The microleakage of composite and compomer restorations following cavity preparation with an Erbium-YAG Laser

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Abbreviations

ADJ:	amelodentinal junction
Ar-F:	argon fluorine
Av:	average
BisGMA:	bisphenol-glycidyl methacrylate
Ca:	calcium
CRI:	cavity wall/tooth restoration interface
CO_2:	carbon dioxide
DCMA:	dicarbonic acid dimethacrylate
Dia:	diameter
EDA:	electronic dental anaesthesia
EGMA:	ethylene glycol dimethacrylate
Er:YAG:	erbium yttrium aluminium garnet
Er:Cr:YAG:	erbium chromium yttrium aluminium garnet
FDA:	Food and Drug Administration
HEMA:	2-hydroxyethyl-methacrylate
Hz:	Hertz
Ho:YAG:	holmium yttrium aluminium garnet
IR:	infra-red
mJ:	millijoule
MPa:	megapascal
μg:	micrograms
μm	micrometre/micron
μs:	microsecond
mm:	millimetre
NH_2:	ammonium
NHS:	National Health Service
nm:	nanometre
nsec:	nanosecond
Nd:YAG:	neodymium yttrium aluminium garnet
OH:	hydroxyl
PO_4:	phosphate
pps:	pulses per second

PRR:	pulse repetition rate
PSI:	pounds per square inch
SEM:	scanning electron microscopy
TEGMA:	triethylene glycol dimethacrylate
Th:YAG	thullium yttrium aluminium garnet
UK:	United Kingdom
UV:	ultraviolet
W:	watt
Xe-Cl:	xenon chorine
YAG:	yttrium aluminium garnet

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Declaration

All the work submitted herein is the original work of the author

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Summary

Over the last thirty years there has been a marked decline in the caries experience in children in the United Kingdom. However, the results of recent epidemiological studies have shown that this trend has slowed down considerably, and may even have reversed in some age groups. Furthermore, there is an increasing cohort of children with significant levels of untreated dentinal decay. Anxiety is a major barrier to the uptake of dental care in the United Kingdom, the two most common stressors being cited as the dental drill and the local anaesthetic needle. The use of the hard tissue laser has been proposed as one operative mode of cavity preparation that obviates the use of both of these anxiety-precipitating stimuli.

This *in vitro* study investigated the affect of one such instrument, the Erbium-YAG laser, on the microleakage of standardised Class V cavities at the amelodentinal junction in extracted human premolar teeth. Extracted premolar teeth were selected and randomly divided into three groups (A, B and C). Each tooth hosted one test cavity prepared with one of three laser energies (200 mJ, 240 mJ or 300 mJ with a 100 mJ finish), and one control cavity, prepared with a conventional diamond bur in a high-speed handpiece. The cavities were restored with either a composite resin or a compomer material; groups A and B were restored with a fourth generation bonding agent, Scotchbond Multi-Purpose and Z100 composite resin and were stored in 0.12% thymol solution for 24 hours and three months respectively. Cavities in group C were restored using a fifth generation bonding agent, Compoglass Single Component Adhesive and a polyacid-modified resin, Compoglass and were then stored for three months. Following storage and thermal stressing (eight hours), microleakage was assessed using a dye penetration technique and single section numerical scoring system. The data was then analysed using the Kruskal-Wallis and Mann-Whitney U tests.

For the pulse energies used, it was found that the Er:YAG laser varied in its effect on both the enamel and dentine margins when compared to conventional

preparation. At the enamel margin, preparation with either of the three pulse energies compared favourably to the use of the diamond bur for both materials. However, optimum cavity sealing was achieved with energies of at least 240 mJ. In comparison, dentine leakage following laser preparation was comparable to that found with conventional preparation for all laser parameters when Compoglass was used. However, there were statistical differences in leakage at the dentine margins of Z100 restorations. Lower energies of 200 mJ or higher with a low finish such as the 300 mJ with 100 mJ finish used in this study provided better long-term marginal adaptation in dentine for this material. Of these two laser energy subgroups, the 300 mJ with 100 mJ finish compared favourably with conventional cavity preparation.

It was therefore concluded that, within the constraints of this study, cavity preparation with the Er:YAG laser did not have a deleterious effect on the microleakage of Class V restoration when compared to conventional preparation, providing care was taken with the choice of laser parameters for dentine and enamel for the restorative material used.

1 *Introduction*

1.1 Dental caries

Dental caries is defined as 'a bacterial disease of the calcified tissues of the teeth characterised by demineralisation of the inorganic, and destruction of the organic, substance of the tooth' (Soames & Southam, 1993). Several aetiological theories have been proposed (Blackwell, 1955). However, Miller's Chemoparasitic Theory of 1889, now referred to as the acidogenic theory, is currently the most accepted.

1.2 Caries: a public health concern

Caries is a potentially infectious and transmissible disease (Keyes, 1960) and, along with its sequelae, has been recognised throughout history. Lesions have been found in the teeth of Neolithic skulls and there are several references to caries-related pain and discomfort in the classical and historical literature. However, enamel caries was uncommon and when it did occur, it usually progressed slowly. Caries of the root surface was more common and was inevitably related to periodontal disease.

In the eighteenth century, the pattern and incidence of caries began to rise significantly in Europe and North America. As with any change in the prevalence or nature of a disease, several causative factors have been given for this change. However, a significant correlation between the consumption of refined sugars and the incidence of caries has been noted (Hardwick, 1960). The industrial revolution led to changes in lifestyle and the traditional dietary patterns of much of the population. This, along with developments in the manufacture, distribution and marketing of sucrose, led to an increase in sugar consumption which in 1957, was twice that of 1880 (Hardwick, 1960). The increasing availability of sucrose resulted in a population of children and young

adults who exhibited rapidly advancing coronal caries with its associated sequelae of pain and infection, to the extent that, at the inauguration of the National Health Service (NHS) in 1948, dental caries was considered a major and increasing public health problem in the United Kingdom (UK).

The first twenty to thirty years of dentistry in the NHS involved extensive management of the damaging effects of caries and its sequelae. However, with an improvement in the knowledge of the nature and management of the disease, a reduction in the incidence of caries in children and adults has been seen during the last twenty years (Todd & Lader, 1991c; Downer, 1994). Several factors have been implicated in this reduction such as improved oral hygiene and dietary control, and the increased use of antibiotics. However, many experts believe that the most important factor is the increased exposure to fluoride, particularly in toothpaste (Bratthall *et al.*, 1996). While this improvement in the oral health of the nation is to be applauded, the most recent surveys suggest that the decline in caries levels has now slowed down considerably and may even have started to reverse in younger individuals (Todd & Lader, 1991c; Downer, 1994).

Of concern also, is the volume of untreated caries. A decrease in the restorative index in 1983 of 72% to 1993 of 58% in 12 year olds is set against the marked rise in the proportion of that age group which is caries free (21% to 50% during the ten year period). This suggests that there is a core of children with relatively high caries levels who are not being reached by the dental care services currently (Downer, 1994). A similar scenario is found in the adult population of the UK.

There are several possible reasons for this, for example, poor co-operation, cost and non-attendance. The most recent national adult and child dental health surveys in the United Kingdom enquired about the frequency of dental attendance (Todd & Lader, 1991b; O'Brien, 1994). When edentulous people were excluded, only 50% of adults and 59% of 5 year-old children were regular attenders. In order to further reduce the levels of decay, and to restore current active decay, it is essential that there is an increase in the number of people attending the dentist for regular care.

1.3 Barriers to dental care

Several barriers to regular dental care have been reported. Other than the demographic variables; gender, age, education and social class (Berggren & Meynart, 1988), a lack of symptoms or concern and dental fear are reported as the main reasons for not seeking regular dental care (Friedl *et al.*, 1995; Murray, 1996).

In the 1988 Adult Dental Health Survey in the United Kingdom, anxiety was found to be a major barrier to dental care for non-attenders (Todd & Lader, 1991a). However, 39% of regular attenders also expressed some level of fear. In addition, dental anxiety is associated with an increase in caries incidence, untreated lesions (O'Brien, 1994), cancelled and missed appointments and avoidance of dental care (Kleinknecht *et al.*, 1973). As such it is fast becoming the dental public health problem of the twenty first century.

Studies investigating the origin of dental anxiety have highlighted learned responses from family members and peers (Shoben & Borland, 1954), previous traumatic dental experiences (Bernstein *et al.*, 1979) and personality traits as aetiological factors. However, the greatest fear-provoking factors in the dental environment have been reported as fear of the drill and local anaesthesia needle (Rankin & Harris, 1984). In addition, surveys of dentists have highlighted the management of anxious patients as the most stress-producing feature of their daily work (O'Shea *et al.*, 1984). In light of this, in addition to continued measures to reduce the levels of decay, significant resources have been invested into the research and development of alternative methods of treatment to provide a means of managing the ever increasing cohort of dentally-anxious individuals.

1.4 Managing the anxious individual

To date, alternative methods to manage the anxious patient have fallen into two major categories; firstly, behavioural management techniques such as information provision, distraction, biofeedback and neurolinguistic programming, all of which increase the individual's coping skills, and secondly, modifications to conventional dental treatment. The latter has included

pharmacological methods which alter the individuals' level of consciousness to allow conventional dental treatment. Such treatment modalities have included the use of general anaesthesia, nitrous oxide inhalation sedation and intravenous or oral sedation. In addition, modifications to the two dental stressors, the local anaesthetic needle (Quarnstrom & Libed, 1994; Meechan & Winter, 1996; Moderesi *et al.*, 1996) and the dental drill have been investigated. The options for the latter are considered further in Section 2.9. However, the use of a laser as an optical cutting device has been advocated as one means of modifying conventional treatment which does not require local analgesia (Goldman *et al.*, 1965; Keller & Hibst, 1997).

To be accepted as an alternative to the dental drill, the use of the laser must fulfil certain criteria. These are discussed more fully in Section 2.10, but one essential quality is that the use of the laser in cavity preparation should not adversely affect the longevity of the restoration placed. This study looks at one aspect of this; the efficacy of an Erbium-YAG laser on the microleakage (marginal seal) of direct composite and compomer fillings.

2 *Literature Review*

2.1 Introduction

An investigation into the effect a laser has on the marginal seal of restorations requires an understanding of the physical phenomenon of microleakage and the factors that influence it. This review of the literature begins with a brief description of the tissues found in the crown of a tooth. A knowledge of the structure and composition of these tissues, enamel, dentine and pulp, is essential if the interaction of restorative materials and lasers with these tissues is to be fully appreciated. Current direct restorative materials are then reviewed, looking particularly at the developments in the field of aesthetic materials. Following this, microleakage is discussed. In this section, the process of microleakage and methods of its assessment are first described. Microleakage in composite and compomer resins, the two materials used in this study, is then considered, with particular emphasis on the material factors and the restorative techniques purporting to control it. Finally, a brief review of the use of lasers in dentistry is given, before considering the Erbium YAG laser more fully.

2.2 Composition and structure of the dental crown

The dental crown is composed of two hard tissues, enamel and dentine, and a soft tissue, the pulp. Extracted permanent premolars were used in this study and therefore this review will be restricted to a description of the features of the structure and composition of these tissues in permanent, vital crowns which are pertinent to this study.

2.2.1 Enamel of the permanent tooth

Mature human enamel is a unique body tissue; it is acellular, it is the only mineralised epithelial tissue and is also the hardest and most calcified tissue in the body. Its physical properties vary over the crown surface; thickness, of the

order of 2.5 mm, and hardness are greatest at the incisal/cuspal tip and decrease steadily to the cervical margin and fissure region. In health, enamel provides a protective covering for the underlying dentine and pulp and consists of 96–97% inorganic and 0.4–0.8% organic matter and 3% water by weight (86%, 2% and 12% by volume respectively).

2.2.1.1 The enamel prism

The basic structural units of human enamel are the enamel prisms (rods). Formed as a mineralised secretory product of the ameloblasts, they are 'key-hole'-shaped in cross-section, with a head and tail region, and can be seen throughout the whole of the enamel tissue except for the surface 20–40 μm. They are thin structures with an average diameter of 5 μm and follow an undulating course from the amelodentinal junction (ADJ) to the subsurface. In the cervical area, where the enamel is thin, the rods are short and the surface enamel is prismless (Gwinnett, 1967).

2.2.1.2 The mineral phase of enamel

The principle component of the rods is the apatite crystal. With the exception of the tail region, where there is a shift in crystal orientation, these are arranged with their long axis parallel to the long axis of the rod. They are elongated hexagons, 30 nm thick, 65 nm wide and several microns in length. Their basic crystallographic formula is that of hydroxyapatite; $Ca_{10}(PO_4)_6(OH)_2$. However, enamel crystals vary from other apatite crystals in the body in that they are slightly deficient in calcium, and there are minor substitutions of strontium, carbonate, magnesium, lead and fluoride ions in the crystal lattice. With the exception of fluoride, these ions cause a small increase in the solubility of the crystal at acidic pHs. The application of acid solutions to enamel results in two changes; firstly, preferential dissolution of the crystals in the rod head area occurs leaving a roughened surface. Secondly the enamel is partially demineralised to several microns below the surface, leaving hollow crystal cores and spaces between the partially demineralised crystals. When dry, these zones can be penetrated with resins. These changes form the basis of the acid-etching procedure used to provide micromechanical retention for composite resins and related materials (Section 2.7.2.1). The depth of the etch pattern varies between

acids, with highly dissociated acids such as phosphoric producing deeper patterns than weaker acids such as polyacrylic, citric and maleic acids for the same application time (Meryon *et al.*, 1987; Glasspoole & Erickson, 1994).

