapatite samples were wet polished. The calcium hydroxide sample was dry polished and cleaned with xylene on a cotton-tipped swab to remove the polishing compound around the edges of the interface.

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[9] LECO Wet Belt Sander, LECO Corporation, St. Joseph, MI.
[10] Polymet Polisher, Buehler, Ltd., Evanston, IL.
[11] Metal Graphic Polishing Wheels, Buehler, Ltd., Evanston, IL.
[12] Metadi II Diamond Polishing Compound, Buehler, Ltd., Evanston, IL.
[13] Metal Graphic Polishing Wheels-Microcloth, Buehler, Ltd., Evanston, IL.

The Varian Vacuum Evaporator(TM)[14] was used to carbon coat samples for viewing with the Scanning Electronmicroprobe(TM)[8]. Photographs were taken of each sample at 125X, 500X, and 4,000X (Figures 7-15).

For the dentin chip preparations, the chips were examined under the light microscope, also, in order to estimate chip dimensions.

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[14] Varian VE10 Vacuum Evaporator, Carbon Coater

Part Two: Experimental Sample with Non-standardized Apex

The preparation of ten teeth for Part Two was similar to that described for Part One except that the apex was not reduced and the apical opening was not standardized to a size #25 file. The preparation of the canal and placement of the dentin chip barrier used the same technique. A #10 file was placed to the true working length following canal preparation to check for unintentional blockage. The apparatus used for testing the barrier was the same.

All samples with non-standardized apex contained tissue in the canals prior to treatment. These samples were measured for permeability prior to preparation of the canal, immediately following canal preparation, and following the placement of a dentin chip barrier.

RESULTS

Part One: Hydraulic Conductance with Standardized Apex:

The hydraulic conductance rate was calculated from the average of quadruplicate flow measurements through each standardized sample in the chamber device. Conductance is listed in Table II, expressed in units of microliters-per-second per psi driving pressure.

Before barrier placement, flow averaged 68.4 μl/sec/psi for all 30 teeth (range 33.2-80.5 μl/sec/psi). Standardization of the apical opening was effective in reducing the variability of hydraulic conductance. The conductance standard deviation was 10.5 μl/sec/psi which represents only 15.4 percent of the mean conductance (compare with the variability of the non-standardized root conductances listed in Table V).

The standardized root segments were then used as controls to compare the effectiveness of each barrier (Table II). The mean results for the ten teeth in which autogenous dentin chips were used as the barrier material showed a reduction in flow from 74.5 μl/sec/psi prior to placement of the barrier to 0.0010 μl/sec/psi after the barrier was placed. Thus, the barrier reduced hydraulic conductance to 0.0013 percent of its control value. The mean result for the ten teeth in which dry calcium hydroxide powder was used as the barrier material showed a reduction in flow from 67.1 μl/sec/psi to 0.0012 μl/sec/psi. The calcium hydroxide barrier reduced hydraulic conductance to 0.0018 percent of its control value. The mean result for the ten teeth in which durapatite was used as the barrier material showed a reduction in flow from 63.5 μl/sec/psi to 0.0220 μl/sec/psi. The durapatite barrier reduced hydraulic conductance to 0.0350 percent of its control value. Six of the ten samples of the dentin chip group and six of ten samples of the calcium hydroxide group had no measurable leakage (less than 0.5 μl in ten minutes). All samples of the durapatite group had measurable leakage.

An analysis using Student's two-tail t-Test presented in Table III showed that mean conductance for both autogenous dentin chips and calcium hydroxide powder were significantly different from the durapatite at the $p=0.05$ level, but the dentin chips and the calcium hydroxide were not significantly different from each other. Also, no statistically significant difference was shown between the standardized groups prior to placement of the barriers.

Part Two: Scanning Electron Micrographic Evaluation:

Scanning electron micrographs (S.E.M.) were made of the barriers of selected teeth to evaluate the physical appearance. Dentin chip Sample DC7 at 125X, 500X, and 4,000X (Figures 7-9) showed a dense barrier of uniform consistency. It appeared to be similar in consistency and density to the surrounding root dentin. Calcium hydroxide barrier Sample CH6 at 125X, 500X, and 4,000X (Figures 10-12) showed less density with a uniform consistency. It had the appearance of granular, uniform, machined powder particles. The calcium hydroxide sample was well condensed but appeared more porous than the dentin chip at the highest magnification. Durapatite barrier Sample TCP6 at 125X, 500X, and 4,000X (Figures 13-15) showed good density but inconsistent uniformity. The particles were grossly inconsistent in size. At the highest magnification, large voids were apparent. The consistency, uniformity, and density of the barrier was consistent with the increased flow found in durapatite barriers as compared to the autogenous dentin chips and the dry calcium hydroxide powder.

Part Two: Particle Size Microscopic Evaluation:

Prior to placement of autogenous dentin chips, the apical barrier particle size was determined under the light microscope using a calibrated reticule. The particles appeared to be on the average of 132 X 33.5 microns, ranging from 10 X 10 microns to 260 X 70 microns. The particles appeared to be fibrillar and filamentous in nature (Figure 16).

Part Three: Hydraulic Conductance with Non-Standardized Apex:

Three separate measurements of hydraulic conductance were made for the ten non-standardized root segments (Table V). The first measurements were made prior to preparation of the canal with visible tissue remaining in the canal. The second time measurements were made following preparation of the canal, and a third set was made following placement of an autogenous dentin chip barrier.

The mean flow was reduced from 0.0436 μl/sec/psi for pre-treatment root segments to 0.0025 μl/sec/psi for the same root segments following preparation of the canal space, and the flow was further decreased to 0.0002 μl/sec/psi for the same root segments following placement of the autogenous dentin chip barrier. This resulted in a mean percent reduction from the initial control to the final measurement of 0.4358 percentage. The initial flow measured by the chamber device averaged 0.0436, ranging from 0.0018 to 0.2135 μl/sec/psi. The standard deviation of these control values was comparatively greater than the standardized apex.

An analysis using a Student's two-tail t-Test presented in Table VI showed that mean conductance for both the post-preparation samples and the post-barrier placement samples were significantly different from the pre-preparation sample at $p=0.05$ level, but that the post-preparation sample and the post-barrier placement samples were not significantly different from each other.

The preparation of the canal space prior to placement of the barrier which resulted in significant reduction of the flow probably was caused by compaction of dentin debris and/or tissue remnants against the apical constriction. Although not statistically significant, the placement of the autogenous dentin barrier, when flow had not already been totally eliminated by canal preparation, decreased flow further.

DISCUSSION

REVIEW OF RESULTS

The variability of conductance seen in untreated roots was effectively reduced by preparing the root apex to a standard size.

The autogenous dentin chip barrier produced a further reduction of hydraulic conductance to 0.0013 percent of the control level, while the calcium hydroxide barrier produced a reduction to 0.0018 percent of the control. The durapatite barrier produced a reduction of only 0.0350 percent of the control.

The autogenous dentin chip barrier and the calcium hydroxide barrier showed statistically significant less leakage when compared to the durapatite barrier but were not significantly different from each other ($p=0.05$ and $N=10$). Scanning electron micrographs showed the autogenous dentin chip barriers to be uniformly dense, consistent, and similar to the surrounding root dentin. The calcium hydroxide barriers appeared to be consistent but less dense than the dentin chip barriers, while the durapatite barriers were inconsistent in particle size and were the least dense, showing voids between particles at higher magnifications.

The non-standardized root segments showed a reduction in conductance that was statistically signficant ($p=0.05$ and $N=10$) from canal preparation alone. Although conductance was further reduced following the placement of the autogenous dentin chip barrier in the non-standardized root, this reduction was not significant.

The fact that these barriers are effective in reducing conductance at 20 psi indicates their ability to prevent extrusion of debris beyond the barrier during root canal obturation.

The consistency of the material and the size of the particles enhance placement as well as influence the density of the barrier resulting in decreased conductance. The autogenous dentin chips and the calcium hydroxide powder were very effective barriers. The use of each barrier clinically may depend upon case selection.

The fact that all non-standardized samples exhibited a reduction in conductance upon preparation alone indicates the difficulty encountered during clinical preparation. During preparation, the packing of canal debris into the apex occurs. Steps must be taken to minimize the amount of debris in an effort to adequately clean the full length of the canal while debris is removed.

