MARGINAL SEAL OF CERVICAL RESTORATIONS

A thesis submitted to the University of Sydney in support of my candidature for the degree of Master of Dental Surgery (1988)

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INTRODUCTION

An ideal restorative material should "adhere and perfectly adapt to the cavity wall, be free of irritant substances, have the appearance of the tooth, and match it both in mechanical and thermal properties" (Wilson and Prosser 1982). Although no material presently available fulfils these exacting requirements, two restorative systems have been developed which approach the ideal with respect to appearance and potential for attachment to the hard tooth tissues, that is, composite resins used with appropriate bonding techniques and the glass-ionomer cements.

Using knowledge gained from industrial treatments of metal surfaces, Buonocore in 1955 reported bonding of an acrylic restorative material to human enamel surfaces after etching with acid. The following year, treatment of dentine surfaces with a weak acid and the use of an intermediary resin was found to establish a bond between an acrylic and dentine (Buonocore et al. 1956). The many advantages of bonding dental restorative materials to hard tooth tissues soon became apparent. If a reliable bond could be established, the result would be smaller fillings of greater longevity, conservative repair of incisal edge fractures and malformed teeth, and treatment of superficial caries and non-carious cervical lesions without cavity preparation (Jordan et al. 1977, Flynn 1979, Asmussen and Munksgaard 1985a). Most significantly, perhaps, bonding to hard tooth tissues would allow sealing of susceptible pits and fissures for the prevention of caries (Buonocore 1963).

Formulation of a resin system superior in many respects to the acrylic resins, and subsequent particle reinforcement of this resin (Bowen 1963), resulted in the marketing of the first composite
resins more than two decades ago. Since then, it has become accepted that, when proper procedures are used, composite resins bond reliably to acid-etched enamel and improved marginal sealing of these restorations has resulted. A review of the literature reveals, however, that obtaining an adequate seal is more elusive where enamel is absent and margins are positioned in dentine or cementum. This is despite continued research and the formulation of numerous intermediary bonding resins in recent years.

Not long after the first composite resins were marketed, a report was made of a new dental filling material derived from the silicate cements (Wilson and Kent 1971). This glass-ionomer cement has been found subsequently to adhere to both enamel and dentine, and also to exhibit slow release of fluoride ions. It has not, however, achieved the popularity of the composite resins and this appears to result from limitations in strength, colour match and handling characteristics.

Recently it has been shown that composite resins are capable of bonding to glass-ionomer cement with a bond strength equivalent to the cohesive strength of the glass-ionomer cement used. This has led to the use of glass-ionomer as a base covered with a veneer of composite resin in an effort to overcome the disadvantages of both materials and achieve a superior restoration, that is, a combination of the marginal sealing potential of the glass-ionomer cements with the superior strength and surface qualities of composite resins. The purpose of this investigation was to compare the capabilities of restorative techniques presently available to achieve a seal, in vitro, where the cavosurface margins of the cavities were placed in both enamel and in cementum on the root surface.
CHAPTER 1
BONDING TO HARD TOOTH TISSUES

1.1 THE NATURE OF HARD TOOTH TISSUES

When considering the nature of hard tooth tissues in the context of bonding with dental restorative materials, it is necessary to consider tissue development, both macroscopic and microscopic structure and chemical composition. All these features influence the ability of the tissues to form a bond, and may also serve to explain why a particular bonding mechanism may succeed with one tissue type but fail when applied to a second.

Development

The embryologic origin of the hard dental tissues helps to explain differences in their structure and chemical composition. Enamel is the product of cells with epithelial origin, and these cells function by secreting an organic matrix which subsequently mineralizes (Gwinnett 1975, Fejerskov and Josephson 1986). Dentine and cementum, in contrast, result from cells of mesenchymal origin which produce collagen as their main structural protein, and this subsequently becomes associated with mineral deposits (Gwinnett 1975, Ten Cate and Torneck 1982, Fejerskov and Josephson 1986). During tooth development, the mesenchymal cells producing dentine, the odontoblasts, retreat towards the centre of the tooth leaving long, slender cell processes which become incorporated within a dentinal tubule (Ten Cate and Torneck 1982), whereas the cell processes of the enamel-forming ameloblasts remain as less significant Tomes' processes (Fejerskov and Josephson 1986).
Macroscopic Appearance

Enamel covers the anatomic crown of the tooth and has a generally smooth surface (Gwinnett 1975). It is thickest over the cusps and incisal edges and thinnest at the base of pits and fissures and in the cervical region (Gwinnett 1975, Silverstone 1982, Fejerskov and Thylstrup 1986). Dentine, on the other hand, comprises the bulk of the tooth and gives support to both enamel and the cementum covering the root surface (Gwinnett 1975). Dentine is usually considered inseparable from the centrally-located pulp tissue (Gwinnett 1975, Ten Cate and Torneck 1982), giving rise to the term dentine-pulp complex (Ten Cate and Torneck 1982).

Microscopic Appearance

Enamel is composed of rod-shaped structures, called enamel prisms, which are approximately five microns in diameter and run from the dentino-enamel junction to the enamel surface (Meckel et al. 1965, Gwinnett 1975, Silverstone 1982, Fejerskov and Thylstrup 1986). Prisms do not run a straight course to the enamel surface but, especially in the inner two thirds of enamel, there is considerable decussation or crossing of groups of prisms (Gwinnett 1975). Three main types of prism shape and arrangement have been described (Silverstone 1982), the most common of which resembles a keyhole (Meckel et al. 1965). The prisms themselves are made up of tightly packed crystals with organic material and water in the intercrystalline spaces (Silverstone 1982, Fejerskov and Thylstrup 1986).

Other features of enamel which hold significance for bonding include incremental lines representing manifestations of tissue development, localized accumulations of organic material such as
enamel tufts, lamellae and spindles, enamel pores, and the presence of prismless enamel. Prismless enamel, as the name suggests, is devoid of characteristic prism markings and the crystals are usually oriented perpendicularly to the surface and densely packed (Gwinnett 1975, Silverstone 1982). Prismless enamel is found most commonly in the cervical region and when present in permanent teeth is usually 20-30 microns thick (Silverstone 1982).

Dentine is characterized by dentinal tubules which traverse its entire thickness in a generally S-shaped course and contain extensions of odontoblast cell processes (Gwinnett 1975, Ten Cate and Tornneck 1982). There is some controversy as to how far the cell processes of the odontoblasts extend into the tubules, but several studies have shown that the processes are confined to the pulpal one third in coronal dentine (Brannstrom and Garberoglio 1972, Thomas 1979) and the pulpal one half in mid-root dentine (Thomas 1979).

Dentine tubules measure approximately one micron in diameter (Gwinnett 1975), but variation is observed, with a larger diameter found at the pulpal aspect than at the periphery (Gwinnett 1975, Mjor 1986). In cross-section, the dentinal tubule is ringed by a relatively hypermineralized peritubular zone (Gwinnett 1975, Ten Cate and Tornneck 1982, Mjor 1986) and intertubular dentine, containing abundant collagen, further separates the tubules (Gwinnett 1975, Mjor 1986). The substance of dentine is a collagenous matrix and ground substance into which crystals are deposited (Ten Cate and Tornneck 1982). These crystals are, however, smaller than those of enamel (Gwinnett 1975, Silverstone 1982).

Cementum exists in two forms, acellular and cellular (Selvig 1965, Gwinnett 1975, McCulloch and Melcher 1982). Acellular
cementum generally covers the coronal one half to one third of the root surface and varies from 20 to 130 microns in thickness, depending on age (McCulloch and Melcher 1982, Furseth et al. 1986). It is a finely lamellated tissue with incremental lines running parallel to the root surface (Selvig 1965) and comprises a meshwork of collagen fibres coated with crystals which are similar to those of dentine (McCulloch and Melcher 1982). Cellular cementum, which usually covers the apical one half to two thirds of the root surface (McCulloch and Melcher 1982, Furseth et al. 1986), also comprises mineralized collagen but, in addition, contains cementocytes located in lacunae (McCulloch and Melcher 1982). These lacunae are connected by fine channels, or canaliculi, which are occupied by cementocyte cell processes (Selvig 1965, Gwinnett 1975, Furseth et al. 1986).

**Chemical Composition**

Mature enamel contains, by weight, 96-97 per cent inorganic material, 1 per cent organic material and 2-3 per cent water and, by volume, 86-89 per cent inorganic, 2 per cent organic and 9-12 per cent water (Silverstone 1982, Fejerskov and Thystrup 1986). The inorganic or mineral phase comprises principally calcium and phosphate in a 2:1 ratio by weight, with calcium making up, on average, 37 per cent of enamel (Silverstone 1982). The calcium and phosphate are most commonly found as a form of calcium hydroxyapatite (Gwinnett 1975). Also present are fluoride, carbonate, chlorine, sodium and other trace elements (Gwinnett 1975, Silverstone 1982). The concentration of these elements tends to be greater at the surface than in deeper enamel, with the exception of carbonate, which has the highest concentration adjacent to the dentino-enamel
junction, and fluoride, which peaks in concentration at the enamel surface and at the dentino-enamel junction (Silverstone 1982).

Water is present in a loosely bound form and also in a more firmly bound state (Gwinnett 1975, Silverstone 1982). A relatively greater volume of water is present in deeper enamel than at the surface (Gwinnett 1975, Silverstone 1982), perhaps as a result of differences in organic content (Gwinnett 1966) or the dynamic fluid flow occurring from dentine to enamel (Bergman 1963).

The organic content of enamel is a complex mixture of proteins with a characteristic amino acid composition, including high proline and glycine concentrations (Gwinnett 1975, Silverstone 1982). The larger part of this protein gel is lost during mineralization and the remaining material is concentrated at the prism peripheries (Silverstone 1982). An organic salivary deposit, or cuticle, has also been described on the enamel surface in vivo (Meckel 1965), and may extend as a network several microns within the surface layer of slightly damaged enamel.

Dentine also comprises water and both organic and inorganic phases, however, its actual composition differs from that of enamel. By weight, dentine is considered to comprise 70 per cent inorganic material, 18-20 per cent organic material and 10-12 per cent water (Ten Cate and Torneck 1982, Mjor 1986). The volume of components, which is probably more significant when considering bonding potential (Beech 1982), is 45 per cent inorganic, 33 per cent organic and 22 per cent water (Ten Cate and Torneck 1982). The inorganic phase, like enamel, is mainly hydroxyapatite, however, the crystals formed are much smaller and more randomly distributed than those of enamel (Gwinnett 1975, Mjor 1986). There are significant concentrations of fluoride, lead and zinc,
especially in deep dentine, and citrate is present in concentrations ten times greater than that of enamel (Gwinnett 1975). Other inorganic salts, such as carbonates, sulphates, and calcium phosphates other than hydroxyapatite, are also present (Mjor 1986).

The organic phase of dentine comprises largely collagen (Ten Cate and Torneck 1982, Mjor 1986) which amounts to about 17 per cent of the total tissue (Mjor 1986). Smaller amounts of proteoglycans, lipids, polysaccharides and citric acid are also present (Gwinnett 1975, Mjor 1986), with the citric acid found in close association with hydroxyapatite (Mjor 1986). The water present in dentine is largely associated with the dentinal tubules, with tissue fluids also contained between the wall of the tubule and the odontoblastic process (Mjor 1986).

Cementum is the least mineralized of the three dental hard tissues, with mineral content approximately 65 per cent by weight, organic content 23 per cent and the remaining 12 per cent made up of water (Furseth et al. 1986). As with enamel and dentine, the mineral component is principally calcium and phosphate present in the form of hydroxyapatite (Gwinnett 1975, McCulloch and Melcher 1982, Furseth et al. 1986). Varying amounts of trace elements are also found, notably fluoride, and these may be present in high concentrations in surface cementum which has been exposed to the oral cavity (Furseth et al. 1986). Similar to dentine, the major part of the organic material is collagen, with the addition of ground substance (McCulloch and Melcher 1982, Furseth et al. 1986). The ground substance is thought to be principally proteoglycans and glycoproteins and to have an important water binding capacity (Furseth et al. 1986).
1.2 THE NATURE OF BONDING

Definitions

In the dental literature there is disagreement regarding the terms used to describe the so-called "adhesive" restorative materials and their retention mechanisms. Buonocore in 1975(a) described adhesion as "the attraction exerted between the molecules at the surfaces of different materials when these materials are bought into contact" and used bonding to describe "the attachment of dental adhesives to enamel and dentine". The term bonding, therefore, did not attempt to identify a mode of attachment but simply implied that attachment took place. The alternative mode of attachment, also described by Buonocore in 1975(a), was mechanical retention, that is "mechanical gripping or interlocking in surface irregularities, such as pores, cavities and capillaries". This relationship between bonding, adhesion and mechanical retention is illustrated diagramatically in Figure 1.1 and has been used subsequently by others (Phillips 1982, Beech 1982).

Alternatively, the American Society for Testing and Materials, as reported by Patrick in 1961, defined adhesion as "the state in which two surfaces are held together by interfacial forces, which may consist of chemical forces or (mechanical) interlocking forces, or both". In 1974, the Council on Dental Materials and Devices issued a further statement, "an adhesive material for use in dental restorative procedures is a substance that would bond to enamel, or dentin, or both, without reliance on interlocking effects or the retention form of the prepared cavity" - "and effect a seal of that restoration in the oral environment". This later definition recognized the need to specify more carefully the mechanical
Figure 1.1  THE RELATIONSHIP OF BONDING AND ITS COMPONENTS, ADHESION AND MECHANICAL RETENTION - adapted from Buonocore 1975a.
component of bonding and an increasing awareness of the cavity sealing potential of newer restorative materials.

Failure to distinguish the adhesive and mechanically retentive aspects of bonding does, however, make comparing and contrasting the bonding abilities of dental materials more difficult. For the purposes of this investigation, therefore, the definitions of bonding, adhesion and mechanical retention will be those outlined by Buonocore in 1975(a). It is also important for the purposes of this investigation to distinguish bonding and its' components from the ability to seal, or close securely. A dental restorative material which is well retained by mechanical interlocking may leak (Beech 1982). By obtaining adhesion, however, leakage at the bond interface should be substantially reduced, if not eliminated (Buonocore 1963, Beech 1982).

Adhesion

The science of adhesion includes many theories in explanation of the nature of forces between surfaces but none, at present, have proved comprehensive (Kinloch 1980, Beech 1982). These theories involve thermodynamic and mathematical concepts which have been dealt with in summary (Kinloch 1980) and related to the problems of adhesion in biological systems (Baier et al. 1968). Adhesion in biological systems appears more complex than that involved in the adherence of paper, wood or metal, however, the general concepts of the forces of molecular attraction which are responsible for holding materials together are still applicable.

The molecular forces of attraction involved in adhesion may be divided into two classes, usually called physical and chemical forces (Buonocore 1975a, Beech 1982). Physical forces, which may
also be termed van der Waals' or secondary forces, include both permanent and induced dipole-dipole interactions and non-polar dispersion effects (Buonocore 1975a, Beech 1982). Hydrogen bonding is a type of dipole-dipole interaction (Beech 1982) and involves stronger attraction between materials than other physical forces (Buonocore 1975a). These physical forces exist between all atoms and determine state, that is solid, liquid or gas, and are responsible for such properties of materials as tensile strength, surface tension and viscosity (Buonocore 1975a). They are, however, active only at short range and are not durable in an aqueous environment (Beech 1982).

Chemical forces of molecular attraction are stronger than physical forces, and include ionic, covalent and metallic linkages (Buonocore 1975a), of which only the first two are capable of forming bonds with hard tooth tissues (Beech 1982). Ionic bonds result from electron transfer between atoms, are active at longer range than physical forces and may dissociate in the presence of water (Buonocore 1975a, Beech 1982). Covalent linkages, which are formed by electron sharing, are commonly found in organic compounds (Beech 1982) and with these bonds, water is not able to destroy the adhesion (Buonocore 1975a). When chemical forces do occur they increase bond strength and impart greater heat, water and chemical resistance to the bond (Buonocore 1975a).

**Mechanical Retention**

Strong attachment of two substances may be obtained simply by mechanical means, rather than molecular attraction (Phillips 1982). This mechanical bonding may be gross, or macroscopic, such as with pins or undercuts, or achieved by penetration of material
into microscopic or submicroscopic irregularities in the substrate surface (Buonocore 1975a). In addition, it seems likely that where a material can fill microscopic irregularities, there might also be the molecular proximity necessary to effect molecular attraction, especially initially (Buonocore 1975a, Beech 1982). For this reason, when considering bonding to enamel surfaces through acid-etching, the bond may initially involve physical forces of attraction which, however, may not subsequently survive in the aqueous environment, leaving the mechanical retention to endure (Buonocore 1975a).

1.3 IMPEDIMENTS IN BONDING TO HARD TOOTH TISSUES

A liquid will bond to one or more substances only if it is able to wet the surface of these substances (Buonocore 1975a). Wetting is a result of attractive intermolecular forces and has been described as "the process of obtaining molecular nearness" (Buonocore 1975a). As well as the properties of the individual restorative materials which will be discussed in subsequent chapters, wetting, and therefore bonding ability, are chiefly affected by the presence of moisture at the bonding site, the surface composition of the hard tooth tissues and the existence of contaminants on the tissue surfaces.

The Effects of Moisture

The presence of water can interfere with the establishment of a bond simply by acting as a physical barrier. Gross amounts of water must, therefore, be removed in order to obtain intimate contact between tooth structure and restorative material (Buonocore 1975a). As described in the previous section, however, some water
exists as an integral part of hard tooth tissues and cannot be removed without destroying their structure. As a consequence of this, in order to establish long-term bonding the adhesive material must successfully compete with water at the interface between tooth and restoration (Beech 1982). Physical forces, therefore, are not sufficient to give long-term retention and it is necessary to ensure the occurrence of either mechanical interlocking or primary bond formation, or both (Beech 1982).

Surface Characteristics of the Hard Tooth Tissues

As the forces involved in bonding are of such a local nature, the properties of teeth which influence bonding are those of the outermost surface (Glantz 1977). When dealing with hard tooth tissues, the volume of a low density constituent, such as the organic phase, can be considerable and subsequently exert a significant influence on bonding potential (Beech 1982), despite representing only a small part of the total weight.

Of the hard tooth tissues, enamel most closely approximates a homogeneous solid. The organic material constitutes a low percentage by volume and has a fairly even distribution through the inorganic phase (Buonocore 1975a). The high percentage of inorganic material, with its greater rigidity and high surface energy, is inherently more favourable for bonding than dentine (Glantz 1977, Beech 1982). Dentine, with a more heterogeneous nature and larger volume of low surface energy organic material, presents greater difficulty in bonding (Buonocore 1975a). It has been speculated, also, that bonds involving the organic matter of dentine are unlikely to be stable due to collagen turnover (Driessens 1977).
As the character of cementum is similar to that of dentine, it could be expected that cementum would show the same bonding difficulties.

In order to improve bonding potential, prior modification of the tooth surface has been suggested (Causton 1982). This can be achieved in a number of ways, but principally by either altering the surface energy of the tissue or by the use of chemical bridges, or primers, between the two surfaces to be joined. The use of surface modifiers and primers will be discussed further in the chapters dealing with individual restorative materials.

**Surface Contaminants**

Natural tooth surfaces contain thin organic films of low surface energy and these are thought to originate from protein-containing organic phases of the hard tooth tissues (Glantz 1977). In addition, two other low surface energy films may serve to contaminate the tooth surface and impede bonding. Substances from oral fluids may be physically or chemically adsorbed onto tooth surfaces (Buonocore 1975a) and the existence of this low energy film is thought to be a protective mechanism, especially in the case of enamel (Glantz 1977). An organic film resulting from cavity cutting procedures may also cover the tooth surface (Buonocore 1975a), and this has been termed the "smear layer" (Diamond and Carrel 1984). The presence of this smear layer on dentine has also been shown to have protective functions (Diamond and Carrel 1984).

Removal of surface contaminants should only be considered if they interfere with bonding (Buonocore 1975a). In relation to enamel it has proved an advantage in bonding to remove surface organic films and increase surface energy by acid pretreatment,
however, removal of the dentinal smear layer remains controversial (Diamond and Carrel 1984). In smear layer removal, there appears to be much variation in the effects on bonding depending on both the type of cavity cleanser and the restorative material used. These variable results will be discussed in the chapters devoted to the individual restorative materials.
CHAPTER 2
THE GLASS-IONOMER CEMENTS

Glass-ionomer cement was first reported by Wilson and Kent in 1971 and represented a logical development from dental silicate cements. Originally intended for the restoration of anterior teeth and erosion lesions, general cementation and cavity lining (Wilson and Kent 1972), the glass-ionomer cements have also been used to restore deciduous teeth and seal pits and fissures (McLean and Wilson 1977b).

2.1 COMPOSITION, SETTING AND STRUCTURE

The glass-ionomer cements contain:
Polyalkenoic acids, of molecular weight between 10,000 and 30,000.
Ion-leachable aluminosilicate glasses.
Water, as a reaction medium (Wilson and Prosser 1982).
Tartaric acid, to control working and setting characteristics (Prosser et al. 1982).

The original formulations were supplied as a powdered glass and an aqueous solution of acids which, when mixed together, formed a paste. Subsequent incorporation of the acids in dry form with the glass powder, which is activated by the addition of water, proved advantageous and further modifications to the powder have resulted in a snap-setting cement (Atkinson and Pearson 1985).

The setting of glass-ionomer cement can be represented as an acid-base reaction (Wilson 1977):

\[
\text{Glass (base) + Polyacid} \rightarrow \text{Polysalt gel + Silica gel}
\]

\[
\text{POWDER LIQUID MATRIX PARTICLE COATING}
\]
Setting, or cement formation, takes place in several overlapping reactions (Crisp and Wilson 1974a). Initially, acids attack the powder and liberate ions from the outer layers of glass particles (Crisp and Wilson 1974b). Then, with increased pH, cations and anions precipitate as salts, initially calcium polysalts and, later, aluminium polysalts (Crisp and Wilson 1974a, Crisp et al. 1974). Finally, long term reactions and diffusion processes occur, including hydration (Wilson et al. 1979).

The set structure of glass-ionomer cement has some resemblance to composite resin materials (Wilson 1977) but differs in that the glass particles are included in the setting reaction. This results in a graded interface between filler and matrix (Wilson and Prosser 1982) which acts as a stress-relieving buffer (Wilson 1977).

2.2 CHARACTERISTICS

Typical values for some physical properties of glass-ionomer cements are outlined in Table 2.1. Various forms of glass-ionomer cement are available but, for the purposes of this review, discussion will be limited to those designed for use as base or lining materials and as restorative cements. Other important cement characteristics to be discussed include pulpal responses, fluoride release and optical qualities, such as translucency and surface finish.

Pulp inflammation may occur after the application to dentine of mechanical or chemical irritants from cavity preparation or restorative materials (Pameijer et al. 1981) or through thermal shock as restorative materials set (Crisp et al. 1978). The glass-ionomer cements, however, have been shown to produce a mild pulpal reaction in vivo (Dahl and Tronstad 1976, Kawahara et al.
<table>
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<th>MATERIAL PROPERTYS AND UNITS</th>
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<td>140-175 Wilson and Prosser 1982</td>
<td>46-205 Smith et al. 1987</td>
<td>221-284 Raptis et al. 1979</td>
</tr>
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<td>13-14 Wilson and Prosser 1982</td>
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<td>13 Espe W.Germany</td>
<td>8 Espe W.Germany</td>
<td>46-70 Raptis et al. 1979</td>
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<tr>
<td>POLYMERIZATION SHRINKAGE (% by Volume)</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
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1979, Pameijer et al. 1981) and the maximum temperature rise during setting has been found to be small, if it occurs at all (von Fraunhofer and Williams 1974, Crisp et al. 1978). In deeper cavities it has been suggested, nevertheless, that zinc oxide-eugenol or calcium hydroxide materials should be used under the glass-ionomer cement (Tobias et al. 1978, Cooper 1980).