Because of its high inorganic content, enamel is a brittle tissue and is susceptible to fracture along the prism borders. The organic material, found in the intercrystal space, provides a network for the crystals which strengthens the enamel by reducing the tendency for the crystals to fracture and separate. Nevertheless, if enamel prisms at the margin of a cavity are left unsupported by dentine, they are likely to fracture, resulting in breakdown of the cavity margin.

In addition, the high inorganic content is responsible for the optical and thermal properties of the tissue. Hydroxyapatite has absorption bands in the ultraviolet (UV) and mid- to far-infra-red (IR) regions because of the phosphate, carbonate and hydroxyl groups in the crystal structure. Water also has a similar absorption pattern. Thus, on impinging the surface of healthy enamel, the majority of light in the visible and low- to mid-IR ranges is either reflected or transmitted. This has significance for the appearance of a tooth, and has clinical implications for the use of transillumination in the diagnosis of caries, for the therapeutic effects of lasers on enamel, and on the polymerisation of photopolymerised restorative materials.

2.2.1.3 *The organic phase of enamel*

The organic matrix comprises the minor component of mature enamel and is distributed, with water, between the hydroxyapatite crystals to form the prism sheath. It is made up of soluble and insoluble protein, peptides, lipids and citric acid, the majority of which are produced by the ameloblasts. Unlike some of the inorganic components of bone, dentine and cementum, they are not fibrous collagen proteins and are therefore unique among the mineralised tissues. In addition to supporting the inorganic phase (Section 2.2.1.2), organic material is found as ribbon-like structures, the lamellae and tufts, found mainly in the inner part of the enamel.

Enamel has a low thermal conductivity and coefficient of thermal expansion ($11.4,10^{-6}\ ^{\circ}C^{-1}$), and a high thermal capacity. These properties serve to protect the

underlying structures from the environmental variations found in the oral cavity and also have a bearing on the tissue interactions which occur when lasers are used to 'cut' (ablate) enamel (Section 2.10.3).

2.2.2 Dentine of the permanent tooth

Dentine forms the bulk of the tooth, providing a cushion for the overlying brittle enamel and protection to the pulp. It differs from enamel in structure, composition and function, the most significant difference being the vital nature of the tissue which enables continued post-eruption development in response to both physiological and pathological stimuli. The cells conveying vitality to dentine are the odontoblasts and the sensory neurones, both of which are located, with the dentinal fluid, in the lumen of the dentinal tubules. Their cell bodies are found in the periphery of the pulp and therefore dentine vitality is also dependent on the health of this tissue. For this reason, when considering post-eruptive changes, it is customary to consider the pulp and dentine as one entity, the pulpodentinal complex.

Dentine is deposited incrementally throughout life in a rhythmic manner unless environmental factors stimulate a localised increase in production. Thus it can be classified into distinct types based on the location, matrix calcification, structure and developmental pattern (Table 2.1). Pathological stimuli such as caries, wear, iatrogenic and non-iatrogenic trauma, and irritant chemicals can stimulate the formation of tertiary (reparative) dentine and sclerotic (translucent) dentine. These form part of the defensive mechanism of the pulpodentinal complex and their formation is considered further in Section 2.2.3.

Mature dentine has a low coefficient of thermal expansion (8.3, 10^{-6} $^{\circ}C^{-1}$) and is approximately 70% mineral, 20% organic matrix, and 10% water by weight (50% mineral, 30% organic and 20% water by volume).

2.2.2.1 The mineral phase of dentine

While trace amounts of calcium carbonate, fluoride, magnesium, zinc and other minerals are found in dentine, the principal mineral component, like enamel, is hydroxyapatite. The organisation and mineralisation of the tissue differs from that of enamel. In dentine, the crystals (calcospherites) are in the form of

Table 2.1 Classification of coronal dentine by location, patterns of mineralisation and development

Location	Pattern of mineralisation	Developmental pattern
Intertubular dentine: found around and between dentinal tubules	***Globular dentine:*** formed by fusion of calcospherites	***Primary dentine*** formed before and during active eruption
Intratubular dentine: (Peritubular): hypermineralised structure formed and found within dentinal tubules	***Interglobular dentine:*** hypomineralised matrix between fusing calcospherites found between mantle and circumpulpal dentine in the crown.	***Secondary dentine:*** forms as a result of physiological stimuli beginning when teeth come into occlusion
Mantle dentine: first dentine to form in crown and becomes outer coronal dentine. Merges with the enamel at the ADJ in a scalloped margin	***Sclerotic (translucent, transparent) dentine:*** hypermineralised, progressive deposition occluding intratubular dentine i.e. change within deposited dentine	***Tertiary (reparative) dentine:*** formed in response to a pathologic stimulus; caries, cavity preparation, wear, trauma
Circumpulpal dentine: closest to pulp and forms the bulk of the dentine. Is formed after mantle deposition		

flattened plates of approximate dimension 60–70 nm in length, 20–30 nm in width, and 3–4 nm in thickness. Mineralisation occurs by the fusion of numerous crystals (globular mineralisation).

When compared to the other mineralised tissues of the body, the mineral content of dentine makes it harder than cementum or bone, but five times softer than enamel. Furthermore, the post-eruptive changes result in variations in hardness within the tissue. For example, with ageing, extensive deposition of hydroxyapatite may occur (sclerotic and intratubular dentine). This results in the dentine becoming more brittle, harder, less resilient and more yellow in colour, whereas carious dentine is much softer than both sclerotic and non-sclerotic dentine. This has clinical significance in both the diagnosis of caries and the assessment of cavity preparation. The variation in mineral also has implications for the use of lasers as an 'optical drill' (Section 2.10.3.7).

2.2.2.2 *The organic phase of dentine*

The odontoblast processes play an important role in the production of dentine in that they are responsible for the synthesis and secretion of the components of the organic matrix. Collagen makes up approximately 91–92% of the matrix and provides the structural framework for dentine. It may also play a role in the initiation of mineralisation. The remaining 8–9% consists of seven broad categories of non-collagenous macromolecules. While the detailed function of these organic components is beyond the scope of this review, it would appear that they are important factors in the growth, development and repair of the vital mineralised tissue (Piesco, 1994). The relatively high organic content enables dentine, unlike enamel, to deform slightly under compression. This and the 'hydraulic shock absorber' effect of the fluid-filled dentinal tubules dissipate the forces of mastication, thus providing the cushioning of the overlying brittle enamel. The organic matrix also gives resilience and strength to the dentine. In health, this is beneficial to the pulp. However, its rigidity produces a chamber with low compliance and therefore if the pulp becomes inflamed, irreversible pulpal damage can occur.

2.2.2.3 *The dentinal tubules*

The most prominent feature of dentine is the dentinal tubules. In the crown, they extend from the ADJ in an S-shaped curve. They provide a path by which bacteria (Kidd & Joyston-Bechal, 1997) and other noxious stimuli can gain direct entry to the pulp once the protective enamel layer is breached. In addition, they are thought to act as 'optical fibres' transmitting radiation from the ADJ to the pulpal tissues (Zijp & Ten Bosch, 1991). The tubules are tapered and branched, the narrowest, and most pronounced branching occurring near the ADJ. Tubule density also varies between the occlusal and cervical dentine, with the lowest density found in the outer third of the latter (Fosse *et al.*, 1992).

The continued deposition of dentine, coupled with a lack of internal remodelling, effectively reduces the size of the pulp chamber over time resulting in an increased density (40,000 mm^{-2}) of wider dentinal tubules towards the pulp chamber. The tubules therefore represent a much larger proportion of the dentine volume near the pulp (28% by volume) when compared to the ADJ (4% by volume). The clinical implications of this are obvious; the deeper the cavity, the greater the number of tubules that are at risk from bacterial penetration, cavity preparation and the application of potentially harmful substances, and therefore the greater the potential for causing pulpal damage.

2.2.2.4 *Dentine permeability*

Unlike enamel, dentine is relatively permeable; in a vital tooth, fluids can readily flow across or through the dentine tubule complex from the pulp to the ADJ (transdentinal permeability), or in the reverse direction when the enamel is damaged or lost (Brännström & Nyborg, 1972). The water content of dentine is proportional to the cross-sectional area and density of the tubules and therefore increases towards the pulp. Fluid arising from the cut surface of the dentinal tubules is formed as a transudate of plasma and is always under slight positive pressure. This flow of dentinal fluid has a protective function; when irritants such as bacterial toxins gain access to the pulp via the tubules, an inflammatory response is provoked. The resulting increase in pulpal pressure causes an increase in dentinal fluid flow which cleanses the tubules and hinders the entry of bacteria into the pulp. In addition, this is also indirectly responsible for

initiating the production of sclerotic and reparative dentine (Section 2.2.3). Thus dentinal fluid flow is important for the defence mechanism of the pulpodentinal complex. However, conversely, the fluid movement also produces pain and can affect the marginal adaptation of restorations adversely (Stuever *et al.*, 1971). Furthermore, dentine wetness can also influence the bonding of restorative materials to dentine (Section 2.7.2.2). Dentine permeability is reduced by a reduction in size or patency of the dentinal tubules. This is achieved by sclerosis and obliteration of the tubules, or by sealing the tubules with either a smear layer, formed during instrumentation (Section 2.7.2.2), a resin-reinforced hybrid layer, formed by the newer generations of dentine bonding agents (Section 2.7.2.2) or by the direct application of a restorative material.

The application of acid to dentine enlarges the dentinal tubule orifices and may also degrade the collagen matrix (Gwinnett, 1984). In addition, when present, the smear layer is removed by the application and subsequent removal of the acid (Gwinnett, 1984; Meryon *et al.*, 1987). Thus etching increases the permeability of dentine. Acids are applied to dentine in the total etching procedures used with the more recent dentine bonding agents (Section 2.7.2.2), but the effect of the procedure on the pulp has until recently, been controversial (Kanca, 1990; Retief *et al.*, 1992; Cox & Suzuki, 1994). The adverse pulpal changes seen following acid application are now considered to arise either from irritation by components in the restorative material or from microleakage, the effects of which are enhanced by the increase in dentine permeability, rather than from the direct action of the acid itself.

2.2.3 Dental pulp

As noted in Section 2.2, the dynamic changes seen in the structure and function of dentine are dependent on the presence of an intact, vital pulp. In the crown, the dental pulp is confined within the pulp chamber, the size of which reduces with age because of the continued deposition of dentine. The pulp consists of loose connective tissue and contains cells which provide odontogenic, nutritive, sensory and defensive functions (Chiego, 1994). When mature, pulp can be divided into two compartments; the odontogenic zone and the pulp proper. The odontogenic zone, situated in the periphery of the pulp chamber, includes the odontoblast cell bodies, the cell-free zone, the cell-rich zone and the parietal

plexus of nerves. The pulp proper consists primarily of fibroblasts and their extracellular matrix, blood vessels and nerves. The blood vessels are composed of venules and arterioles of between 100 to 150 μm and 50 to 150 μm in diameter respectively, and terminal capillaries. These capillaries anastomose with the venules deep to the odontoblastic layer and provide the oxygen and nutrients necessary for cellular metabolism. The nerve supply consists of sensory and postganglionic sympathetic nerve fibres. From the peripheral parietal plexus, non-myelinated nerves traverse the cell-rich and cell-free zones and the odontoblast layer to enter the odontoblast tubule alongside the odontoblast processes. At present, three major theories have been proposed to explain how pain is transmitted through dentine; the transduction theory, the direct innervation theory and the hydrodynamic theory. The initiation of pain as a result of rapid dentinal fluid flow was noted in Section 2.2.2. Evidence of this nature has resulted in the hydrodynamic theory being the current favourite; when dentinal fluid is disturbed, the nerve terminals in the dentinal tubules and odontoblast layer are stimulated, initiating an action potential and hence pain.

In addition to stimulating pain receptors, the flow of dentinal fluid also results in the release of inflammatory mediators, invoking an inflammatory reaction. If of a sufficient size and duration, irreversible pulp damage and necrosis may occur. However, as noted in Section 2.2.2, the inflammatory exudate also initiates the defensive mechanism; increased flow of dentinal fluid, stimulation of tubular sclerosis within the dentine, and the production of reactionary dentine at the pulpodentinal interface. Sclerosis is dependent on the presence of intact odontoblast cell bodies (Johnson *et al.*, 1969), whereas reparative dentine is thought to be formed principally by pulpal fibroblasts (Trowbridge, 1981; Tziafas, 1998). Thus it would appear that dentine permeability is a key factor in determining the response of the pulp to injury.

The relative components of the pulp's response to injury is, in part, dependent on the nature of the stimulus; sclerosis and reparative dentine formation takes time resulting, for instance, in a decrease in dentine permeability of 60–80% within the first week following cavity preparation (Pashley *et al.*, 1983). However, some stimuli are of such a size that irreversible pulpal damage predominates. For example, animal models have shown that a temperature rise of less than 5.5°C had no adverse affect on the pulp. However, above this temperature 15% of

pulps were found to necrose. This rose to almost 100% with an increase in temperature of 11°C (Zach & Cohen, 1965). It would appear therefore that pulp tissue is sensitive to changes in temperature. This has bearing on the restoration of teeth since it is essential that cavity preparation and material setting reactions do not result in temperature changes in excess of 5.5°C.