ADEQUACY OF METHODS

Teeth were prepared in such a manner that placement in a chamber device allowed measurement of conductance through the apical barrier. To eliminate the influence of formalin or other preservatives on tissue and barriers, the teeth were fresh frozen until used and stored at 100 percent humidity between procedures. Pilot studies completed on teeth stored in formalin indicated that the methylcellulose coating would not set nor would the delrin washer bond to the dentin surface. Freshly frozen teeth glued to the washer and then coated with methylcellulose remained bonded and sealed, if the teeth were used immediately. Some mounted teeth, left overnight in 100 percent humidity, leaked grossly. Teeth that showed leakage could be reglued to the washer and sealed. Well-bonded samples were difficult to remove from the washer.

Pilot studies also indicated that teeth with intact apical constrictions and apical foramen had various conductance rates whether the canals were prepared or not. This variability was reduced by cutting back the apical opening so that a size #25 file could be placed one to two millimeters into the apical portion of the root (Figure 2).

Thirty teeth with the clinical crown removed and the apical canal diameter standardized gave a rate of conductance that showed a standard deviation of 15.4 percent of the mean, while ten non-standardized samples showed a standard deviation of 171.3 percent of the mean conductance.

The experimental apparatus (Figure 6) was designed to measure the time for a meniscus to flow one millimeter in a specifically sized pipette at a given pressure. As a result of pilot studies, it was determined that once the apical canal size was standardized and barriers placed, 20 psi pressure allowed reproducible conductance measurements.

The resistance of the measurement system was the sum of resistance of long lengths of small bore tubing and the resistance of the chamber device itself. Using distilled water at a uniform temperature, tests made using a standardized root segment in the chamber device with and without a barrier showed little variation in the resistance of the entire system. The calculated hydraulic conductance for the apparatus with no root segment in the chamber was 87.3 μl/sec/psi. The mean conductance of 30 root segments in the chamber before barrier placement was 68.4 μl/sec/psi. Thus, the apparatus itself contributed 78.4 percent of the total resistance, and 21.6 percent was due to the standardized root segment. When barriers were placed in the root segments, the resulting hydraulic conductance values were so small that there was no doubt that resistance was due to the barrier and not due to the system used to measure the conductance.

For the high conductance (low driving pressure) measurements, attempts to maintain pressure at 20 mm Hg with a sphygmomanometer bulb were difficult. Readings were consistently plus or minus one mm Hg. The residue of water coating the syringe walls after each run could have influenced the rate of fill.

The canal preparation utilized a crown down preparation developed by Pappin (1982) as described previously. Standardized samples were more easily irrigated and the apical patency more easily maintained prior to placement of the barriers than were the non-standardized samples. These teeth were frequently blocked during preparation and gave a conductance of less than 0.5 μl at ten minutes following preparation of the canal. Apical patency was not easily maintained because tissue and dentin debris blocked the apical constriction of all teeth. No attempt was made to remove the pulp tissue with a barbed broach prior to preparation. The fresh frozen extracted teeth with visible tissue in the canal space (prior to preparation) frequently had tissue remnants remaining apically after using Gates Glidden drills. When a needle and syringe were used to irrigate initially, after Gates Glidden preparation, or after enlarging the apical opening with a #25 file, the irrigant exited only occlusally. Only after the canal was cleared of tissue remnants and debris using a #10 file forcibly would water freely pass through the apex. It appeared that the blockage was not just dentin debris created during filing but also pulp tissue. Soft tissue remnants were resilient to instrumentation and general dentin debris was not. In Sample CH5, water passed freely through the apex after the pulp tissue was removed totally using a #35 file; however, when the canal preparation was completed to a #60 file, the apex was blocked.

Fuller and Zakariasen (1982) studied apical barriers using autogenous dentin chips generated by hand filing and gouging the canals following preparation. Their different results may have been due to non-uniformly sized chips. In the present study, a #4 Gates Glidden drill in a slow speed handpiece was used coronally in the canal to generate dentin chips. These chips were then swept down the canal and packed as described previously. The use of the handpiece-driven drill was an attempt to generate dentin chips of a more uniform particle size. The dentin chips appeared as very small dustlike particles in the orifice of the canal and were shown to be of more consistent particle size averaging 132 X 33.4 microns.

Fuller and Zakariasen (1982) showed different results when they used calcium hydroxide barriers. The calcium hydroxide was carried to place in fairly large increments using an amalgam carrier. In the present study, a Messing Gun was used to place small increments of material which were more easily controlled and more likely to be densely packed into the apical region. The sweeping action with coarse paper points and the counterclockwise, up-and-down motion of an instrument one size larger than the apical canal followed by decreasingly smaller instruments resulted in placement of the barrier at one millimeter, plus or minus one-half millimeter, short of the terminus of the canal. The barrier was tested and measured from the occlusal opening and the apical opening of the root so that its thickness could be determined. These measurements were made before and after testing. Frequently during testing, barrier material was lost from the apical side, reducing the final thickness.

It was also noted that leakage might occur initially as pressure was applied to the barrier. However, it appeared to stabilize, and the leakage stopped. No further leakage occurred on these occasions even when the pressure was increased to 27 psi. The barriers that leaked initially under pressure may not have been originally compacted enough but were compacted and made more dense later on by the water pressure. The loss of barrier thickness during testing seemed to have no effect on leakage. Barriers ranged from one-half millimeter to one-and-one-half millimeters, and none leaked.

An attempt to analyze the compactness of the barriers and the particle arrangement was made using scanning electron micrographs. Samples were prepared as described previously. Evaluations were difficult because of sample cracking from dessication during S.E.M. preparation for viewing. Calcium hydroxide samples also showed striations in the dentin adjacent to the barrier probably due to the dry grinding and polishing (Figures 10-12). Durapatite barriers showed voids at higher magnification and inconsistent particle size at lower magnifications (Figures 13-15). Particle size of the durapatite was not less than 210 microns or greater than 250 microns. It is possible that compaction of the barrier apically could result in production of smaller particles. The U.S.P. calcium hydroxide powder has an average particle size of two to five microns according to Roberts and Brilliant (1975). The autogenous dentin chips generated by a #4 Gates Glidden drill were found to be fibrillar or filamentous in appearance under the light microscope. They were heterogenous in size ranging from the longest, 260 X 70 microns, to the smallest, 10 X 10 microns. The average size was 132 X 34 microns. Dentin dust generated by the Gates Glidden drill was placed on a slide in synthetic mounting resin and cover slipped. A ten-power eyepiece produced increments of two microns on the stage for measurement of particle size using an ocular reticule scale. Light microscope photographs (Figures 16-19) showed crystal size at 10X, 40X, 100X, and 160X to be fibrillar and collagenous in nature. This feature added to the ability of dentin to produce well compacted barriers similar to the calcium hydroxide particles, whereas the durapatite particles were more rigid, less flexible, and were not easily compacted, thus producing voids at higher S.E.M. magnifications.

COMPARISON OF RESULTS WITH WORK BY OTHERS

Zakariasen (1982) and Zakariasen and Fuller (1982) reported on the effects of intentional apical plugging with dentinal filings and calcium hydroxide powder on apical sealability. These investigators proposed an *in vivo* study to determine which type of plug would result in the most effective apical seal following lateral condensation of gutta percha. They used two-percent aqueous methylene blue dye after the barriers were placed, and the canals were obturated to evaluate leakage both longitudinally as well as volumetrically. The stained teeth were decalcified in nitric acid to place the methylene blue back into solution. A spectrophotometric analysis of this solution was used to determine the amount of leakage. Their study indicated that the dentin chip plug had the greatest leakage, while the calcium hydroxide plug had the least leakage. The final file used in preparing the canal was used in a push-pull movement to generate the dentinal filings. The particle size generated by this technique was random and likely to produce non-uniform chips. Randomly sized dentinal filings do not fit together as closely as do finely machined three to five micron calcium hydroxide particles. The leakage from the dentinal filings in their study compares similarly to leakage achieved with durapatite in our study.