During study of the chemical erosion of dental cements it was shown that glass-ionomer cements elute silica, sodium and fluoride ions over time (Crisp et al. 1976). Investigations of the time dependence of fluoride release found that ion elution was most rapid during the first days after setting and much slower thereafter (Crisp et al. 1976, Maldonado et al. 1978, Wilson et al. 1985). Causton, in 1981, found fluoride leaching ceased after six months exposure to water but this was later disputed in a 20 month study (Wilson et al. 1985).

Penetration of fluoride ions into enamel and dentine around glass-ionomer cement restorations has been demonstrated (Swartz et al. 1980, Wesenberg and Hals 1980a) and, using artificial caries techniques, cariostatic effects were observed within dentine and enamel adjacent to glass-ionomer restorations (Kidd 1978, Wesenberg and Hals 1980b).

Glass-ionomer cements have been regarded as having poor appearance when compared with composite resin materials (Council on Dental Materials and Devices 1979). This was attributed to a lack of translucency (Wilson and Prosser 1982), which has been improved with the introduction of newer cements (Atkinson and Pearson 1985). The translucency of glass-ionomer cements has been considered closer to that of dentine than enamel (Crisp et al. 1976),
which somewhat limited their usage in replacing large areas of labial enamel (McLean and Wilson 1977b).

Surface finish also contributes to an acceptable appearance. Using a profilometer, the roughness of glass-ionomer cement was found to be five times greater than that of a microfilled composite and three times greater than that of a conventional composite resin (Lambrechts and Vanherle 1982). Despite improvements, the newer formulations of glass-ionomer cement have been found to be comparable only with conventional composite resins (Atkinson and Pearson 1985).

The surface finish achieved using a matrix during the setting of glass-ionomer cement appears to be the best obtainable, and any subsequent use of hand or rotary instruments reduces the quality of this surface (Knibbs and Pearson 1984). If finishing is required, disc-type rotary instruments, used with a layer of petroleum jelly, are recommended (Pearson 1983, Hardwick and de Wet 1985).

2.3 BONDING TO HARD TOOTH TISSUES

As glass-ionomer cements are highly ionic materials, they appear to compete successfully with water in the oral environment and form hydrogen bonds with enamel apatite (Hotz et al. 1977, McLean and Wilson 1977a, Wilson and Prosser 1982). Controversy surrounds the nature of the final bond with enamel. Metal ion bridges have been suggested (Hotz et al. 1977, Powis et al. 1982) but a study using infrared spectroscopy showed polyacrylates to bond strongly with hydroxyapatite and, in the process, displace phosphate and calcium ions (Wilson et al. 1983).

The mechanisms of adhesion to dentine appear similar to those of enamel but attachment to collagen may also be obtained (Hotz et
al. 1977, McLean and Wilson 1977a). The possible mechanisms for adhesion of glass-ionomer cements to enamel and dentine have been termed "physico-chemical" bonding (Hotz et al. 1977, Council on Dental Materials and Devices 1979).

2.4 IMPROVEMENT IN BONDING TO HARD TOOTH TISSUES

Glass-ionomer cements will adhere to untreated enamel or dentine in vitro with tensile bond strengths at 24 hours in the range 3-10 MPa for enamel and 2-5 MPa for dentine (Levine et al. 1977, Vougliouklakis et al. 1982, Powis et al. 1982, Aboush and Jenkins 1986). Shear bond strengths to dentine in vitro at seven days were found to be in the order of 4 MPa (Causton and Johnson 1979a, 1982). Adhesive failure at the tooth-restoration interface was observed when tensile bond strengths were below 3.5 MPa (Powis et al. 1982). Cohesive failure in the cement was observed at values higher than 3.5 MPa and, although some combined cohesive and adhesive failures were also found, it was concluded that a ranking of bonding efficiency could be made using the mode of bond failure (Hotz et al. 1977).

A recent study using Rhesus monkeys compared in vivo and in vitro 24 hr tensile bond strengths of glass-ionomer cement to dentine (Tyler et al. 1987). In vivo bond strengths were found to be weaker but all bond failures were cohesive, leading to the suggestion that dentinal fluid flow affected the physical properties of the cement and resulted in a weaker bond.

Attempts at improving adhesion of glass-ionomer cements have been directed principally at the weaker dentine bond and with mixed results. Researchers have concluded that surface treatments for improving bonding must be tailored to suit the particular cement
(Causton and Johnson 1979a, Vougliouklakis et al. 1982, Kalili et al. 1987) and that, even so, there is doubt whether the amount of improvement is a fair return for the extra work involved (Causton and Johnson 1979a).

Simple cleansers such as pumice and water and dilute hydrogen peroxide have been used in attempts to remove surface contaminants and obtain effective wetting. Although widely recommended, they show no bond strength enhancement (Hotz et al. 1977, Powis et al. 1982, Aboush and Jenkins 1986).

Citric acid was recommended (McLean and Wilson 1977c) but later found to mildly etch enamel (Vougliouklakis et al. 1982) and open dentinal tubules (Aboush and Jenkins 1986), effects which were considered undesirable and unnecessary (Powis et al. 1982). Citric acid has been described as a potential irritant and is not advised for use on freshly-cut dentine (Tobias et al. 1978). Bond strength enhancement was found to vary considerably depending on the cement used (Vougliouklakis et al. 1982, Aboush and Jenkins 1986).

The density of hydroxyapatite mineral under glass-ionomer cements affects the bond strength (Causton and Johnson 1979a). Accordingly, mineralizing solutions have been used to increase the calcium content of dentine (Levine et al. 1977, Peddye 1981, Causton and Johnson 1982). Salts other than calcium may be absorbed by the dentine surface, for example ferric chloride (Shalabi et al. 1981), but all have shown inconsistency in enhancing bonds with glass-ionomer cements.

Chelating agents, which alter tooth surfaces by dissolving calciferous material, have shown questionable or no improvement in bonding glass-ionomer cement to dentine (Powis et al. 1982) and no
consistency between cements (Vougliouklakis et al. 1982, Kalili et al. 1987).

Several other cleansers have been suggested which may be less irritant to tissues and more effective in promoting adhesion to enamel and dentine; principally aqueous solutions of tannic acid, polyacrylic acid and dodicin (Powis et al. 1982). Using thin films and cement applied under pressure, adhesive bonding was claimed to almost equal the tensile strength of the glass-ionomer cement. Further investigations, using cement in bulk and non-pressure application, have cast doubt on the ability of polyacrylic acid to increase adhesion, especially in the short term (Hinoura et al. 1986, Aboush and Jenkins 1987). Significant improvement over other surface treatments was found, however, after seven days and thermal cycling when using polyacrylic acid (Hinoura et al. 1986).

2.5 **FACTORS INFLUENCING BOND VIABILITY.**

Although glass-ionomer cements show some adhesion to tooth structure without prior surface modification, factors which affect wetting and intermolecular contact will influence bonding. It is accepted that the tooth surface should be clean in order to establish an adhesive bond (Council on Dental Materials and Devices 1979) and a smooth surface is advantageous (Aboush and Jenkins 1986). Removal of surface contaminants and subsequent effects on bond strength have been discussed in section 2.4.

Positive pressure on the setting cement will result in less porosity and intimate contact between cement and tooth structure. To achieve this, syringes for placement and use of a matrix during setting are recommended (Mount 1981). If the setting reaction has proceeded too far before the cement
is applied to the tooth surface, adequate wetting and adhesion will not be achieved (Wilson 1977). A recent study found, however, that if the material is fluid enough to be manipulated the bond will not be jeopardized (Shaefer et al. 1987).

Premature or careless finishing of the glass-ionomer cement may disrupt bonding. It is suggested that finishing be delayed at least one day (Mount and Makinson 1982) although this may not be necessary for the new, snap-setting cements (Aboush and Jenkins 1986).

Control of the environment during the early stages of setting is essential to obtain a strong cement and optimal adhesion. The hydrolytically unstable nature of the predominant calcium polyacrylate crosslinks early in the second stage of setting means exposure to an aqueous environment at that time will disrupt the setting process (Causton 1981). A relationship between early exposure to water and reduced compressive strength (Causton 1981) and other physical properties (Mount and Makinson 1982) has been reported. It is necessary, therefore, to protect the cement from moisture for one hour after placement (Causton 1981) using a varnish (Mount and Makinson 1982) or light-cured bonding resin (Mount 1986a). As well, the glass-ionomer cement will dehydrate rapidly if exposed to air during initial setting. This produces shrinking and cracking which may result in poor appearance and place stress on the newly-formed bonds, leading to loss of adhesion (Mount 1981). The use of a protective coating during the early stages of setting will overcome these problems.

The low tensile strength of glass-ionomer cements makes them brittle materials and so not suggested for use in thin sections (Wilson 1977, Council on Dental Materials and Devices 1979). It
has been observed clinically that complete retentive failures occur in shallow lesions of less than 1mm (Lawrence 1979) and partial marginal failure in the shallow extensions of erosion lesions (Charbeneau and Bozelli 1979).

The thermal expansion co-efficient of glass-ionomer cements closely resembles that of tooth structure so thermal stresses experienced in the oral environment would be expected to have little or no effect on the bond. A study of the setting stress of glass-ionomer cements found that, although setting contraction was considerable (4 per cent by volume), overall shrinkage stress reached only 40 per cent of the value for composites (Feilzer et al. 1986). These researchers concluded that the glass-ionomer cement and dentine bond had a better chance of surviving contraction stresses than the composite and dentine attachment.

2.6 THE BOND WITH COMPOSITE RESIN

More than a decade ago glass-ionomer cements were suggested as cavity lining materials (Wilson and Kent 1972) and then specifically as a replacement for lost dentine beneath composite resin restorations (McLean and Wilson 1977b). Only recently, with the discovery that a bond could be established with composite resin, has glass-ionomer cement been considered as an intermediary layer between composite resin and dentine (Wilson and Prosser 1984).

The principal mechanism for achieving composite resin attachment to glass-ionomer cement is by mechanical interlocking, but there also exists the potential for an adhesive bond. Norling and Duke in 1985 reported strong bonding of composite resin to unetched glass-ionomer cement using a trifunctional molecule; a vinyl group
copolymerizing with the composite resin and amino and silane groups interacting with the glass-ionomer cement.

Mechanical interlocking of composite resin with glass-ionomer cement is achieved after acid pretreatment of the glass-ionomer cement, in a similar manner to acid-etching enamel. Bond strengths which exceed the cohesive strength of the glass-ionomer cement itself have been reported (McLean et al. 1985, Sneed and Looper 1985, Hinoura et al. 1987a, Hassan and Nathanson 1987) and represent a marked improvement over unetched glass-ionomer cement (Hinoura et al. 1987a, Smith and Soderholm 1987) or an unetched but roughened surface (McLean et al. 1985, Hinoura et al. 1987a).

The use of glass-ionomer cement as an intermediary layer in bonding composite resin to dentine is well accepted in clinical dentistry, although several areas of controversy still exist in technique. The etching time, cement maturity before etching and the bonding agent used all affect the bond viability, as does the glass-ionomer cement chosen and possibly also the type of composite resin used.

The affects of variations in etching time have been investigated either by scanning electron microscope examination of the etched glass-ionomer surface or by measuring the strength of the bond between glass-ionomer cement and composite resin. Using replicas, McLean et al. in 1985 concluded that etching with phosphoric acid for 60 seconds caused erosion of the cement surface. A similar observation of erosion was made by Smith in 1986 but he suggested that after etching for 60 seconds the surface integrity was essentially destroyed. Considerable particle loosening was observed after 45 seconds, but if the glass-ionomer cement was etched for 30 seconds or less this loosening did not occur. Smith
also concluded that no difference could be found between liquid etched specimens and those etched with acid gel.

Using Class V cavities lined with various glass-ionomer cements in vitro, an investigation was made of the effects of no etching and 10, 20, 30, 60 and 90 second etch times on the cement surfaces (Quiroz and Lentz 1987). These researchers concluded that 10 to 20 second etching was optimal, that unetched surfaces were unsuitable for bonding and 90 second etching resulted in severe degradation of the cement surface. Similarly, severe degradation of the cement was observed after etching for 120 seconds (Hassan and Nathanson 1987) but only moderate loss was found for 30 second and 60 second etching times.

Two investigations of shear bond strengths between glass-ionomer cement and composite resin showed a 60 second etch time produced higher bond strength values than etching for 30 seconds (Smith and Soderholm 1987, Hassan and Nathanson 1987). The former study found, however, that no statistical difference existed between bond strengths achieved after etching for 60, 30 and 15 seconds and recommended a 15 second etch to avoid destruction of the cement surface and possible exposure of underlying dentine. Hassan and Nathanson concluded that, although higher bond strengths were achieved with 60 seconds of etching, the strengths achieved with both 30 and 60 seconds exceeded the cohesive strength of glass-ionomer cement.

Washing time to remove the acid-etchant has also been found to affect the bond formed between glass-ionomer cement and composite resin. Reducing washing time from 30 seconds to five seconds resulted in a 40 per cent reduction in tensile bond strength and an
adhesive failure mode (Hinoura et al. 1987a), therefore a shortened washing time is not recommended.

The relationship between cement maturity before etching and subsequent bond strengths achieved between glass-ionomer cement and composite resin has been investigated. Using glass-ionomer restorative cements and 60 second etching, it was concluded that etching and bonding prior to 20 minutes from starting to mix gave sub-optimal tensile bond strengths (Wexler 1984). In a later study using three fast-setting cements a similar relationship was found between cement maturity and tensile bond strength (Chin and Tyas 1987). Although these cements were recommended by the manufacturers as being able to be etched after four to five minutes from starting to mix, optimal strengths were obtained after 15 minutes. These researchers, however, concluded that there was difficulty in assessing the clinical implications of these bond strength variations resulting from differing cement maturity.

The choice of bonding agent to be used between glass-ionomer cement and composite resin also influences the bond viability. Although bonding agents are generally considered to have low viscosity, great variation has been shown in contact angles formed by these resins against glass-ionomer cement surfaces (Mount 1987). It is not surprising, therefore, that bond strength values have also been found to differ depending on the bonding agent used.

Two light-cured agents gave higher tensile bond strengths than a chemically cured agent (Hinoura et al. 1987a) but no investigations were made of viscosity differences or chemical composition. In a subsequent study (Hinoura et al. 1987b), the highest bond strengths were obtained using the lowest viscosity bonding agents and bond failure occurred cohesively in the glass-ionomer cement.
Hassan and Nathanson in 1987 found that dentine bonding agents gave significantly higher bond strengths than enamel bonding agents when tested using shear bond strengths at seven days. These investigators did not, however, examine either chemical composition or viscosity of the resins used.

Cohesive strength of the glass-ionomer cement would be expected to affect the viability of attachment of composite resins as the point of bond failure after acid etching is usually within the glass-ionomer cement, as has been mentioned previously. Several studies have shown that, as a general rule, higher strength glass-ionomer cements show stronger bonding to composite resin (Hinoura et al. 1987a, Chin and Tyas 1987). The latter researchers suggested this reflected the superior mechanical properties of some cements.

Wexler in 1984 found that bond strength depended on the cohesive strength of the cement and suggested factors such as powder to liquid ratio, cement thickness and cement maturity would, in turn, affect the cohesive strength. Increased bond strength values were found by Wexler between composite resin and glass-ionomer restorative cements when the film thickness was increased from 0.15mm to 0.45mm. A combination of increased film thickness and greater cement maturity resulted in a further increase in bond strength.

The influence of composite resins with varying polymerization shrinkage values on the viability of the bond with etched glass-ionomer cement has not been investigated. It is possible to speculate, however, that materials with lower shrinkage values might form stronger or more durable bonds but, as the weakest point of the composite resin and glass-ionomer combination is still the
cohesive strength of the cement, the difference in shrinkage values may not be clinically significant.

2.7 CLINICAL SURVEYS

The first clinical survey using glass-ionomer cement to restore non-retentive, cervical erosion or abrasion lesions was reported soon after the cement was commercially released (McLean and Wilson 1977c) and was closely followed by others (Charbeneau and Bozell 1979, Lawrence 1979, Flynn 1979). All reported some early dislodgement or partial loss of restorations and poor colour matching with tooth structure in the first six months. In those studies which were followed up, subsequent loss rate fell dramatically (McLean and Wilson 1977c, Flynn 1979) but marginal deterioration and wear were observed (Flynn 1979). In later studies using improved formulations of glass-ionomer cements to restore cervical erosion or abrasion lesions it was found that colour and translucency were improved and loss rates fell, but the pattern of early loss was still observed (Mount 1986b, Tyas et al. 1986, Knibbs 1987).

Clinical surveys of Class III restorations with a more retentive cavity design showed complete retention (Osborne et al. 1987) or almost complete retention (Mount 1986b) after several years. Significant deterioration in marginal adaptation and some cavo-surface discolouration were observed over three years when compared with a bonded composite resin restoration (Osborne et al. 1987), leading to the suggestion that a composite resin veneer over the glass-ionomer cement may prove superior.

Using non-retentive cervical erosion or abrasion lesions, Tyas et al. in 1987 reported a clinical evaluation of the bond between
composite resin and etched glass-ionomer restorative cements. A retention rate of only 62 per cent after one year was achieved when the glass-ionomer cement was etched, but this increased to 94 per cent when both enamel and cement were etched. Failure of the restorations usually occurred at the interface between composite and glass-ionomer, with the cement remaining intact. Marginal staining was also assessed in this study and the vast majority of restorations with etching of both enamel and cement showed no evidence of marginal staining after two years. Those with etching only of the glass-ionomer cement showed staining in more than half the restorations assessed. Tyas and his co-workers concluded that the effectiveness of the bond between etched glass-ionomer cement and composite resin was similar to that mediated by dentine bonding agents and that additional retention was required from etched enamel or an undercut cavity.
The composite resin system was a natural progression from unfilled acrylic resin, which showed limitations of low strength, poor abrasion resistance and a high co-efficient of thermal expansion (Phillips 1981). Composite resins were introduced by Bowen in 1963 for use in Class III, IV and V restorations or areas without occlusal loading (Rupp 1979). After considerable research, changes and improvements have resulted in composite resins being used in or considered for nearly every aspect of operative dentistry (Leinfelder 1985).

3.1 COMPOSITION, SETTING AND STRUCTURE

Composite resins are "three dimensional combinations of at least two chemically different materials with a distinct interface separating the components" (Phillips 1981) and so can be described in three parts, or phases (Craig 1981, Leinfelder 1985).

The matrix phase consists principally of high and low molecular weight organic monomers and additives which initiate setting, control the setting reaction and stabilize the set material (Bowen 1979). The dispersed phase is made up of reinforcing fillers of different physical and chemical properties. The proportion of filler and its' particle size varies among composite resins (Craig 1981). Organofunctional silanes make up the interfacial phase and these give some degree of covalent bonding between matrix and dispersed filler (Bowen 1979, Craig 1981). The conversion of monomers present in the matrix phase to polymers results in setting, or curing, of the composite resin.
Setting is initiated by either chemical or photochemical means (Craig 1981).

Since their inception, the composite resins have seen many variations of the three-phase formulation. The main areas of advancement have been in composition and geometry of the filler, resulting in improvements in physical and mechanical properties (Raptis et al. 1979, Farah and Dougherty 1981, Lutz and Phillips 1983, Leinfelder 1985) and modes of curing (Craig 1981, Pollack and Blitzer 1982).

3.2 CHARACTERISTICS

Microfilled composite resins are more often used to restore cervical cavities because of their polishability and translucency. Typical values for some physical properties of microfilled composite resins are listed with those for glass-ionomer cements in Table 2.1. Other important properties include pulpal responses, fluoride release and optical qualities, such as surface finish and translucency.

No composite resins have been marketed with long-term fluoride leaching but experimental formulations have been reported (Craig et al. 1981) and found to inhibit secondary caries in vitro (Plummer et al. 1981). An experimental dentine bonding agent containing fluoride has been developed (Turpin-Mair et al. 1987) but no caries inhibiting effect was observed in vitro at the gingival margin when compared to a glass-ionomer restorative cement (Erickson et al. 1987).

Composite resins have been considered toxic materials and may cause chronic pulpitis if placed in unlined cavities (Stanley et al. 1979). There is some disagreement, however, as to which
component of the material is responsible for pulpal irritation. Removal of methacrylic acid from the composite resin was ineffective in reducing pulpal inflammation (Stanley et al. 1975) but a study of the irritant potential of eight other individual constituents showed none cause significant inflammation in vivo (Stanley et al. 1979). When composite resin components were combined, both resin and catalyst systems proved to be cytotoxic in vitro, even at low dilutions (Anderson et al. 1987). A recent review of microbial microleakage and pulpal inflammation suggested that chemical toxicity may be of less importance than had previously been thought, and that the presence of bacteria in the microspace between restoration and cavity wall had a cause and effect relationship with pulpal inflammation (Browne and Tobias 1986).

An advantage of composite resin is the ability to closely match the colour and translucency of enamel and dentine (Cook et al. 1984). There is evidence, however, that the internal colour of composite resins is unstable and that surface staining occurs with time (Asmussen 1985).

Finishing and polishing these materials has always presented problems (Phillips 1981, Van Noort 1983) and a poorly finished surface will give an inferior visual effect, allow plaque accumulation and increased surface staining. The introduction of microfilled composites has resulted in restorations with a smooth, highly reflective surface (Farah and Dougherty 1981, Leinfelder 1985). The smoothest surface is achieved by using a matrix during polymerization of the composite material (Dennison et al. 1981, Bauer and Caputo 1983). If finishing is necessary, the use of graded polishing discs is recommended (Lambrechts and Vanherle 1982, Reinhardt et al. 1983, Quiroz and Lentz 1985).
3.3 BONDING TO ENAMEL

Unlike glass-ionomer cements, composite resin materials alone do not bond to hard tooth tissues and so, to establish a useful bond, several methods of surface modification must be employed. Surface modification of enamel can be divided into those techniques which enhance mechanical interlocking, and those which make use of an intermediary adhesive layer to connect tooth structure and composite resin.

Buonocore, in 1955, used acid decalcification of the enamel surface to achieve a strong bond with acrylic resin. This bond is believed to be mechanical in nature (Pahlavan et al. 1976, Jordan et al. 1977, Asmussen 1985) and bonding can be explained by several factors, including an increase in surface area, the exposing of an organic framework around which the resin would lock and the exposure of a fresh, reactive enamel surface (Buonocore 1955). This technique of etching enamel with acid has been studied in detail (Buonocore 1975b, Silverstone and Dogon 1975) and generally accepted for use in restorative dentistry (Asmussen 1985). Though widely used, several aspects of the acid-etch technique remain controversial, principally cavosurface design, the need for additional retentive undercuts and the use of an intermediary bonding resin.

Etched, bevelled cavosurface margins were shown to have greater potential in reducing marginal leakage than etched, butt-joint cavities, in vitro (Eriksen and Buonocore 1976, Luescher et al. 1977, Crim et al. 1984) and in vivo (Qvist 1985). On the contrary, Retief et al. in 1982 found cavosurface configuration had no significant effect on marginal leakage, in vitro.

Reliance on the bond formed by acid-etching enamel is the most conservative approach to restoration using composite resins. Total
reliance on this bond may not be advisable, however, especially at the cervical margin where little or no enamel is available for bonding (Van Noort 1983). Although acid-etching was largely effective in preventing leakage in saucer-shaped, non-retentive cavities filled with composite resins (Eriksen and Buonocore 1976), undercut areas for retention are still advocated (Rupp 1979).

Placing low viscosity bonding resins on etched enamel walls prior to inserting a composite resin restoration is not necessary to obtain minimal leakage (Ortiz et al. 1979, Retief et al. 1982). Also, little difference in depth of penetration of resin tags into etched enamel using filled and unfilled resins has been demonstrated (Pahlavan et al. 1976, Asmussen 1977). Investigations of bonding in vitro showed no improvement in tensile strength (Soetopo et al. 1978) or transverse strength (Mitchem and Turner 1974) with the use of unfilled resins prior to placing composite resin, but the increased frequency of failure within the enamel suggested better adaptation (Mitchem and Turner 1974). Using shear and tensile testing in conjunction with thermal cycling, Rider et al. in 1977 concluded that while bond strengths were unaffected, the use of intermediary resins could produce a more durable bond.