2.3 Direct restorative materials

2.3.1 Introduction

On completion of the cavity preparation, the tooth is restored. The principal purposes of restoring a carious tooth are to restore the integrity of the tooth surface, to prevent further damage from carious attack and to protect the pulp, and to improve function and aesthetics. To achieve this, the restoration must seal the cavity hermetically against the oral environment. The ideal material therefore should:

- not irritate the dental pulp
- adapt well to the cavity wall with minimal shrinkage during the setting process
- not be adversely affected by moisture
- not exhibit dimensional change after placement in the cavity
- be resistant to attrition
- have the capacity to withstand the forces of mastication
- permit minimal tooth tissue removal for retention purposes

Properties of secondary importance are the colour and aesthetics, low thermal conductivity and ease of manipulation. In short, the material should duplicate the physicochemical properties of the virgin tooth. A material that fulfils all these criteria has yet to be created.

A range of restorative materials has been developed. In this study, two direct restorative materials were used and therefore the following review will be restricted to the consideration of current materials and developments in this group.

2.3.2 Dental amalgam

Over the last forty years, there have been major advances in the field of direct restorative materials. However, despite this, dental amalgam remains one of the most widely used of the available materials. It is tried and tested, having been used for many years (Molin, 1992), and provides the standard for several parameters against which all direct filling materials are compared.

Amalgam is produced at the chairside by mixing liquid mercury with amalgam alloy; a combination of silver, tin, copper and sometimes zinc, palladium, indium, and selenium. When freshly titurated it is reasonably easy to use; it has a plasticity that permits convenient packing into a cavity and is not overly technique-sensitive. When used under the correct clinical conditions, amalgam restorations maintain anatomical form and have a reasonably adequate resistance to marginal fracture. In addition, they exhibit reduced marginal leakage over time because of the production of corrosion products (Pickard & Gayford, 1965) and exhibit reasonable longevity. Furthermore, when compared with other direct materials, the material is inexpensive.

However, there are drawbacks to dental amalgam. It exhibits a brittleness and toughness that are less than desirable. It is also subject to corrosion and galvanic action: while corrosion initially reduces microleakage, prolonged corrosion will result in marginal breakdown. This is exacerbated by the lack of adhesion to tooth structure. In the past, it was thought that galvanic action was responsible for the post-operative sensitivity experienced after the placement of some amalgam restorations, but this is now not considered an aetiological factor. Whilst this has been of concern to the dental profession, the reported cases of amalgam toxicity related to oral galvanism and corrosion have been of greater public concern (Molin, 1992). The validity of the claims relating to amalgam toxicity has been refuted. However, despite this several countries have placed restrictions on the use of the material. This, and the ever increasing patient expectation for tooth-coloured fillings (Roulet, 1988), has added weight to the need for a strong aesthetic replacement for amalgam.

There are currently four categories of direct aesthetic filling materials on the market; composite resins, glass-ionomer cements, resin-modified glass-ionomer

cements and polyacid-modified resins. While the materials are considered here as four separate material types, on the basis of their setting reactions they can be thought of as providing a continuum (Burgess *et al.*, 1996).

2.3.3 Composite resin materials

A 'composite' is 'a combination of two chemically different materials with a distinct interface separating the components, and having properties which could not be achieved by any of the components acting alone' (Bowen *et al.*, 1972). There are three main constituents in a composite resin; the organic phase (the resin matrix), the interfacial phase (the coupling agents), and the dispersed phase (the reinforcing fillers). Clinical experience using the early composite resins showed that, while they were an improvement over the original acrylic resins, they had a number of significant disadvantages; marginal leakage and staining, inadequate strength in high-stress areas, a lack of antibacterial action, porosity, surface wear and poor finishing. Attempts to improve these deficiencies have been made by addressing two areas, namely that of bonding to enamel and dentine and the composition of the resin material itself.

Composite resins do not bond directly to either enamel or dentine. The development of bonding agents has attempted to redress this deficit and is discussed further in Sections 2.7.2.1 and 2.7.2.2. Modifications to the three phases of the resin has led to the development of a wide range of commercially available materials and will be considered in the following three sections. As this study is concerned with the microleakage of restorations, this review will focus mainly on the material changes that have influenced this.

2.3.3.1 The organic phase: resin technology

The resin contributes the ability to be moulded at ambient temperatures coupled with a setting by polymerisation achieved in a conveniently short time. While analyses of proprietary composite resins on the market demonstrate variations in the composition of the monomer (Ruyter, 1985), the majority of materials have been based on the viscous liquid Bis-GMA monomer. Bis-GMA is an acronym for bisphenol-glycidyl methacrylate, its full name being 2,2-bis[p-(2-hydroxy-3 methacryloxypropoxy)phenylene]-propane. It is formed by the reaction of

bisphenol A and glycidyl methacrylate and is a bifunctional aromatic dimethacrylate with two phenyl groups to increase the rigidity of the molecule, and hydroxyl groups which are thought to provide some intermolecular hydrogen bonding. The large molecular size and chemical structure of Bis-GMA results in the production of a resin with lower volatility and polymerisation shrinkage, more rapid hardening and the production of a stronger, stiffer resin when compared to the earlier materials based on methylmethacrylate. Blending of the filler particles is difficult because of the viscosity of the material and therefore, a fluid diluent monomer such as triethylene glycol dimethacrylate (TEGMA) or ethylene glycol dimethacrylate (EGMA) is used to reduce the viscosity. TEGMA is the most commonly used. However, because of its lower molecular weight, it also increases the polymerisation shrinkage (Davidson, 1986). A balance between the need for an increased filler content and improved handling characteristics, against the detrimental effect of the increased contraction on curing is therefore necessary.

Other monomer systems have been used in which all, or part of, the Bis-GMA has been replaced by aliphatic or aromatic urethane dimethacrylates. These have a lower viscosity, lower water absorption, greater toughness and greater response to UV or visible light curing (Peutzfeldt, 1997).

The degree of polymerisation is crucial to the clinical performance of any resin system and is dependent on the conversion percent of double bonds and the network formation. This is influenced by two factors; the type of resin in the organic matrix and the mode of curing.

The size of the Bis-GMA monomer molecule coupled with the rapid increase in viscosity means that reactive methacrylate groups find it increasingly difficult to migrate to the reaction site, with the result that a relatively high concentration of acrylate or dimethacrylate groups remain unreacted after setting. While this reduces the contraction due to polymerisation, it also has a detrimental effect on the mechanical properties of the material (Asmussen, 1982). The addition of carboxylic anhydrides (Peutzfeldt & Asmussen, 1991), aldehydes (Peutzfeldt & Asmussen, 1992a) and ketones (Peutzfeldt & Asmussen, 1992b), the use of heat treatment (Bausch *et al.*, 1981) and spiro-orthocarbons which expand on curing

(Cook *et al.*, 1984) and curing under a continuous stream of argon (Rueggeberg & Margeson, 1990) have all been found to increase the degree of polymerisation.

The conversion of the oligomers or monomers to the polymer matrix occurs by free-radical addition polymerisation. In the early composite resins, this was initiated by chemical or photochemical means, the latter using light in the UV range (Craig, 1981). However, since the late 1970s, polymerisation of the majority of new composite resins has been achieved with light in the visible spectrum. In these materials the initiator comprises a mixture of a diketone, commonly camphorquinone, and an amine reducing agent such as dimethylaminoethyl methacrylate or dimethyl-p-toludine (Taira *et al.*, 1988). Camphoquinone rapidly forms free radicals in the presence of the amine and light in the blue region of 470 nm. Materials are dispensed in pots, syringes or compules. The wavelength initiating polymerisation is in the spectrum which has been implicated in retinal damage (400–500 nm) and there was initial concern that this might pose a health risk to operators (Davidson, 1985; Ellingson *et al.*, 1986). However, Moseley *et al* (1987) found that an exposure of between 40 and 100 minutes per day was required before the risk of visual damage was significant. These light cured materials offered several advantages over those that were chemically cured. A summary of these is given in Table 2.2.

2.3.3.2 *The dispersed phase: filler technology*

The most significant changes in the commercial composites have been made through alterations in the filler component. The filler contributes several beneficial characteristics to the mechanical, thermal, and physical properties of the polymer; rigidity, hardness, strength and modulus of elasticity are increased and the coefficient of thermal expansion and degree of polymerisation shrinkage are reduced. In addition, a translucent filler enhances the optical properties of the resin. These factors are controlled by the type, concentration, particle size and distribution of the filler and to date six categories have been defined (Lutz & Phillips, 1983; Bayne *et al.*, 1994). These are described in Table 2.3. The fillers have generally been made from mined minerals or melted glasses. However, more recently, filler particles have been produced by a synthetic sol-gel process. This process is one in which a metal carboxylate and a metal oxide sol are mixed

Table 2.2 Chemical versus light curing

	Chemical curing	Light curing
Advantages	Uniform cure Uniform polymerisation shrinkage No additional equipment	Single-paste formulation: No mixing Reduced porosity Adequate working time: Suitable for incremental packing: Improved marginal adaptation Optimal restoration of colour, opacity, translucency and morphology Command set More complete surface cure Optimal physical properties Improved wear resistance Instant finishing possible Good colour stability and matching
Disadvantages	Short working time Long setting time Poor colour stability and matching Delayed finishing Mixing required Increased porosity Polymerisation inhibited by O_2 Degree of polymerisation is mass dependant: thin margins may be not be cured sufficiently, large cavities are difficult and time consuming	Additional equipment necessary Technique sensitivity: Limited depth of cure (dependant on shade and light-resin distance) Polymerisation shrinkage towards light source Premature setting with intense operating light Polymerisation inhibited by O_2 Cost of material Potential retinal damage

Table 2.3 Filler types found in composite resin

Filler	Preparation	Shape	Material	Av. Dia.	Advantages	Limitations
Traditional macrofiller	grinding or crushing	splinter	quartz, glass, borosilicate or ceramic	0.1–100 μm	60–80% filler loading	poor wear resistance
Microfiller	hydrolysis & precipitation	sphere	Pyrogenic silica	0.05–0.1 μm	good polishability	resulting viscosity limits filler loading
Microfiller–based complexes						
Splintered prepolymerised	milling cured pyrogenic silica/resin mixture	splinter	Pyrogenic silica/resin	1–200 μm	attain maximum inorganic loading with microfillers	filler loading has adverse influence on aesthetic properties
Spherical polymer-based	incorporating pyrogenic silica into partially cured polymer spheres	sphere	Pyrogenic silica/resin	1–25 μm	attain maximum inorganic loading with microfillers	filler loading has adverse influence on aesthetic properties
Agglomerated	artificially agglomerated microfillers	sphere	Pyrogenic silica	1–25 μm	attain maximum inorganic loading with microfillers	filler loading has adverse influence on aesthetic properties
Nanofiller	sol-gel process	sphere	Pyrogenic silica	0.005–0.01 μm	Permit filler levels of 90–95% (by wt)	*To be evaluated*
Fibre-fillers		sphere	glass ceramic	(Max. Length: 300 μm)	improved fracture toughness and wear resistance	*To be evaluated*
Megafiller		sphere	ß-quartz glass	0.5–2 mm	minimise resin volume, reduced polymerisation shrinkage	shrinkage at insert/resin interface weakens restoration

and form a gel by dehydration. The gel is heat treated and then ground to produce fillers (Ferracane, 1995).

Several classifications of composite resin have been described (Lutz & Phillips, 1983; Willems *et al.*, 1992; Bayne *et al.*, 1994), based on the filler particle size and loading (Figure 2.1). The traditional (conventional) composites were simply a mixture of traditional macrofiller particles and resin monomers. The early materials contained filler particles in the range of 1–50 μm. However, as milling procedures have been refined, the range of sizes has increased to 0.1–100 μm. Quartz was popular in these materials because of its chemically inert nature and its favourable index of refraction (Bowen, 1979). However, its hardness made it difficult to make fine particles and gave problems in composite polishing. This, combined with the radiolucent nature of the material and relatively high coefficient of expansion (Bowen, 1979), led to the demise of quartz as a filler and to the use of glass fillers. These contributed to the radiopacity of the restoration and, being softer than quartz, facilitated fine filler production. While polymerisation shrinkage was reduced, the smooth surface hydrolysis of the interfacial bonds and wear of the resin matrix resulted in protrusion and eventual loss of the filler (Lambrechts *et al.*, 1982) and thus the wear resistance of these materials posed a severe limitation.

Since the early materials, composites have tended towards a decrease in filler size. The homogenous microfilled composite was introduced in 1977, and contained microfillers, extremely small diameter silica particles (0.01 –0.1 μm). The size of the particles, while giving a material which could be polished to a high lustre, limited the filler loading because of the increased viscosity of the resin. To overcome this, an indirect method of filler blending was introduced; prepolymerised blocks of resin containing a high filler loading of silica were ground to produce filler particles of 5–30 μm diameter (Willems *et al.*, 1992). These were blended with resin and more silica filler to produce the final heterogeneous microfilled resin (Söderholm, 1985). However, despite this, very few of these materials attained a 50% loading (Willems *et al.*, 1992). The materials had excellent aesthetics with good polishability. However, they exhibited poorer physical properties, including a greater polymerisation shrinkage, than the conventional composites (Lutz & Phillips, 1983).

To combine the physical properties of the macrofillers with the polishabililty of the microfillers, hybrid materials were developed. These contained a blend of conventional barium or strontium glass particles, together with some submicron particulate silica. The early hybrid materials used filler loadings of about 75% of the macrofiller particles (1–50 μm) and 8% of the submicron size (average 0.04 μm), and in so doing, achieved a total filler of 83% or greater (McCabe, 1990). More recently there has been a tendency towards smaller conventional filler particles of less than 1 μm diameter (Willems *et al.*, 1992). While the use of the microfillers reduces the wear difference between the conventional fillers and the matrix, the surface of hybrid restorations is not as smooth nor as wear resistant as the heterogeneous microfilled materials (Lutz & Phillips, 1983).