Zakariasen (1982) and Fuller and Zakariasen (1982) also reported the results of an S.E.M. analysis of dentin and calcium hydroxide apical plugs when the teeth were split longitudinally through the apical foramen and viewed at 200X and 2000X. The calcium hydroxide plugs were consistently dense in appearance and the particles were consistent in size although smaller. The calcium hydroxide particles appeared to be more densely packed and better adapted to the canal wall compared to dentin chip plugs. The dentinal plugs revealed large and inconsistent particle size, loosely packed and not well adapted to the canal wall. As noted above, the technic for generating dentinal filings resulted in inconsistent, large particles which could not compare with the calcium hydroxide particles in compaction and adaptation against canal walls. The dentinal barriers in this study showed particles of a consistent size, and the plug was as dense as the adjacent dentin. The dentin particle size compared favorably with the three to five micron size of the calcium hydroxide powder.

Zakariasen (1982) and Secrist et al. (1982) reported the permeability of thermomechanically condensed gutta percha canal fillings with and without apical barriers. Leakage measured longitudinally was the same as leakage in teeth filled with laterally condensed fillings with apical dentin barriers and apical calcium hydroxide barriers. The dentinal filings were generated as in Fuller and Zakariasen (1982). The inconsistent particle size obtained by these investigators remains a criticism.

Yee et al. (1984) utilized Ca^{45} and autoradiographic studies as well as S.E.M. examination to determine the leakage of apical dentin barriers. The barriers were placed with consecutively larger files, and the barriers produced were tested for completeness at one file through five file sizes. The group instrumented with four file sizes showed significantly less leakage than any of the other groups at $p \leq 0.01$. The dentin chips (generated with handfiles) were probably inconsistent and markedly random in particle size. They concluded that dentin barriers could occur inadvertently during instrumentation, and the resistance to penetration by the isotope would vary according to the density of the barrier. With their technic, the dentin barrier formation was a gradual packing of particles of dentin into the apical region of the canal, usually over residual pulp tissue. As preparation continued, a greater proportion of hard tissue particles was generated in proportion to the initial soft tissue. Hession (1976) found that canal instrumentation tended to force filing debris apically, even though the pulp tissue had been removed chemically before instrumentation. He found that 59.5 percent of the apices that were patent initially were completely or partially blocked after instrumentation.

Zakariasen et al. (1984) and Morela et al. (1984) evaluated leakage of four types of apical barriers with linear dye studies (two-percent methylene blue) and S.E.M. analysis. The four types of apical barriers consisted of: (1) dentinal barriers created by intracanal dentin filings; (2) refined dentinal filings created by a highspeed bur and commercially available powders of (3) calcium hydroxide, and (4) zinc oxide. Following placement of the barrier, all canals were obturated with gutta percha and sealer. The linear dye studies showed canals filled only with plugs of zinc oxide powder and refined dentin leaked more than canals filled with gutta percha and sealer with no plug. Plugs of calcium hydroxide powder and intracanal generated dentin filings plus regular root canal fillings showed the least leakage. The S.E.M. analysis showed the zinc oxide powder to have the smallest and most uniform particle sizes, least porosity, and best adaptation to the canal walls. Calcium hydroxide ranked next in these qualities, followed by the intracanal generated dentin filings, and then the refined dentin filings. The intracanal generated dentin filings and the refined dentin filings plugs exhibited porosities in the apical portion of the plugs and more variation plug to plug. These technics again could only generate random, inconsistent particle size from gouging the wall of the canal with hand instruments or high speed burs. The irrigation with NaOCl could possibly result in small particles of barrier being placed in suspension and removed during the drying of the canal.

Another study completed by Jacobsen et al. (1985) used two-percent methylene blue dye and S.E.M. examination to determine the extent of leakage in teeth with and without apical plugs that were either obturated with gutta percha or left unfilled. The greatest degree of apical leakage occurred ($p \leq 0.01$) in teeth filled only with apical dentin plugs. The S.E.M. examination showed numerous empty spaces both at the interface between the plug and the dentinal wall and in the core of the plugs. The dentin plug was generated by forcing dentin chips into the apex by vigorous instrumentation using alternatively larger and smaller sized files. The compaction of dentin was discontinued when it became impossible to pass the final file to the original instrumentation length. This technic produced dentin filings of large and random particle size.

Zakariasen et al. (1985) studied the effect of the length of the apical dentin plug and its effect on linear dye leakage using two-percent methylene blue. They found that a four-millimeter plug showed more leakage than a one-millimeter plug. All plugs were created by filing the canal wall, turning the file counter-clockwise to carry the filings to the apex. All experimental samples showed greater leakage than controls filled with laterally condensed gutta percha and sealer. The technic for generation of dentin filings produced random, inconsistent particle sizes that produced porous, inconsistent apical plugs. Four-millimeter plugs were not as effective as one-millimeter plugs due to the inability to place and pack the increased bulk of material.

CLINICAL IMPLICATIONS

Clinically, the intentionally placed apical barrier must prevent overextension of filling materials into the periradicular tissues and separate these toxic materials from contacting living tissue. The barrier must be biocompatible with periradicular tissues and ideally stimulate closure or sealing of the root canal in its most apical aspect. It must also provide a resistant wall against which filling materials can be compacted or condensed. A review of the literature indicates that autogenous dentin chips, calcium hydroxide, and durapatite are materials biologically compatible with periradicular tissues. Autogenous dentin chips and calcium hydroxide have been reported to stimulate apical closure of the apical foramen with cementum.

This study attempted to show that these barriers were mechanically stable and capable of withstanding specific hydrostatic pressures applied to them. If leakage occurred, an attempt was made to measure the hydraulic conductance through the barriers to determine if there were significant differences in the hydraulic permeabilities of the several materials. It was determined that autogenous dentin chips and calcium hydroxide provided a resistant barrier and showed minimal hydraulic conductance through the barrier at 20 psi hydrostatic pressure.

It seems clear that apical barriers of biocompatible materials such as autogenous dentin chips and calcium hydroxide readily provide an effective immediate barrier that prevents overextension of filling materials into the periradicular tissues.

PROPOSED PROJECTS

This study has developed a method by which other materials could be tested as barriers to determine the adequacy of such materials.

An attempt to place these barriers *in vivo*, either using an animal or human study, prior to extraction of teeth could be used to determine if similar results are achieved.

An animal study could be devised that would allow determination of hydraulic conductance through barriers placed in teeth using pressure transducers *in vivo* and utilize clinical forces of lateral condensation of gutta percha.

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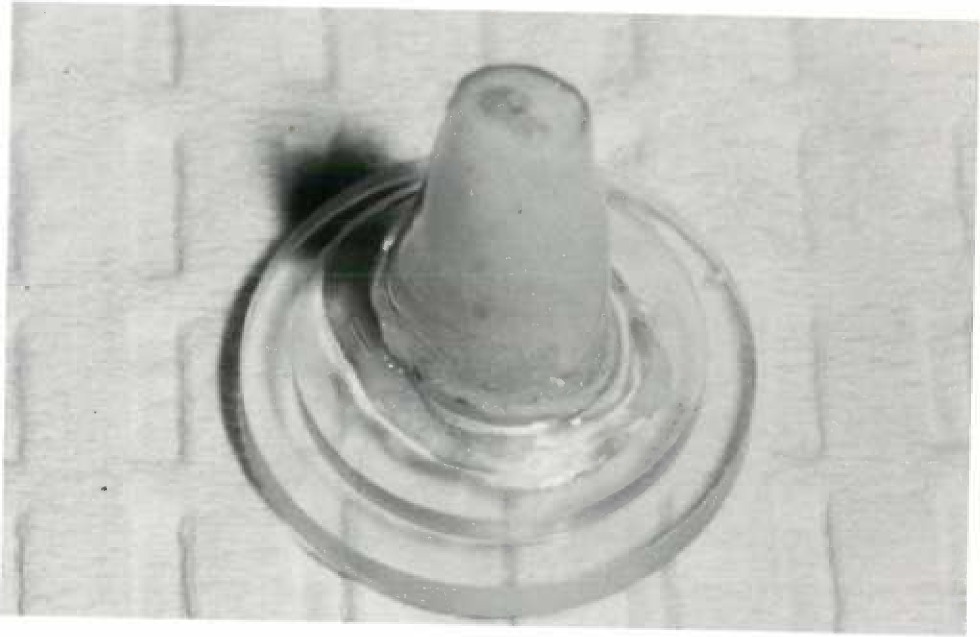

Figure 1. Beveled root section glued to delrin disc with cyanoacrylate glue then coated with methylcellulose prior to preparation.