Clinically, the frequency of marginal discolouration and marginal gaps was markedly reduced with the use of low viscosity bonding agents (Hansen et al. 1984), as was marginal leakage both in vivo and in vitro (Hembree and Andrews 1976a, b). Since so much conflicting evidence exists, the clinicians must ultimately decide, and one recommendation is that, as it does no harm, a bonding agent should be used (Rupp 1979).

The predominant hydroxyapatite component of enamel has potential for chemical bonding to substances capable of interacting
with calcium and phosphate or incorporating the bound water in the 
apatite lattice (Causton 1982). These possibilities will be 
considered during discussion of bonding composite resins to the 
inorganic phase of dentine.

3.4 BONDING TO DENTINE

Although reliable bonding of composite resins to enamel can be 
achieved by acid-etching, similar treatment of dentine gives rise 
to bonds of low strength (Causton 1982, Asmussen and Munksgaard 
1985a) and provides little protection against marginal leakage 
(Eriksen and Buonocore 1976). Regardless of the ability to form 
visible bonds, the use of acid on dentine may amplify the 
undesirable pulpal response to the composite resin material 

Since mechanical interlocking fails to provide an adequate 
bond, attempts have been made to obtain attachment of composite 
resin to dentine using an intermediary adhesive layer. Two 
approaches have found clinical acceptance, firstly primers and more 
recently a layer of glass-ionomer cement, both of which can attach 
to both dentine and composite resin. The use of glass-ionomer 
cements in bonding composite resin to dentine has been discussed in 
the preceding chapter.

Primers are chemicals capable of forming bridges between two 
different substances (Causton 1982), and usually consist of 
bifunctional molecules which interact with both dentine and 
composite resin (Asmussen and Munksgaard 1985a). These molecules 
contain a methacrylate group for copolymerization with the resin, a 
spacer, and a functional group for reaction with the dentine 
surface. Referred to as dentine adhesives or dentine bonding
agents, these molecules can be readily grouped by the nature of their interaction with either the organic or inorganic phases of dentine. As described in Chapter 1, an obstacle to adhesive bonding is the presence of a smear layer on the dentine surface. To obtain optimum bond formation either the adhesive must strengthen this layer or it must be removed before the adhesive is applied (Bowen 1979, Asmussen 1985). Consequently, many primers are preceded by some form of surface treatment (Causton 1982).

**Bonding to the Inorganic Phase of Dentine.**

Buonocore and others, in 1956, reported durable bonding of acrylic resin to dentine using a phosphoric acid ester. Limited penetration of this primer into both dentine and the restorative resin was demonstrated (Kramer and Lee 1960) and the bonding mechanism is considered to involve attraction between active phosphate groups and calcium ions at the dentine surface (Asmussen 1985).

The weak point of the bond proved to be the easily hydrolyzed linkage of the phosphate to the resin (Causton 1984, Asmussen and Munksgaard 1985a) resulting in a significant decrease in bond strength after storage in water (Aquilino et al. 1987a). Primers consisting of modified phosphate esters have been marketed and a wide range of shear and tensile bond strengths reported (Council on Dental Materials, Instruments and Equipment 1987).

These dentine bonding agents should be most effective at high calcium concentrations and they have, in fact, been found to give stronger bonds to enamel and highly mineralized, superficial dentine than to deeper, less mineralized dentine (Nakamichi et al. 1983, Causton 1984, Solomon and Beech 1985, Stanford et al. 1985).
Causton in 1984 found increased bond strengths to deep dentine after surface treatment with a mineralizing solution but another study reported reduced or unchanged bond strengths after mineralizing pretreatments (Solomon and Beech 1985). These conflicting findings may have resulted from differing original mineral content of the dentine used, or simply that the former study used unerupted teeth which would presumably be less mineralized and respond more readily to pretreatment.

A second mechanism of obtaining adhesion to the inorganic phase of dentine involves formation of chelate bonds with calcium (Bowen 1965 a,b,c). Adhesives with chelating potential have been formulated and have found commercial use (Retief 1975). Bond strengths to dentine were initially low, but improved with the use of calcifying solutions (Causton et al. 1981, Nakabayashi et al. 1982) and combinations of adhesives (Jedrychowski et al. 1981, Bowen et al. 1982). Bowen et al. in 1982 reported bonds of such magnitude that cohesive failures occurred in the composite resin and dentine as well as at the tooth-restoration interface, but this has not been substantiated (Jedrychowski et al. 1981, Fagan et al. 1986).

To achieve a viable bond as many as ten steps are required, some of which are time-consuming (Causton et al. 1981, Eliades et al. 1985). Such complexity has led researchers to question the clinical viability of this adhesive system (Causton et al. 1981, Fagan et al. 1986), especially as bond strengths obtained were similar to values found using a simpler and quicker phosphate ester system (Fagan et al. 1986).
Bonding to the Organic Phase of Dentine

An early mechanism suggested for bonding to the organic phase of dentine was grafting to collagen using catalysts (Causton 1982). More recently, urethanes containing isocyanate groups which react with collagen sidechains have been used as primers (Antonucci et al. 1980) but bond strengths obtained were probably too low to be clinically viable (Asmussen and Munksgaard 1983).

Acid chlorides have been investigated (Asmussen and Munksgaard 1983) and bonding suggested through reaction with hydroxy and amino groups present in collagen. Low bond strengths were probably due to preferential bonding of acid chlorides with the water always present in surface dentine (Asmussen and Munksgaard 1985b).

Based on the investigations of isocyanates and acid chlorides, attempts were made to formulate an adhesive able to operate successfully in an aqueous environment. Aldehydes were used, mainly formaldehyde (Asmussen and Munksgaard 1984) and glutaraldehyde (Munksgaard and Asmussen 1984), in combination with monomers such as hydroxy ethylmethacrylate (HEMA). Eventually, a formula was reached where the methacrylic monomer couples, in situ, to the reaction product of an aldehyde and dentine (Asmussen 1985). Strong tensile and shear bond strengths to dentine have been reported (Eliades et al. 1985, Asmussen and Munksgaard 1985b, Finger and Ohsawa 1987, O'Brien et al. 1987, Stangel 1987) and the formation of marginal contraction gaps greatly reduced (Asmussen and Munksgaard 1985b). Another study, however, found tensile bond strengths between composite resin and dentine mediated by this system to be much lower than those previously reported and dependant on the composite resin used (Oden and Oilo 1986).
Strong bond formation to dentine using the glutaraldehyde/HEMA system (GLUMA) is conditional upon first cleansing with a mild chelating agent, a fact which may account for the low shear bond strengths found using GLUMA with no dentine pretreatment (Norman et al. 1987). The bond strength of composite resin to dentine mediated by GLUMA was found to increase slightly (Finger and Ohsawa 1987) or was unaffected by storage in water (Eliades et al. 1985, O'Brien et al. 1987), an encouraging sign for bond durability in the oral environment. No suggestion is made that GLUMA will mediate bonding to enamel and a separate enamel bond is supplied with the commercial product.

3.5 FACTORS INFLUENCING BOND VIABILITY

Bonding of composite resins to tooth structure requires a reliable mechanical or physico-chemical interaction between the resin and cavity walls. Influences on bond formation and maintenance include manipulation and placement techniques, physical properties of the materials and subsequent interaction with the oral environment.

In order to obtain the intimate contact necessary for bond formation, correct placement techniques are essential and adequate isolation must be used to avoid contamination of the bonding surface (Rupp 1979, Bauer and Henson 1984) and to optimize the physical properties of the material (Bauer and Henson 1984). Once placed, the bond strength achieved should be capable of resisting the stresses occurring during polymerization contraction. Composite resins vary in the amount of shrinkage occurring during polymerization but, in general, the lower viscosity materials have increased shrinkage (Hansen 1982), a relationship which favours macrofills over microfilled resins (Asmussen 1985).
The contraction stress for a microfilled composite resin in Class V cavities has been found to reach 20MPa within five minutes (Davidson et al. 1984). The composite restoration remained attached to the etched enamel walls but detached from the dentine margins despite the use of a commercial phosphate ester bonding agent. It would seem that, as no dentine bonding agent available shows consistent bonds to dentine of 20MPa (Council on Dental Materials, Instruments and Equipment 1987), the stresses of polymerization contraction will cause disruption and marginal gap formation. Several factors have been suggested, however, which may reduce contraction stresses to a level consistent with bond formation between composite resins and dentine. These factors are principally cavity design variables, placement techniques and curing mechanisms.

Using the width of marginal contraction gaps as a measure of bonding efficiency in dentine cavities and using dentine bonding agents, a number of conclusions have been reached on optimal cavity design. The width of the marginal contraction gap was found to be independent of cavity depth in butt-joint cavities but increased with cavity diameter (Hansen 1986). Increasing the radius of the cavity base increased the marginal contraction gap to a greater extent than increasing the radius of the cavity cavosurface (Hansen and Asmussen 1985). A highly significant decrease in marginal gap width was found with increasing cavosurface angle (Hansen 1984). Clinically, the bond between dentine and composite resin might be improved using less traditional cavity designs rather than a butt-joint preparation (Hansen and Asmussen 1985).

Placement of composite resins in increments has been advocated (Rupp 1979) but a two-phase placement in layers parallel to the
cavity base failed to reduce the width of the marginal contraction gaps (Hansen 1986). Oblique layers resulted in a 25 per cent reduction in gap width in dentine cavities without the use of bonding agents (Hansen 1986), a finding consistent with the effects of increased cavosurface angle and radius of cavity base on contraction gaps. No difference was found when the first oblique layer was placed coronally or apically (Hansen 1986) but in cavities with both enamel and dentine margins, it is suggested that the first increment be placed apically to enable contraction towards the dentine margin without competition from the stronger bond between enamel and composite resin (Davidson 1986).

Light-cured composites attain high bond strength and shrinkage stress within one minute of curing being initiated but chemically-cured composite resins take much longer (Davidson et al. 1984). This suggests that incremental packing is most advantageous with light-cured materials (Davidson 1986) and should be aided by light-curing dentine bonding agents.

If stresses have resulted from polymerization shrinkage or marginal contraction gaps have formed, they may be minimized by subsequent water sorption of the composite resin. This water sorption, or hygroscopic expansion, probably occurs in all restorative resins (Hansen 1982) and the extent depends on filler content and monomer composition (Asmussen 1985). The greater the filler content, the less hygroscopic expansion, a relationship which favours microfilled resins and helps compensate for their initial high shrinkage. This aspect of the behaviour of composite resins suggests final finishing of restorations be delayed until complete water sorption has occurred. This may take 28 days or more, depending on the type of composite resin (Hansen 1982).
Clinically, it is desirable for thermal dimensional changes of restorative materials to approximate those of tooth structure in order to control marginal leakage (Powers et al. 1979). The thermal expansion co-efficients of composites remain well above those of hard tooth tissues (Raptis et al. 1979), so composite resins will tend to shrink more on cooling than the surrounding tooth structure and create a gap (Asmussen 1985). Bonding through acid-etching and dentine adhesives will prevent this contraction as long as the bonds formed are strong enough and the compensation from hygroscopic expansion is sufficient to reduce the stresses occurring during thermal changes.

3.6 CLINICAL SURVEYS

In clinical surveys of cervical erosion or abrasion lesions restored using composite resins and primers, assessment of the efficacy of the bond between composite resin and dentine is made more difficult if the enamel margin is also etched and bonded. It has been argued that the restoration is retained simply by the etched enamel (Doering and Jensen 1986). A method of assessing dentine adhesion involves determination of retention and sealing without acid-etching enamel (Vanherle et al. 1986) and may be the only true way to evaluate the bond in the oral environment (Dennison et al. 1986).

Using cervical erosion or abrasion lesions with no enamel modification, retention rates for composite resins used with primers have proved disappointing, especially when compared with glass-ionomer cements in the same situation. The requirement for provisional acceptance of an adhesive material is a minimum 95 per
cent retention after six months (Council on Dental Materials, Instruments and Equipment 1981) which, at this stage, has not been met.

Clinical surveys using microfilled composite resins and phosphate ester primers have found retention rates at six months of 85 per cent (Vanherle et al. 1986), 76 per cent (Doering and Jensen 1986), 86 to 89 per cent (Dennison et al. 1986) and 59 to 81 per cent (Tyas et al. 1986). At one year retention rates were 74 per cent (Doering and Jensen 1986), 74 to 80 per cent (Dennison et al. 1986) and 54 to 75 per cent (Tyas et al. 1986). After two years of clinical service, retention rates of 64 to 70 per cent were record-
ed (Dennison et al. 1986). Glass-ionomer restoratives, used in the same situation and with polyacrylic acid pretreatment, showed complete retention at both six months and one year (Doering and Jensen 1986) and 97.5 per cent retention at one year without dentine pretreat-
ment (Tyas et al. 1986).

A study of the retention of a primer designed to bond with the organic phase of dentine and used with a microfilled composite resin found 77 per cent of cervical restorations were retained after 18 months, compared with 100 per cent of glass-ionomer cement restorations (Horsted et al. 1986). When the enamel was etched and bonded as well, retention rates equalled those obtained using a glass-ionomer cement.

Other problems associated with clinical use of dentine bonding agents included a high incidence of marginal deficiency and detect-
ability of margins with time (Dennison et al. 1986), increased marginal discolouration (Tyas et al. 1986) and some pulpal necrosis after restoration (Vanherle et al. 1986).
CHAPTER 4

INVESTIGATIONS OF MARGINAL SEAL

4.1 INTRODUCTION

The absence of a seal at restoration margins may contribute to staining, adverse pulpal response, post-operative sensitivity and recurrent caries (Going 1972, Bauer and Henson 1984, Crim and Garcia-Godoy 1987). Microleakage, defined as "the passage of bacteria, fluids, chemical substances, molecules and ions between the tooth and its' restoration" (Bauer and Henson 1984), may be used in an attempt to predict the marginal sealing ability of restorative materials. An assessment of marginal sealing ability may also be made by visualization of the tooth-restoration interface in order to determine the presence or absence of marginal gaps.

4.2 INVESTIGATIONS OF MICROLEAKAGE

The occurrence of microleakage around dental restorations has been of concern for over a hundred years. In the late nineteenth century, Fletcher investigated the penetration of "coloured fluids" around dental amalgam placed in glass tubes (Black 1908). Since then, researchers have utilized all the components of microleakage, that is fluids, bacteria, chemical substances, molecules and ions, in their investigations.

Many researchers have adopted methods making use of restored teeth and exposing them to fluids containing detectable substances, most often dyes, stains, isotopes or bacteria. These substances penetrate microgaps which may be present at
the tooth-restoration interface and are subsequently detected either visually, autoradiographically or after culturing.

These penetration and percolation methods rely on subjective or qualitative assessment and usually require the specimen to be destroyed by sectioning in order to make the microleakage assessment. Destruction of the specimens means longitudinal assessment is possible only by intermittent sacrifice of a portion of the specimen group. Sectioning does, on the other hand, allow comparison of the marginal sealing ability of different aspects of the cavity, principally the occlusal and gingival margins. This comparison is not possible when a single result or reading is gained for each restoration.

Several of these methods of qualitative microleakage investigation may be used in vivo, but the teeth must usually be extracted for evaluation. An exception to this rule is a recently reported method using percolation of hydroxyl ions (Leinfelder et al. 1986, Isenberg et al. 1987).

Originally, air pressure was the only method available for quantitative assessment of microleakage. Now, sensitive quantitative results can be achieved using neutron activation analysis, electrical conductivity measurements, generation of artificial carious lesions and radiochemical diffusivity, as well as a recent variation on the air pressure technique (Derkson et al. 1986).

Neutron activation can be used in vitro and in vivo but requires specimen sacrifice which may limit its use in long term studies. The conductimetric method is restricted to use in vitro but allows longitudinal assessment of microleakage. Evaluation of microleakage by generation of artificial carious lesions is used in vitro and assessment requires sectioning of the specimens. Quanti-
fication is possible where the depth of wall lesions is chosen as the evaluation parameter (Kidd 1976a). Diffusion of radiochemicals allows quantitative, longitudinal assessment of microleakage, with the levels of tracer being monitored by either spectrometry or a scintillation counter.

These methods of evaluating microleakage around dental restorations are summarized in Table 4.1 and have been reviewed in detail by Going in 1972 and 1979, Kidd in 1976(b) and Bauer and Henson in 1984.

4.3 METHODS OF VISUALIZING RESTORATION MARGINS

Assessment of the ability of dental restorative materials to seal cavity margins may be made by examining the tooth-restoration interface for the presence or absence of marginal gaps. Observation of these gaps and measurement of gap width can be achieved by several visualization methods, either directly or by using a replica of the original.

Direct visualization is one of the oldest methods used to study marginal sealing ability. As long ago as 1861, Tomes examined the margins of amalgam restorations with a microscope to determine whether they remained closed (Black 1908). For direct visualization of the tooth-restoration interface a microscope is usually necessary, as the limit of human visual acuity is reportedly in the order of 50 microns (Going 1972). Dye staining may also aid detection of marginal gaps when combined with microscopy (Zidan et al. 1987, Phair et al. 1987). Reflected light microscopy has been widely used and quantitative assessment of gap width is possible using measuring eyepieces (Wing and Lyell 1966, Asmussen and Jorgensen 1972, Hansen 1986) or micrographs (Ehrnford and Derand 1984).
### Table 4.1

**MICROLEAKAGE INVESTIGATIONS - A SUMMARY OF METHODS.**

<table>
<thead>
<tr>
<th>METHOD</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td><strong>AIR AND LIQUID PRESSURE</strong></td>
<td>Harper 1912</td>
</tr>
<tr>
<td>Application: In vitro</td>
<td>Fiasconaro and Sherman 1952</td>
</tr>
<tr>
<td>Evaluation: Quantitative,</td>
<td>Granath and Svenssen 1970</td>
</tr>
<tr>
<td>non-destructive</td>
<td>Derkson et al. 1986</td>
</tr>
<tr>
<td><strong>BACTERIAL PENETRATION</strong></td>
<td>Fraser 1929</td>
</tr>
<tr>
<td>Application: In vitro and in</td>
<td>Mortensen et al. 1965</td>
</tr>
<tr>
<td>vivo</td>
<td>Brannstrom and Nyborg 1971</td>
</tr>
<tr>
<td>Evaluation: Qualitative,</td>
<td></td>
</tr>
<tr>
<td>destructive</td>
<td></td>
</tr>
<tr>
<td><strong>FLUID AND ION PERCOLATION</strong></td>
<td>Nelsen et al. 1952</td>
</tr>
<tr>
<td>Application: In vitro and in</td>
<td>Leinfelder et al. 1986</td>
</tr>
<tr>
<td>vivo</td>
<td>Isenberg et al. 1987</td>
</tr>
<tr>
<td>Evaluation: Qualitative,</td>
<td></td>
</tr>
<tr>
<td>non-destructive</td>
<td></td>
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<tr>
<td><strong>ISOTOPE PENETRATION</strong></td>
<td>Armstrong and Simon 1951</td>
</tr>
<tr>
<td>Application: In vitro and in</td>
<td>Phillips et al. 1961</td>
</tr>
<tr>
<td>vivo</td>
<td>McCurdy et al. 1974</td>
</tr>
<tr>
<td>Evaluation: Qualitative,</td>
<td>Hembree and Andrews 1976a,b</td>
</tr>
<tr>
<td>destructive</td>
<td></td>
</tr>
<tr>
<td><strong>DYE AND STAIN PENETRATION</strong></td>
<td>Grossman 1939</td>
</tr>
<tr>
<td>Application: In vitro</td>
<td>Tani and Buonocore 1969</td>
</tr>
<tr>
<td>Evaluation: Qualitative,</td>
<td>Christen and Mitchell 1966</td>
</tr>
<tr>
<td>destructive</td>
<td>Wu et al. 1983</td>
</tr>
<tr>
<td><strong>ARTIFICIAL CARIES</strong></td>
<td>Silverstone 1966</td>
</tr>
<tr>
<td>Application: In vitro</td>
<td>Ellis and Brown 1967</td>
</tr>
<tr>
<td>Evaluation: Quantitative,</td>
<td>Hals and Nernaes 1971</td>
</tr>
<tr>
<td>destructive</td>
<td>Kidd 1976a</td>
</tr>
<tr>
<td><strong>CONDUCTIMETRIC</strong></td>
<td>Jacobsen and von Fraunhofer 1975</td>
</tr>
<tr>
<td>Application: In vitro</td>
<td>von Fraunhofer and Hammer 1984</td>
</tr>
<tr>
<td>Evaluation: Quantitative,</td>
<td></td>
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<tr>
<td>non-destructive</td>
<td></td>
</tr>
<tr>
<td><strong>NEUTRON ACTIVATION</strong></td>
<td>Going et al. 1968</td>
</tr>
<tr>
<td>Application: In vitro and in</td>
<td>Meyer et al. 1974</td>
</tr>
<tr>
<td>vivo</td>
<td></td>
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<tr>
<td>Evaluation: Quantitative,</td>
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<td>destructive</td>
<td></td>
</tr>
<tr>
<td><strong>RADIOCHEMICAL DIFFUSION</strong></td>
<td>Crisp and Wilson 1980</td>
</tr>
<tr>
<td>Application: In vitro</td>
<td>Shen and Tsutsumi 1983</td>
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<tr>
<td>Evaluation: Quantitative,</td>
<td></td>
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<tr>
<td>non-destructive</td>
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Since the 1960's, scanning electron microscopy (SEM) has been extensively used in direct visualization of the tooth-restoration interface. SEM has advantages over light microscopy in possessing greater depth of focus, higher resolution, a large range of magnification, the ability to view large specimens from all angles and the production of three dimensional image effects (Boyde and Knight 1969, Barnes 1972, Saltzberg et al. 1976). Factors which limit direct visualization by SEM include specimen destruction, the production of artefacts during specimen preparation and that evaluation cannot take place in the oral environment (Going 1972, Bauer and Henson 1984).

The use of a replica or "copy of an original obtained by means of a reproducing procedure" (Lambrechts et al. 1981) has proved particularly valuable in overcoming the problem of specimen artefacts in SEM (Barnes 1972, Kidd 1976b, Bauer and Henson 1984), and especially in the assessment of marginal gaps (Bergvall and Brannstrom 1971, Roulet and Michellod 1984). Replication also obviates the need for destruction of the original, allowing assessment of the same structure on a longitudinal basis (Boyde and Knight 1969, Barnes 1972, Going 1979).

The negative replica is obtained using an elastomeric impression material and a positive produced either in resin (Grundy 1971, Barnes 1972), or by electroplating the negative and then casting in resin or dental stone (Lambrechts et al. 1981). If a resin replica alone is used it must be coated with a conducting medium before SEM examination (Grundy 1971).
4.4 COMPARISON OF IN VITRO AND IN VIVO INVESTIGATIONS

Most researchers agree that the relationship between the marginal sealing ability of restorations evaluated in the laboratory and that occurring clinically has not been established. Attempts to compare in vivo and in vitro findings have presented a conflicting picture with regard to microleakage, and only one direct comparison has been reported for visualization of restoration margins.

Nelsen et al. in 1952 found a correlation between in vivo and in vitro observations of fluid percolation at the margins of resin fillings subjected to thermal stress. Hals and Simonsen in 1972, using caries produced around amalgam fillings in vivo, found the pathogenesis of the carious lesions to correspond with in vitro lesions described by Hals and Nernaes in 1971, although the lesions themselves were not identical. Investigations of microleakage around dental restorations in vivo using a radioisotope have reported results similar to those found in companion in vitro studies (McCurdy et al. 1974, Hembree and Andrews 1976a,b) and McCurdy et al. in 1974 concluded that laboratory microleakage tests were suitable for screening dental restorative materials. As well, a recently reported method using percolation of hydroxyl ions also found the results of in vivo microleakage to be almost identical to those obtained in a laboratory study (Leinfelder et al. 1986, Isenberg et al. 1987).