Current materials are sophisticated formulations with a broad range of particle sizes and filler loadings. The newer materials contain a smaller mean particle size and have fewer of the macrofillers than the composites of a decade ago. The majority of the current materials in commercial use are 'hybrid' materials of two size ranges (Ferracane, 1995) and are classified as mid-way filled and compact-filled with classifications of ultrafine and fine in each (Figure 2.1)(Willems *et al.*, 1992).

Overall, the trend in fillers in composite resins has been from relatively low to high filler loadings, large to small particle size, and from hard to relatively soft fillers. However, despite these changes, the problem of polymerisation shrinkage still remains a concern. Providing the increase in viscosity does not have an adverse effect, an increase in filler loading reduces the polymerisation shrinkage. However, Shen and Sarrett (1992) demonstrated that when the degree of polymerisation shrinkage was the same, the resin composite with the lower filler content was able to delay microleakage longer than the material with the higher filler content.

In an attempt to further reduce the degree of polymerisation shrinkage, recent research has focused on the development of experimental resins containing nanofillers (Table 2.3). These fillers permit overall filler levels of 90–95% by weight and as a result there is a significant reduction in polymerisation shrinkage when compared to other composite resins (Bayne *et al.*, 1994). Other recent

studies, in contrast to the trend of using fillers of decreasing size, have used glass fibres as reinforcing fillers and have reported improvements in the fracture toughness and wear resistance of the material (Li *et al.*, 1993)

An alternative to conventional composites which results in reduced polymerisation shrinkage (Donly *et al.*, 1989; George & Richards, 1993) and reduced microleakage (Bowen & Setz, 1986) has also been developed. 'Megafilled' composite restorations are produced by filling the bulk of the cavity with one of a number of shapes and sizes of beta-quartz glass inserts. The inserts are surrounded by light cured composite and bond to the resin via a silane-coupling agent.

2.3.3.3 *The interfacial phase: coupling agents*

The bond between the filler and resin matrix is essential for maximum physical, mechanical and optical properties. Two modes of bonding have been used; micromechanical and more commonly, chemical. In the former, a porous filler surface is produced by either etching with strong acid (Bowen & Reed, 1976) or sintering the particles together (Ehrnford, 1983). The mechanical bond is achieved by resin flow into the porosities.

Chemical bonding involves the coating of the filler particle with a coupling agent. The most commonly used agent is γ-methacryloxypropyltrimethoxy silane (Söderholm, 1985). This is a bifunctional molecule; a methacylate group at one end of the molecule bonds covalently with the resin, and a silane group at the other end is capable of bonding ionically with the filler. A bifunctional coupling agent cannot be used for microfilled composites because of the organic nature of the filler. In these materials bonding occurs by polymerisation. However, there is a tendency for the bond strength to be poor because there are very few methacylate molecules available in the highly cured filler, and micromechanical entanglement of matrix into filler is limited because of the viscosity of the matrix.

2.3.4 Glass-ionomer cements

Derived from silicate cements and polycarboxylate materials, glass-ionomer cement has been available since 1975 and, until recently, was the only truly chemically adhesive filling material available in dentistry. It sets via an acid-base

reaction between ion-leachable calcium aluminium fluorosilicate glass powder and the polymers and copolymers of acrylic and maleic acid. The precise mechanism of bonding to enamel and dentine is unclear, but the most likely theory is that it is achieved via ionic bonding of carboxylate groups in the cement to apatite calcium ions, resulting in an ion-exchange layer between the cement and the dentine. This mechanism would account for the greater bond strength found with enamel (5 MPa) than with dentine (1–3 MPa). The bond forms in the presence of water but is not stable and breaks down. However, it re-forms over and over again, thus providing a dynamic bond between the tooth and cement (Ellis *et al.*, 1990). Additional bonding between the carboxylic acid groups of the glass-ionomer cement and the reactive groups within the dentine collagen, either by hydrogen bonding or by metallic ion bridging, has been suggested (Craig, 1997). The setting reaction occurs in four stages; salt formation, sol/gel formation, hardening (continuation of the sol/gel formation), and hydration with water bound to a salt, acid groups and a gel (Wilson & McLean, 1988). This reaction is demonstrated by the presence of a clearly identified ion exchange layer adjacent to the dentine in desiccated specimens.

The material is dispensed as either a powder and liquid or in an encapsulated form. In the earliest materials, the polymer acid was incorporated in the liquid, and the glass powder made up the powder. More recently, the handling properties have been improved by blending freeze-dried polymer acid and tartaric acid with the glass powder, which is then mixed with water.

While the cements exhibit a degree of polymerisation shrinkage similar to composite resins, it occurs over a longer period of time and is compensated for by flow. It is therefore of less significance than the contraction experienced by the resins. This, plus their coefficient of thermal expansion (8–16, 10^{-6} $°C^{-1}$) which is similar to that of tooth structure (8–11, 10^{-6} $°C^{-1}$) has resulted in a material that exhibits little microleakage when compared to the composite resins (Mohanda & Reddy, 1993). In addition, the cement matrix contains significant quantities of fluoride ions that readily diffuse to the surface of the restoration. The fluoride ions are either washed away by the saliva, or undergo a reaction with the surrounding tooth substance, thereby increasing the acid resistance of the tissue (Mukai *et al.*, 1993). The low incidence of leakage and the slow release of fluoride would suggest that glass-ionomer restorations were less likely to be subject to

caries. Indeed, several clinical investigations found that secondary caries rarely developed adjacent to glass-ionomer materials (Knibbs, 1988; Mejàre & Mjor, 1990). However, these studies were of short duration, and more recently, secondary caries has been reported as the main reason for the replacement of glass-ionomer restorations in general practice (Mjör, 1996; Wilson *et al.*, 1997). Nevertheless, the bonding to enamel and dentine and the low microleakage are favourable properties. In spite of this, the clinical applications of glass-ionomer cements are limited because of their prolonged setting time which delays finishing and polishing for approximately 24 hours, their sensitivity to moisture during initial hardening, dehydration, their rough surface texture and opaqueness, and their inferior strength and wear resistance.

2.3.5 Resin-modified glass-ionomer cements

The resin-modified materials are a variant of the glass-ionomer material and were developed to improve the handling and working characteristics of the original formulation, while utilising some of the advantageous properties of composite resin. They are fluoride-releasing, multi-cured materials and are more aesthetic and less technique sensitive than the conventional glass-ionomers. The materials are predominantly glass-ionomer, up to 80%, with 20% light-cured resin and they are dispensed as two component systems. The powder is similar to the powder in conventional glass-ionomer systems, but the liquid is hydroxyethylmethacrylate (HEMA), water and a polyacid, with or without pendant methacrylate groups. The setting reaction occurs in two stages. The first, an acid-base reaction, produces a gel through polyvalent metal-ion cross-linking of the polyacid-sol. When placed on the tooth, free carboxylate groups form a dynamic bond with apatite. The second stage involves a photoinitiated setting reaction between methacrylate molecules grafted on to the polyacrylic acid chain and the methacrylate groups of the HEMA or polyHEMA. The resultant cross-linking causes rapid hardening and increased strength to the material. In addition, some materials such as Vitremer (3M Dental Products, St Paul, MN, USA) exhibit a third setting reaction. This material has an auto-cure initiator-catalyst system for resins which starts when the powder and liquid ingredients are mixed together (Christensen, 1997). In common with the

conventional materials, desiccated specimens show a well delineated ion exchange layer at the dentine interface (Hallett & Garcia-Godoy, 1993).

Resin modified glass-ionomer materials have significantly better mechanical properties, lower water solubility and moisture sensitivity and reduced brittleness than the conventional glass-ionomer materials. They also exhibit comparable fluoride release (Forsten, 1995) and improved bond strengths to dentine (Lin *et al.*, 1992). However, one distinct disadvantage of these materials is their limited light-curing depth. The maximum depth of cure is 2 mm and therefore renewed mixing may be necessary for materials dispensed as a powder and liquid when the material is used in deeper layers.

2.3.6 Polyacid-modified composite resins

The polyacid-modified composite resins (compomers), introduced in 1991 as a one-paste restorative material avoided the necessity of renewed mixing for large cavities. Like the resin-modified glass-ionomer cements, compomers combine the favourable properties of the base material, in these materials, composite resin, with those of the glass-ionomer cements. They are used in combination with a fifth generation dentine bonding agent, and therefore avoid the time-consuming techniques of the fourth generation agents.

There has been considerable confusion in the published literature over nomenclature, with resin-modified glass-ionomer cements referred to as compomers and *vice versa.* McLean *et al* (1994) distinguished the two materials by their setting characteristics. They noted that while both had an acid-base setting reaction, the reaction for the compomers was not sufficient to allow curing in the dark and therefore these materials relied on photopolymerisation to achieve adequate curing. Moreover, these materials lacked the ion-exchange bonding mechanism seen with the resin-modified glass-ionomer materials.

Containing approximately 30% glass-ionomer cement, compomers are primarily light-cured, low fluoride-releasing composite resins with single component bonding systems. Bonding is achieved by the formation of a hybrid layer with modification of the smear layer. In addition to this micromechanical retention, adhesion via ionic bonds between phosphate groups in the primer and calcium

ions in hydroxyapatite is also claimed for some materials, though it is not found with the compomer material used in this study The materials also have good handling characteristics and excellent colour matching.

Burgess *et al* (1996) compared the mechanical properties of the current direct aesthetic materials. Whilst the compomer materials had improved mechanical properties over the conventional glass-ionomer cements and the resin-modified materials, they exhibited greater polymerisation shrinkage (% volume). In addition, the polymerisation shrinkage and wear of the material did not compare favourably to that of the composite resin materials. Therefore, with the exception of selected clinical situations in the permanent dentition, these materials are usually recommended for the restoration of primary teeth only. Use in the permanent dentition is restricted to restorations in low-stress areas and provisional Class I and Class II restorations. Furthermore, in common with the composite resins, the use of compomers is limited to areas which can be reached by polymerising light.

2.3.7 The causes of restoration failure

The purpose of restoring a carious tooth and the ideal properties of direct restorative materials were outlined in Section 2.3.1. In addition to these criteria, it is essential that the restoration is durable. Studies investigating the reasons for failed restorations have frequently recorded discoloration and material degradation. The incidence of these findings has decreased as the quality of the materials has improved (Kidd *et al.*, 1992). However, the most common reason cited for the replacement of restorations round the world is secondary caries (Kidd *et al.*, 1992; Mjör & Toffenetti, 1992; Mjör & Um, 1993; Friedl *et al.*, 1995; Mjör, 1996; Wilson *et al.*, 1997).

Histological examination of the secondary carious lesion reveals two regions; the 'outer lesion' in the surface enamel, formed as a result of primary attack, and the 'wall lesion' formed in the cavity wall (Hals & Nernaes, 1971). The wall lesion is formed as a result of the flow of bacteria, fluids, ions and molecules etc. between the cavity wall and the restoration. This flow, known as microleakage, is clinically undetectable. In addition to the development of secondary caries, microleakage has also been implicated in the development of discoloured

margins, pulpal changes, and post-operative sensitivity (Brännström & Nyborg, 1972; Bauer & Henson, 1984; Brännström, 1986). It is essential therefore, that microleakage is controlled if the long-term integrity of the restoration is to be assured.

2.4 Microleakage

Microleakage arises because of the presence of a microspace (marginal gap) at the cavity wall/restoration interface (CRI). This gap is formed as the result of dimensional instability arising from polymerisation shrinkage, differences in the coefficients of thermal expansion between the restorative material and the tooth, and the lack of complete adaptation and adherence of the material to the cavity wall (Browne & Tobias, 1986). Thus material and cavity preparation factors influence the degree of microleakage seen at the CRI.

In this study, microleakage is used to evaluate the influence cavity preparation with the Erbium:YAG (Er:YAG) laser has on the seal of Class V composite and compomer restorations. The literature covering microleakage is immense and therefore, unless otherwise indicated, the following review will be confined to the assessment of composite and compomer restorations in Class V cavities, the restorations under investigation in this study.

2.5 Methods of assessing microleakage

2.5.1 Introduction

A test for microleakage should fulfil certain criteria: it should be relatively inexpensive, require minimal specialist equipment and should be technique and operator insensitive. In addition, the test should provide a measure that is both clinically relevant and representative of the cavity as a whole. Finally, longitudinal assessment should be possible. That the ideal test has yet to be found is reflected in the wide range of tests reported in the literature. To date, the marginal gap at the CRI has been assessed by measuring the penetration of tracer molecules and bacteria, and the flow of fluids or an electric current along the CRI, by visual examination of the CRI, or by simulation of the carious lesion.

All meet certain of the criteria, but none provide the 'ideal' test. In this study, microleakage was assessed by measuring the penetration of an organic dye, methylene blue, along the CRI. A detailed review of the other techniques is beyond the scope of this thesis. However, a summary of their advantages and disadvantages is given in Table 2.4.

2.5.2 Penetration of tracer molecules

Studies involving the use of tracer molecules are the most commonly reported in the field of microleakage. Four types of tracer have been described; organic dyes, radioactive isotopes, non-radioactive chemical tracers and neutron activated ions. The latter is an expensive technique and is rarely used. The review of the technique has therefore been limited to the summary of its advantages and disadvantages found in Table 2.4.