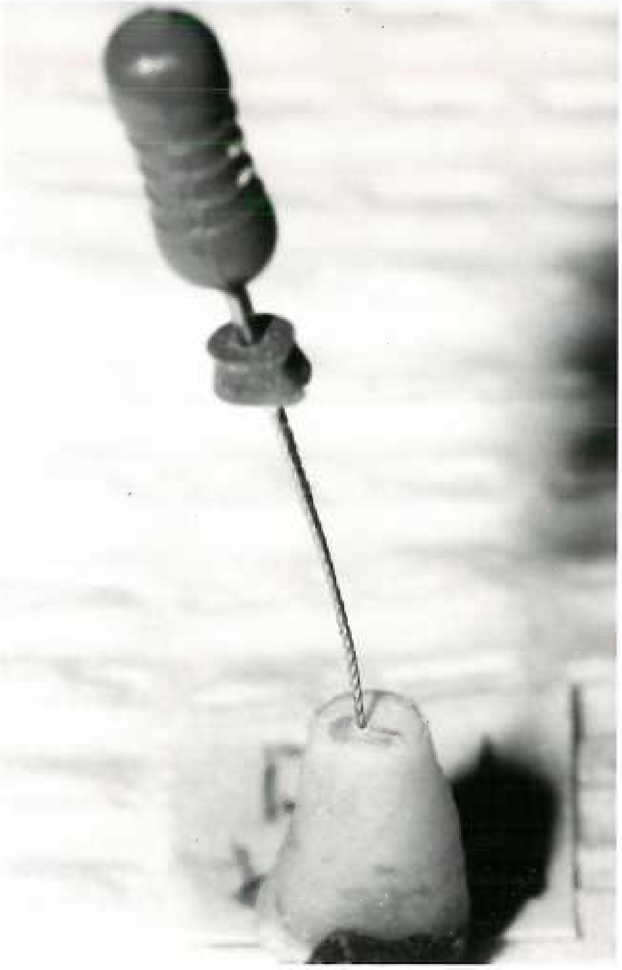

Figure 2. Beveled root section demonstrating the preparation of the last one to two millimeters of the apical opening to a size twenty-five file.

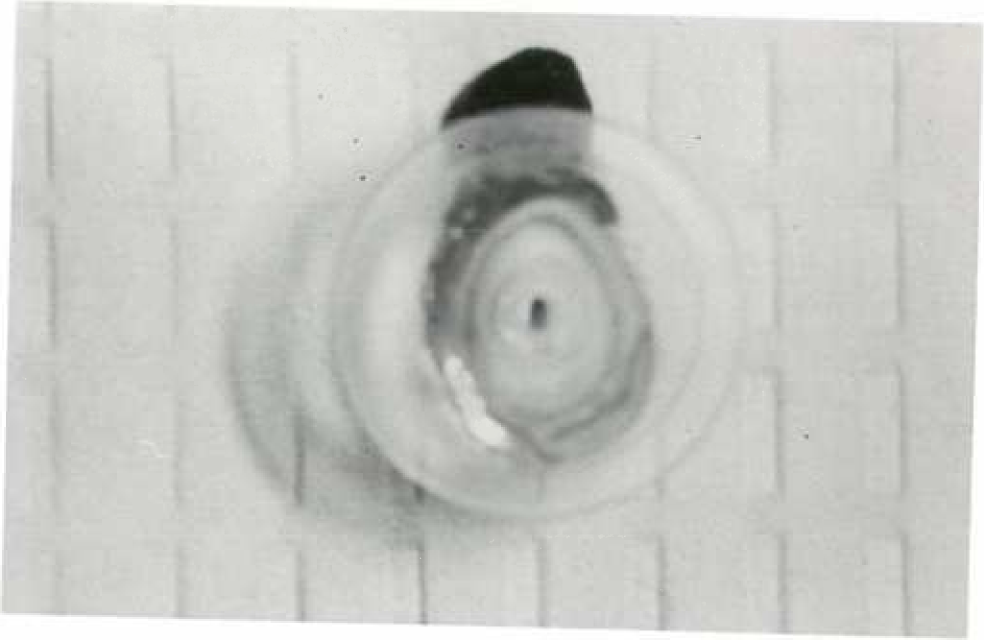

Figure 3. Beveled root section with a patent apical opening prior to barrier placement.

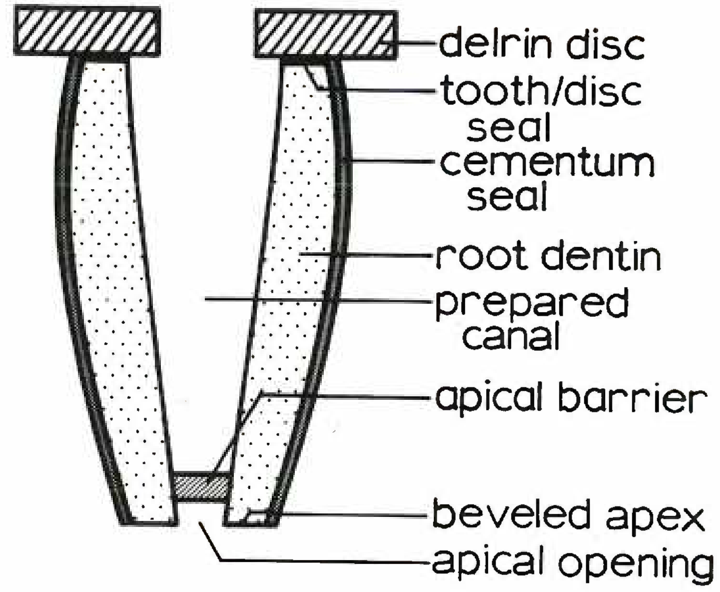

Figure 4. Schematic illustration demonstrating the root segment, delrin disc, apical barrier, the glued interface with cyanoacrylate, the coating of methylcellulose (fingernail polish), and the standardized beveled apex.

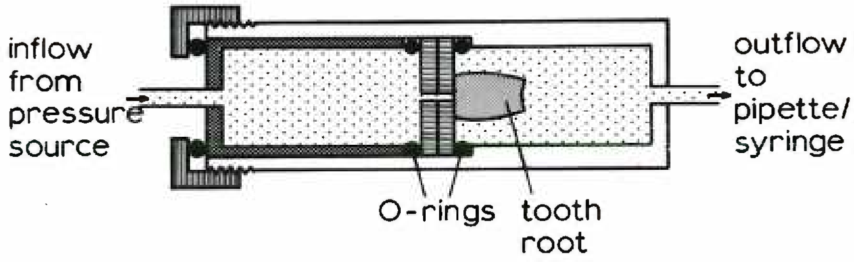

Figure 5. Schematic illustration of the chamber device demonstrating the placement of the root segment and the relationship of flow from the pressure source through the chamber and root segment to the pipette measuring device.

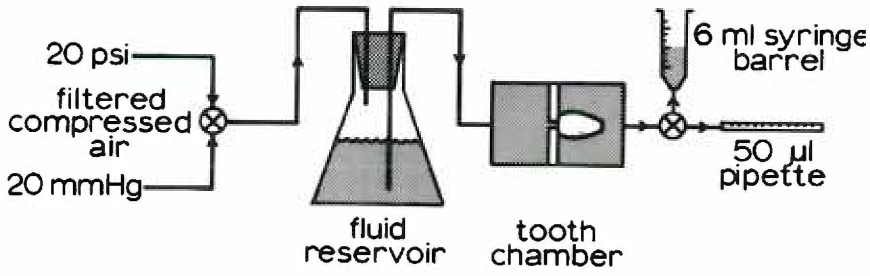

Figure 6. Schematic illustration of the apparatus necessary to vary the flow from low pressure of 20 millimeters of mercury to high pressure of 20 pounds per square inch and measurement of resultant flows using a 50-microliter pipette or a six-milliliter syringe barrel. Filtered compressed air was passed through the reservoir to produce hydrostatic pressure at the interface of the apical barrier.