In contrast, Going et al. in 1968 evaluated microleakage around a variety of restorative materials using a neutron activation method and found in vivo uptake to be greater than that in vitro by a factor of up to six times. No mention was made, however, of the time elapsed between restoration and evaluation so the
effects of thermal stress in vivo cannot be taken into consideration, and the in vitro specimens were not thermal cycled. Also, Loiselle et al. in 1969, using amalgam restorations placed in bilaterally paired teeth and extracted after two weeks, found fluorescent dye uptake in vitro to exceed that in vivo by a factor of ten. Stuever et al. in 1971 tested the margins of composite restorations using the same experimental regimen as Loiselle et al. 1969 and similarly found a discrepancy in leakage scores in vivo and in vitro. These researchers concluded that the differences found reflected the effects of pulpal hydrostatic pressure.

Bergvall and Brannstrom in 1971 measured marginal gap width in vitro using identical restorations and similar techniques to those of a previous in vivo study measuring bacterial film thickness at the restoration and cavity interface (Brannstrom and Nyborg 1971). After comparing the results, they concluded that the width of spaces measured in vitro could exist in vivo.

4.5 VARIABLES INFLUENCING IN VITRO INVESTIGATIONS

In order to simulate conditions found in the oral cavity and to achieve a closer correlation with in vivo findings, in vitro investigations of marginal seal have incorporated a number of variable factors in the experimental regimen. Inclusion, exclusion or variations in the extent of thermal cycling, load cycling and pulpal hydrostatic pressure simulation may influence the outcome of marginal seal investigations, as may the mode and duration of storage of the extracted teeth. Variations in these factors also make comparison of investigations difficult and sometimes of doubtful value.
Thermal Cycling

Most methods of assessing microleakage in vitro include thermal cycling as part of the experimental regimen (Kidd 1976b, Bauer and Henson 1984), as do in vitro visualization studies of restoration margins (Reich and Volkl 1986, Roulet and Rosansky 1986). Since the first observations of marginal percolation as a result of temperature fluctuations (Nelsen et al. 1952), it has often been suggested that this fluid exchange is due to differences in the co-efficients of thermal expansion of tooth structure and restorative materials (Going 1972, Kidd 1976b, Bauer and Henson 1984). Thermal cycling is used in order to simulate temperature fluctuations occurring in the oral environment, however, conflicting reports have been made as to its effectiveness, especially in microleakage assessment.

Some researchers have shown thermal cycling to be more potent in demonstrating leakage than no cycling at all (Crim and Mattingly 1981, Crim et al. 1985) but others have suggested thermal cycling may not be a significant factor in assessing microleakage (Guzman et al. 1969, Maldonado et al. 1978, Glyn Jones et al. 1979, Lacefield et al. 1982). Peterson et al. in 1966 noted that, although leakage patterns of cycled and non-cycled specimens were similar, a trend towards greater penetration occurred with an increasing number of cycles. A recent study, however, has shown that the degree of dye penetration was not significantly different regardless of the total number of cycles (Crim and Garcia-Godoy 1987).

Little agreement exists among researchers concerning the details of thermal cycling, principally the number of cycles, the time of immersion of specimens and the temperature range required...
to reproduce a clinical situation. In determining the number of thermal cycles needed to simulate clinical conditions, it has been speculated that in vitro thermal cycling within a range of temperatures recorded in the oral cavity causes as much damage within a few thousand cycles as occurs in vivo over several years (Lloyd et al. 1978). A complication of thermal stress, either in vitro or in vivo, is enamel crack propagation which has been reported by these researchers as being initiated within 2000 thermal cycles and to be especially pronounced in the cervical region. By changing the pattern of dye penetration, the results of microleakage studies may be confused by the presence of these cracks.

Temperature ranges reported in microleakage investigations have included upper limits of 45-60°C and lower limits of 0-15°C. Thermal tolerance in the oral cavity was initially reported as being between 4°C and 60°C, resulting in temperatures recorded under acrylic restorations of 9°C and 52°C (Nelsen et al. 1952). Subsequent studies have found the upper range of thermal tolerance to be 45-55°C (Plant et al. 1974, Peterson et al. 1966) and that drinking iced water (0°C) created temperatures at the tooth surface of 10-15°C (Peterson et al. 1966).

The duration of immersion of specimens in the warm and cold baths has varied from a few seconds to several hours (Kidd 1976b). As the maximum thermal gradient in enamel reportedly develops within the first second after exposure to a temperature variation (Lloyd et al. 1978), it would seem that long exposure times are unnecessary to achieve maximum benefit from thermal cycling. This suggestion has been supported by Crim et al. in 1985, who found no
difference in the degree of marginal leakage occurring around restorations subjected to dwell times of 30 seconds or four seconds.

Load Cycling

Fluid percolation at the margins of restorations as a result of mechanical factors present in the oral environment was demonstrated by Jorgensen in 1970. A later study of the deformation of various cavities placed in axially loaded human teeth showed these cavities to be dimensionally unstable (Jorgensen et al. 1976). After restoration of these cavities with composite resin, marginal gaps were observed during load cycling, however, the incidence of marginal gaps decreased when peripheral enamel was etched prior to placement of the composite material.

Load cycling has not been widely used in the experimental regimen of marginal seal investigations but the effects of cyclic loading on microleakage patterns have been investigated. Raadal in 1979, using occlusal fissure sealants, found increased leakage when load cycling was combined with thermal cycling, in comparison to results obtained using thermal cycling alone. In contrast, Stewart et al. in 1986, using Class V cavities bounded by enamel, found no significant difference in leakage produced by thermal cycling when compared with load cycling at varying load levels. A leakage pattern similar to that obtained using dentine bonding agents, composite resins, cervical cavities and thermal cycling was reported after load cycling under similar circumstances (Erickson and Jensen 1986). These researchers found that the root surface margins showed greater leakage after load cycling, while the enamel margins were able to resist microleakage.
As with thermal cycling, little consensus exists among researchers regarding the details of load cycling, especially with respect to load magnitude, duration of loading and the number of loading cycles needed to reproduce oral conditions. The positioning of the load is also subject to variation, with some loading the occlusal surface (Jorgensen et al. 1976, Raadal 1979, Erickson and Jensen 1986) and others the restoration (Stewart et al. 1986). A machine to simulate mastication has been suggested as a more accurate method of load cycling, but this system is expensive and complicated (Stewart et al. 1986).

Storage of Teeth

In vitro studies of marginal sealing ability almost invariably make use of extracted human teeth to prepare cavities and place restorations. Questions have been raised regarding changes in tooth structure, and particularly dentine, occurring after extraction and the effect any changes may have on the bonding potential of restorative materials. The two main areas of concern are the duration of tooth storage prior to use, and the storage medium employed.

Causton and Johnson in 1979(b) reported a 50 per cent decrease in shear bond strength of a polycarboxylate cement to dentine in the first four hours after extraction, and concluded that the ability of dentine to form bonds is dependant on its' freshness. Subsequently, storage time has been shown to have little effect on adhesion of glass-ionomer cement to dentine (Aboush and Jenkins 1983) or composite resin to dentine mediated by primers (Mitchem and Gronas 1985, Williams et al. 1985, Stackhouse et al. 1986). In another study, however, it was concluded that time after extraction
could significantly effect bonding to dentine, but the direction and magnitude of the change depended on the adhesive system (Beech et al. 1986).

A number of media have been reported for tooth storage prior to marginal seal investigations. These included alcohol (Phair and Fuller 1983), tap water (Welsh and Hembree 1985, Crim and Chapman 1986a), normal saline (Fuks et al. 1985) and formalin (Reich and Volk 1986). Although no reports have been made on the effects of storage media on microleakage patterns, studies have been made of the effects of storage conditions on other aspects of bonding composite resin to dentine. Jorgensen et al. in 1985 reported no change in contraction gap width when teeth were stored in tap water or aqueous chloramine, but gap size was occasionally affected by storage in saline. Storage in distilled water, saline, or distilled water with thymol was found to have no effect on bond strengths of composite resin to dentine mediated by a dentine bonding agent (Aquilino et al. 1987b).

Pulpal Hydrostatic Pressure

The absence of a vital pulp and accompanying pulpal hydrostatic pressure suggests that, even with adequate storage methods, the use of extracted teeth in studies of the marginal seal of restorative materials cannot completely reproduce in vivo conditions. Pulpal hydrostatic pressure has been observed to inhibit, in vivo, adhesion of dentine bonding agents (Braem et al. 1986) and also to alter microleakage patterns (Stuever et al. 1971).

A laboratory system which simulates pulpal hydrostatic pressure in prepared human teeth has been reported and used to test sealing properties and bond strengths to dentine (Terkla et al. 1987,
Mitchem et al. 1987). Bond strengths to dentine of composite resins used with several primers in simulated physiological conditions were found to be significantly lower when compared to a standard laboratory test (Mitchem et al. 1987). This finding corresponds to in vivo observations and future investigations of marginal sealing ability in vitro may well include this simulation of hydrostatic pressure produced by a vital pulp.
CHAPTER 5
MARGINAL SEAL OF CERVICAL RESTORATIONS
- IN VITRO FINDINGS

5.1 INTRODUCTION

A number of in vitro studies have demonstrated that cavities restored with composite resin bonded to acid-etched enamel exhibit little microleakage (Hembree and Andrews 1976b, Ortiz et al. 1979, Wu et al. 1983) and a low incidence of marginal gap formation (Zidan et al. 1987). When enamel is not present and margins involve dentine or cementum, microleakage and gap formation are more often observed (Bauer and Henson 1984).

Several restorative techniques have been introduced which reportedly bond successfully to dentine and cementum and improve the marginal seal. These include the glass-ionomer restorative cements, composite resins in combination with dentine bonding agents and, more recently, glass-ionomer cement used with a veneer of composite resin.

Cervical lesions occurring in response to caries, erosion and abrasion often have both enamel and dentine or cementum margins, and are frequently encountered in clinical practice (Sognnaes et al. 1972, Council on Dental Research and Council on Dental Therapeutics 1983, Mount 1986a). Cervical restorations are often used, therefore, to investigate and compare the marginal sealing ability of restorative techniques with respect to both gingival dentine or cementum margins, and occlusal enamel margins.
5.2 MICROLEAKAGE INVESTIGATIONS

The results of investigations of microleakage occurring around cervical restorations are usually presented in two parts, that is the findings at the occlusal margin and those at the gingival margin.

The Occlusal Margin

Using butt-joint cavities bisected by the cemento-enamel junction, Phair and Fuller in 1985 found microleakage at the etched occlusal enamel margins of composite resin restorations to be slight or non-existent after thermal cycling. No leakage of dye was found using an enamel bond and a dentine bonding agent, but leakage up to one fourth of the cavity depth was found using a dentine bonding agent claimed to chelate with calcium. Under similar experimental conditions, cavity design and dye penetration assessment, Gordon and others in 1986(a) found no leakage at the occlusal margin using Scotchbond, however slight leakage was found using an unfilled resin and another dentine bonding agent. A statistically significant difference was found between the results obtained using Scotchbond, when compared with the other two bonding agents.

Using similar cavities but a harsher thermal cycling regime and a less precise dye penetration scale, Crim and Chapman in 1986(a) found a significant difference in the ability of two primers to resist microleakage of dye at the occlusal margin. The primers were designed to bond with the inorganic component of hard tooth tissue and complete resistance to leakage occurred in approximately 45 to 92 per cent of cases. No significant difference was found when cavities were restored in a single-step, bulk procedure
or an incremental method where the gingival portion was placed first. These researchers also compared the same primers with two other dentine bonding agents, one of which was Scotchbond, under the same experimental conditions but utilizing an enamel bevel (Crim and Chapman 1986b). Only 10 per cent of restorations showed any dye penetration at the occlusal margins and no penetration along the axial wall was observed. As before, the leakage pattern was not altered by incremental placement when compared with a bulk technique.

Gordon et al. in 1986(b) investigated eight combinations of bonding agents and composite resins in V-shaped cervical cavities. After thermal cycling only two dentine bonding agents managed to completely prevent dye penetration at the occlusal margin, the poorest leaked in 60 per cent of cases and all proved superior to the enamel bonding resin. In another study carried out by Fuks et al. in 1985 using V-shaped cavities centred at the cemento-enamel junction and restored using Scotchbond with Silux, microleakage was evaluated after thermal cycling. No leakage of dye was found in 95 per cent of specimens compared with 90 per cent when an enamel bond was used. The difference in leakage scores did not, however, appear to be significant.

Microleakage at the occlusal margins of glass-ionomer restorative cements placed in kidney-shaped cervical cavities has been investigated (Lacefield et al. 1982, Phair and Fuller 1983, Thornton et al. 1987). After thermal cycling, Lacefield and co-workers found the average isotope penetration to be more than half way to the base of the cavity. Thornton et al. in 1987 found that no specimens prevented leakage and the majority showed penetration to the base of the cavity. They concluded that the 50°C
differential used in thermal cycling further weakened the already weak bond between enamel and the glass-ionomer cement. Phair and Fuller in 1983 reported catastrophic leakage at the occlusal enamel margin of glass-ionomer cement restorations. These researchers suggested that the poor results could be attributed to dehydration as the teeth were stored in 70 per cent alcohol prior to use. It is also possible that the surface protection provided by a commercial cavity varnish was insufficient during the critical period after initial setting.

Gordon et al. in 1986(b) investigated microleakage occurring as the occlusal margins of V-shaped cervical cavities restored with a glass-ionomer restorative cement. Leakage was prevented in only one of ten restorations after thermal cycling, the majority exhibited dye penetration past the dentino-enamel junction, however extensive penetration along the adjacent gingival wall was not observed. This finding was contrary to that of Hembree and Andrews in 1978, who used an early glass-ionomer restorative cement under similar experimental conditions. No penetration of an isotope was found at the occlusal margins after one day, three months or six months, and only minimal leakage after storage for one year.

A single report has been made of microleakage occurring at the occlusal margins of cervical cavities restored with a variety of composite resins placed over an etched glass-ionomer cement (Gordon et al. 1985). These researchers found significantly less dye penetration was exhibited by a microfilled resin than a hybrid or small particle macrofilled composite at the occlusal margin, with average leakage scores for the microfilled composite confined to well within enamel.
The Gingival Margins

McComb et al. in 1986, using circular cavities prepared at the cemento-enamel junction, Scotchbond and a variety of composite resin materials, found leakage occurred at the gingival margins after thermal cycling. After assessment, it was found that chemically-cured Scotchbond prevented leakage in 60 per cent of cases and the same primer in light-cured form prevented leakage in only 30 per cent of cases. The difference, however, was not found to be significant and both forms of Scotchbond represented an improvement over an enamel bonding resin when used with the same composite resin. A microfilled resin proved superior to a hybrid variety in preventing leakage when combined with the same primer, and when different insertion techniques were used it was found that the percentage of restorations showing no leakage was highest with horizontal incremental placement and when a cervical matrix was used.

Hudson et al. in 1987 also used circular cervical cavities, phosphate ester primers, one of which was Scotchbond, and thermal cycling to investigate penetration of a silver nitrate solution at the gingival margins of microfilled composite restorations. No statistical difference was found between the two primers used and failure to prevent leakage occurred in 100 per cent and 95 per cent of cases respectively. The majority of restorations exhibited leakage short of the axial wall.

Several microleakage investigations have been made using butt-joint Class V cavities prepared at the cemento-enamel junction and restored with composite resins and dentine bonding agents (Phair and Fuller 1985, Gordon et al. 1986a, Crim and Chapman 1986a). All three studies found microleakage at the gingival root
surface margins to be greater than at the occlusal enamel margins. Phair and Fuller in 1985 found all materials leaked severely at the gingival margin after thermal cycling. A primer designed to chelate with calcium leaked less than an unfilled resin, but the average leakage score occurring with the primer still represented dye penetration to the junction of the axial and gingival walls. Gordon et al. in 1986(a) found the results using Scotchbond to be superior and differ significantly from an unfilled resin in preventing penetration of silver nitrate after thermal cycling. The average extent of leakage obtained using Scotchbond, however, again approximated the gingivo-axial line angle.

Significantly different leakage patterns were found when two primers designed to bond with the inorganic component of dentine were used with the same composite resin and after thermal cycling (Crim and Chapman 1986a). Despite the significantly different patterns, both primers prevented leakage at the gingival margin in virtually no cases, while leakage along the axial wall was often observed. This study also found incremental or bulk insertion techniques did not alter microleakage patterns, although bulk insertion showed a general trend towards less severe leakage.

Crim and Chapman in 1986(b) then compared the ability of several combinations of primers and composite resins to prevent microleakage after thermal cycling using cervical Class V cavities with bevelled enamel margins. Scotchbond used with Silux proved more effective than several other primers designed to bond with the inorganic component of dentine. Using Scotchbond, leakage was prevented in 35 per cent of cases and in no case was leakage observed along the axial wall. Leakage patterns were again found to be unaffected by placement in increments when compared with a
bulk technique, and gingival leakage was found to be more severe than occlusal leakage.

Cavities simulating V-shaped grooves resulting from cervical abrasion or erosion and restored with composite resin have been used to investigate microleakage (Fuks et al. 1985, Welsh and Hembree 1985, Gordon et al. 1986b). Greater leakage was found to occur at the gingival than occlusal margins in these studies, a similar finding to that of the studies already mentioned which used cervical cavities of more conventional design. Fuks et al. in 1985, using Scotchbond with Silux, found that leakage was prevented in only 45 per cent of cases after thermal cycling. A further 45 per cent showed dye penetration to the full depth of the cavity or beyond. Leakage was less using Scotchbond than with an enamel bonding resin and this difference was found to be significant. A similar experimental regimen but different primers and a macrofilled composite were used by Welsh and Hembree in 1985. They found no primer was capable of preventing leakage at the gingival margin after one week, three months and six months. The average score for all systems corresponded to isotope penetration along the entire interface of the restorative material and cavity wall. These results were contrary to those of another study (Gordon et al. 1986b), which obtained a wide range of leakage results but did find several primer and composite resin combinations which were able to prevent dye penetration after thermal cycling. One of these was Scotchbond used with Silux, a combination which prevented leakage in 50 per cent of cases.

McComb and co-workers in 1986 investigated microleakage occurring at the gingival margins of glass-ionomer cement restorations placed in circular cervical cavities. No leakage was
found around 90 per cent of restorations after thermal cycling and when leakage did occur it was, on average, confined to the one-third of the tooth and restoration interface closest to the cavo-surface margin.

Microleakage occurring at the gingival margins of glass-ionomer cement restorations has also been studied using Class V cavities situated at the cemento-enamel junction (Lacefield et al. 1982, Phair and Fuller 1983, Thornton et al. 1987). Lacefield et al. found average penetration of an isotope to extend almost to the gingivo-axial line angle after thermal cycling but no cavity pretreatment. Pretreatment with citric acid resulted in average isotope penetration being reduced after thermal cycling, but the difference was not found to be significant. Thornton et al. in 1987 found extensive leakage occurring at the gingival margins of glass-ionomer cement restorations after polyacrylic acid conditioning and thermal cycling. No restorations prevented leakage and more than 50 per cent showed leakage extending along the entire base of the cavity. Catastrophic leakage occurring at the gingival margins was observed by Phair and Fuller in 1983 after citric acid conditioning and thermal cycling. The magnitude of leakage was similar to that occurring at the occlusal enamel margins, a finding also made by Lacefield et al. 1982 and Thornton et al. 1987.

Cervical cavities simulating V-shaped abrasion lesions have been used to investigate leakage occurring around glass-ionomer cement restorations (Welsh and Hembree 1985, Gordon et al. 1986b). Although minimal isotope penetration between the tooth and restoration at the gingival margin was reported after thermal cycling by Welsh and Hembree in 1985, the scoring system used made precise
leakage assessment difficult. One specimen completely resisted leakage after storage for one week and the remainder exhibited leakage which corresponded to isotope penetration anywhere between the gingival cavosurface and the full depth of the V-shaped groove. This was similar to the observations of Gordon et al. 1986(b) who found that, although no specimens completely resisted leakage, the majority showed penetration of a silver nitrate solution no further than the depth of the V-shape after polyacrylic acid pretreatment and thermal cycling. Gingival leakage was observed to be greater than that occurring at the occlusal enamel margin in both these studies.

One investigation has been reported of microleakage occurring at the gingival margins of cervical cavities restored with a variety of composite resins placed over an etched glass-ionomer cement (Gordon et al. 1985). Butt-joint cavities were pretreated with polyacrylic acid before the Ketac-Bond lining was applied to the axial and gingival walls but leaving the gingival cavosurface margin uncovered. After one minute, the lining cement and enamel surfaces were etched for 60 seconds, then a bonding agent and composite resin placed and cured. After thermal cycling, dye penetration was assessed and the average leakage score obtained. Using Silux, average leakage of dye occurred along less than one third of the gingival wall and the specimens showed no dye penetration between the glass-ionomer and composite resin.
5.3 SCANNING ELECTRON MICROSCOPE INVESTIGATIONS OF CAVOSURFACE MARGINS.

The cavosurface margins of cervical restorations have been investigated in vitro using scanning electron microscopy by Reich and Volkl 1986 and Roulet and Rosansky 1986. Both studies used replicas, assessed the margins both before and after thermal cycling, and included glass-ionomer restorative cement, composite resin and combined glass-ionomer-composite resin restorations.

Class V cavities with both gingival and occlusal margins bevelled were prepared by Reich and Volkl in 1986, then restored with several combinations of glass-ionomer cement and/or composite resin. In general, these researchers found that with increased thermal cycling more marginal openings were observed, but that the patterns established after 2000 cycles were not altered by further cycling. Observation of the occlusal margin before thermal cycling showed glass-ionomer restorative cement performed poorly, with 40 per cent marginal openings, and all other restorative techniques showed openings along five per cent or less of the length of the margin. After 2000 thermal cycles, the best result was achieved with a combination of Ketac-Bond and composite resin, which displayed openings along 25 per cent of the occlusal marginal length. The poorest performance was again the glass-ionomer restorative cement, with 60 per cent marginal opening.

At the gingival margin, all restorative techniques showed between 20 and 50 per cent marginal openings before thermal cycling. After 2000 thermal cycles, the best result was obtained with glass-ionomer restorative cement, with 50 per cent of the margin open, while the other techniques showed between 90 and 100 per cent marginal openings. In conclusion, Reich and Volkl in 1986
suggested that, at the gingival margin, the combined glass-ionomer and composite resin restoration provided a superior marginal seal when compared with composite resin alone, but that glass-ionomer restorative cement provided the best seal of all techniques investigated.

Roulet and Rosansky in 1986 used cylindrical cavities with an enamel bevel and a butt-joint cementum margin to assess the marginal behaviour of two glass-ionomer-composite resin combinations, a microfilled composite resin and a glass-ionomer restorative cement. Assessment of the margins was carried out using the criteria outlined by Reich and Volkl 1986.

At the occlusal margin, all restorative techniques showed a low incidence of marginal openings before thermal cycling, that is less than 5 per cent, and only the glass-ionomer cement, Ketac-fil, was affected significantly by thermal cycling. At the gingival margin, the combined glass-ionomer-composite resin restorations showed fewer marginal openings before thermal cycling than either composite resin or glass-ionomer restorative cement. After 2000 cycles, the percentage of marginal openings increased dramatically and no difference could be found between restorative materials. The interface between composite resin and glass-ionomer cement in the combined restorations was also assessed and the bond found to be intact and not adversely affected by thermal cycling.

Roulet and Rosansky in 1986 concluded that, although superior when placed, the marginal integrity of the combined glass-ionomer cement and composite resin restoration was equal to both glass-ionomer restorative cement and composite resin restorations after thermal cycling.
5.4 COMBINED INVESTIGATIONS OF MICROLEAKAGE AND SCANNING ELECTRON MICROSCOPY OF CAVOSURFACE MARGINS.

Several studies have used microleakage assessment in conjunction with scanning electron microscopy of restoration margins to investigate the marginal seal of cervical restorations (Lee and Swartz 1970, Al-Hamadani and Crabb 1975, Stanninec et al. 1986). The two earlier studies were, however, confined to cavities with entirely enamel boundaries, and none of the three investigations included either glass-ionomer restorative cements or the glass-ionomer cement-composite resin combination. Despite wide variation in materials used and experimental regimen, a finding was made by both Al-Hamadani and Crabb in 1975 and Stanninec et al. in 1986, that the leakage scores obtained were in general agreement with the scanning electron microscope observations.