Variations in experimental methodology have been reported for the other three types of tracer, and there are also differences in the way in which the leakage is assessed. However, by far the most recent reported studies have used an *in vitro* immersion method: following preparation, the restored tooth is sealed by wax or nail varnish leaving a window surrounding the restoration. It is then immersed in the tracer solution for a predetermined period, before being rinsed and assessed for microleakage. A variety of leakage 'scoring' methods have been used. The most common method of evaluating leakage for dye, and indeed the method used in this study, has been to measure the tracer penetration along the CRI in one plane of section. There are inherent errors in this which are common to the three tracer techniques and it is therefore pertinent to consider these before describing the individual techniques.

2.5.2.1 Single section assessment of microleakage

Following dye immersion, the tooth is sectioned through the mid-point of the restoration and each section is examined under magnification. The leakage is either measured with a measuring ocular, or is assigned a numerical score which increases with the degree of leakage. Several scoring systems have been described. Routinely, both sections are scored and the worst score is taken for each margin.

Table 2.4 A summary of the advantages and disadvantages of some microleakage tests

Technique	Advantages	Disadvantages
Penetration of bacteria		
a. Culturing techniques	Of some clinical relevance Punch sampling permits analysis of several points along the CRI of tooth sections Tooth sectioning is not required for all techniques Assesses the viability of bacteria *In vivo* maturing is possible	Require specialised techniques and equipment, and a trained microbiologist Qualitative measure: the presence or absence of bacteria/clouding only accounts for gaps of >0.5–1.0 μm Origin of bacteria is not defined Stringent sterility conditions required Antibacterial properties of materials will influence results
b. Histobacteriological techniques	Of some clinical relevance Measures depth of penetration *In vivo* maturing is possible	As for culturing techniques, and : Specimen sacrifice is necessary and serial extractions required Gram negative bacteria may not be readily detected May not detect all types of organisms Viability of bacteria is not assessed Bacteria may be lost during processing
Artificial caries	Clinically relevant test	Subjective measurement (depth of cavity) Specimen sacrifice is mandatory and therefore longitudinal assessment is not possible Process is time consuming and requires specialist equipment Limited use with acid-etched restorations; mild demineralisation seen with acid etching has a similar microscopic appearance to areas of demineralisation seen in early carious lesions results in difficulties in interpretation
Neutron activation analysis	Provides a quantitative analysis for *in vitro* and *in vivo* maturing studies	Technique is costly, hazardous and requires specialist equipment and nuclear engineers The area of leakage is not defined and absorption of the tracer at sites other than the restorative margins cannot be distinguished *In vivo* immersion required single-standing teeth
Flow of fluids or electrical current	Longitudinal assessment possible since specimen sacrifice is unnecessary Quantitative analysis. Less vulnerable to preparation errors when compared to tracer methods leakage assessment not limited to a plane of section	Direction of leakage is the reverse to that seen clinically and therefore 'blind-ending' leakage channels are not detected—may under-represent microleakage Specialist equipment is required *In vivo* investigation is not possible
a. Air pressure	As above	passage of air prevents the stagnation which may be expected clinically along the CRI and may have a drying effect on the tooth and restoration. May get leakage of air through clinically sound tooth tissue. Leakage is difficult to localise and photograph
b. Liquid pressure	As above Possible to visualise leakage with a dye. Simulates fluid shifts due to permeability of dentine found *in vivo*	Variations in dentine permeability because of ageing, following cavity preparation and inter-tooth variations
c. Electrochemical	As above No drying effect	Enamel, dentine and material conductance may influence results Does not differentiate between conductance at CRI and within tooth substance and restorative materials
Visual examination	Observes adaptation of restorative material Longitudinal assessment is possible if limited to the marginal gap at the enamel surface only	Indirect measure Assessment of external surface only gives no indication of depth of gap Depth assessment requires sample sacrifice and prohibits longitudinal assessment Polishing of restorations and preparation of specimen may produce artefacts
a. Light reflected microscopy	Photographs provide a permanent record of gap size Visualisation of gap can be enhanced by use of fluorescent resin *In vivo* and *in vitro* assessment of external surface of restoration is possible with the use of replicas	Very limited depth of focus and resolution Latter may be improved with use of metal-shadowed replicas Smear produced during polishing and sectioning may block gap or produce artefacts
b. Scanning electron microscopy	Greater depth of focus and resolution than light microscopy and is possible to examine large specimens through every possible angle Micrograph provides a permanent record Longitudinal study *in vivo* and *in vitro* is possible using replicas	Expensive and specialised equipment required Assessment of gap depth necessitates specimen sacrifice Artefacts may be produced during sectioning or as a result of drying during processing. The use of replicas or ion etching reduce these errors

As noted in Section 2.5.2, there are inherent limitations and errors associated with this method of assessment: the sacrifice of the tooth precludes any longitudinal assessment of microleakage for that particular specimen and the scoring, despite being carried out by more than one examiner is somewhat subjective. Indeed, it is impossible to obtain quantitative, objective measurements with the scoring systems described. However, a major problem, irrespective of the sophistication of the measurements and the statistical analysis employed, is the interpretation of the results from a two dimensional image into a three-dimensional model. Expressing the degree of leakage as a numbered score (Saunders *et al.*, 1990), or a calibrated measurement (Pintado & Douglas, 1988; Douglas *et al.*, 1989) can be affected by the position and angle of sectioning and is unlikely to provide a true pattern of leakage. The leakage found at one section is also not necessarily representative of the whole cavity (Roydhouse, 1968); Mixson *et* al (1991) reported an increased leakage at the end-surfaces of the restorations. Variation in leakage is particularly likely when investigating dentine bonding where the distribution of organic and inorganic components is not uniform, the bonding is unlikely to be a continuous uniform attachment. In their pilot study, using a non-radioactive chemical tracer method, Wenner *et al* (1988) scored six surfaces of three sections and found that the probability of a false negative exceeded 33% if only one random site was scored.

The use of the worst score of both sectioned surfaces attempts to reduce the effect of these limitations. However, other methods of scoring and assessment have been described for each penetration technique. These will be described in the relevant sections.

2.5.2.2 *Organic dye penetration*

In one of the earliest reported studies on the use of a dye, Fletcher (1895) (In Blackwell, 1955) studied the shrinkage of amalgam using an organic dye. Since then the technique has seen several modifications. The early studies investigating non-composite materials, used roughened glass tubes to simulate the dental tissue surface (Grossman, 1939; Massler & Ostrovsky, 1954), but more recently, extracted human or bovine teeth have been used.

The degree of dye penetration can be influenced by the experimental conditions and properties of the tooth and dye. For instance, dye penetration is reduced through sclerotic and secondary dentine, whereas, the penetration of dye along the restoration/tooth interface in studies investigating the leakage of root fillings, was found to increase when the entrapped air within the tooth/restoration system was removed. This was achieved by placing the restored tooth in a vacuum before immersion into the dye solution (Goldman *et al.*, 1989; Spånberg *et al.*, 1989)

Perhaps of greater significance is the choice of dye. Dyes are provided as solutions or particle suspensions, and their behaviour is influenced by the size of the molecule or particle, polarity and type and concentration of the dye. The penetration time of different concentrations of the same dye have been found to vary between five minutes and one hour (Christen & Mitchell, 1966). Any interaction between the dye, restorative material and tooth tissues is also of importance. Some dyes have the propensity to bind to tooth substance or the restorative material. For example, preparations of basic fuchsin solutions have been shown to bind preferentially with carious dentine (Kidd *et al.*, 1989). While valuable for the manufacture of caries-disclosing agents, the use of tracers with this property confounds microleakage assessment.

Methylene blue is one of the most commonly used dyes. It penetrates the water compartment of the tooth easily, and is readily detected under visible light. However, a wide variety of types and concentration of dye and immersion times have been used which precludes direct comparisons between most studies (Taylor & Lynch, 1992). In addition, colouration of the bonding layer may also give false positive scores (Feilzer *et al.*, 1995b).

Modifications of the single section scoring system described in Section 2.5.2.1 have included the use of weighted scores (Glyn Jones *et al.*, 1979), the evaluation of the proportion of the cavity margin at the tooth surface which is stained (Itoh *et al.*, 1981) and the average of several sections (Déjou *et al.*, 1996). However, these systems are all limited by their qualitative nature. Several workers have recently evaluated the microleakage seen with combinations of different bonding agents and composite resins using a quantitative method of dye penetrations analysis, the dye-recovery spectrophotometric test (Rigsby *et al.*, 1990; Liu *et al.*,

1993). In this method, first described by Douglas and Zakariasen in 1981, dye penetrating the CRI is recovered by immersing a restored section of the tooth in 50% nitric acid. The dye concentration is then determined spectrophotometrically and the microleakage scored as 'μg of dye' per restoration. This method allows the direct measurement of leakage volumetrically and is easily executed, giving minimal human error. However, it does not differentiate between enamel and dentine leakage and there is also the tendency for artificially high results because the recovered dye will include any dye penetration of the tooth tissue surrounding the restoration. Rigsby *et al* (1990) compared the quantitative leakage assessment, as evaluated by the dye-recovery spectrophotometric test, with a qualitative dye penetration technique for three dentine bonding/resin restorative systems and found that, despite the use of different dyes, the rank orders for microleakage were the same for the two tests. One variation of the dye-recovery technique is the use of image analysis apparatus linked to a stereomicroscope. This permits quantification of both the length of dye penetration at the restoration/tooth interface (Fayyad & Ball, 1987) and the percentage area of dye penetration in dentine (Glyn Jones *et al.*, 1988).

An alternative use of spectrophotometry using a rhodamine B dye tracer was described by Harashima *et al* (1992). A restored 'plate' of tooth was mounted on a jig with a thermocycling 'line' on one side and a detection 'line' on the other. Hot and cold solutions of the dye were alternately cycled in the former, and dye leakage in the latter was measured at varying time intervals using a spectrometer. While there are obvious limitations in the use of a tooth 'plate', this technique permitted a quantitative, longitudinal analysis.

Another technique which does not require specimen sacrifice, has been described by several workers and has been used for longitudinal analysis; following exposure to the dye, the margins of the restoration at the tooth surface were examined to establish the proportion showing staining (Tsuchiya *et al.*, 1986). Whilst this gave an indication of marginal adaptation of the surface, it gave no measure of the extent of dye penetration towards the pulp. It does, however, permit *in vivo* maturation and evaluation (Itoh *et al.*, 1981) which is in contrast to all the other techniques described so far.

In summary, allowing for its limitations, dye penetration continues to be the most commonly used test for microleakage. It is simple, inexpensive and, by relying on a physical effect, does not require the success of a chemical reaction or the use of hazardous materials. The technique also allows for the placement of at least two restorations in one tooth, thus permitting both control and test restorations to be placed in the same tooth. This reduces some of the errors incurred by inter-tooth variations in dentine and enamel.

2.5.2.3 *Radioactive isotopes*

Several workers have used autoradiography to demonstrate isotope presence with composite restorations (Oritz *et al.*, 1979; Hembree, 1984; Saunders *et al.*, 1990; Hall *et al.*, 1993). With this technique, penetration of radioactive tracers along the CRI is detected on a radiograph. Accurate evaluation is dependent on the experimental technique, the choice of isotope, and the resolution of the autoradiograph: the depth of marginal penetration of the isotope is influenced by the ionic exchange and chemical reactivity of the ion, as well as the physical and chemical nature of the filling material (Going *et al.*, 1960). Several isotopes have been used, the most common being ^{45}Ca as $CaCl_2$ because it is easily obtained and, as weak beta emitter, produces clear autoradiographs. However, ionic exchange with the calcium of apatite crystals can occur and will interfere with the recognition of the true pattern of leakage. As an alternative, some workers have used isotopes with a very long half-life such as ^{14}C-urea. This allows the repeat production of autoradiographs without loss of activity or change in the darkening of the film .

The resolution of the autoradiograph is influenced by:

- the choice of isotope; the use of an isotope with lower energy gives greater resolution.
- the tooth/emulsion distance; the smaller the distance, the better the resolution
- the length of exposure time of the film; longer exposure times result in poorer resolution.
- the development of the autoradiographs

The technique has several limitations in its use as a detector of microleakage: difficulties can arise in interpreting the films because the solubility of the tracer

solutions and the propensity for isotope absorption of many restorative materials can lead to contamination of the specimen (Going *et al.*, 1960). In addition, the separation of the film from the tooth for processing means that the exact relationship between the image and the underlying tooth structure is lost. The use of a strip-on film allowing the tooth and film to remain in contact during processing and assessment has gone some way to address these problems (Martin, 1951). In common with dye penetration studies, the qualitative nature of the assessment, and the variety of exposure times to the radioisotope solution renders direct comparison between many studies impossible.

In an attempt to avoid the errors these, and the use of a single section technique, incur, two quantitative techniques have been described; the radiochemical diffusion method (Söremark & Bergman, 1961; Crisp & Wilson, 1980) and the reverse radioactive absorption technique (Vasudev *et al.*, 1981; Herrin & Shen, 1985). Although not without their own limitations, both have the advantage of allowing longitudinal analysis of the specimen.

2.5.2.4 *Non-radioactive chemical tracers*

Relying upon the reaction of two or more chemicals, the use of non-radioactive chemical tracers is second only to dye penetration studies in popularity. In recent studies, leakage has been detected by the sequential penetration of two colourless chemical tracers, a silver salt, commonly silver nitrate, and an organic radiographic developer such as benzene 1,4-diol (hydroquinone), which react to produce an opaque precipitate. Silver grains are deposited where the two chemicals come into contact.