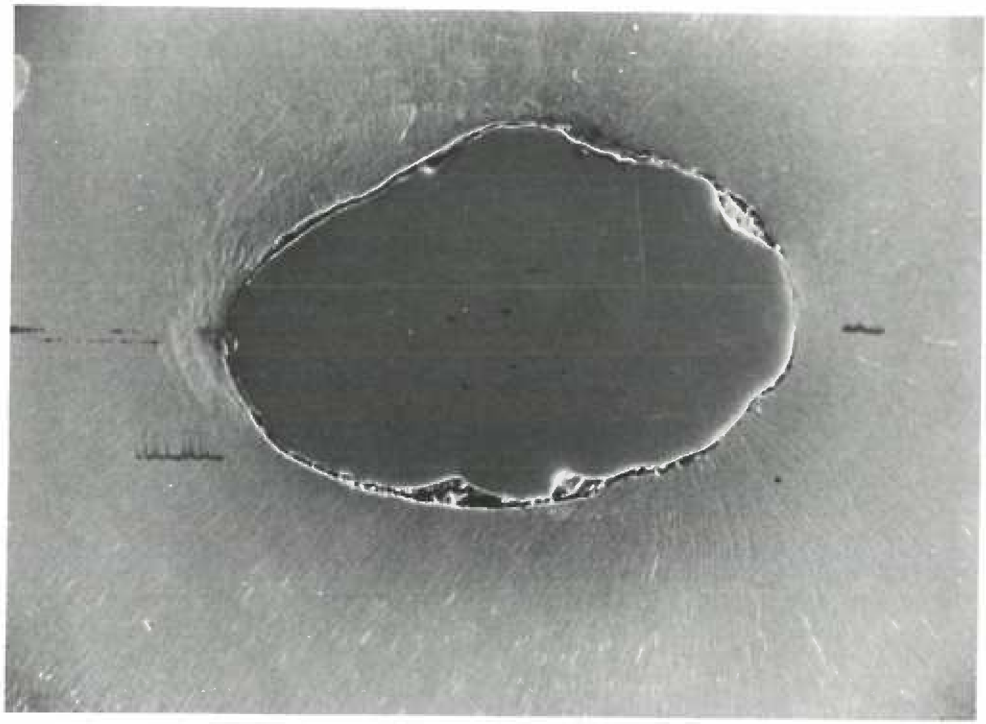

Figure 7. Scanning electron micrograph of the dentin chip barrier (DCB) at 125X, approximately 2 mm from root end. Note dentine tubules running radially from prepared canal. Space between DCB and dentin is an S.E.M. preparation artifact.

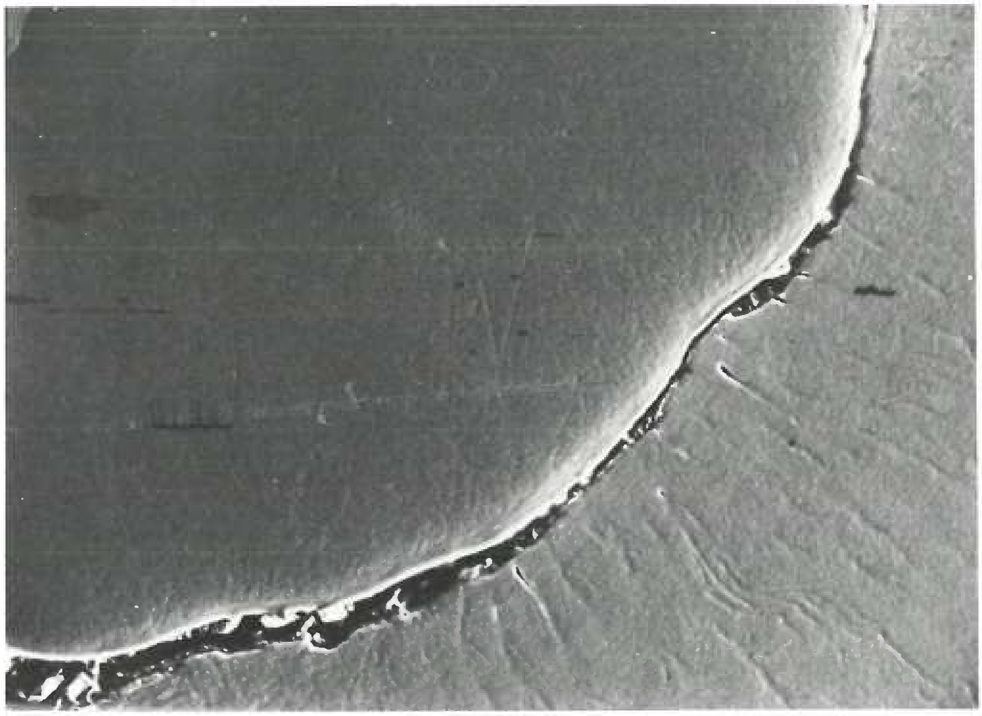

Figure 8. Scanning electron micrograph of the dentin chip barrier at 500X. Note small number of open dentin tubules and similar appearance of natural dentin and polished dentin chip plug.

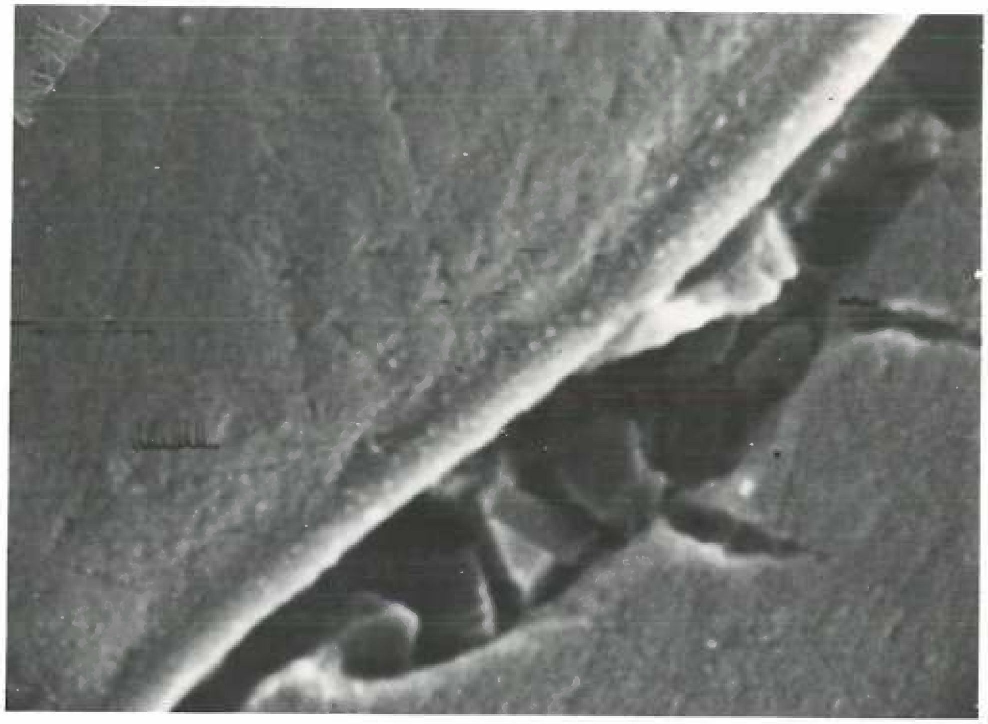

Figure 9. Scanning electron micrograph of the dentin chip barrier at 4000X. Note particles in artifact space. These may be loose dentin chips, dentin particles, or pieces of polishing abrasive.