Isotope penetration and scanning electron microscopy were used by Lee and Swartz in 1970 to investigate the marginal seal of four composite resins in comparison with an amalgam, a silicate and an unfilled resin. Class V cavities with butt-joint enamel cavosurface margins were restored, polished and thermal cycled. Subsequently, the restored teeth were either immersed in an isotope solution, sectioned and assessed for leakage, or prepared for direct viewing with the scanning electron microscope. It was found that all specimens exhibiting isotope leakage at the tooth-restoration interface also showed an interfacial gap. Unexpectedly, however, several specimens which had resisted leakage exhibited a marginal gap, leading these researchers to conclude that the isotope penetration technique required improvement. They did not however, consider the possibility of artefact production during preparation of the specimens for viewing, although testing of the
silicate had been curtailed when fissures were observed and attributed to dehydration. On the basis of these findings, Lee and Swartz in 1970 suggested no correlation could be established between percolation and gap size.

A study similar to Lee and Swartz in 1970 was undertaken by Al-Hamadani and Crabb in 1975 using three composite resins in Class V enamel-bounded cavities. Their assessment of dye penetration revealed more severe leakage along the gingival margin than at the occlusal aspect. Observation of marginal gap formation showed, with one exception, no gap present at the occlusal margin, but at the gingival margin gaps were frequently observed. These findings appeared to represent a correlation between leakage scores and the presence of marginal gaps.

A combination of dye penetration and scanning electron microscopy was used by Stanninéc et al. in 1986 to study changes in interfacial gap widths and marginal leakage produced by temperature changes. Microleakage results showed the occlusal enamel margin to be more resistant to leakage when compared to the gingival margin, which exhibited extensive leakage in all cases. Observations in the scanning electron microscope showed that at the occlusal aspect, three of eight restorations had closed margins, while at the gingival margin all eight restorations exhibited gaps. Stanninéc et al. in 1986 concluded that marginal leakage correlated with both the presence and size of interfacial spaces.
5.5 SUMMARY

After discussion of in vitro findings related to the marginal seal of cervical restorations it is possible, despite wide variation in materials, experimental regimen and assessment methods, to make a number of general observations. Initially, the majority of both microleakage investigations and scanning electron microscope studies of cavosurface margins concluded that a superior seal is obtained at the occlusal enamel margin than at the gingival root surface margin. Then, although few restorative techniques showed the ability to produce a complete and reliable seal at either margin after thermal cycling, it appeared that bevelled, etched enamel restored with composite resin and a bonding agent resulted in the most effective seal. In the third instance, when microleakage assessment was combined with scanning electron microscopy of cavosurface margins, a correlation could be observed between leakage and gap formation where replicas were used for the microscopy.

Any attempt, however, to compare the performance of different restorative techniques with regard to gingival marginal sealing ability proved more difficult. Variations in cavity design, material combinations, pretreatment procedures, thermal cycling regimes and assessment methods, in this instance, made any definite conclusions on the consistent superiority of any one material or restorative technique virtually impossible.

In addition to observations of a general nature, discussion of findings related to the marginal seal of cervical restorations also revealed two other aspects of interest. With regard to the performance of composite resins in resisting microleakage, two studies concluded that less leakage occurred using a microfilled
composite than a hybrid variety (Gordon et al. 1985, McComb et al. 1986), and it was also found that a microfill performed better than a small particle macrofill (Gordon et al. 1985). These findings would seem surprising given the greater polymerization shrinkage of microfilled materials.

In the manipulation of composite resins, several studies concluded that no significance difference could be found in microleakage performance between bulk or incremental placement at either the occlusal or gingival margin (Crim and Chapman 1986a,b). In another study, horizontal incremental placement appeared superior to diagonal placement in preventing gingival microleakage in composite resin restorations, however, the difference was not statistically significant (McComb et al. 1986). These findings contrast with the projections of Davidson in 1986, and the findings of a marginal gap width study carried out by Hansen, also in 1986.
ORIGINAL INVESTIGATION
PURPOSE AND SCOPE OF THE INVESTIGATION

The absence of a seal at restoration margins may contribute to marginal staining, adverse pulpal response, post-operative sensitivity and recurrent caries. Acid-etching of enamel margins, often used in combination with bevelling and a low viscosity bonding resin, has resulted in improved sealing of composite resin restorations. Introduction of the glass-ionomer cements, with their potential for adhesion to hard tooth tissues, has also resulted in a seal being achieved where restoration margins are bounded by enamel. A review of the literature revealed, however, that obtaining an adequate seal is more elusive where enamel is absent and margins are positioned in dentine or cementum. The use of primers, or dentine adhesives, with varying modes of attachment to composite resin and dentine, have been advocated to improve sealing, and glass-ionomer restorative cements have also been widely used. More recently, glass-ionomer cements have been suggested as an intermediary layer between composite resin and dentine to enhance marginal sealing.

The main purpose of this investigation was to compare the performance of four restorative techniques in sealing the margins of cavities bounded by both enamel and dentine or cementum. Initially, investigation was made of microleakage occurring around restorations placed in cervical cavities using the four techniques by means of tracer dye penetration and thermal cycling. Secondly, the presence or absence of gaps at the cavosurface margins of the
same cervical restorations was investigated, at two stages of the thermal cycling procedure, using scanning electron microscopy. Finally, as an adjunct, an investigation was made of the effects of different etch times on the surface of a glass-ionomer cement designed for use as an intermediary layer between composite resin and dentine.
CHAPTER 6

METHOD I. AN INVESTIGATION OF MICROLEAKAGE OCCURRING AROUND CERVICAL RESTORATIONS, AS MEASURED BY PENETRATION OF A TRACER DYE.

6.1 COMPONENTS OF THE INVESTIGATION

Teeth

Sound maxillary and mandibular premolars were obtained from patients undergoing orthodontic treatment. After extraction the teeth were rinsed with tap water and stored at 4°C under humid conditions in sealed specimen jars until needed. Storage time between extraction and use in the study was at least 24 hours and no more than four months.

Each tooth was scrutinized before inclusion in the study. The buccal and lingual surfaces were examined* and those showing cracking or grazing from the extraction procedure were discarded. Those teeth not exposed to long-term fluoride ingestion, either from the local water-supply or systemic supplements, were also rejected.

At the time of cavity preparation and restoration the periodontal ligament remnants were mechanically removed** and the teeth cleansed with a pumice and water slurry on a bristle-brush at low speed. After cleansing, the teeth were placed in deionized water from which they were subsequently removed only during cavity preparation and placement of the restoration.

** Morse Scaler (1). Neos Dental, Switzerland.
Materials and Equipment

Materials and equipment used in the preparation and evaluation of specimens are detailed in Tables 6.1, 6.2 and 6.3. The manipulation of all materials conformed to the manufacturers' directions unless otherwise stated. Ambient temperature remained at 24°C±2°C.

6.2 THE METHOD OF INVESTIGATION

The 40 teeth selected for use were restored on both buccal and lingual surfaces, making a total of 80 restorations. Each buccal and lingual surface was randomly allocated for restoration with a particular technique, either group K, restored using Ketac-Fil, group KS, using Ketac-Bond and Silux, group SS, using Scotchbond, Ketac-Bond and Silux, or group GS, restored using GLUMA, Ketac-Bond and Silux; making a total of 20 restorations for each technique. The relationship between groups and restorative techniques is outlined in Table 6.4.

Cavity Preparation

Uniform 3mm diameter cavities were prepared on the selected tooth surfaces using a water-cooled, pear-shaped, tungsten carbide bur* at high speed. One bur was used for ten cavities and then discarded. The cavities were carefully positioned so half was coronal (occlusal) to the cemento-enamel junction and half apical (gingival) to the cemento-enamel junction.

The cavity extended axially approximately 1.5mm. Cavity dimensions were checked with a calibrated probe** and the margins

* Komet H245 008. W. Germany.
** Star Dental. U.S.A.
# Table 6.1

### MATERIALS USED IN THE PREPARATION OF SPECIMENS

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>FORM</th>
<th>BATCH No.</th>
<th>MANUFACTURER</th>
</tr>
</thead>
<tbody>
<tr>
<td>KETAC-BOND : radiopaque</td>
<td>10g. bottle powder and</td>
<td>8000</td>
<td>Espe</td>
</tr>
<tr>
<td>polymaleinate glass-</td>
<td>12ml. bottle liquid</td>
<td>0010</td>
<td>W. Germany</td>
</tr>
<tr>
<td>ionomer bonding base</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KETAC-FIL : polymaleinate</td>
<td>premeasured, sealed</td>
<td>68/2/301/54</td>
<td>Espe</td>
</tr>
<tr>
<td>glass-ionomer dental</td>
<td>capsules (50)</td>
<td>R 11aa</td>
<td>W. Germany</td>
</tr>
<tr>
<td>restorative</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SILUX : visible light-cure,</td>
<td>single paste Shade U 3g.</td>
<td>5 L 4</td>
<td>Dental Products/3M.</td>
</tr>
<tr>
<td>microfill restorative</td>
<td>2.7ml. tube</td>
<td></td>
<td>U.S.A.</td>
</tr>
<tr>
<td>DELTON : light-curing pit</td>
<td>single 2.7ml. liquid</td>
<td>6E6102</td>
<td>Johnson &amp; Johnson.</td>
</tr>
<tr>
<td>and fissure sealant-clear</td>
<td></td>
<td></td>
<td>U.S.A.</td>
</tr>
<tr>
<td>SCOTCHBOND : light-cured</td>
<td>5ml. resin and</td>
<td>5W1</td>
<td>Dental Products/3M.</td>
</tr>
<tr>
<td>dental adhesive</td>
<td>5ml. liquid</td>
<td>SK3</td>
<td>U.S.A.</td>
</tr>
<tr>
<td>GLUMA BOND : for bonding</td>
<td>single 5ml. bottle</td>
<td>4134Z</td>
<td>Bayer Dental</td>
</tr>
<tr>
<td>a resin based filling</td>
<td></td>
<td>281085</td>
<td>W. Germany</td>
</tr>
<tr>
<td>material to dentine and</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>cementum</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BAYER RESIN L : for adhesive</td>
<td>single 5ml. bottle</td>
<td>090885</td>
<td>Bayer Dental</td>
</tr>
<tr>
<td>filling therapy (acid-etch technique) with resin based filling materials.</td>
<td></td>
<td>41132</td>
<td>W. Germany</td>
</tr>
<tr>
<td>G.C. DENTIN CONDITIONER : a</td>
<td>single liquid 25g.</td>
<td>220861</td>
<td>G.C. Dental Industrial</td>
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<tr>
<td>10 per cent poly acrylic acid solution.</td>
<td></td>
<td></td>
<td>Corp. Japan.</td>
</tr>
<tr>
<td>ETCM GEL : 37% Orthophosphoric acid</td>
<td>gel 6ml. bottle</td>
<td>5PT1</td>
<td>Dental Products/3M.</td>
</tr>
<tr>
<td>GLUMA CLEANSER : aqueous solution of EDTA</td>
<td>single 5ml. bottle</td>
<td>4143Z</td>
<td>Bayer Dental</td>
</tr>
<tr>
<td></td>
<td></td>
<td>251185</td>
<td>W. Germany</td>
</tr>
<tr>
<td>NAME and DESCRIPTION</td>
<td>MANUFACTURER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>-------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SILAMAT : mechanical triturator</td>
<td>Vivadent Schaan-Liechtenstein.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GURR FUCHSIN (BASIC) : microscopy staining material. 25g powder</td>
<td>BDH Chemicals Ltd., Poole, England.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLTENE PRESIDENT : polyvinylsiloxane high precision impression material. Light and regular body.</td>
<td>Coltene AG. Altstatten. Switzerland.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESPE-APPLIC-SYSTEM : to enable pre-measured encapsulated material (Ketac-Fil) to be mixed automatically and applied directly into the cavity.</td>
<td>Espe Seefeld/Oberay W. Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNIVERSAL INVESTMENT No4 : a dental stone of water/powder ratio 0.32</td>
<td>Investo Manufacturing Co. Camellia. NSW. Australia.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.3

EQUIPMENT USED IN THE EVALUATION OF SPECIMENS

<table>
<thead>
<tr>
<th>NAME and DESCRIPTION</th>
<th>MANUFACTURER</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPIMOUNT : epoxy mounting medium.</td>
<td>Epirez Australia Pty.</td>
</tr>
<tr>
<td></td>
<td>Villawood. N.S.W. Aust.</td>
</tr>
<tr>
<td>11-1180 ISOMET : low speed saw.</td>
<td>Buehler Ltd.</td>
</tr>
<tr>
<td>Used with</td>
<td>Lake Bluff. Ill. U.S.A</td>
</tr>
<tr>
<td>DIAMOND WAFERING BLADE : No. 11-4244</td>
<td>Buehler Ltd.</td>
</tr>
<tr>
<td></td>
<td>Lake Bluff. Ill. U.S.A</td>
</tr>
<tr>
<td>BINOCULAR LIGHT MICROSCOPE with REFLECTING LIGHT SOURCE :</td>
<td>Carl Zeiss</td>
</tr>
<tr>
<td>No. 223806</td>
<td>W. Germany.</td>
</tr>
<tr>
<td>JSM - 35C SCANNING MICROSCOPE</td>
<td>Olympus, Tokyo, Japan.</td>
</tr>
<tr>
<td>ILFORD FP4 : medium speed black and white film</td>
<td>Joel Ltd.</td>
</tr>
<tr>
<td></td>
<td>Tokyo, Japan.</td>
</tr>
<tr>
<td></td>
<td>Ilford Ltd.</td>
</tr>
<tr>
<td>GROUP</td>
<td>RESTORATIVE TECHNIQUE</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>K</td>
<td>KETAC-FIL, a glass-ionomer resorative cement</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>KS</td>
<td>KETAC-BOND, used as a base to replace lost dentine, with a surface veneer of SILUX</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>SILUX in combination with the dentine bonding agent, SCOTCHBOND, and KETAC-BOND lining the axial wall.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>GS</td>
<td>SILUX in combination with the dentine bonding agent, GLUMA, and KETAC-BOND lining the axial wall.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* One specimen = one restoration
explored* to ensure minimum irregularity.

Cavosurface margins were finished to approximately 90° using high speed and the tungsten carbide bur**. Cavities to be restored with composite resin were modified at the occlusal cavosurface margin to form a 45°, 1mm wide enamel bevel with the high speed bur. In all cavities a retentive groove was cut, in dentine, along the gingivoaxial line angle, in the gingival half of the cavity, using a round steel bur*** at low speed. A cross-section of the cavity before modification of the occlusal margin is illustrated in Figure 6.1.

Horizontal reference grooves were placed on the tooth surface at least 2mm from the cavity margin for subsequent identification of the restorative technique used.

Restorative Techniques

The prepared cavities were restored by a single operator using one of four techniques. A representative buccolingual, longitudinal section of each restoration is illustrated in Figures 6.2 and 6.3.


Immediately cavity preparation was completed the internal surfaces were treated with a 10 per cent polyacrylic acid conditioner. The conditioner was applied on a sponge pellet****

---

* K6 Ivoclar. U.K.
** Komet H245 008. W. Germany.
*** Ash Rd. PC ½. U.K.
**** Dental Products/3M. U.S.A.
dentino-enamel
junction

start of the gingival retentive groove

Figure 6.1  BUCCOLINGUAL, LONGITUDINAL SECTION SHOWING THE CAVITY DIMENSIONS AND CONFIGURATION PRIOR TO MODIFICATION OF THE OCCLUSAL MARGIN.
Figure 6.2  BUCCOLINGUAL, LONGITUDINAL SECTIONS SHOWING A FINISHED RESTORATION FROM GROUP K (LEFT) AND GROUP KS (RIGHT).
Figure 6.3  BUCCOLINGUAL, LONGITUDINAL SECTION SHOWING A FINISHED RESTORATION FROM GROUP SS OR GROUP GS.
with a constant rubbing action for 20 seconds. The residue was removed with a continuous, 20 second duration water stream from a triplex syringe then the cavity was dried with air from the same source.

The Ketac-Fil restorative material was mixed and placed into the cavity in two increments. The first, small increment was syringed into the cavity and adapted to the walls and retentive groove with a plastic* instrument. The second, larger increment was placed to slight excess, also with a syringe. A matrix** was adapted immediately and held in place with constant, light pressure.

After five minutes the matrix was gently removed and varnish*** applied immediately. The varnish was allowed to dry before the tooth was replaced in deionized water. No finishing was undertaken at this time.

2. Group KS, restored using Ketac-Bond as a base to replace lost dentine, with a surface veneer of Silux.

Immediately cavity preparation was completed, the internal surfaces were treated with a 10 per cent polyacrylic acid conditioner. The conditioner was applied as previously described for 20 seconds, the residue was then removed with a continuous, 20 second duration water stream from a triplex syringe and the cavity dried.

* Ash 179. U.K.
** Hawe Transparent Cervical Matrices. Hawe Neos Dental, Switzerland.
*** Espe. Seefeld/Oberay, W. Germany
Ketac-Bond was dispensed, mixed using a glass slab and metal spatula and then placed using a Dycal applicator*. The Ketac-Bond was placed to slight excess on all dentine surfaces within the cavity including the gingival cavosurface margin. The bevelled enamel margin was avoided where possible.

Six minutes from starting to mix (Mount 1986c) the base was contoured and excess removed from the enamel margins using a round steel bur** at low speed. On completion of contouring, acid-etch gel was applied with a brush to the enamel bevel and Ketac-Bond surfaces and left in place for 60 seconds. The gel was then removed with a continuous, 20 second duration air and water stream and the etched surfaces dried with air. In several cases it was necessary to apply the etchant for a further 15 seconds, followed by washing and drying, in order to achieve the uniform, dull, white appearance of adequately etched enamel (Buonocore and Sveen 1975). The Ketac-Bond surface was not etched for longer than 60 seconds.

When adequate etching was established, Delton resin was dispensed and applied sparingly with a brush to all etched areas. A gentle stream of air was used to spread the resin thinly after which it was cured for 20 seconds with a visible-light source.

Silux composite resin was dispensed, adapted to the cured resin surfaces with a Teflon instrument (supplied by the manufacturer) and a matrix*** applied. The matrix was held in place with steady, light pressure and the composite resin cured for 40 seconds

* L.D. Caulk Co. U.S.A.

** Ash Rd. PC ½. U.K.

*** Hawe Transparent Cervical Matrices. Hawe Neos Dental, Switzerland.
using a visible light-source. To ensure complete polymerization, the curing time was divided into two increments; 20 seconds from the mesial aspect and 20 seconds from the distal. The matrix was removed two minutes after curing and the tooth replaced immediately in deionized water. No finishing was undertaken at this time.

3. **Group SS, restored using Silux, in combination with the dentine bonding agent, Scotchbond, and Ketac-Bond lining the axial wall.**

Immediately the cavity preparation was completed, a glass-ionomer bonding base was placed. Ketac-Bond was dispensed, mixed, then placed using a Dycal applicator* to completely cover the axial wall of the cavity. The bevelled enamel margin was avoided where possible, as was the gingival cavosurface margin and the gingival retentive groove.

Six minutes from starting to mix, any excess Ketac-Bond was removed from the gingival retentive groove and enamel surfaces with a round steel bur** at low speed. Acid-etch gel was then applied with a brush to the enamel bevel and Ketac-Bond surfaces. Care was taken to avoid the etch gel contacting the gingival dentine margin. After 60 seconds, the gel was removed with a continuous 20 second duration air and water stream and the etched surfaces then dried gently with air. In several cases it was necessary to apply the etch gel to the enamel for a further 15 seconds, as previously described. The Ketac-Bond surface was not etched for longer than 60 seconds.

* L.D. Caulk Co. U.S.A.

** Ash Rd PC ½. U.K.
When adequate etching was achieved, Scotchbond was dispensed, mixed, then applied sparingly to all cavity walls and margins. A gentle 10 second duration air stream from a triplex syringe was used to evaporate the solvent component, then the Scotchbond was cured for 10 seconds with a visible-light source.

Silux was dispensed and placed into the cavity in two oblique layers. The first layer was adapted into the gingival retentive groove and against the axial wall and gingival cavosurface margin, then cured for 20 seconds. The second layer was placed against the enamel bevel and extended to the gingival cavosurface margin. A matrix* was applied, held in place with steady, light pressure and the composite resin cured from mesial and distal directions for a total of 40 seconds. The matrix was removed two minutes after curing and the tooth replaced immediately in deionized water. No finishing was undertaken at this time.

4. **Group GS, restored using Silux, in combination with the dentine bonding agent, GLUMA, and Ketac-Bond lining the axial wall.**

Immediately the cavity preparation was completed, a glass-ionomer bonding base, Ketac-Bond, was mixed and placed, as described previously, to completely cover the axial wall of the cavity. The bevelled enamel margin was avoided where possible, as was the gingival cavosurface margin and the gingival retentive groove.

Six minutes from starting to mix, any excess Ketac-Bond was removed from the gingival retentive groove and enamel surfaces with

* Hawe Transparent Cervical Matrices. Hawe Neos Dental, Switzerland.
a round steel bur* at low speed. Acid-etch gel was then applied with a brush to the enamel bevel and Ketac-Bond surfaces for 60 seconds, after which the gel was removed with a continuous 20 second duration air and water stream and the etched surfaces then dried gently with air. In several cases it was necessary to re-etch for a further 15 seconds, then wash and dry again, in order to obtain adequately etched enamel. The Ketac-Bond surface was not etched for longer than 60 seconds.

When adequate etching was achieved, GLUMA cleanser was applied to the gingival dentine cavosurface margin and gingival retentive groove on a sponge pellet** with constant rubbing action. After 60 seconds the residue was removed with a continuous, 20 second duration, water stream from a triplex syringe and then dried with air.

GLUMA Bond was dispensed and applied with a brush to the dentine of both the gingival cavosurface margin and gingival retentive groove. After 60 seconds the GLUMA Bond was gently dried with a 10 second duration air stream. A layer of enamel bond, Resin L, was dispensed and applied sparingly to all cavity walls and margins then a gentle, ten second duration air stream was used to spread the resin thinly over the cavity surfaces.

Silux composite resin was dispensed, placed, and cured in the cavity in two, oblique layers as previously described. A matrix*** was used to confine the composite resin under light pressure whilst

* Ash Rd PC ½, U.K.

** Dental Products/3M Co. U.S.A.

*** Hawe Transparent Cervical Matrices. Hawe Neos Dental, Switzerland.
being cured from mesial and distal aspects for a total of 40 seconds. The matrix was removed two minutes after curing and the tooth replaced immediately in deionized water. No finishing was undertaken at this time.

Finishing

Clinically, restorations are finished after placement in order to achieve appropriate contour, surface smoothness and to minimize discrepancies at the tooth-restoration margin. Seven days after placement, all restorations were finished and polished using Sof-Lex flexible discs at slow speed with no lubrication. A contouring disc was used to remove excess restorative material, then medium, fine and super-fine discs were used sequentially to achieve a polished surface. The restoration was explored* and considered adequately finished when no irregularity was found at the tooth-restoration interface and a high gloss was achieved over the surface of the composite resin restorations.

Thermal Cycling

In this study, the restored teeth were subjected to thermal stress at two stages; one day after placement of the restorations and then one day after finishing the restorations. One day after placement of the restorations the teeth were subjected to 100, one minute thermal cycles. A cycle consisted of 25 seconds at 8°C ± 2°C, 5 seconds transfer between baths, 25 seconds at 48°C ± 2°C, and 5 seconds to transfer again. The 8°C bath contained basic

fuchsin dye at a concentration of 0.25 per cent in deionized water. The 48°C bath contained deionized water only.