The technique is said to provide a severe test of microleakage because of the small size of the silver ion (0.056 nm) (Douglas *et al.*, 1989). However the extent to which the silver is precipitated is limited to the penetration of the larger developer molecule. Nevertheless, this technique, in combination with scanning electron microscopy (SEM) has been used, more recently, to identify the exact plane of leakage at the dentine/restoration interface (Sano *et al.*, 1994).

Many of the characteristics of chemical tracer studies are in common with the dye penetration techniques (Section 2.5.2.2). However, the ready penetration of the

black silver stain along the dentinal tubules of an intact dentine surface, particularly where the dentine tubules are parallel to the cavity margin, can make interpretation difficult (Pintado & Douglas, 1988; Douglas *et al.*, 1989).

Several methods have been used to reduce the limitations of the single section scoring system. Various multiple-surface scorings have been tested; the average score (Swift & Hansen, 1989) and the highest score (Wenner *et al.*, 1988) of six surfaces have been used. Two three-dimensional techniques have also been described, one employing a computer reconstruction from digitised serial images of parallel abraded sections (Gale *et al.*, 1994), and the other using a clearing method involving citric acid, alcohol and glycerol or methyl salicylate (Marinelli & Eichmiller, 1993; Tay *et al.*, 1995).

One final technique utilising the chemical properties of a tracer material is worthy of note because of its potential as a longitudinal *in vivo* detection agent. Leinfelder *et al* (1986) developed a technique whereby the cavity was lined with a calcium hydroxide base, and the release and 'reverse' penetration of hydroxyl radicals was measured at the external surface of the restoration with litmus paper. This technique, although providing only qualitative data, is reliable, biologically compatible and simple to execute. However, the sensitivity of the test has yet to be evaluated.

2.5.3 *In vivo* versus *in vitro microleakage*

A major limiting component of many of the techniques available for investigating microleakage is the *in vitro* nature of the test. Many workers have questioned the clinical relevance of such tests and have modified the technique to include a period of *in vivo* maturing of the restored teeth prior to extraction and analysis. The results of such tests, when compared to those carried out completely *in vitro,* have varied. Swartz and Phillips (1961) found that the *in vitro* microleakage for a number of restorative materials was comparable to that obtained when the restorations had matured *in vivo* (Phillips *et al.*, 1961). However these results differed from those of Going *et al* (1968) who found that the *in vivo* leakage was greater than the *in vitro,* and Barnes *et al* (1993) who found the reverse to be true. Some of these discrepancies will be because of the differences in experimental method and the leakage test employed. However other factors such as the

influence of pulpal hydrostatic pressure, mechanical loading and temperature change are also contributory. These will be considered briefly.

2.5.3.1 *Pulpal hydrostatic pressure*

Stuever *et al* (1971) investigated the effect of pulpal hydrostatic pressure on the microleakage of composite restorations. They found that vital restored teeth which had been immersed in the tracer dye prior to extraction exhibited significantly lower leakage than either vital teeth immersed post-extraction, or root filled teeth immersed *in vivo*. Their results compared favourably with a similar study of amalgam restorations and offered an explanation for the greater *in vitro* leakage found by Going *et al* (1968) which was referred to in the previous paragraph.

2.5.3.2 *Mechanical loading*

The *in vitro* development of both permanent and transitory gaps at the CRI of amalgam restorations in axially loaded teeth was first demonstrated in 1970 by Jörgenson *et al* . This gap formation has since been associated with an increase in bacterial penetration at the margins of Class V composite restorations in functional teeth *in vivo* (Qvist, 1983). This phenomenon, known as 'mechanical percolation' is due to differences in the viscoelastic properties of restorative materials and enamel and dentine.

Several workers have investigated the influence of mechanical loading on the *in vitro* marginal adaptation of composite resins with conflicting results. Margins placed entirely in etched enamel or bonded dentine were found to be able to withstand mechanical stresses (Stewart *et al.*, 1986; Munksgaard & Irie, 1988). However, when the restoration was placed at the cervical margin and subjected to both thermal and mechanical stresses, gap formation was not seen at the enamel/resin interface, but there was evidence of leakage at the dentine/resin margin (Rigsby *et al.*, 1992) These results suggest that thermal and mechanical cycling has a synergistic effect on microleakage at the resin/dentine interface.

2.5.3.3 *Temperature change*

The increase in microleakage seen with a change in temperature which was reported by Rigsby *et al* (1992), was first described in 1952 when fluid was seen at the margins of gold, amalgam and acrylic restorations which had been warmed by the fingers (Nelsen *et al.*, 1952). This phenomenon, known as thermal percolation, arises because of the difference in the coefficients of thermal expansion of enamel, dentine and the restorative material, and to a lesser degree, on the effect of the expansion of the fluid occupying the marginal gap at the CRI.

In an attempt to make the investigations more clinically relevant, it is common to include a thermal stress component, thermocycling, in tests of microleakage. A wide range of thermocycling conditions have been reported: temperatures have ranged from 0–68°C, which approximate the maximum range of temperatures tolerated in the mouth (Barclay, 1998). Immersion times have varied from minutes to several hours with between 1 and 5,000 cycles. However, as the teeth are exposed to the extremes of temperature for a maximum of one second (Youngson *et al.*, 1998) shorter dwell times are now more commonly used.

Despite the continued use of thermocycling in studies investigating the microleakage of composite restorations, the effect of the thermal stressing has yielded conflicting results. Alongside Rigsby *et al* (1992) several workers have found that this component resulted in increased leakage (Lee & Swartz, 1976; Crim & Mattingly, 1981; Crim *et al.*, 1985; Eakle, 1986), which occurred gradually rather than in a step-wise manner (Momoi *et al.*, 1990). However, other workers have found that it had no significant effect (Kidd *et al.*, 1978; Wendt *et al.*, 1992). Whilst variations in experimental technique must be taken into account when comparing these results, the apparent contradiction in results reflect inherent differences in the composite resins, in particular the effect of hygroscopic expansion (Asmussen, 1976; Kidd *et al.*, 1978; Arends *et al.*, 1984). This will be discussed further in Section 2.7.1.

2.6 Microleakage in composite resin restorations

Of all the dental materials ever developed, marginal leakage is the greatest concern for composite resins because they have no germicidal or antibacterial

properties, and there is no increase in sealing with age. The main cause of gap formation at the CRI is the significant shrinkage that occurs during polymerisation. This varies between, and within, the different generations of resins but has been shown to be of the order of 1.67–5.68 volume percent (Goldman, 1983). Polymerisation shrinkage has also been implicated in crack formation at the enamel margins (Asmussen & Jorgensen, 1972; Asmussen, 1975) although cavity preparation with a bur has also been found to have a similar effect (Section 2.9.1).

During polymerisation, shrinkage of the material occurs as the long monovalent bonds are converted into shorter, stronger covalent bonds. This results in the build up of internal stresses within the material. In the initial stages of curing, these forces are balanced by adhesive forces between the material and the cavity wall. However, as soon as the internal stresses exceed these forces, gap formation occurs. The degree of gap formation is therefore dependent on the balance between the forces of adhesion and contraction. In addition, the formation of a gap in one area of the cavity reduces the tensile stresses within the material and may permit perfect adaptation at other areas of the cavity. The contraction forces are also reduced by substantial shrinkage perpendicular to the free surface of the restoration resulting in a wall-to-wall contraction that is less than the volumetric contraction of a resin. Thus the magnitude of the stresses that develop in composite resins during curing is dependent on the volume of shrinkage and on the ability of the material to yield and therefore flow. To minimise microleakage, these stresses must kept as small as possible and therefore it is essential that polymerisation shrinkage is controlled.

2.7 The control of polymerisation shrinkage

Polymerisation shrinkage has been reduced by either altering the composition of the materials so that certain properties can be controlled to advantage, or by utilising certain restorative techniques. In essence they all achieve the desired effect by either shifting the balance of the contraction/adhesion forces in the curing material (increasing the strength of adhesion to the cavity wall or reducing the development of tensile stresses) or by reducing the gap size after polymerisation is complete.

2.7.1 The resin composition

The changes in resin and filler technology seen over the years were highlighted in Section 2.3.3. Alterations to the composition of the resin can affect the physicochemical properties of the material which in turn influences gap formation at the CRI. Such material properties include the degree of polymerisation shrinkage and water absorption, and both the coefficient of thermal expansion and thermal diffusivity of the material.

2.7.1.1 The degree of polymerisation shrinkage

The size of the polymerisation shrinkage for a given resin is influenced by the type and volume of both the monomers and fillers. This was covered more fully in Section 2.3.3, but a short précis is appropriate in this section: the Bis–GMA monomer molecules exhibit less shrinkage on polymerisation than the shorter diluent monomers such as TEGMA and therefore a volumetric increase in the longer molecules will result in a reduction in polymerisation shrinkage (Asmussen, 1975). However, this will also incur an increase in the viscosity of the material, resulting in a reduction in the degree of compensatory surface shrinkage and material flow. Furthermore, an increase in the proportion of resin filler reduces the volumetric contraction of the material. However, it has no effect on the wall-to-wall contraction and therefore on the size of the marginal gap seen at the CRI (Asmussen, 1976). This is because the higher filler volume results in an increase in viscosity. These factors account for the reduced shrinkage of the conventional materials over the microfilled.

Polymerisation shrinkage is also affected by the method of polymerisation, light-cured materials exhibiting significantly less polymerisation shrinkage than those that are chemically cured (Asmussen, 1975; Jacobsen, 1976; Goldman, 1983). In addition, variations in light intensity can also affect the integrity of the CRI; lights of lower intensity slow the rate of polymerisation with the result that the visco-elastic stage of curing is prolonged. Increased flow of the material is therefore possible with the resultant formation of smaller marginal gaps (Uno & Asmussen, 1991; Feilzer *et al.*, 1995a; Unterbrink & Muessner, 1995). Prolonging the curing time of the bonding agent has a similar affect (Crim & Abbott, 1988).

2.7.1.2 *The degree of water absorption*

A reduction in microleakage is seen when composite restorations are stored in water prior to testing (Arends *et al.*, 1984) because water is absorbed by the resin resulting in hygroscopic expansion. This can take up to three months to reach equilibrium (Braden *et al.*, 1976; Calais & Söderholm, 1988) and, if of a sufficient size will result in marginal gap closure. Hygroscopic expansion varies considerably between materials, being dependent on the monomer composition (Asmussen, 1976) and the filler content (Calais & Söderholm, 1988). For instance, the presence of hydroxyl radicals is important for the uptake of water. These are present in Bis-GMA, but are absent in monomers such as urethane dimethacrylate whose propensity for water absorption is lower.

The filler volume has an indirect relationship with the degree of hygroscopic expansion and therefore microfilled composites show greater expansion than the macrofilled (Tortenson & Brännström, 1988). This is advantageous since the greater tendency for microfilled composites to form gaps because of polymerisation shrinkage is compensated to a degree by the increased hygroscopic expansion. However, water sorption also has an adverse effect on the strength of the material, particularly those containing amorphous silica spheres (Calais & Söderholm, 1988) and therefore the desire for greater gap reduction must be balanced by the need for optimal mechanical properties.

As noted in Section 2.5.3.3, the degree of hygroscopic expansion also influences the effect temperature has on composite restorations. This is considered further in the following section.

2.7.1.3 *Coefficient of thermal expansion and thermal diffusivity*

Composite restorations contract to a greater degree than enamel and dentine for the same change in temperature because of differences in both the coefficient of thermal expansion and the thermal diffusivity. The thermal expansion of the restorative material is affected by the filler type and volume; an increase in filler volume reduces the effect of temperature on the dimensions of the material. This is particularly so for fused quartz and the special glasses such as lithium aluminium silicate which have zero or negative coefficients of thermal expansion.

However, as noted in Section 2.5.3.3 studies investigating the effect of thermocycling on microleakage have given conflicting results for composite resins. This is due in part to the influence of hygroscopic expansion. A change in temperature was found to have no effect on leakage of restorations when thermocycling was carried out within 24 hours of filling the cavity (Crim & Garcia-Godoy, 1987). However, significant variations were found between materials which had been allowed to expand hygroscopically before thermocycling (Asmussen, 1976). These apparent discrepencies occur principally because of differences in the degree of hygroscopic expansion that occurred for each material. However, the interplay between polymerisation shrinkage, the coefficient of thermal expansion, thermal conductivity, creep characteristics and the elastic limit of the material were also important. In general, when cooling from a high temperature, elastic strains in the material counteract any initial change in gap size at the CRI for materials that have been hygroscopically expanded. Once this strain is eliminated further cooling results in the formation of marginal gaps (Asmussen, 1974a). In contrast, some materials exhibit an increased gap size when the maximum temperature is increased. This occurs primarily because exposure to the higher temperature results in plastic deformation of the material (Asmussen, 1974b). In addition, temperature changes in the clinical range have also been found to reduce the yield strength and elastic modulus of similar Bis–GMA resins (Draughn, 1981).

The apparent conflict in the results of studies which have investigated the effect of temperature on microleakage has led some workers to question the validity of incorporating a thermocycling component in the experimental regimes of *in vitro* studies (Kidd *et al.*, 1978). However, others have concluded that the use of thermocycling leakage experiments to analyse the effect of the coefficient of thermal expansion should be discontinued, but that thermocycling should be incorporated into any experiment that was investigating the effect of hygroscopic expansion and possible hydrolisation of the bond to dentine on microleakage (Wendt *et al.*, 1992).