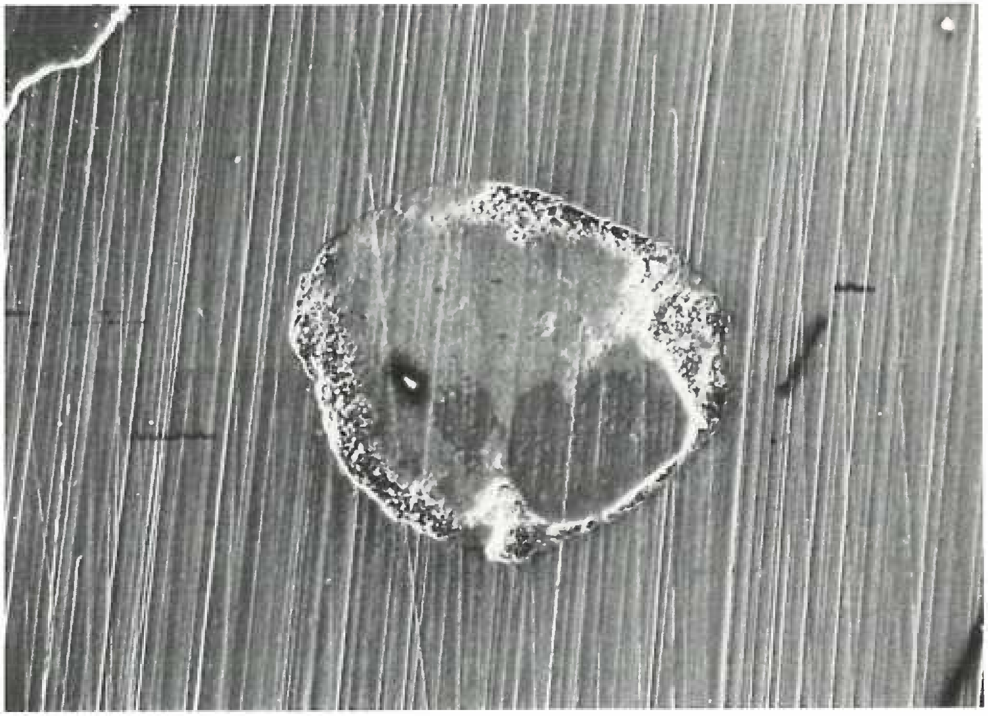

Figure 10. Scanning electron micrograph of the calcium hydroxide barrier at 125X. Note cross striations in dentin and plug due to dry polishing technique required. Note also inconsistent density of plug possibly due to condensation variables or impaction of root dentin on top of calcium hydroxide due to polishing techniques required.

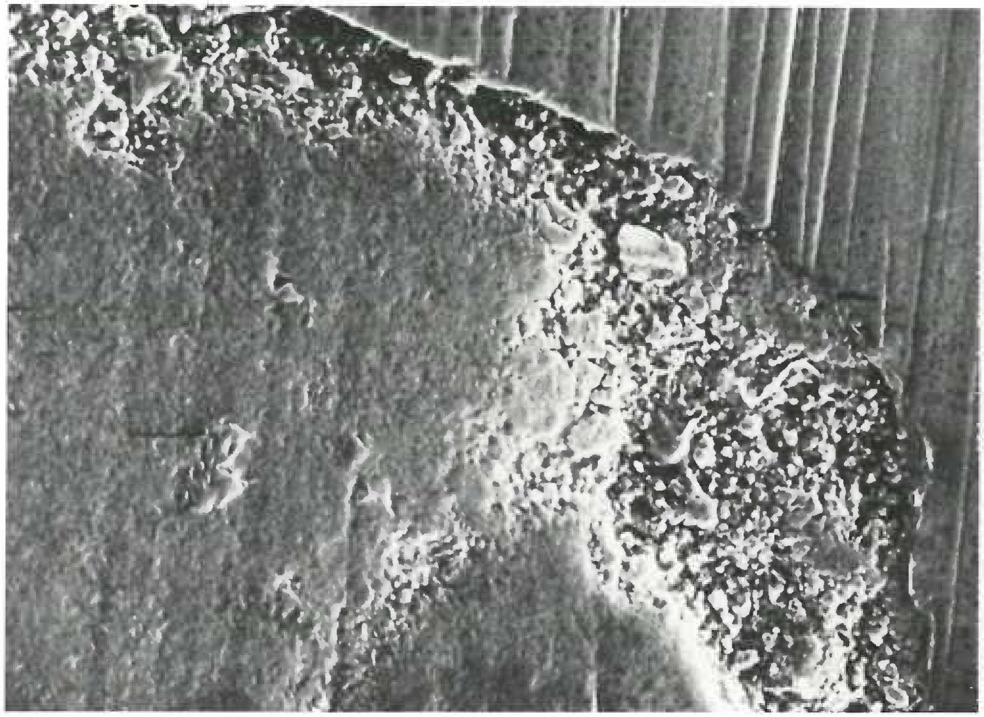

Figure 11. Scanning electron micrograph of the calcium hydroxide barrier at 500X. Note inconsistent density of plug.

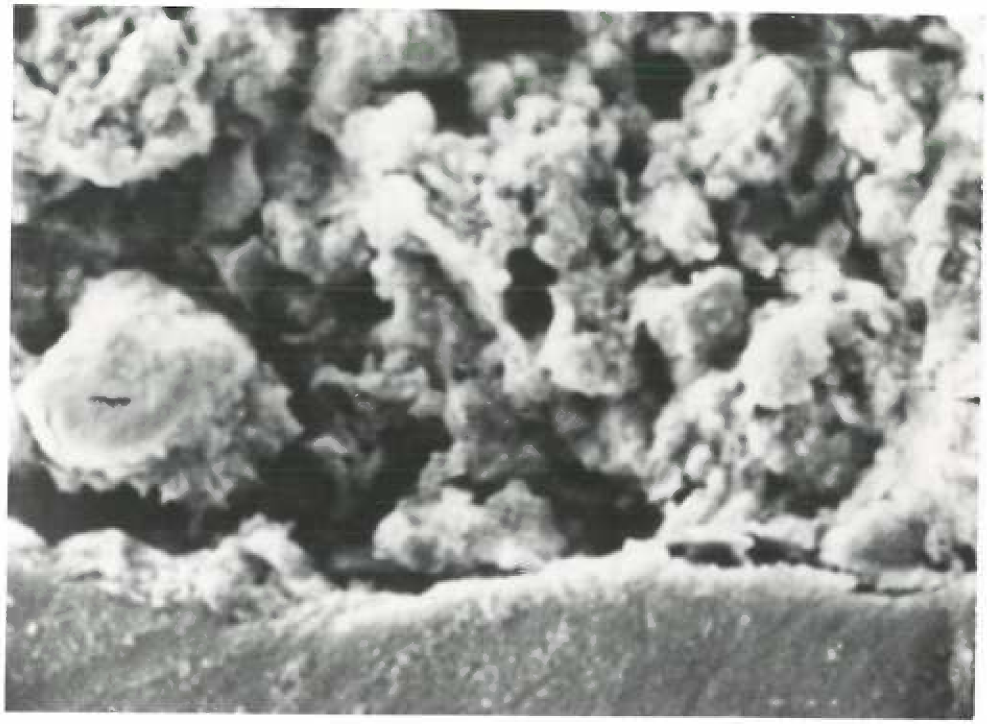

Figure 12. Scanning electron micrograph of the calcium hydroxide barrier at 4000X. Note consistent particle size.

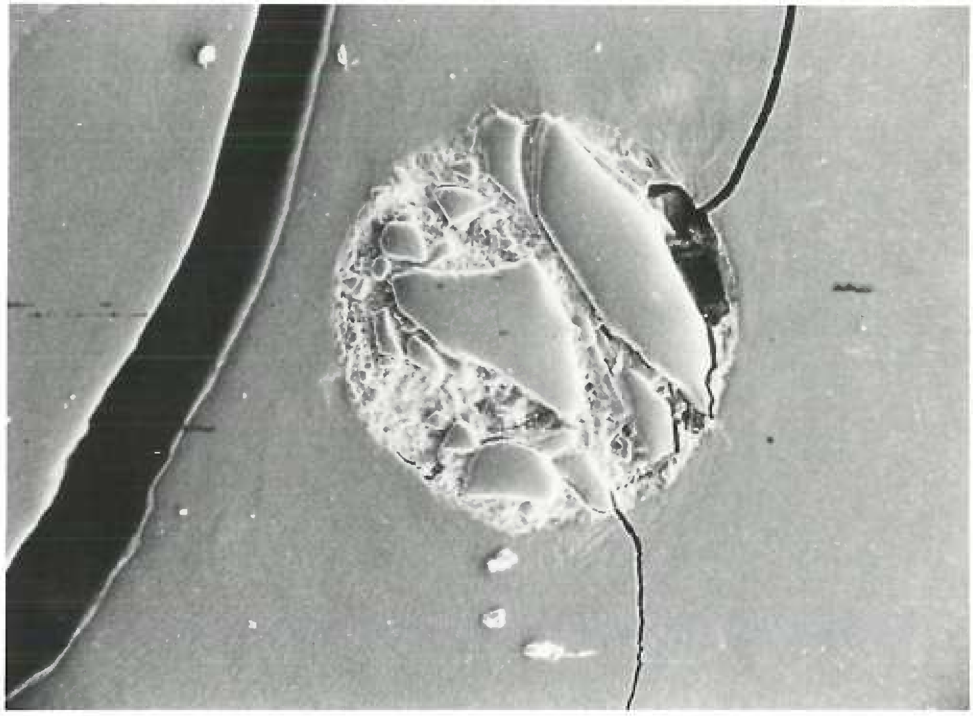

Figure 13. Scanning electron micrograph of the durapatite barrier at 125X. Note cracked dentin due to S.E.M. preparation. Also note gross discrepancy in particle size of plug.