In order to avoid apical ingress of the dye during thermal cycling, the root tip of each tooth was removed and glass-ionomer restorative cement* applied to the apex (Wenner et al. 1985). The tooth surface and glass-ionomer cement were sealed with two coats of nail polish so that only the restoration surface and a 1mm wide band of surrounding tooth structure were exposed. The nail polish was re-applied in the same manner after the restorations were polished and before the second stage of thermal cycling. At both stages the teeth were replaced in deionized water at 37°C as soon as the nail polish was dry, to await the thermal cycling procedure.

The second and principal stage of thermal cycling was initiated one day after finishing procedures were completed, that is eight days after the restorations had been placed. The teeth were subjected to 200, one minute cycles per day for a total of ten days and 2000 cycles. The teeth were stored at 37°C in deionized water between cycling episodes. The fuchsin dye in the 8°C bath was changed after 1000 cycles to ensure the correct concentration was maintained.

Microleakage Evaluation

On completion of thermal cycling, the teeth were rinsed with deionized water, dried and mounted for sectioning using Epimount in cylindrical moulds. An Isomet saw fitted with a diamond blade was used to obtain between three and five 0.75mm wide, buccolingual, longitudinal sections from each restored tooth. The teeth were

* Ketac-Fil. Espe. Seefeld/Oberay, W. Germany.
continually bathed with deionized water during sectioning. When cutting was complete, all sections of each tooth were placed in a separate, labelled container for subsequent examination. Any teeth exhibiting apical leakage of dye were discarded.

Three surfaces of the sections obtained from each specimen were chosen, at random, and examined for dye penetration at the tooth - restoration interface using a reflecting light source, and binocular microscope at X16 magnification. The degree of penetration was scored and recorded for both occlusal and gingival margins using a standardized system adapted from Stanninec et al. 1986, and illustrated diagramatically in Figure 6.4.

Grade N - corresponds to no dye penetration occurring at the tooth - restoration interface.

Grade P - indicates partial dye penetration along the occlusal wall contained by the dentino-enamel junction and along the gingival wall by the start of the gingival retentive groove.

Grade W - corresponds to dye penetration past the dentino-enamel junction along the occlusal wall, and past the start of the retentive groove along the gingival wall, but not including the axial wall in either case.

Grade T - refers to total dye penetration along the occlusal or gingival walls and extending onto the axial wall.
Figure 6.4  THE SYSTEM USED TO SCORE DYE PENETRATION FOR THE OCCLUSAL AND GINGIVAL MARGINS.
Examples of surfaces evaluated using the system illustrated in Figure 6.4 are shown in Figure 6.5. A surface from group K can be seen in Figure 6.5a and shows grade W leakage at the occlusal margin and grade T at the gingival margin. Figure 6.5b illustrates a surface from group KS which exhibits grade N, or no leakage, at the occlusal margin and grade W at the gingival margin. A representative surface from either of groups SS and GS is shown in Figure 6.5c, with grade P leakage observed at the occlusal margin and grade T at the gingival margin.

An identifying mark was placed on those surfaces examined and the scoring procedure repeated one week later. Table 6.5 shows the number of disagreements between the first and second evaluations of microleakage at both gingival and occlusal margins. A disagreement was recorded if, on the second evaluation, a grade was assigned to a particular surface and margin which did not correspond to that awarded for the same margin and surface in the first evaluation. In no instance was there disagreement between non-consecutive grades.

The total number of disagreements between the first and second evaluations was 18 from a total of 384 microleakage scores recorded, or 4.6 per cent. Group K showed more than twice the number of disagreements (8.3%), when compared with groups KS (3.1%), SS (4.1%) and GS (3.1%).

The results expressed subsequently in this study are those of the first evaluation. The results for each restorative technique at both occlusal and gingival margins have been presented in the groupings provided by the grading system used.
Figure 6.5  EXAMPLES OF SURFACES EVALUATED USING THE SCORING SYSTEM ILLUSTRATED IN FIGURE 6.4
Table 6.5

NUMBER OF DISAGREEMENTS BETWEEN FIRST AND SECOND MICROLEAKAGE EVALUATIONS

<table>
<thead>
<tr>
<th>Group</th>
<th>Margin Evaluated</th>
<th>No. of Surfaces</th>
<th>No. of Disagreements</th>
<th>No. of disagreements between grades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N-P</td>
</tr>
<tr>
<td>K</td>
<td>occlusal</td>
<td>48</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>gingival</td>
<td>48</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>KS</td>
<td>occlusal</td>
<td>48</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>gingival</td>
<td>48</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>SS</td>
<td>occlusal</td>
<td>48</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>gingival</td>
<td>48</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>GS</td>
<td>occlusal</td>
<td>48</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>gingival</td>
<td>48</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>384</td>
<td>18</td>
<td>8</td>
</tr>
</tbody>
</table>
Statistical Analysis

As the grading system used in this study resulted in non-parametric microleakage scores, a mean value could not be calculated for the occlusal and gingival margins of each restorative technique. A Chi-Square test was therefore applied in order to find the significance of any differences occurring between restorative techniques and occlusal or gingival margins in their ability to limit microleakage.

A (2 x 4) form of the Chi-Square test (Gibbons 1975) was used with degree of freedom (d.f) calculated from the equation

\[ d.f = (r-1)(c-1) \]

where \( r \) corresponds to the number of rows and \( c \) to the number of columns.

The Chi-Square value (\( x^2 \)) was obtained using

\[ x^2 = \sum \frac{(O - E)^2}{E} \]

where \( O \) corresponds to observed results and \( E \) to expected results.

Differences between restorative techniques and occlusal and gingival margins in their ability to limit microleakage were regarded as significant when the calculated value of \( x^2 \) exceeded the table value at the 0.001 level of confidence (\( \alpha = 0.001 \)), that is \( x^2 \) was greater than 16.266 for d.f = 3. The null hypothesis, that no difference existed in the extent of leakage between observed and expected frequencies that could not be due to chance, was disproved and the alternative hypothesis accepted, that is that a difference existed.
CHAPTER 7

METHOD II. A SCANNING ELECTRON MICROSCOPE INVESTIGATION OF THE CAVOSURFACE MARGINS OF CERVICAL RESTORATIONS.

7.1 COMPONENTS OF THE INVESTIGATION

In Method I, 80 restorations were placed in cervical cavities using four restorative techniques. At random, 10 restorations from each of groups K, KS, SS and GS, were chosen for use in this investigation. The restorations, 40 in total, were examined at two stages of the experimental regimen carried out for Method I, that is, after the restorations were finished following initial thermal cycling, and again after the second thermal cycling episode. The combined experimental regimens for Methods I and II are illustrated in Figure 7.1. The equipment used in specimen preparation and evaluation is listed in Tables 6.2 and 6.3.

7.2 THE METHOD OF INVESTIGATION

Specimen Preparation

The cavities were prepared, restored and the first stage of thermal cycling carried out as described in Method I. The restorations were finished using graded Soflex discs as previously described, then the restored tooth surfaces were immediately rinsed with deionized water, dried and replicated. Light-body silicone material was mixed and syringed onto the surface of the restoration and its' immediate periphery, then spread with a gentle stream of compressed air. A rectangular plastic tray was filled with regular-body material and the tooth, coated with its' thin layer of light-body silicone, was pressed firmly into the tray. After seven minutes from commencing to mix, the restored tooth was removed from
40 teeth divided randomly into four groups

Each tooth had a buccal cavity and a lingual cavity prepared and assigned to a particular restorative technique (Table 6.4)

- $K_1$ and $K_5$
- $K_2$ and $K_5$
- $S_1$ and $G_1$
- $S_2$ and $G_2$

- Yes
- Yes
- Yes
- Yes

Seven days storage and 100 thermalcycles

Yes
Yes
Yes
Yes

Finishing

Yes
No
Yes
No

Replication

Yes
Yes
Yes
Yes

2000 thermalcycles in basic fuchsins

Yes
No
Yes
No

Replication

Yes
Yes
Yes
Yes

Microleakage evaluation

Yes
No
Yes
No

Margins examined

Figure 7.1. The combined experimental regimen for methods I and II
the impression and the experimental regimen for Method I resumed immediately.

Meanwhile, the negative image thus obtained was subjected to a gentle compressed air stream to remove any loose particles, then a positive copper model was fabricated following the method outlined by Lambrechts et al. in 1981. Initially the impression surface was made electroconductive with a layer of submicroscopically fine silver powder, the powder being brushed into the impression and burnished onto the surface to ensure a thin, continuous layer. The excess powder particles were then carefully removed with compressed air and the metallized impressions placed in a copper plating bath. To avoid air entrapment during immersion, a small amount of copper sulphate solution was syringed into the impression to wet the surface before placement in the bath. A current of approximately 25 mA per specimen was used for 24 hours to obtain adequate plating of the impressions. The apparatus used for copper plating is illustrated diagramatically in Figure 7.2.

When plating was completed, the copper coated impression was rinsed with tap water, dried, then poured up with dental stone. One hour later, the replica was removed from the impression and mounted, using an aluminium stub and carbon dag, for subsequent examination with the scanning electron microscope.

This replicating, copper plating and mounting procedure was repeated using the same ten specimens from each restorative technique following the second and principle stage of thermal cycling carried out in Method I. After the second replication, the restored teeth were mounted in epoxy, sectioned and evaluated for microleakage as described in Method I.
Figure 7.2  THE APPARATUS USED FOR COPPER PLATING;

where mA = milliammeter, A = anode (pure copper), C = cathode (the impression),
R = rheostat, E = electrolyte
(acidulated copper sulphate solution)
and Ct = continuous current.
Examination of the Specimens

The copper plated replicas were examined with a scanning electron microscope, using an accelerating voltage of 15kV and secondary electron detection. Each was examined initially at low magnification and adjustment made, if necessary, to the orientation to ensure the long axis of the tooth was positioned horizontally on the viewing screen. An area of both the occlusal and gingival margin was then located, as shown by the shaded areas in Figure 7.3, and examined for the presence or absence of a marginal gap. Photographs were obtained for all replicated specimens from both the occlusal and gingival margins at x44, x220, x440 and also, if required, at x1000, x2200 and x4000, using black and white film and a camera factor of one-half. Where indicated, measuring bars were included on the photomicrographs; these bars have an accuracy of ± 10 per cent.

As illustrated in Figure 7.3, all photomicrographs obtained of the occlusal margin were oriented so coronal enamel was present to the left-hand side of the tooth-restoration interface, and restorative material to the right-hand side. In the case of the gingival margin this orientation was reversed, resulting in the restorative material appearing to the left-hand side of the photomicrograph, and the root surface to the right. An attempt was made to achieve the same orientation and locate the same marginal area on the two replicated specimens obtained from the same restoration.
Figure 7.3 ILLUSTRATION OF THE METHOD USED TO LOCATE AND ORIENTATE AREAS OF THE OCCLUSAL AND GINGIVAL MARGINS, where R = restoration, E = enamel, RS = root surface.
CHAPTER 8

METHOD III. A SCANNING ELECTRON MICROSCOPE INVESTIGATION OF THE EFFECTS OF ETCH TIMES ON THE SURFACE OF A GLASS-IONOMER CEMENT.

8.1 COMPONENTS OF THE INVESTIGATION

Eight sound premolar teeth were obtained, stored, selected and prepared for use as described in Method I (section 6.1). Materials and equipment used in specimen preparation and evaluation are listed in Tables 6.1, 6.2 and 6.3.

8.2 THE METHOD OF INVESTIGATION

Specimen Preparation

Eight cervical cavities were prepared for restoration with composite resin as described in Method I (section 6.2). Immediately cavity preparation was completed, the surfaces were treated with a 10 per cent polyacrylic acid conditioner. The conditioner was applied as previously described, the residue then removed with a continuous, 20 second duration water stream from a triplex syringe, and the cavity dried.

Ketac-Bond was dispensed, mixed and placed to slight excess on all dentine surfaces within the cavity, including the gingival cavosurface margin. The bevelled enamel margin was avoided where possible.

Six minutes from starting to mix, the base was contoured where necessary and excess removed from the enamel margin using a round steel bur* at low speed. On completion of contouring, the

* Ash Rd. PC18. U.K.
specimens were divided into four groups of two specimens each. In the first group, no further modification was undertaken. In the second group of specimens, acid-etch gel was applied with a brush to the enamel bevel and Ketac-Bond surfaces and left in place for 15 seconds. The gel was then removed with a continuous, 20 second duration air and water stream and the etched surfaces dried with air. A further two specimens, forming the third group, had both bevelled enamel and Ketac-Bond surfaces etched for 30 seconds, then the gel removed and the specimen dried, as previously described. Specimens in the fourth group were etched in a similar manner but for 60 seconds, then the gel was removed and the etched surfaces dried.

For the first group, the specimen surfaces were replicated immediately after contouring of the Ketac-Bond base, and for the other three groups replication was undertaken immediately the etching, washing and drying procedure was completed. Replication was carried out as described in Method II (section 7.2), then positive copper replicas were fabricated and prepared for examination, also as previously outlined.

Examination of the Specimens

The specimen replicas were examined using a scanning electron microscope with accelerating voltage of 15kV and secondary electron detection. Each specimen was examined initially at low magnification for orientation, and adjustment made if necessary to ensure the long axis of the tooth was positioned horizontally on the viewing screen, in a similar manner to Method II (section 7.2.). Images were then obtained of the glass-ionomer cement surface and the
glass-ionomer cement and enamel interface at x440 and x1000 magnifications and photographs taken using black and white film and a camera factor of one-half.

In a similar manner to that used in Method II, all photomicrographs obtained of the enamel and glass-ionomer cement interface were oriented so that the enamel was situated on the left and the cement situated on the right-hand side.
CHAPTER 9

RESULTS I. AN INVESTIGATION OF MICROLEAKAGE OCCURRING AROUND CERVICAL RESTORATIONS, AS MEASURED BY PENETRATION OF A TRACER DYE.

9.1 INTRODUCTION

Using the method described, microleakage occurring around restorations placed in cervical cavities was investigated, in vitro, by examining:

i. The influence of four different restorative techniques.

ii. The influence of cavosurface margin position, either in enamel (occlusal margin) or on the root surface (gingival margin).

Tables 9.1 - 9.4 present data for the microleakage of restorations from the four restorative techniques, namely:

Group K, restored using Ketac-Fil, a glass-ionomer restorative cement.

Group KS, restored using Ketac-Bond as a base to restore lost dentine, with a surface veneer of Silux.

Group SS, restored using Silux in combination with the dentine bonding agent, Scotchbond, and Ketac-Bond lining the axial wall.

Group GS, restored using Silux in combination with the dentine bonding agent, GLUMA, and Ketac-Bond lining the axial wall.
In Tables 9.1 - 9.4, the results are presented for both occlusal and gingival margins and show both the number and percentage of surfaces evaluated and the number of surfaces occurring in each of leakage grades N, P, W and T. For example, in Table 9.2, a total of 48 surfaces (or 100 per cent) were evaluated at the gingival margin of group KS, of which 2 (or 4.17 per cent) showed grade N leakage, 20 (or 41.67 per cent) grade P, 11 (or 22.92 per cent) grade W and the remaining 15 (or 31.25 per cent) exhibited grade T leakage. The results presented in Tables 9.1 - 9.4 are subsequently illustrated by means of histograms, Figures 9.1 - 9.4. The results for the occlusal margins of the four restorative techniques are illustrated in Figure 9.5, and the gingival margins in Figure 9.6. The results of statistical analysis of the data are presented in Tables 9.5 - 9.7.

9.2 GENERAL OBSERVATIONS

No restorative technique completely resisted microleakage at either the occlusal or gingival margins under these experimental conditions. At the occlusal margin, no technique totally confined leakage to the enamel cavity wall, although two groups did so in more than 85 per cent of cases. The gingival margin of all groups exhibited greater leakage than the occlusal margin, with one group showing the worst grade of leakage, grade T, at the gingival margin in almost 100 per cent of surfaces examined compared with no cases of grade T at the occlusal margin of the same group. The disparity in occlusal and gingival microleakage was found to be statistically significant in all cases.

In restorations using glass-ionomer cement as a lining or base material in combination with composite resin, when leakage occurred
Table 9.1

MICROLEAKAGE RESULTS FOR GROUP K

<table>
<thead>
<tr>
<th>Margin Evaluated</th>
<th>No. of Surfaces Evaluated</th>
<th>No. of and (%) of Surfaces per grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusal</td>
<td>48 (100%)</td>
<td>9 (18.75%) 18 (37.5%) 9 (18.75%) 12 (25%)</td>
</tr>
<tr>
<td>Gingival</td>
<td>48 (100%)</td>
<td>0 (0%) 3 (6.25%) 31 (64.58%) 14 (29.17%)</td>
</tr>
</tbody>
</table>

Table 9.2

MICROLEAKAGE RESULTS FOR GROUP KS

<table>
<thead>
<tr>
<th>Margin Evaluated</th>
<th>No. of Surfaces Evaluated</th>
<th>No. of and (%) of Surfaces per grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusal</td>
<td>48 (100%)</td>
<td>30 (62.5%) 12 (25%) 6 (12.5%) 0 (0%)</td>
</tr>
<tr>
<td>Gingival</td>
<td>48 (100%)</td>
<td>2 (4.17%) 20 (41.67%) 11 (22.92%) 15 (31.25%)</td>
</tr>
</tbody>
</table>
Figure 9.1 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR GROUP K.
Figure 9.2 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR GROUP KS.
Table 9.3

MICROLEAKAGE RESULTS FOR GROUP SS

<table>
<thead>
<tr>
<th>Margin Evaluated</th>
<th>No. of Surfaces Evaluated</th>
<th>No. of and (%) of Surfaces per grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusal</td>
<td>48</td>
<td>20 (100%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 (41.67%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 (37.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 (20.83%)</td>
</tr>
<tr>
<td>Gingival</td>
<td>48</td>
<td>0 (100%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 (0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (2.08%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47 (97.92%)</td>
</tr>
</tbody>
</table>

Table 9.4

MICROLEAKAGE RESULTS FOR GROUP GS

<table>
<thead>
<tr>
<th>Margin Evaluated</th>
<th>No. of Surfaces Evaluated</th>
<th>No. of and (%) of Surfaces per grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusal</td>
<td>48</td>
<td>39 (100%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 (81.25%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (16.67%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 (2.08%)</td>
</tr>
<tr>
<td>Gingival</td>
<td>48</td>
<td>14 (100%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 (29.17%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 (8.33%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 (62.5%)</td>
</tr>
</tbody>
</table>
Figure 9.3 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR GROUP SS.
Figure 9.4 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR GROUP GS.
Table 9.5  COMPARISON OF LEAKAGE AT THE OCCLUSAL MARGIN OF THE FOUR GROUPS

<table>
<thead>
<tr>
<th>Comparison</th>
<th>A difference found at 0.001 level</th>
<th>Leakage observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>K : KS</td>
<td>Yes</td>
<td>K &gt; KS</td>
</tr>
<tr>
<td>K : SS</td>
<td>No*</td>
<td>K &gt; SS</td>
</tr>
<tr>
<td>K : GS</td>
<td>Yes</td>
<td>K &gt; GS</td>
</tr>
<tr>
<td>KS : SS</td>
<td>No</td>
<td>Similar</td>
</tr>
<tr>
<td>KS : GS</td>
<td>No</td>
<td>Similar</td>
</tr>
<tr>
<td>SS : GS</td>
<td>Yes</td>
<td>SS &gt; GS</td>
</tr>
</tbody>
</table>

* but was significant at 0.01 level

Table 9.6  COMPARISON OF LEAKAGE AT THE GINGIVAL MARGIN OF THE FOUR GROUPS

<table>
<thead>
<tr>
<th>Comparison</th>
<th>A difference found at 0.001 level</th>
<th>Leakage observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>K : KS</td>
<td>Yes</td>
<td>K &gt; KS</td>
</tr>
<tr>
<td>K : SS</td>
<td>Yes</td>
<td>SS &gt; K</td>
</tr>
<tr>
<td>K : GS</td>
<td>Yes</td>
<td>K &gt; GS</td>
</tr>
<tr>
<td>KS : SS</td>
<td>Yes</td>
<td>SS &gt; KS</td>
</tr>
<tr>
<td>KS : GS</td>
<td>Yes</td>
<td>Trend unclear</td>
</tr>
<tr>
<td>SS : GS</td>
<td>Yes</td>
<td>SS &gt; GS</td>
</tr>
</tbody>
</table>

Table 9.7  COMPARISON OF LEAKAGE AT THE OCCLUSAL AND GINGIVAL MARGINS OF EACH GROUP

<table>
<thead>
<tr>
<th>Comparison</th>
<th>A difference found at 0.001 level</th>
<th>Leakage observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>K occlusal : K gingival</td>
<td>Yes</td>
<td>K occlusal &lt; K gingival</td>
</tr>
<tr>
<td>KS occlusal : KS gingival</td>
<td>Yes</td>
<td>KS occlusal &lt; KS gingival</td>
</tr>
<tr>
<td>SS occlusal : SS gingival</td>
<td>Yes</td>
<td>SS occlusal &lt; SS gingival</td>
</tr>
<tr>
<td>GS occlusal : GS gingival</td>
<td>Yes</td>
<td>GS occlusal &lt; GS gingival</td>
</tr>
</tbody>
</table>
it was invariably at the tooth - restoration interface, with the composite and glass-ionomer bond remaining impervious to dye.

9.3 MICROLEAKAGE OCCURRING AROUND CAVITIES RESTORED USING KETAC-FIL, A GLASS-IONOMER RESTORATIVE CEMENT.

The results, as presented in Table 9.1 and Figure 9.1, showed microleakage occurring at the occlusal margins of group K to be evenly distributed over the four leakage grades. At the gingival margins, however, Ketac-Fil failed to prevent leakage in any surface examined and more than 90 per cent of surfaces exhibited leakage in one or other of the two worst leakage grades.

Statistical analysis of the data indicated a significant difference in the extent of occlusal and gingival leakage for group K at $\alpha = 0.001$, as shown in Table 9.7. By observation, leakage occurring at the gingival margin was greater than that found at the occlusal margin.

9.4 MICROLEAKAGE OCCURRING AROUND CAVITIES RESTORED USING KETAC-BOND, AS A BASE TO REPLACE LOST DENTINE, WITH A SURFACE VENEER OF SILUX.

Microleakage scores at the occlusal margins of group K$s$ showed that a seal was maintained in 62.5 per cent of surfaces examined, and no surfaces exhibited grade T, the worst leakage grade. At the gingival margin, few surfaces exhibited no leakage but only 54 per cent showed one of either of the worst two leakage grades. These leakage patterns are shown in Table 9.2 and Figure 9.2.

As shown in Table 9.7, a statistical difference was found in the extent of gingival leakage compared with occlusal leakage at
0.001. By observation, leakage at the gingival margin was found to be greater than that occurring at the occlusal margin.

9.5 MICROLEAKAGE OCCURRING AROUND CAVITIES RESTORED USING SILUX IN COMBINATION WITH THE DENTINE BONDING AGENT, SCOTCHBOND, AND KETAC-BOND LINING THE AXIAL WALL.

The results, as presented in Table 9.3 and Figure 9.3, show microleakage occurring at the occlusal margin was either prevented completely or confined to enamel in almost 80 per cent of surfaces examined. Only 20 per cent of surfaces showed leakage penetrating into dentine and in no case did leakage extend along the axial wall. At the gingival margin, however, the ability of this restorative technique to prevent microleakage was poor, with 98 per cent of surfaces exhibiting the worst grade of dye penetration, grade T.

Statistical analysis of the data indicated a significant difference in occlusal and gingival leakage for group SS, at \( \alpha = 0.001 \), as shown in Table 9.7. By observation, the gingival margin showed a greater degree of leakage than the occlusal.

9.6 MICROLEAKAGE OCCURRING AROUND CAVITIES RESTORED USING SILUX IN COMBINATION WITH THE DENTINE BONDING AGENT, GLUMA, AND KETAC-BOND LINING THE AXIAL WALL.

Microleakage scores at the occlusal margins of group GS showed a complete seal in 81 per cent of surfaces examined and only 2 per cent of surfaces with leakage into dentine. The gingival margin exhibited a different pattern, as is shown in Table 9.4 and Figure 9.4. Although almost 30 per cent of surfaces showed no leakage, 62 per cent showed penetration of dye to include the axial wall, the
most severe grade of leakage. Very few scores were found in the grades between these two extremes.