2.7.2 Restorative techniques

A plethora of specific restorative approaches have been reported, all purporting to control polymerisation shrinkage. These are discussed in the following five sections.

2.7.2.1 Increased bonding to enamel

The first reported use of an acid conditioning agent to enhance the bonding of polymers to enamel was by Buonocore in 1955. Since then, it has become a standard technique for the adhesion of composite resin to enamel and there have been many studies reporting an improvement in bond strength (Oritz *et al.*, 1979; Crim & Mattingly, 1980; Retief *et al.*, 1982; Phair & Fuller, 1985). The increased adhesion is the result of an interplay of factors. The effect of acid pre-treatment on enamel was described in Section 2.2.1. This selective removal of mineral increases the surface area, surface energy and wettability of the conditioned surface, resulting in increased resin flow and tag formation and therefore increased micromechanical attachment. Bonding is also enhanced by the formation of secondary bonds between the resin and enamel. Their formation results in the net gain of thermodynamic free energy which increases the flow of the resin. This, combined with the increased wettability of the etched surface, enhances tag formation (Soetopo *et al.*, 1978).

In his initial investigations, Buonocore used an 85% solution of phosphoric acid for 60 seconds. However, a regime of 35% phosphoric acid with a 15 second etch has been found to be equally effective (Crim & Shay, 1987) with the additional advantages of a reduction in both the restoration time and the loss of enamel .

Buonocore also considered that dry, uncontaminated enamel was important for optimal bond strength, and advised that visual assessment of the frosted appearance of the enamel was essential. However, the recent introduction of wet bonding techniques (Section 2.7.2.2) has meant that the enamel etch pattern is not readily visualised. Some workers have found that drying the cavity surface to ensure the adequacy of the enamel etch and then rewetting before applying the dentine primer has circumvented this problem without jeopardising the bond to dentine (Gwinnett, 1994). However, there is evidence to suggest that the

presence of moisture may have an adverse affect on the enamel bond strength (Swift & Triolo, 1992).

The degree of leakage reduction following acid pre-treatment is not uniform and factors such as the location of the restoration have also been found to influence the enamel bond. Leakage at the gingival enamel margins of Class V cavities is consistently worse than that seen at the occlusal margins (Eriksen & Buonocore, 1976; Crim & Mattingly, 1980; Retief *et al.*, 1982; Marzouk & Bhaiji, 1989). This is because the enamel is thinner in the cervical area and therefore small enamel fractures may occur during cavity preparation, polymerisation shrinkage, or polishing the restoration (Buonocore & Sheykholeslani, 1973; Amsberry *et al.*, 1984). In addition, the ultrastructure of the enamel in this area has an irregular prismatic structure in which the surface layer is frequently prismless (Gwinnett, 1967) resulting in poorer bonding characteristics.

In addition, the efficacy of the composite bond to enamel is dependant on the ability of the bond to resist the tensile stresses which develop in the resin as a result of polymerisation contraction. A balance between the material factors outlined in Section 2.7.1 is therefore important (Shortall *et al.*, 1985; Powis *et al.*, 1988). In light of this, modifications of the conventional acid-etch restorative procedure have been developed which reduce the magnitude of the tensile stresses within the restoration. These modifications can be classified into four principal types; the use of materials to provide dentine bonding, the use of high-viscous composite filling materials with non-composite resins of low viscosity, changes to the cavosurface angle of the restorations, and modification of the restorative technique.

2.7.2.2 *Increased bonding to dentine*

The ideal restorative material should bond to dentine. The favourable bonding and leakage characteristics of the glass-ionomer cements (Section 2.3.4) have been combined with the positive wear resistance and strength of the composite resins in the sandwich technique (McLean *et al.*, 1985). When care was taken with the technique, the use of both conventional and resin-modified glass-ionomer cements as dentine replacements resulted in a reduction in microleakage (Mount *et al.*, 1992). Other workers have also reported a reduction in microleakage, when

compared to composite resins, with resin-modified glass-ionomer cements as the sole material (Hallett & Garcia-Godoy, 1993; Sidhu, 1994).

While these studies have given favourable results, significant resources have been, and are still being invested into the development of an agent that provides adequate direct dentine bonding of composites without affecting the enamel/composite bond adversely.

Dentine bonding is much more complex than enamel bonding because of the high water and protein content and the vital nature of the tissue (Section 2.2.2). In addition, the lack of homogeneity seen in dentine within and between teeth, and the changes seen with ageing, lead to a lack of uniformity both in bond strengths and in sealing capacity. Whilst most bonding systems have achieved adequate bonding to the dry, superficial dentine, many of the earlier agents did not bond well to the moister deeper dentine (Causton, 1984). Another confounding feature is the presence of the smear layer which covers the dentine following conventional cavity preparation. This is 1–5 μm thick and is a moist, plastic deformable layer of cutting or grinding debris. It contains hydroxyapatite crystals and partially denatured collagen arising mainly from the underlying dentine and adheres to the calcified tissue with a strength of approximately 6 Mpa (Ruse & Smith, 1991). Although it is partially porous, it dramatically reduces fluid flow from the underlying dentinal tubules following cavity preparation (Pashley *et al.*, 1978). In addition, it serves as a cavity liner and dentinal tubule sealer. Most of the reduction in dentine permeability is because of the presence of smear plugs within the tubules. However, if left intact and unchanged, the smear layer above the plugs interferes with the close adaptation of restorative materials and provides a substrate for the formation of microleakage channels (Pashley *et al.*, 1989).

Dentine bonding agents differ both in the way in which adhesion is achieved and in the treatment of the smear layer. However, the basic structure of the adhesive molecule is the same for all materials; it is bifunctional and has a methacrylate molecule which bonds to the polymer at one end and a functional group, designed to react with, and bond to, the dentinal surface at the other end. Bonding may occur with either the inorganic component of dentine, via the calcium ion, or the organic part, via the amino and hydroxyl groups. The dentine

bond should be of sufficient size to overcome the tensile stresses that develop during polymerisation. The stresses generated by polymerisation shrinkage in a box-shaped cavity have been calculated to be of the order of 13–17 MPa (Davidson *et al.*, 1984). It might be expected therefore that bonding agents which, when tested, achieve greater bond strengths than this would prevent microleakage. However, such studies invariably measure bond strength on a flat surface after 24 hours storage in water. The tensile stresses of polymerisation reach a maximum in chemically-cured materials within 15 minutes (Hegdahl & Gjerdet, 1977) and in light-cured materials immediately (Hansen & Asmussen, 1985) and it is the quality of the bond at these times which is important for marginal adaptation. Therefore the clinical relevance of many of the studies reporting dentine bonding strengths must be questioned.

The complexity of dentine bonding is reflected in the number of agents that have been developed commercially over the last thirty years. Dentine bonding agents have been arbitrarily assigned to one of five generations, defined by the chemistry of the materials. Fourth and fifth generation materials were used in this study and therefore a detailed review of the earlier bonding agents is beyond the scope of this thesis. A summary of their salient characteristics is given in Table 2.5.

In contrast to the earlier materials, fourth generation bonding agents have achieved dentine/resin bond strengths comparable to enamel/resin bonding. They use total etch and moist bonding techniques which enhance resin wetting and penetration (Gwinnett & Kanca III, 1992; Kanca III, 1992): acid-etched dentine is hydrophobic and, unlike enamel, the surface energy of dentine does not increase following etching (Attal *et al.*, 1994). In the fourth generation materials, the wettability of the acid-etched dentine is improved by the use of primers with both hydrophilic and hydrophobic groups. This in turn facilitates the flow and infiltration of the adhesive resin on the dentine. Bonding is achieved by hybridisation (Section 2.7.2.2.1) and, in addition to the improved bond strengths achieved, the moist bonding conditions required are more favourable for the *in vivo* situation than the dry bonding conditions required by earlier agents. Studies using these bonding agents have shown reduced microleakage at the dentine margins (Linden & Swift, 1994) and greater retention rates (Van Meerbeek *et al.*, 1994) compared to their predecessors.

Table 2.5 The five generations of dentine bonding agents

Generation	Examples	Characteristics	Bond
1st	Cervident Cosmic Bond Servitor Palavav	Bipolar molecules attempted to achieve chemical bonding to inorganic phase of dentine and polymer. Very weak bonding *in vivo* due to hydrolysis of PO_4–Ca bond. Instability of active agents in solution Difficulties in obtaining bulk polymerisation Retentive cavity form recommended Post-operative sensitivity common	2MPa
2nd	*Halophosphorous esters of Bis–GMA* Scotchbond Dentine bonding Agent (J&S) Creation Bonding Agent Prisma Universal Bond	Ionic bond with reactive PO_4 group & Ca which co-polymerises with polymer Attempted to use smear layer Dentine and enamel bonding claimed Weak adhesives and require retentive cavity preparations Instability of ionic bond in water due to hydrolysis and thermal fluctuation. A proportion of double bonds of methacrylate groups within the agent neutralise in time, thereby limiting their ability to form covalent bonds with resin Post-operative sensitivity experienced	4–7 MPa
	Polyurethanes Dentine Adhesit Dentine Bonding Agent	Isocyanate groups bond to surface bound hydroxyl radicals to from CO2 which results in increased porosity Slow setting Attempted to use smear layer Limited solubility in water does not allow further reaction with NH_2 in collagen Compatible only with composite resins with available OH or NH_2 for covalent bonding Post-operative sensitivity experienced	3–6 MPa
3rd	Gluma Tenure Mirage bond All-Bond Scotchbond II	two-component primer and adhesive system dentine surface modified prior to resin application complete or partial removal of smear layer Three bonding approaches: primary chemical, secondary chemical, mechanical (hybridisation) More complicated and time consuming than 1st and 2nd agents, but reduced need for retentive cavity form Reduced post-operative sensitivity, but poor retention after 3 years Bonding to metals possible	10 MPa
4th	Gluma 2000 Pertac Bond Scotchbond Multi-purpose Syntac Bond All Bond II Tenure	Several components Reduced technique sensitivity and improved performance on moist surfaces or in high humidity Speed of application may pose clinical difficulty Similar bond strengths to enamel and dentine bonding achieved by hybridisation Total etch and moist dentinal bonding used Reduced post-operative sensitivity	>15 MPa
5th	Prime & Bond 2:1 Syntac Single component (Compoglass SCA) Bond 1 One step Tenure Quick F	Single component: priming and bonding in one bottle Moist bonding No mixing Post-operative sensitivity eliminated Etching not mandatory for all materials	> 15 MPa

Adhesives in the fourth generation of materials are distinguished by their numerous components and the increased clinical complexity of restorative procedures. The perception of complexity has led more recently, to the development of the fifth generation, one component, one bottle systems. Known as self-etching or self-priming systems, these agents use acidic priming solutions which diffuse through water-filled channels in the smear layer to the overlying dentine. They enlarge the channels and demineralise the upper surface of the underlying dentine. As the primer etches, the demineralised smear layer and exposed collagen fibres of the dentine are simultaneously infiltrated with HEMA and an acidic co-monomer which in turn co-polymerise to form the hybrid layer. In the earlier bonding agents, the smear layer was a confounding factor in the achievement of adequate bonds to dentine. However, the converse appears to be true for the fifth generation agents because of the hydrophilic nature of the primers which incorporate both the conditioned smear layer and dentine into the hybrid layer. The maintenance of the smear layer and its inclusion in the hybrid layer has three possible advantages. Firstly, the smear layer physically seals the dentinal tubules. Secondly, there is not the increase in dentine permeability and dentinal fluid flow following conditioning that is seen when the layer is removed with the fourth generation materials. The relevance of this is expanded further in Section 2.7.2.2.1. Thirdly, dentine penetration by the primer and resin is shallower than that achieved by the earlier hybridising materials (0.5-2.0 μm compared to 1–5 μm). Pashley and Carvalho (1997) speculated that this resulted in a thinner, but more uniform hybrid layer which in turn would lead to a higher quality of bond and reduced microleakage

2.7.2.2.1 Hybridisation

The primary site of bonding in all fourth and fifth generation agents is the hybrid layer. This zone was first described by Nakabayashi *et al* (1991): acid conditioning by either the direct application of acids, or the indirect dissolution by acidic components in the primer removes or modifies the smear layer before decalcifying the dentine surface. The resulting conditioned dentine surface is primarily an unsupported network of inter- and intratubular collagen. Decalcification of the highly calcified intratubular dentine also produces funnelling of the dentinal tubules. Hydrophilic monomers penetrate the collagen

network and dentinal tubules to a depth of 1–5 μm and polymerise *in situ* to create the hybrid layer. The bond strength to dentine is thought to correlate better with the bonded surface area rather than to the depth or volume of the resin penetration (Pashley & Carvalho, 1997), and therefore tubule concentration has a significant influence on bonding.

This resin-reinforced zone is highly acid-resistant and remains intact even after the dissolution of enamel and dentine in hydrochloric acid. In addition to providing micromechanical retention and to sealing the tubules, the hybrid layer effectively stops dentinal fluid flow and provides an effective barrier against bacteria, molecules and components of the overlying composite resin (Leinfelder, 1993). The hybrid layer also has a relatively low Young's Modulus of Elasticity and may play a role, albeit small, in stress relief during polymerisation shrinkage.