Figure 14. Scanning electron micrograph of the durapatite barrier at 500X.

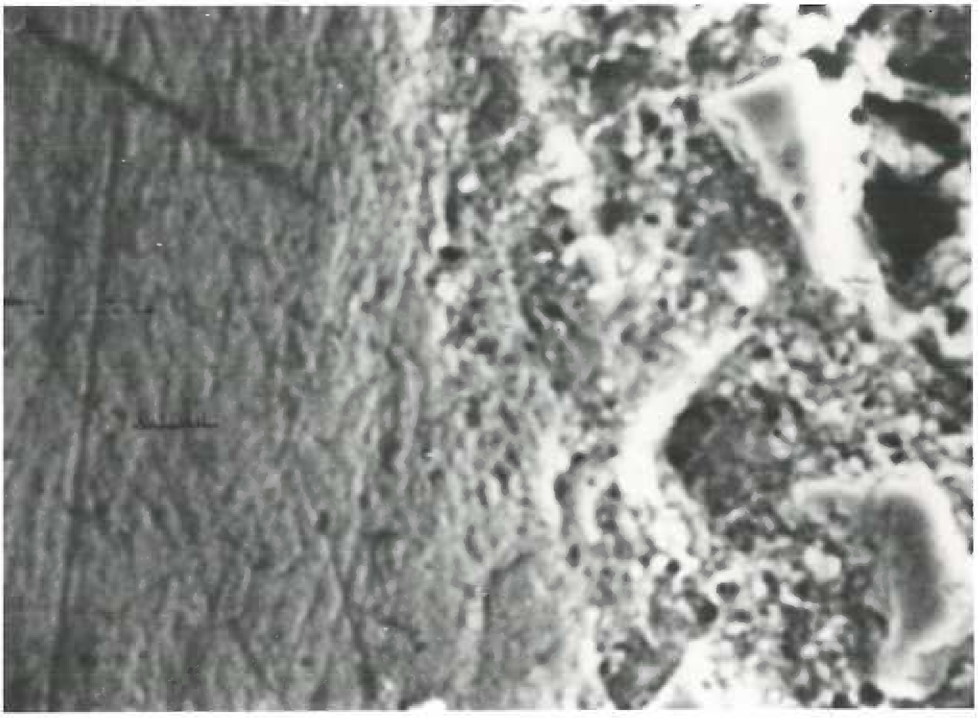

Figure 15. Scanning electron micrograph of the durapatite barrier at 4000X.

Figure 16. Photomicrograph of dentin chips generated by a #4 Gates Glidden drill at 10X. Average chip measured 132 X 34 microns. Note fibrillar and filamentous nature of chips.

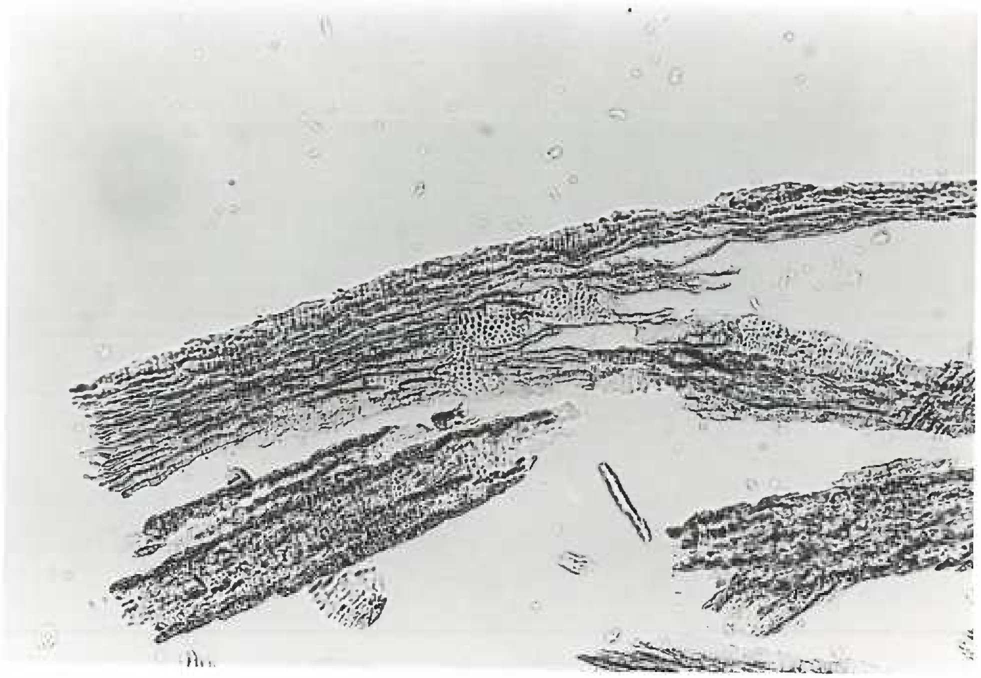

Figure 18. Photomicrograph of dentin chips generated by a #4 Gates Glidden drill at 100X.

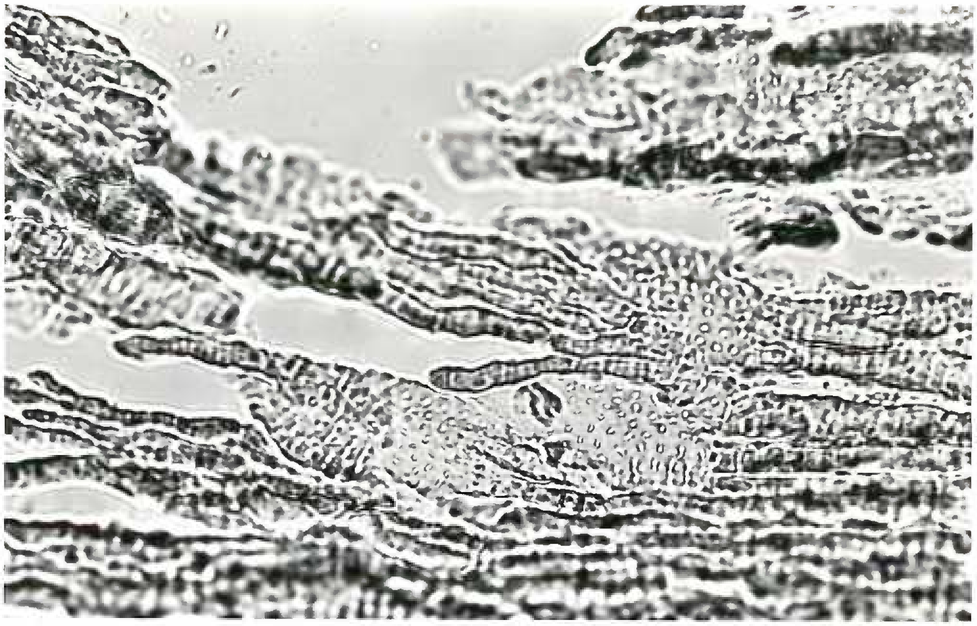

Figure 19. Photomicrograph of dentin chips generated by a #4 Gates Glidden drill at 160X.