Statistical analysis again showed a significant difference in the extent of leakage occurring at the occlusal and gingival margins at $\alpha = 0.001$, as can be seen in Table 9.7. It was apparent that greater leakage occurred at the gingival margin in this group.

9.7 MICROLEAKAGE OCCURRING AT THE OCCLUSAL MARGINS OF THE FOUR RESTORATIVE TECHNIQUES.

Microleakage data recorded for the occlusal margins of the four groups, K, KS, SS and GS is illustrated in Figure 9.5. Statistical analysis of the microleakage patterns is presented in Table 9.5. The Ketac-Fil restorations (group K) appeared to provide the least reliable seal at the occlusal margin. The extent of leakage occurring in group K was found to be significantly different to that of groups KS and SS at $\alpha = 0.001$ and significantly different from the pattern obtained for group SS at $\alpha = 0.01$. The ability of Ketac-Fil to prevent leakage in less than 20 per cent of cases is in marked contrast to the results achieved using the other restorative techniques, where leakage was prevented in 42 per cent, 62.5 per cent and 81 per cent of cases respectively.

A statistical difference was found at $\alpha = 0.001$ when the occlusal leakage patterns of groups SS and GS were compared and, by observation, group SS exhibited greater leakage than group GS. When groups KS and SS were compared, no statistical difference could be found in the extent of occlusal leakage, despite differences in the number of surfaces exhibiting no leakage.
Figure 9.5 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR THE OCCLUSAL MARGINS.
Similarly, although the GLUMA-Silux combination prevented leakage in 81 per cent of surfaces examined, no statistical difference could be found between this group and group KS, which prevented occlusal leakage in 62.5 per cent of cases. It is difficult, therefore, to ascertain which of groups GS and KS provided a superior seal at the occlusal margin under this set of experimental conditions.

9.8 MICROLEAKAGE OCCURRING AT THE GINGIVAL MARGINS OF THE FOUR RESTORATIVE TECHNIQUES.

For groups K, KS, SS and GS, microleakage scores obtained at the gingival margin are shown in Figure 9.6. Statistical analysis of the patterns of gingival leakage for the four techniques is presented in Table 9.6. The Scotchbond-Silux combination, group SS, showed the least capacity to seal at the gingival margin, with almost all surfaces showing total leakage. Statistical comparison showed a significant difference at $\alpha = 0.001$ between group SS and the leakage patterns obtained for the other three groups.

Cavities restored with Ketac-Fil, although appearing to seal better than those of group SS, showed a statistically significant difference ($\alpha = 0.001$) in the extend of gingival leakage when compared with groups KS and GS. By observation, both groups KS and GS exhibited less leakage at the gingival margin than group K.

Although a statistically significant difference was found at the 0.001 level between gingival leakage scores obtained for groups GS and KS, it was unclear which restorative technique exhibited superior sealing ability. Marginal leakage around the Ketac-Bond and Silux restorations was distributed over all leakage grades, whereas the seal around the GLUMA-Silux combination either remained intact or failed completely.
Figure 9.6 ILLUSTRATION OF MICROLEAKAGE RESULTS FOR THE GINGIVAL MARGINS.
CHAPTER 10

RESULTS II. A SCANNING ELECTRON MICROSCOPE INVESTIGATION OF THE CAVOSURFACE MARGINS OF CERVICAL RESTORATIONS.

10.1 INTRODUCTION

Using the method described previously, replicas were prepared of the surface of cervical restorations placed using four techniques. The replicas were prepared at two stages during testing and the performance of the four restorative techniques investigated by examining photomicrographs for:

i. The presence or absence of gaps, or breaks in continuity, along the occlusal margin after 100 thermal cycles and then after 2100 thermal cycles.

ii. The presence or absence of gaps along the gingival margin after 100 thermal cycles and then after 2100 thermal cycles.

iii. Comparison of the width of any gaps which were observed.

Representative photomicrographs of the occlusal margins of the four restorative techniques are shown in Figures 10.1 - 10.4, and the gingival margins in Figures 10.5 - 10.8. High magnification images of the marginal gaps observed for the four restorative techniques are shown in Figure 10.9, with the addition of bars for measurement.

10.2 OCCLUSAL MARGINS

The occlusal margin of group K, the Ketac-Fil restoration is shown in Figure 10.1. After 100 cycles, the margin exhibited slight irregularity remaining after finishing procedures but no
evidence of a marginal gap at either x220 or x440 magnification (Figure 10.1a,b). After a further 2000 cycles, the margin remained irregular and a marginal gap could just be observed at x220 and was quite apparent at higher magnifications. The gap appears to run an intermittent and winding course but to be fairly uniform in width (Figure 10.1d). Although the gap appears contained within the restorative material (Figure 10.1e), the irregularity of the margin makes it difficult to ascertain the exact position of the interface between the enamel and cement.

Figure 10.2 shows the occlusal margin of group KS, the Ketac-Bond and Silux restoration. After 100 cycles, evidence of the finishing procedures can be seen (Figure 10.2a) and deeper grooving of the composite resin surface serves to demarcate the resin and enamel. A view of the area at higher magnification (Figure 10.2b) shows detail of the grooves but no evidence of a marginal gap. After a further 2000 cycles, the marginal area remains unchanged and again there is no evidence of gap formation (Figure 10.2c,d).

The occlusal margin of group SS, the Scotchbond, Ketac-Bond and Silux restoration, is shown in Figure 10.3. After 100 cycles, surface debris remaining from the finishing procedures can be seen at the interface of the enamel and restorative material, as well as small fractures occurring in the adjacent composite resin (Figure 10.3a). There is, however, no evidence of marginal gap formation. A view at the same magnification after a further 2000 cycles shows less surface debris but the same fractured areas remain within the composite material. A higher magnification view (Figure 10.3c) shows detail of a fracture site, with obvious jagged tearing of the restorative material. Again, no evidence of a marginal gap can be seen after further cycling.
Figure 10.1  OCCLUSAL MARGIN OF GROUP K, THE KETAC-FIL RESTORATION

a Enamel-restoration interface after 100 cycles, original magnification x220.

b Same area, original magnification x440.

c Enamel-restoration interface after 2100 cycles, original magnification x220.

d Same area, original magnification x440.

e Same area, original magnification x2200.
Figure 10.2  Occlusal margin of group KS, the Ketac-Bond and Silux Restoration

a  Enamel-restoration interface after 100 cycles, original magnification x44.

b  Same area, original magnification x220.

c  Enamel-restoration interface after 2100 cycles, original magnification x44.

d  Same area, original magnification x220.
Figure 10.3 OCCLUSAL MARGIN OF GROUP SS, THE SCOTCHBOND, KETAC-BOND AND SILUX RESTORATION

a Enamel-restoration interface after 100 cycles, original magnification x220.

b Enamel-restoration interface after 2100 cycles, original magnification x220.

c Same area showing detail of fracture within the restoration, original magnification x1000.

Figure 10.4 OCCLUSAL MARGIN OF GROUP GS, THE GLUMA, KETAC-BOND AND SILUX RESTORATION

a Enamel-restoration interface after 100 cycles, original magnification x220.

b Enamel-restoration interface after 2100 cycles, original magnification x220.
Figure 10.4 shows the occlusal margin of group GS, the GLUMA, Ketac-Bond and Silux restoration. After both 100 and 2100 cycles, the polishing grooves are well defined within the composite resin, in a similar manner to those of group KS, but there is no evidence of the fracture sites observed in group SS. Again a marginal gap cannot be observed at either stage.

10.3 GINGIVAL MARGINS

The gingival margin of group K, the Ketac-Fil restoration is shown in Figure 10.5. Slight irregularity of the margin can be seen after finishing procedures and 100 cycles, in a similar manner to the occlusal margin of the same restoration (Figure 10.1). No evidence of marginal gap formation can be seen, however, at either x220 or x440 magnification. After a further 2000 cycles, a gap is easily visible at x220 magnification (Figure 10.5c), and is situated well within the body of the cement. The gap has a continuous, winding course (Figure 10.5d) but loss of cement substance seems to have occurred at intervals, resulting in variations of width (Figure 10.5e).

Figure 10.6 shows the gingival margin of group KS, the Ketac-Bond and Silux restoration. After 100 cycles, an irregular interface can be seen between the restoration and root surface, with considerable debris remaining from finishing procedures (Figure 10.6a). Clearly visible also is a well-defined gap adjacent to the interface which at low magnification appears to run a fairly uniform, continuous course. At a higher magnification (Figure 10.6b), the gap exhibits features similar to the composite resin fracture reported previously (Figure 10.3c). The jagged, torn
configuration makes it difficult, however, to judge whether the gap is continuous or intermittent.

After completing a further 2000 cycles, the marginal gap appearing at the gingival margin of group KS has become quite distinct and shows a clearly continuous course, even at lower magnification (Figure 10.6c). The gap does not appear to have vertical sides, as though some overlapping occurred when the restoration was initially placed. Residual restorative material can be seen attached to the cavity wall and projections of material into the gap also appear from the bulk of the restoration. Figure 10.6d shows a higher magnification of these projections and from their configuration it could be suggested that they consist of cement from the Ketac-Bond base.

The gingival margin of group SS, the Scotchbond, Ketac-Bond and Silux restoration, is shown in Figure 10.7. After 100 cycles, the interface between restoration and root surface appears well defined and a marginal gap can just be perceived at x440 magnification. The gap does not appear continuous, and its intermittent nature is confirmed by higher magnification views of the same area (Figure 10.7b,c). The section of marginal gap which can be seen in Figure 10.7b shows the space filled with particulate material, possibly debris from finishing procedures.

The marginal gap is clearly visible at lower magnification after a further 2000 cycles (Figure 10.7d). The walls appear vertical, although still following a slightly uneven course, and some debris can still be seen in the gap space. A higher magnification view of the same area accentuates the sharpness of the break between cavity wall and restoration, with no evidence of residual restorative material projecting from either surface.
Figure 10.8 shows two examples of the gingival margin of group GS, the GLUMA, Ketac-Bond and Silux restoration. Figure 10.8a-f shows the presence of a marginal gap from this group, while Figure 10.8g-j is representative of a margin which has remained intact.

After 100 cycles, the interface between the restoration and cavity wall in the first example (Figure 10.8a) appears well defined, however a marginal gap cannot be clearly seen at this magnification. At x2200 and x4000, however, the presence of a gap can be verified but in this case, also, it appears intermittent. The irregular outline and areas of overlapping occurring along the interface again resemble the composite resin fractures observed previously (Figure 10.3c).

After a further 2000 cycles, a continuous gap is clearly visible at the interface between restoration and cavity wall (Figure 10.8d). The walls appear vertical and run a regular course. At higher magnification, residual restorative material can be seen still attached to the root surface and fracture of the composite resin has also occurred (Figure 10.8f).

In the second example, the interface between restoration and root surface after 100 cycles follows an irregular outline (Figure 10.8g) and the two materials do not appear level (Figure 10.8h). The irregularity and level discrepancy found in this case suggests the presence of excess restorative material in the form of an overlap. A marginal gap or break in the restorative material cannot be observed at either magnification. After a further 2000 cycles, the gingival margin of this example appears unchanged (Figures 10.8i,j), with the same irregular interface and no evidence of gap formation.
Figure 10.5 GINGIVAL MARGIN OF GROUP K, THE KETAC-FIL RESTORATION

a  Root surface-restoration interface after 100 cycles, original magnification x220.

b  Same area, original magnification x440.

c  Root surface-restoration interface after 2100 cycles, original magnification x220.

d  Same area, original magnification x440.

e  Same area, original magnification x2200.
Figure 10.6 GINGIVAL MARGIN OF GROUP KS, THE KETAC-BOND AND SILUX RESTORATION

a Root surface-restoration interface after 100 cycles, original magnification x440.

b Same area, original magnification x2200.

c Root surface-restoration interface after 2100 cycles, original magnification x440.

d Same area, original magnification x2200.
Figure 10.6
Figure 10.7  GINGIVAL MARGIN OF GROUP SS, THE SCOTCHBOND, KETAC-BOND AND SILUX RESTORATION

a  Root surface-restoration interface after 100 cycles, original magnification x440.

b  Same area, original magnification x2200.

c  Same area, original magnification x2200.

d  Root surface-restoration interface after 2100 cycles, original magnification x440.

e  Same area, original magnification x2200.
Figure 10.8  GINGIVAL MARGIN OF GROUP GS, THE GLUMA, KETAC-BOND AND SILUX RESTORATION

a Root surface-restoration interface after 100 cycles, original magnification x440.

b Same area, original magnification x2200.

c Same area, original magnification x4000.

d Root surface-restoration interface after 2100 cycles, original magnification x440.

e Same area, original magnification x2200.

f Same area, original magnification x4000.
Figure 10.8
Figure 10.8 (continued)

**g** Root surface-restoration interface after 100 cycles, original magnification x220.

**h** Same area, original magnification x2200.

**i** Root surface-restoration interface after 2100 cycles, original magnification x220.

**j** Same area, original magnification x2200.
10.4 COMPARISON OF MARGINAL GAP WIDTHS

Figure 10.9 shows high magnification images of the five marginal gaps observed and described in the preceding sections. Of these, one occurred at the gingival margin of each of the four restorative techniques (Figure 10.9b-e) and one was observed at the occlusal margin of group K, the Ketac-Fil restoration (Figure 10.9a).

The narrowest gap appeared to be that occurring at the occlusal margin of the Ketac-Fil restoration, with a width of approximately 1-2 microns. Groups SS and GS show a similarity in gap configuration, and gap width for these two restorations appears to be a uniform 3-4 microns (Figure 10.9b,c).

The example of group K (Figure 10.9d) shows a marked variation in width along the gap occurring at the gingival margin. Where cement substance has been lost, the width is approximately 10-12 microns, however, elsewhere gap widths appear as small as 2-3 microns.

Group KS presents what appears to be a wide gap, approximately 14-16 microns (Figure 10.9e). The overlapping configuration of the margin, however, makes estimation of the width difficult, especially as the space appears to narrow just below the surface.
Figure 10.9  COMPARISON OF MARGINAL GAP WIDTHS

a  Enamel-restoration interface of group K, original magnification x2200.

b  Root surface-restoration interface of group GS, original magnification x2200.

c  Root surface-restoration interface of group SS, original magnification x2200.

d  Root surface-restoration interface of group K, original magnification x2200.

e  Root surface-restoration interface of group KS, original magnification x2200.
CHAPTER 11

RESULTS III. A SCANNING ELECTRON MICROSCOPE INVESTIGATION OF THE EFFECTS OF ETCH TIMES ON THE SURFACE OF A GLASS-IONOMER CEMENT.

11.1 INTRODUCTION

Using the method described, replicas were prepared of the surface of a glass-ionomer cement, Ketac-Bond, which had been placed in cervical cavities, allowed to set for six minutes, contoured then acid-etched for various intervals of time. Photomicrographs were obtained of both the cement surface and the interface between enamel and cement and examined for:

i. Changes, if any, occurring in the topography of the cement after etching for 15, 30 or 60 seconds, when compared with an untouched surface.

ii. Loss of cement substance after contouring and etching for 15, 30 and 60 seconds, when compared with the adjacent enamel surface.

Photomicrographs of the cement surfaces are shown in Figure 11.1, and those of the cement and enamel interface in Figure 11.2.

11.2 GENERAL OBSERVATIONS

The crazing, or series of small cracks, observed on some Ketac-Bond surfaces during restorative procedures carried out for Method I was also found on the replicated Ketac-Bond surfaces. This phenomenon did not occur in all specimens and could not be correlated with etch times. Examples of this crazing can be seen in Figure 11.1a,b,d and Figure 11.2c,d,e.
11.3 **THE GLASS-IONOMER CEMENT SURFACE**

If the crazing is disregarded, unetched, uncontoured cement shows a continuous but slightly irregular surface at x440 magnification (Figure 11.1a). At higher magnification some porosity is observed but individual glass particles are not discernible (Figure 11.1b).

After etching for 15 seconds, a substantial increase in surface roughness is observed (Figure 11.1c), with loss of the gel matrix and protrusion of the underlying glass particles. Several voids are visible between the exposed glass particles and at least one particle appears to have separated completely from the surrounding cement.

After etching for 30 seconds, the cement surface has deteriorated further (Figure 11.1d). A greater number of glass particles appear dissociated from the main mass of cement and the number and size of voids has increased. Gel matrix bridges can still be seen, however, connecting several of the exposed glass particles.

The pattern of surface irregularity and matrix erosion observed after 60 seconds of etching (Figure 11.1e) appears similar to that occurring after 30 seconds. Voids, however, appear to have enlarged, and this may be the result of loss of glass particles, or coalescence of several voids after destruction of the gel matrix bridges.

11.4 **THE ENAMEL AND GLASS-IONOMER CEMENT INTERFACE**

The interface between enamel and Ketac-Bond for a specimen which had been contoured but not etched can be seen in Figure 11.2a. The enamel surface shows ridging and grooving consistent
Figure 11.1  THE GLASS-IONOMER CEMENT SURFACE

a  Six minutes from starting to mix, original magnification x440.

b  Same area, original magnification x1000.

c  After etching for 15 seconds, original magnification x1000.

d  After etching for 30 seconds, original magnification x1000.

e  After etching for 60 seconds, original magnification x1000.
Figure 11.2  THE ENAMEL AND GLASS-IONOMER CEMENT INTERFACE

a  Unetched but contoured, original magnification x440.

b  Etched for 15 seconds, original magnification x440.

c  Etched for 30 seconds, original magnification x440.

d  Etched for 60 seconds, original magnification x440.

e  Same area, original magnification x1000.
with preparation procedures carried out using rotary instruments. The cement exhibits a uniform, roughened surface but individual glass particles cannot be distinguished from the surrounding matrix. The surfaces of the cement and enamel appear flush.

After 15 seconds of etching, the cement and enamel surfaces still appear in the same plane (Figure 11.2b). The enamel surface shows the effects of initial acid dissolution, with the ridges and grooves from cavity preparation being less pronounced. Considerable roughening of the Ketac-Bond surface can be seen, as well as protrusion of individual glass particles.

Figure 11.2c shows the interface after etching for 30 seconds and a distinct difference in levels of the enamel and cement surfaces is now apparent. The enamel surface shows a substantial increase in roughness and the emergence of a distinct prism pattern. The cement surface shows characteristic voids, and distinct glass particles surrounded by the remaining matrix.

The enamel and cement interface after 60 seconds of etching is shown in Figure 11.2d,e. The enamel surface exhibits a typical prism pattern as a result of selective acid dissolution. The cement surface shows further protrusion of glass particles and the presence of large voids. Cracking or crazing has again occurred within the body of the cement, in a manner consistent with that observed in specimens etched for shorter periods or not etched at all. An alteration in levels can be observed at the enamel and cement interface but, possibly due to greater etching of the enamel, there does not appear to have been a substantially greater loss of cement substance.
CHAPTER 12
DISCUSSION

12.1 INTRODUCTION

The absence of a seal at the margins of dental restorations has been considered a major disadvantage of most available restorative techniques. Improvement in the sealing ability of restorations has been achieved where margins are situated in enamel, however where enamel is absent and margins must be placed in dentine or cementum, obtaining a seal remains elusive. This study has confirmed the inability of four commonly used restorative techniques to provide a seal against microleakage, or to wholly resist gap formation at the cavo-surface margins of cervical cavities. The observations of poor sealing against microleakage and gap formation were especially pronounced at the gingival margins, which were situated on the root surface.

12.2 EXPERIMENTAL METHODS

Teeth

The teeth used in this study were sound and showed minimal extraction damage, exhibiting qualities similar to the teeth used in other microleakage investigations (Phair and Fuller 1983, Bauer and Henson 1985, Gordon et al. 1985, Hudson et al. 1987). The storage time between extraction and use in this study was at least 24 hours and no more than four months. This was undertaken on the basis that the bonding potential to dentine might be more predictable if freshly extracted teeth were not used in conjunction with aged teeth.
Storage at 4°C in a moist, sealed environment was undertaken to preserve the teeth without the possible deleterious effects and distorted results produced by storage solutions (Phair and Fuller 1983, Jorgensen et al. 1985). When the teeth were eventually used it was observed that pulpal tissues, although blanched, were moist and showed no other signs of deterioration, and that the cut dentine surface was also moist. This storage method appeared successful, therefore, in preserving tooth structure for use in laboratory studies.

**Cavity Design**

Three cavity designs are commonly used in microleakage studies of cervical restorations, namely a cylindrical shape, a Class V configuration and a simulated erosion-abrasion lesion. In this study a cylindrical shape was chosen, principally for ease in standardization and positioning at the cemento-enamel junction but also to facilitate comparison with recent microleakage investigations (McComb et al. 1986, Hudson et al. 1987) and restoration margin visualization studies (Reich and Volk 1986, Roulet and Rosansky 1986).

As described in the majority of other studies using cervical cavities, root surface margins and margins to be restored with glass-ionomer cement were prepared as a butt joint. An enamel cavosurface bevel was placed in cavities to be restored with composite resin in a similar manner to other recent studies (McComb et al. 1986, Crim and Chapman 1986b, Roulet and Rosansky 1986, Hudson et al. 1987).
Restorative Techniques

Manipulation of restorative materials accorded with the manufacturers' directions, with one exception. A six minute delay between starting to mix the Ketac-Bond and applying acid etchant had been suggested (Mount 1986c), contrary to the four minutes recommended by the manufacturer, as increased cement maturity before etching has been linked to higher composite resin - glass-ionomer bond strengths (Wexler 1984, Chin and Tyas 1987). It was observed, however, during restorative procedures that crazing of the Ketac-Bond surface occurred in some specimens after six minutes and prior to the etchant being applied. It is possible that this crazing could be deleterious to the strength of the glass-ionomer cement and therefore adversely affect both the glass-ionomer-dentine and glass-ionomer-composite resin bond. Also, the etchant may contact dentine and be difficult to wash away if the crazing proved to be extensive. If the six minute delay is to be used in the future, further investigation of the occurrence and effects of the crazing would be advisable.

At the time the restorations were placed for this investigation, a 60 second etch for Ketac-Bond was recommended by the manufacturer and used by other investigators (McLean et al. 1985, Sneed and Looper 1985, Gordon et al. 1985, Roulet and Rosansky 1986, Reich and Volkl 1986). Subsequently, however, studies have concluded that etching for a shorter time may be more desirable (Smith 1986, Quiroz and Lentz 1987) and give little reduction in bond strength to composite resin (Smith and Soderholm 1987, Hassan and Nathanson 1987).
Finishing

In this study, finishing procedures were carried out seven days after restoration placement, in contrast to most other studies but in a similar manner to Hudson et al. in 1987. A delay of this length is considered clinically desirable to allow for hygroscopic expansion of Silux (Hansen 1982). A delay of at least one day before finishing is also advised for maturation of glass-ionomer restorative cements (Mount and Makinson 1982, Pearson and Knibbs 1987).

Thermal Cycling

The thermal cycling regimen used in this study involved similar temperatures and bath dwell times to those of other microleakage investigations, however, the total number of cycles used and the timing of cycling interludes varied from the usual. The total number of cycles was similar to that of another team of researchers (Crim and Chapman 1986a,b) but substantially greater than most other studies. In using more severe thermal cycling, the aim was to assess microleakage after a regimen corresponding to a longer period of service in vivo, but to avoid the increased enamel crack propagation occurring from 2000 cycles (Lloyd et al. 1978).

The difference in timing of thermal cycling, that is the use of two stages, was considered necessary because of the longer interval allowed before finishing procedures, and in an attempt to more accurately reproduce in vivo conditions. Other investigations have either finished and thermal cycled almost immediately (Gordon et al. 1986a,b, McComb et al. 1986, Crim and Chapman 1986a,b, Thornton et al. 1987) or polished immediately and stored the specimens for a week before thermal cycling (Phair and Fuller 1983,
Fuks et al. 1985). Neither of these procedures reflects a clinical situation, either with respect to the desirability of delayed finishing, or to the fact that thermal stress begins almost immediately after restoration placement.