TABLE I, CLINICAL DATA (STANDARDIZED APEX)

SAMPLE #	TOOTH #	REASON FOR EXTRACTION	AGE	SEX
DC1	6	periodontal	42	M
DC2	7	periodontal	42	M
DC3	8	periodontal	42	M
DC4	11	periodontal	42	M
DC5	8	periodontal	67	F
DC6	10	periodontal	52	F
DC7	8	periodontal, caries	29	M
DC8	9	periodontal, caries	29	M
DC9	8	periodontal, caries	47	F
DC10	9	periodontal, caries	47	F
CH1	10	periodontal	29	M
CH2	7	periodontal	29	M
CH3	6	periodontal	40	F
CH4	11	periodontal	40	F
CH5	8	periodontal	61	M
CH6	9	periodontal	61	M
CH7	10	periodontal	61	M
CH8	8	periodontal, caries	29	M
CH9	9	periodontal, caries	29	M
CH10	7	periodontal, caries	29	M
TCP1	8	periodontal	50	F
TCP2	9	periodontal	50	F
TCP3	8	prosthetics	59	M
TCP4	9	prosthetics	59	M
TCP5	8	periodontal, caries	55	F
TCP6	7	periodontal	58	M
TCP7	8	periodontal, caries	45	F
TCP8	9	periodontal, caries	45	F
TCP9	10	periodontal, caries	45	F
TCP10	6	periodontal, caries	55	F

NOTE: These teeth were filled after standardizing the apex and grouped by appropriate barrier: DC (dentin chip barrier), CH (calcium hydroxide barrier), TCP (tricalcium phosphate)

TABLE II CONDUCTANCE (STANDARDIZED APEX)

SAMPLE NO./TYPE	AVERAGE HYDRAULIC CONDUCTANCE (NO BARRIER)	AVERAGE HYDRAULIC CONDUCTANCE (WITH BARRIER)	CHANGE IN CONDUCTANCE
DC1	76.0	*0.0000	0.0000
DC2	78.6	0.0007	0.0009
DC3	74.3	0.0063	0.0084
DC4	74.0	0.0000	0.0000
DC5	78.0	0.0000	0.0000
DC6	66.7	0.0014	0.0021
DC7	80.5	0.0016	0.0019
DC8	76.8	0.0000	0.0000
DC9	66.0	0.0000	0.0000
DC10	74.0	0.0000	0.0000
MEAN	74.5	0.0010	0.0013
SD	4.8	0.0020	
CH1	73.5	0.0031	0.0043
CH2	71.6	0.0016	0.0022
CH3	78.2	0.0003	0.0004
CH4	60.9	0.0000	0.0000
CH5	48.4	0.0069	0.0142
CH6	70.8	0.0000	0.0000
CH7	55.7	0.0000	0.0000
CH8	74.4	0.0000	0.0000
CH9	78.3	0.0000	0.0000
CH10	59.2	0.0000	0.0000
MEAN	67.1	0.0012	0.0018
SD	10.3	0.0023	
TCP1	68.5	0.0034	0.0049
TCP2	57.1	0.0146	0.0255
TCP3	73.6	0.0039	0.0053
TCP4	54.9	0.0030	0.0055
TCP5	71.6	0.0060	0.0083
TCP6	63.5	0.0901	0.1419
TCP7	69.0	0.0876	0.1270
TCP8	67.6	0.0083	0.0123
TCP9	33.2	0.0008	0.0023
TCP10	76.2	0.0025	0.0032
MEAN	63.5	0.0220	0.0350
SD	12.6	0.0354	
MEAN (N=30)	68.4	0.0080	
STANDARD DEVIATION	10.5	0.0222	
MINIMUM	33.2	0.0000	
MAXIMUM	80.5	0.0901	

Hydraulic conductance = $\frac{(\text{Volume/Time})}{\text{pressure}}$, conductance values are expressed in μl/sec/psi driving pressure

Change in conductance = $100 \times \frac{\text{conductance after barrier placement}}{\text{conductance before barrier placement}}$

*No fluid movement was detected in ten minutes.

TABLE III: STATISTICAL ANALYSIS (STANDARDIZED APEX)

	T-Test No Barriers	T-Test With Barriers
Autogenous dentin chips (vs) Calcium Hydroxide	t = 0.2335	t = 0.6430
Autogenous dentin chips (vs) Durapatite	t = 0.3545	*t = 3.6979
Calcium Hydroxide (vs) Durapatite	t = 0.1224	*t = 3.6620

*Statistically significant (p=0.05; N=10)

TABLE IV: CLINICAL DATA (NON-STANDARDIZED APEX)

SAMPLE #	TOOTH #	REASON FOR EXTRACTION	AGE	SEX
T1	10	periodontal	37	F
T2	7	periodontal	37	F
T3	9	periodontal	37	F
T4	8	periodontal	37	F
T5	11	caries	58	F
T6	8	caries	58	F
T7	7	caries	58	F
T8	9	caries	58	F
T9	6	caries	58	F
T10	9	patient requested denture	49	M

NOTE: The apices of these teeth were not standardized and the canals were only filled with dentin chips.

TABLE V: CONDUCTANCE (NON-STANDARDIZED APEX)

SAMPLE NO./TYPE	AVERAGE HYDRAULIC CONDUCTANCE (PRE-PREPARATION)	AVERAGE HYDRAULIC CONDUCTANCE (POST-PREPARATION)	AVERAGE HYDRAULIC CONDUCTANCE (POST-BARRIER)	CHANGE IN CONDUCTANCE
T1	0.0018	*0.0000	0.0000	0.0000
T2	0.0472	0.0197	0.0003	0.5295
T3	0.0030	0.0011	0.0010	32.4324
T4	0.0028	0.0019	0.0002	8.5106
T5	0.1455	0.0000	0.0000	0.0000
T6	0.0025	0.0000	0.0000	0.0000
T7	0.2135	0.0000	0.0000	0.0000
T8	0.0022	**69.4017	0.0003	11.6592
T9	0.0095	0.0000	0.0000	0.0000
T10	0.0075	0.0000	0.0002	2.5435
MEAN (N=10)	0.0436	0.0025	0.0002	0.4358
STANDARD DEVIATION	0.0747	0.0065	0.0003	
MINIMUM	0.0018	0.0000	0.0000	
MAXIMUM	0.2135	0.0197	0.0010	

T (Non-standardized teeth, dentin chip only), conductance values are expressed in μl/sec/psi driving pressure.

$$\text{Change in conductance} = 100 \times \frac{\text{conductance after barrier placement}}{\text{conductance before barrier placement}}$$

*No fluid movement was detected in ten minutes.

**Omitted in post-preparation statistical analysis because of over-instrumentation.

TABLE VI: STATISTICAL ANALYSIS (NON-STANDARDIZED APEX)

	T-Test
Pre-Preparation (vs) Post-Preparation of canals	*t = 7.6426
Pre-Preparation (vs) Post-Barrier placement	*t = 5.7836
Post-Preparation of canals (vs) Post-Barrier placement	t = 0.6947

*Statistically significant (p=0.05; N=10)

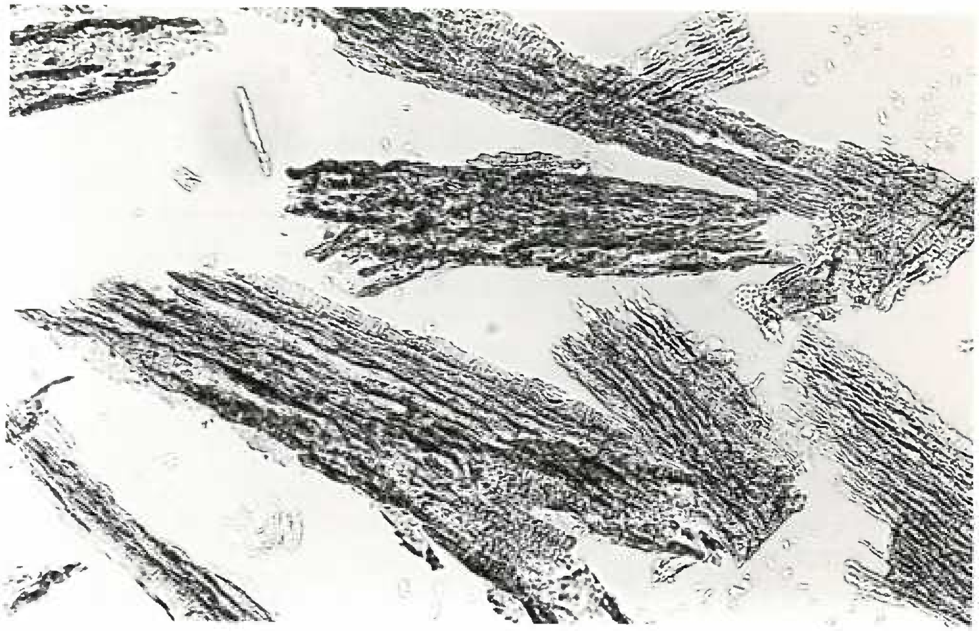

Figure 17. Photomicrograph of dentin chips generated by a #4 Gates Glidden drill at 40X.