Despite the care taken in this study to simulate in vivo conditions, the fact that the general observations and results correlate with those of other studies using more conventional thermal cycling casts doubt as to whether the two stages of cycling are of value.

Evaluation and Statistical Analysis

Adaptation of the scoring system used by Stanninec et al. in 1986 was made in two areas, namely by replacing the numerical value given to each leakage grade with an alphabetic symbol, and by more specifically defining the limits of partial penetration (grade P) along both occlusal and gingival walls.

Using alphabetic symbols made subsequent calculation of a mean value impossible, but did ensure a leakage pattern for each margin which could be compared with others by Chi-Square analysis. A non-parametric scoring system also failed to provide a facility for microleakage assessment of the restoration as a whole, in the manner of other researchers (Crim and Chapman 1986a,b). The predictive value of an overall score is doubtful, however, as poor performance at the gingival margin of a restorative technique could be masked by pooling with better scores obtained at the occlusal margin.

The demarcation of grades P and W at both occlusal and gingival margins, that is using the dentino-enamel junction
and the start of the gingival retentive groove, made for ease of evaluation, especially when compared to other studies using measurements corresponding to one half, one quarter or one third of wall depth (Phair and Fuller 1983, 1985, Gordon et al. 1985, 1986a,b, McComb et al. 1986). The method used in this study to define the border of grades P and W was probably no less accurate, despite cavity orientation changes during sectioning of the various restorations, by being based on structures rather than measurements.

This scoring system gave an excellent correlation between first and second microleakage evaluations for groups KS, SS and GS. In contrast group K, the Ketac-Fil restoration, showed more than twice the number of disagreements and consequently the overall inconsistency level was higher than would otherwise have been expected. The only available explanation for this observation, which has not been reported by other investigators, is that Ketac-Fil, being a slowly maturing cement with the capacity for exchange in an aqueous environment, would more readily absorb the fuchsin stain than either Silux or Ketac-Bond. By absorbing the stain into the restoration adjacent to the cavity interface the dye penetration took on a diffuseness which subsequently led to scoring inaccuracy.

**Copper Plating of the Replicas**

Coating the surface of the replicated specimens with a copper layer resulted in the surface detail reproduction and absence of artefacts necessary to accurately assess the marginal gaps observed in this investigation. No charging effects due to deficiencies in
the copper layer were observed, and clear photomicrographs were obtained at magnifications of up to x4000.

Some specimens did, however, exhibit the presence of surface copper crystals which were most obvious on smooth surfaces and at higher magnifications. Although these crystals did not noticeably distort the structures being observed, they did present problems in differentiating the tooth and restoration surfaces. Several explanations are possible for the presence on some specimens of these discernible crystal shapes. Slight differences in surface area of the impressions being plated could produce variations in the deposition of the copper layer, and any fluctuations in the power supply to the copper plating bath would also affect the deposition rate of the copper and lead to discrepancies in crystal size. It has been suggested that the power fluctuations could be reduced by introduction of a voltage stabilizer to the plating apparatus (Lambrechts et al. 1982).

12.3 THE MICROLEAKAGE INVESTIGATION

General observations

No restorative technique tested in this investigation completely resisted microleakage at either the occlusal or the gingival margin, findings generally consistent with other microleakage studies. Of studies involving glass-ionomer restorative cements leakage was found to occur at the occlusal margin, with one exception (Hembree and Andrews 1978). Differences in either restorative techniques or experimental regimen could not, however, readily account for this contrasting finding. At the occlusal margin of composite resin restorations, the findings of this investigation were similar to some (Gordon et al. 1985, Fuks
et al. 1985, Crim and Chapman 1986a), but contrasted with several others (Phair and Fuller 1985, Gordon et al. 1986a,b, Crim and Chapman 1986b). The contrasting studies found some composite resin restorative techniques to completely resist microleakage while others did not, but no trend was observed as to which material and bonding agent combination was superior.

The finding of this investigation, that no restorative technique tested was capable of providing a reliable seal at the gingival margin, is consistent with other reported studies. These uniform findings have emerged despite vast differences in experimental regimen, cavity design and manipulation of materials.

The gingival margins of all restorative techniques tested in this investigation exhibited more severe leakage than the occlusal margins and the difference was found to be significant; these results are consistent with other microleakage studies except those investigating glass-ionomer restorative cements. Several studies also observed greater leakage at the gingival margin of glass-ionomer cement restorations (Welsh and Hembree 1985, Gordon et al. 1986b) but others found gingival and occlusal leakage to be uniform (Lacefield et al. 1982, Phair and Fuller 1983, Thornton et al. 1987), however statistical analysis was cited only by Thornton et al. in 1987. These conflicting findings may possibly be explained by differences in cavity design, that is greater leakage at the gingival margins was observed in studies using simulated abrasion lesions (Welsh and Hembree 1985, Gordon et al. 1986b), while the remaining studies used more conventional cavity shapes.

That the interface between composite resin and glass-ionomer cement remained uniformly impervious to dye is in agreement with the findings of Gordon et al. in 1985. This observation also
appears consistent with conclusions that the bond strengths obtained between composite resin and etched glass-ionomer cement in vitro exceed the cohesive strength of the cement (McLean et al. 1985, Sneed and Looper 1985, Hinoura et al. 1987a, Hassan and Nathanson 1987).

Microleakage Occurring at the Occlusal Margin

In this study, four restorative techniques were compared on the basis of their ability to resist microleakage at the occlusal enamel margin of cervical cavities. The glass-ionomer restorative cement, Ketac-Fil, provided the least reliable seal, a finding consistent with other studies (Phair and Fuller 1983, Gordon et al. 1986b). Ketac-Fil was found to provide a complete seal in few instances, and a more reliable seal was obtained in studies utilising V-shaped cervical cavities using both an enamel bond and the dentine bonding agent, Scotchbond, in conjunction with a composite resin (Gordon et al. 1986b).

Several studies comparing the performance of Scotchbond with a variety of other bonding agents at the occlusal enamel margin have been reported (Fuks et al. 1985, Gordon et al. 1986a,b, Crim and Chapman 1986b). In contrast to the findings of this study, where Scotchbond provided a seal in less than half the cases examined, Scotchbond provided a complete seal at the occlusal margin (Gordon et al. 1986a) or sealed in more than 90 per cent of cases (Fuks et al. 1985, Gordon et al. 1986a,b, Crim and Chapman 1986b). This discrepancy cannot be attributed to variations either in temperatures used or number of thermal cycles, finishing times, or storage times before thermal cycling. It is possible, however, that the intermittent cycling and water storage used in this study
contributed to breakdown of the bond between enamel and Scotchbond, or composite resin and Scotchbond, and that the dye present in the cold bath may have increased the depth of dye penetration.

In this study, Scotchbond was found to provide an inferior seal compared with the enamel bond, Delton, and the resin supplied with the GLUMA system, at the occlusal margin. Although no reported studies have included the GLUMA system, several microleakage investigations have compared Scotchbond with the performance of other bonding agents (Fuks et al. 1985, Gordon et al. 1986a,b, Crim and Chapman 1986b). Scotchbond was found to provide a more reliable seal than an enamel bonding resin (Fuks et al. 1985, Gordon et al. 1986b), but the difference was found to be significant only in the latter study, and Scotchbond was also found to provide similar sealing ability to three other dentine bonding agents at the occlusal margin (Crim and Chapman 1986b). Comparison of the results of these studies with the present findings is difficult, and possibly of doubtful value, as vast differences exist in resin formulation, viscosity and setting mechanisms, leakage scoring systems and methods of statistical analysis. The unknown and unpredictable consequences of differences in resin formulation and viscosity on bonding, and subsequent sealing ability, may also make questionable any definite conclusions on the superiority of any one of the three bonding agents tested in this investigation.

**Microleakage Occurring at the Gingival Margin**

In this study, the ability of four restorative techniques to resist microleakage at the gingival margin of cervical cavities was compared. The Scotchbond and Silux combination provided the poorest seal, with almost all cases exhibiting extensive leakage,
and was significantly different from the other three techniques. An improved seal was provided by Ketac-Fil, and both the GLUMA system and the Ketac-Bond and Silux combination exhibited even greater resistance to microleakage.

Although no comparisons of the performance of the GLUMA system or the Ketac-Bond and Silux combination have been reported with other restorative techniques, several studies comparing Scotchbond and Silux, Ketac-Fil, and other bonding agent and composite combinations have been undertaken. Scotchbond used with Silux has revealed a range of microleakage results at the gingival margin of cervical cavities, but no studies have reported the ability to form a reliable seal. Under similar conditions to those used in this study, no restoration examined was found to be completely sealed and the leakage occurring was extensive (Hudson et al. 1987).

Other studies have found Scotchbond and Silux to provide a seal at the gingival margin in 30-50 per cent of cases (Fuks et al. 1985, Crim and Chapman 1986b, Gordon et al. 1986b, McComb et al. 1987).

Glass-ionomer restorative cements have also produced a variety of microleakage results at the gingival margin, from minimal leakage (Welsh and Hembree 1985, McComb et al. 1987) to a similar leakage pattern found in this investigation (Gordon et al. 1986b).

When the abilities of Scotchbond and Silux and glass-ionomer restoratives to resist microleakage were compared in two studies, neither corresponded to the findings of this investigation. McComb et al. in 1987 concluded that although the glass-ionomer cement showed less leakage, it was not significantly different from Scotchbond, and Scotchbond was found to produce a superior seal to Ketac-Fil by Gordon et al. 1986(b). These contrasting findings may
be explained by differences in experimental regimen and it is possible, also, that the significant difference found in the present study between the performances of Ketac-Fil and Scotchbond with Silux resulted from harsher thermal cycling than that used by McComb et al. in 1987.

The microleakage results for the GLUMA system and the Ketac-Bond and Silux combination obtained in this study were significantly different, however no clearly superior trend could be observed in either of the leakage patterns. Difficulty exists in suggesting reasons for the occurrence of these patterns of leakage, especially in the case of the GLUMA system, which showed either an intact seal or complete failure of the seal at the gingival margin. It is possible that this pattern resulted from differences in quality, condition or quantity of collagen present in the teeth used. Alternatively, the bond between GLUMA and either hard tooth tissues or composite resin may remain intact through thermal stressing until a specific fatigue point is reached, after which the bond may fail completely and allow microleakage. In vivo microleakage investigations using GLUMA, as well as a better understanding of the bonding mechanisms, may allow more definite conclusions to be drawn on the ability of GLUMA to maintain a reliable seal.

12.4 **THE SCANNING ELECTRON MICROSCOPE INVESTIGATION OF CAVOSURFACE MARGINS.**

**General Observations**

The results of this investigation, that the occlusal margin of all restorative techniques tested proved better able to resist gap formation than the gingival margin, is in agreement with the
findings of other similar studies (Reich and Volkl 1986, Roulet and Rosansky 1986). Where gaps were present at both margins, the gap at the occlusal aspect appeared narrower than the gap observed at the gingival. These findings show some consistency with reports of higher bond strengths with enamel of the restorative materials used in this study, when compared with bond strengths to dentine and cementum (Hotz et al. 1977, Rider et al. 1977, Vougliouklakis et al. 1982, Stanford et al. 1985).

Where gaps were observed after 100 thermal cycles, these gaps were found to be wider and of a more continuous nature after a further 2000 cycles. This finding is also in agreement with other studies, where the incidence of marginal openings increased after 2000 thermal cycles (Reich and Volkl 1986, Roulet and Rosansky 1986).

The Occlusal Margins

No evidence could be found of occlusal marginal gaps where composite resin was bonded to bevelled and etched enamel, at either stage of this investigation. Although the incidence was low, occlusal marginal openings were reported both before and after thermal cycling by Reich and Volkl in 1986 and Roulet and Rosansky in 1986, leading the latter researchers to conclude "that when the enamel etching technique is used and an appropriate cavity preparation, almost perfect margins are obtained with composite resins". That these earlier studies observed some marginal openings is possibly a result of their assessment of the entire margin, while the present investigation was confined to the most occlusal portion. An increase in marginal gap formation could be expected towards the cemento-enamel junction where less, and altered, enamel is
available for bonding. Possibly, also, the storage in water prior to finishing which was carried out in this investigation would result in release of polymerization stresses and subsequent reduction in marginal gap formation.

Although not reported in other similar investigations, fractures or tears were observed within the composite resin in several examples of the Scotchbond and Silux restoration. These fractures were found adjacent to the occlusal margin and appeared unchanged by further thermal cycling. Several explanations are possible for the presence of these fractures; they may have resulted from a characteristic of the Scotchbond itself, its interaction with Silux, or from either polymerization stresses or stresses related to finishing procedures. Further investigation would be required to discover the origin and potential clinical consequences of these composite resin fractures or tears.

General agreement was obtained with other investigations on the poor performance at the occlusal margin of glass-ionomer restorative cement, when compared with composite resin. Thermal cycling was also found to have an adverse affect on the cement margins at the occlusal aspect (Reich and Volkl 1986, Roulet and Rosansky 1986), as found in this investigation, where no gap was observed after 100 cycles but intermittent breaks were observed at the margin after a further 2000 cycles.

The Gingival Margins

At the gingival margin of cervical cavities, Roulet and Rosansky in 1986 found no difference in the performance of the restorative techniques used after 2000 thermal cycles. A similar observation was made in this study, if the GLUMA and Silux
restorations were excluded. The GLUMA and Silux combination performed differently from the other three techniques tested, in that some specimens showed substantial marginal gaps after 100 and 2100 cycles and some showed no gap formation at either stage. No substantiation can be found for this observation of the behaviour of GLUMA and Silux as it has not been included in other reported studies of cavosurface margins. A number of gap-free restorations were found by Finger and Ohsawa in 1987 using GLUMA, however, these were in cylindrical cavities where gaps were measured along the lateral walls and cavity floor, but not at the cavosurface margin. These researchers also tested Scotchbond, but could not report any gap-free restorations.

An observation of this investigation, that the bonding of glass-ionomer restorative cement to dentine was initially satisfactory but deteriorated after a further 2000 cycles, is similar to the findings of one study (Roulet and Rosansky 1986) but contrary to that of another (Reich and Volk1 1986). Reich and Volk1 in 1986 found glass-ionomer restorative cement to provide the best seal at the gingival aspect of cervical cavities, however, this technique still exhibited 50 per cent marginal openings after 2000 cycles.

Where marginal gaps were observed at the gingival margin, their configuration appeared characteristic of the restorative technique employed. In the case of the glass-ionomer restorative cement, Ketac-Fil, the gaps approximated the interface between restorative material and cavity, however, the break appeared to be situated within the cement. This observation correlates with the findings of some bond strength studies to dentine, where cohesive cement failures were observed, or partial adhesive and cohesive

The gaps present at the cavosurface margins of cavities restored with Silux and one of the dentine bonding agents, GLUMA or Scotchbond, showed similar configurations. After 100 cycles, gaps were narrow and intermittent, but after a further 2000 cycles the gaps were wider, continuous and well defined at the interface between composite resin and cavity. The Ketac-Bond and Silux combination showed a third characteristic form, in that although after 100 cycles the intermittent gaps appeared similar to restorations using Silux and the dentine bonding agents, after a further 2000 cycles the similarities had disappeared. Overlapping of the restorative material was observed consistent with the composite resin veneering technique and the course of the gap was irregular, with residual material remaining on the cavity wall and projecting from the bulk of the restoration.

Marginal Gap Widths

When comparison was made of marginal gap widths observed after 2100 cycles, any gaps occurring at the occlusal margin of a restorative technique appeared narrower than those occurring at the gingival aspect of the same restoration. Where gaps occurred at the gingival cavosurface margin, widths ranged from 3-4 microns for composite resin and dentine bonding agents, to 14-16 microns for combined glass-ionomer - composite resin restorations. These findings are in agreement with other studies of marginal gap widths for composite resins with dentine bonding agents in cavities with butt-joint cavosurface margins (Hansen and Asmussen 1985, Finger and Ohsawa 1987).
12.5 COMBINED MICROLEAKAGE FINDINGS AND SCANNING ELECTRON MICROSCOPY OF CAVOSURFACE MARGINS

The results of the microleakage assessment were compared with the scanning electron microscope observations from the four restorative techniques used in this investigation. The microleakage results indicated a poorer seal at the gingival margin than the occlusal margin of all restorative techniques. This was also observed in the scanning electron microscope study, where marginal gaps occurred more frequently at the gingival margin and appeared to be of greater width. Correlation was also found when the individual restorative techniques were assessed at the gingival margin. Marginal microleakage occurring at the gingival aspect of the GLUMA and Silux restoration was found to be completely resisted in some cases, but in others to be extensive. The observation of marginal gaps followed a similar pattern, as some restorations showed intact gingival margins while others exhibited well-defined gaps. The remaining restorative techniques, which exhibited virtually no ability to seal against microleakage at the gingival margin, also showed marginal gap formation in the restorations examined.

At the occlusal margin of the glass-ionomer cement restorations, where few restorations exhibited a seal against leakage, again good correlation was found with observations of marginal gaps. Where occlusal margins were restored with composite resin, however, no marginal gaps were observed although in one group less than half of the restorations had sealed against dye penetration. This one area of disagreement between leakage results and marginal gap observations could be explained by several factors. As only half the restorations included in microleakage assessment were subsequently examined for gap formation, it is possible that the
cases exhibiting marginal gaps were excluded. This is, however, unlikely to have occurred for all three restorative techniques simultaneously. Alternatively, as mentioned during discussion of bonding and adhesion (Section 1.2), a dental restorative material may be well retained by mechanical interlocking but still allow leakage (Beech 1982). The composite resin restorative technique which exhibited a poorer seal than the others at the occlusal margin may have incurred leakage through disrupted bonding, rather than the more obvious route of a marginal gap.

This general correlation of findings when microleakage assessment was compared with scanning electron microscope observations of marginal gaps, is in agreement with conclusions made by Al-Hamadani and Crabb in 1975 and Stanninec et al. in 1986. The correlations found in the present study did contrast with the observations of Lee and Swartz in 1970, however these researchers did not use replicas for viewing in the scanning electron microscope and this may have resulted in the production of artefacts which distorted their findings.

12.6 THE SCANNING ELECTRON MICROSCOPE INVESTIGATION OF ETCHED GLASS-IONOMER CEMENT

General Observations

The observation made in this study of crazing, or a series of small cracks, occurring on the Ketac-Bond surface which was unrelated to etching has not been reported by others. Cracking was reported by Smith in 1986 and Quiroz and Lentz in 1987, but only after considerable etching and in conjunction with cement degradation. It can be speculated that the cause of the crazing was dehydration, in combination perhaps with a longer than
recommended setting time prior to etching. A longer setting time, in fact seven minutes, has been used by others but the glass-ionomer was allowed to set against glass and no crazing was reported (Hinoura et al. 1987a). Therefore, if the benefits of increased cement maturity are to be obtained in the bonding of composite resin to glass-ionomer cement it may be necessary to protect the cement surface during setting, as recommended for restorative cements (Mount and Makinson 1982, Mount 1986a).

The Glass-Ionomer Cement Surface

An unetched, uncontoured surface was considered unsuitable for bonding by Quiroz and Lentz in 1987, and in this study it was observed that an untouched cement surface would offer few opportunities for micromechanical retention. Acid-etching of the cement surface resulted in loss of matrix, exposure of individual glass particles and considerable surface roughening, findings consistent with other studies (Smith 1986, Hassan and Nathanson 1987, Quiroz and Lentz 1987, Hinoura et al. 1987a). The amount of matrix loss was related to etching duration, a finding also made by Hassan and Nathanson in 1987. The cement topography found in this study after 60 seconds of etching did not, however, appear to differ markedly from that occurring after 30 seconds, and certainly the severe degradation reported by Smith in 1986 was not observed. It would be necessary, however, to carry out a profilometric study and also investigate specimen thickness changes before any conclusion could be drawn on this aspect.

It has been suggested that 10 to 20 seconds is the optimum etch time for Ketac-Bond, as judged by uniform appearance and particle exposure (Quiroz and Lentz 1987) and certainly no longer
than 30 seconds (Smith 1986). The observations of this study would tend to support this, principally in view of the dissociation of glass particles from the matrix occurring after 30 and 60 seconds of etching.

The Enamel and Glass-Ionomer Cement Interface

The decrease in cement thickness occurring after 60 seconds, as suggested by Smith in 1986, was not found in this study. A marked difference in the levels of cement and enamel was not observed in any case, after 30 or 60 seconds of etching. As described previously, this may be the result of a corresponding loss of enamel substance during the etching procedure, or possibly that the increased cement maturity may have imparted better resistance to acid dissolution.

Within the limits of this investigation it does not appear, therefore, that disastrous loss of cement substance, with its clinical sequelae of dentine exposure and disrupted bonding, occurs at etch times of longer than 30 seconds when a reasonable layer of cement is placed. Further investigation of cement substance loss would, however, be necessary before clinical recommendations could be made with regard to minimum thickness of glass-ionomer cement layers and etch times.
CONCLUSIONS

This investigation compared the performance of four restorative techniques in vitro in sealing the margins of cavities bounded by both enamel and dentine or cementum. In addition, a study was made of one of the variable factors involved in the use of the combined glass-ionomer cement and composite resin restoration, that is the effects of different etch times on the glass-ionomer cement surface.

It was found that no restorative technique investigated provided a complete and reliable seal against microleakage at either the occlusal or gingival margin, and that, in all instances, the gingival margin exhibited an inferior seal when compared with the occlusal margin. At the occlusal enamel margin an inferior seal was obtained using a glass-ionomer restorative cement than with composite resin and a bonding agent. Two enamel bonding systems, Delton and GLUMA, were found to produce a superior seal when compared with the dentine bonding agent, Scotchbond. At the gingival margin, composite resin and Scotchbond provided the poorest seal against microleakage. The GLUMA system and the composite resin and glass-ionomer cement combination proved more resistant to microleakage than the glass-ionomer restorative cement.

The occlusal margins of all restorative techniques tested proved better able to resist gap formation than the gingival margins, and where gaps were present at both margins, those occurring at the occlusal margin appeared narrower. All gaps observed at the initial assessment were
adversely affected by further thermal cycling. At the occlusal enamel margins, gaps were not observed for the composite resin restorations at any stage, whereas the use of glass-ionomer restorative cement resulted in marginal gap formation after thermal cycling. At the gingival margin, little difference could be found in the performance of the restorative techniques after 2100 cycles, with the exception of the restorations using GLUMA. Some GLUMA restorations resisted gap formation at the gingival margin, at both stages of examination. Where marginal gaps were observed at the gingival margin, their configuration was characteristic of the restorative technique employed.

When the results of microleakage assessment and scanning electron microscope observations of marginal gap formation were compared, a good correlation was found for the four restorative techniques.

Acid-etching of the glass-ionomer cement, Ketac-Bond, resulted in cement topography changes which could be related to etching duration. When compared with enamel etched for the same time period, etching of Ketac-Bond did not appear to result in undue loss of cement substance. If the Ketac-Bond was allowed to set in air for six minutes, however, crazing of the surface was observed which was not related to subsequent contouring or etching procedures.
SUMMARY

Within the limits of this investigation, no restorative technique was able to provide a seal at the margins of cervical cavities in all cases, as evidenced by penetration of a tracer dye and the presence of gaps at the cavosurface margins. It was confirmed, however, that the four restorative techniques tested were able to seal more effectively at the occlusal enamel margin than at margins positioned on the root surface, and that sealing ability varied among the four techniques. Good correlation was found, as well, between the results of microleakage assessment and observations of marginal gaps for the four restorative techniques.

The findings of less than optimal sealing for the four techniques may be attributable to a number of factors, principally the nature of the hard tooth tissues, the efficiency of the bonding mechanisms of the various restorative materials, the effects of surface treatments, manipulative variables and placement techniques, or the effects of stresses present in the oral environment. As the clinical viability and, therefore, usefulness of any restorative technique is influenced by its ability to seal cavity margins, the findings of this investigation suggest the need for further considerations of the role of these factors in obtaining a reliable seal.
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