Water plays an important role in hybridisation. Excessive drying of the conditioned dentine surface, while possibly enhancing the bond to enamel (Section 2.7.2.1) can lead to the collapse of the collagen network. If it is not re-expanded by the application of water or aqueous primers, inadequate infiltration of both the demineralised collagen and widened tubules by the resin will result in reduced bond strengths, an increased susceptibility of the exposed collagen fibrils to slow hydrolytic degradation, and poor sealing of the tubules. All of which incur an increased risk of microleakage and its sequelae of dentine sensitivity and pulpal irritation. The third and fourth generation agents, where the dentine surface is washed and dried between conditioning and primer application, are at greater risk of dehydration than the self-priming fifth generation materials. Effective hybridisation with the earlier hybridising agents, therefore relies on the maintenance of the collagen network and the use of moist bonding and hydrophilic primers are essential components of the procedure.

While the presence of water is important for the maintenance of the collagen network, conversely, excessive water contamination can have an adverse influence on the formation of the hybrid layer. This is because of the formation of blister-like spaces at the primer-dentine interface which results in incomplete sealing of the tubules (Tay *et al.*, 1996). In addition, the water also dilutes the primer monomers. The source of excess water can arise from either the rinsing of

the conditioner or, *in vivo,* from the increase in dentinal fluid flow as a direct result of etching the dentinal tubules (Pashley *et al.*, 1993). Again, of the more recent materials, it is the third and fourth generations of bonding agents that are more susceptible to excesses of water. It is clear therefore, that the quantity of water must be carefully controlled to ensure maximum hybridisation.

When first introduced, the application of acid to the dentine was of concern to some workers (Retief *et al.*, 1992). However, this arose from errors in the interpretation of microleakage (Kanca, 1990) and more recently, total etching has been accepted as a method that does not increase the risk of damage to the pulp. However, if the acid is too aggressive, it may expose collagen fibrils below the hybrid layer, leaving a zone of weak dentine that is susceptible to long term degradation. It is therefore essential that the manufacturers' instructions are followed closely.

2.7.2.3 *The use of low viscosity resins: intermediate bonding and glazing*

The use of a low viscosity bonding resin, or an unfilled resin, placed as an intermediate layer between the composite resin and the cavity surface has been purported to reduce microleakage. While such a resin may improve bonding, its main functions are to act as a relatively flexible stress-absorbing layer between the dentine and composite resin during polymerisation shrinkage (Kemp-Scholte & Davidson, 1990a; Kemp-Scholte & Davidson, 1990b) and to better transmit and distribute stresses induced by thermal changes, water absorption and occlusal forces across the interface (Van Meerbeek *et al.*, 1993).

The results of studies investigating the effect of an intermediate bonding layer on microleakage have been conflicting (Chow, 1980; Amsberry *et al.*, 1984; Prévost *et al.*, 1984; Saunders *et al.*, 1990). This is due to differences in the viscosity of the materials used; in its unpolymerised state, a layer of monomer in the liquid phase is found on the resin surface. With less viscous composite resins, this layer behaves as an 'unfilled' resin. However for the more viscous materials resin flow is reduced and therefore the layer of monomer is unable to provide the same degree of intermediate bonding.

The results of the *in vitro* studies referenced in the above paragraph suggest that an intermediate bonding resin is unnecessary for some resins, but is of benefit for others. However, there was no evidence to suggest that the use of such a bonding resin was detrimental to the sealing capabilities of the resin. In his *in vivo* study, Qvist (1985) reported an improvement in microleakage with an intermediate bonding resin. A similar finding was reported by Chow (1980) using a conventional resin and it may well be that bonding agents are of benefit under the less favourable circumstances experienced *in vivo.*

The use of an unfilled resin applied as a glaze to the surface of the restoration has also been investigated as another means of reducing microleakage. However, as with the intermediate bonding resin, the results of these experiments are conflicting (Amsberry *et al.*, 1984; Qvist, 1985; Reid *et al.*, 1991).

2.7.2.4 *Altering the cavosurface angle of the restorations*

The cavosurface angle of a restoration can be changed by the preparation of a bevel at the cavity margins or by leaving excess filling material finished to a feather-edge over the surrounding tooth surface.

The concept of a 135° bevel at the enamel margin of conventional butt preparations has been proposed by several investigators (Welk, 1976). The proposed advantages for the bevel include an increase in surface area, and therefore number of exposed enamel rods available for acid-etching, a larger surface of the restoration available to compensate for some of the wall-to-wall polymerisation, the distribution of the forces generated by polymerisation contraction over a larger area thus reducing the likelihood of surface grazing (Bowen *et al.*, 1983), and the development of stronger resin/enamel bonds with etched transverse sections of enamel prisms than with longitudinal sections (Munechika *et al.*, 1984).

In vitro studies have yielded conflicting results with several workers concluding that the presence of an enamel bevel does not influence the leakage pattern if etching of the enamel is effective (Retief *et al.*, 1982; Hembree, 1984; Qvist, 1985). While others have found a significant improvement in leakage with the bevelled margin when compared to the butt-joint (Crim & Mattingly, 1980; Grieve &

Glynn Jones, 1980). As noted in Section 2.7.2.1, the degree of leakage found at gingival enamel margins of Class V cavities is consistently worse than at occlusal margins. A gingival enamel bevel has been found to reduce microleakage when compared to a similar preparation at the occlusal margin (Crim & Mattingly, 1980; Hall *et al.*, 1993). From the results of these studies, it was proposed that occlusal bevelling was not advantageous, and tooth structure should be conserved in this area, but that bevelling in gingival enamel should be used where sufficient enamel was available.

The difficulties encountered in achieving adequate bonding to dentine were referred to in Section 2.7.2.2. The influence of a bevel at the gingival margin in Class V restorations placed at the cervical margin was investigated by Uno *et al* (1988). They found that the bevel increased microleakage at the dentine margin while improving the marginal integrity at the enamel margin. However, the differences were not statistically significant.

In addition to the use of bevels, the influence of alternative cavosurface angles and cavity shapes on the microleakage of composite resins has been investigated; the use of a feather-edge finish with a butt-joint, a rounded butt margin and a saucer-shaped cavity have been found to reduce microleakage considerably when compared to the conventional butt-joint restoration with a cavosurface angle of 90° (Eriksen & Buonocore, 1976; Marzouk & Bhaiji, 1989).

2.7.2.5 *Modification of the restorative technique*

Polymerisation shrinkage has been controlled by changing the cavity shape, and by controlling the direction of polymerisation and the volume of polymerising resin.

A significant improvement in marginal adaptation has been found with increasing wall/floor angles in dentine (Hansen, 1984) and enamel cavities (Eriksen & Buonocore, 1976) with the classic attrition-shaped cavity giving the smallest gap sizes and therefore reduced tensile stresses in the material. This is due to the increased area of the restoration free-surface compensating for wall-to-wall contraction. Feilzer *et al* (1987) describe such cavities as having a low C–factor (configuration factor). The direction of polymerisation contraction can

also be controlled by the application of pressure to the restoration surface via a matrix strip (Amsberry *et al.*, 1984).

An increase in cavity size results in increased marginal gap size when composite resin is bonded to enamel or dentine because of the increased volume of polymerising resin (Brännström *et al.*, 1984; Hansen, 1984). Several methods have been advocated for the control of volume; incremental packing (Hansen, 1986), the use of a 'ball' of pre-cured polymer (Welbury & Murray, 1990) or a beta quartz glass-ceramic insert (Section 2.3.3.2), and the provision of an indirect resin restoration (Douglas *et al.*, 1989).

Of these methods, incremental packing is of greatest benefit for the direct Class V restorations used in this study. With this technique, the polymerisation shrinkage of each increment is directed towards the cavity walls rather than to the restoration surface. When compared to bulk packing, this increases the free-surface:volume ratio and effectively lowers the size of the C–factor. Despite improvements in the bond achieved with dentine bonding agents, the dentine/resin bond has continued to be the 'weak link' in composite restorations. Several patterns of packing have been investigated in an attempt to reduce the adverse influence of this and oblique incremental packing has been found to have the greatest positive influence on microleakage when compared to bulk packing or horizontal incremental packing (Hansen, 1986; Saunders *et al.*, 1991; Saunders & Muirhead, 1992). This is particularly so when the first increment is placed occlusally (Crim, 1991), presumably because the early establishment of the enamel bond ensures that the gingival bond is not disrupted. More recently though, the results of studies using the newer dentine bonding agents have suggested that incremental filling is not a critical consideration for adhesives which achieve strong bonds to dentine (Linden & Swift, 1994).

This review of microleakage has so far concentrated on the control of polymerisation shrinkage of composite resin materials. In this study, two materials were used; a hybrid composite resin, and a polyacid-modified composite resin, both with their respective bonding agents. Microleakage in the latter group of materials will also be considered.

2.8 Microleakage in polyacid-modified composite resins

Because of their recent introduction into clinical dentistry, the number of refereed papers on this subject is naturally limited when compared to those reporting the incidence of microleakage with composite resin restorations.

As noted in Section 2.3.6, compomers were developed to enhance the favourable properties of composite resins, namely their good aesthetics, strength and wear resistance, with those of the glass-ionomer cements i.e. low polymerisation shrinkage, bonding to tooth structure and release of fluoride. It would not be unreasonable, therefore, to expect that these materials would exhibit less microleakage than equivalent composite materials and that microleakage at the enamel and dentine margins would be comparable. However, several workers have found a greater incidence of microleakage at both dentine and enamel margins with compomer materials when compared to composite resins (Uno *et al.*, 1997; Owens *et al.*, 1998). In contrast, at the dentine margin, Chersoni *et al* (1997) and Uno *et al* (1997) found no significant difference in leakage with cavosurface angles of 135° and 90° respectively. Studies also vary in their results when the marginal integrity at the enamel and dentine margins of the compomer restorations are compared. Uno *et al* (1997) and Brackett *et al* (1998) found no significant difference in leakage between the two margins. However, other workers have reported greater leakage at the dentine margins (Cortes *et al.*, 1998; Owens *et al.*, 1998). These apparent contradictions reflect differences in the composition and properties of the materials, but equally, restorative factors play a role. As with the composite resins (Section 2.7.2), the effect of different restorative approaches on the microleakage of compomer restorations has been investigated.

As noted in Section 2.3.6, compomer materials achieve micromechanical retention to dentine via the formation of a resin-reinforced hybrid layer with the application of fifth generation, single component bonding agents. Thus the smear layer is modified rather than being removed. The application of highly dissociated acids such as phosphoric to dentine removes the smear layer and results in an increase in the number and size of the resin tags (Chersoni *et al.*, 1997). Studies have shown that such dentine etching prior to primer application reduces the incidence of microleakage at the compomer/dentine interface

(Chersoni *et al.*, 1997; Vichi *et al.*, 1997; Ferrari *et al.*, 1998; Owens *et al.*, 1998). The same pattern of leakage was found with the enamel margin. However, Cortes *et al* (1998) found no significant differences in leakage at either margin between etched and non-etched surfaces with the two compomers they tested.

In contrast to composite resins (Sections 2.7.2.4 and 2.7.2.5), increasing the enamel cavosurface angle at the enamel and dentine margins by increasing the cavity wall/floor angles, or at the enamel margin by bevelling, was found to have no significant effect on microleakage (Uno *et al.*, 1997). However, like the composite resins, the use of a dentine bevel at the gingival margin influenced microleakage at that margin adversely, but resulted in a reduction in the microleakage at the bevelled enamel margin (Owens *et al.*, 1998). Uno *et al* (1997) also reported an increase in the microleakage at enamel and dentine margins with thermocycling.

2.8.1 Summary

From this brief review of the literature pertaining to both the compomer and the composite resin materials (Section 2.6), it can be seen that polymerisation shrinkage is an important factor when considering microleakage in resin-based materials. Ideally such restorations should not exhibit microleakage and therefore to minimise this, it is essential that both the size and direction of the stresses arising during polymerisation shrinkage are controlled. This is achieved by changes to the composition of the restorative material, but in addition, the choice of restorative technique is important.

2.9 Cavity preparation

The cavity, material and restorative factors influencing the control of microleakage were discussed in the previous section. However, of equal importance for the adaptation of the material is the morphology of both the cavity surface and the surrounding enamel and dentine. This is, in part, dependent on the method used for cavity preparation. The microleakage studies reviewed to date have all used conventional methods of cavity preparation, principally the high-speed handpiece and diamond bur with water coolant.

2.9.1 Conventional cavity preparation

Early caries removal revolved around enamel cleaning and dentine excavation with hand instruments. However, the development of the dental treadle engine in 1875, introduced rotary instruments into clinical dentistry (Stephens, 1986). Mechanisms and handpieces were refined and the modern slow, and high-speed air turbine handpieces, with the use of carbide and diamond burs to supplement the early steel and carborundum instruments, have provided an efficient, fast and reliable means of caries removal and cavity preparation, with reduced discomfort and fatigue for both the patient and operator (Peyton & Arbor, 1955).

The morphology of the resulting enamel and dentine surfaces is of interest when considering the microleakage of restorations. Enamel is a brittle tissue (Section 2.2.1.3) and therefore tooth preparation using sharp diamonds would be expected to affect the surface. Xu *et al* (1997) investigated the appearance of the enamel surface following conventional cavity preparation with a diamond bur. Micrographs of the cut surface showed evidence of subsurface damage in the form of median-type cracks and microcracks which extended along the boundaries between the enamel rods. In addition, microcracks were seen within the individual enamel rods. The length of the median-type cracks was proportional to the diamond particle size and also varied with the orientation of the enamel rods, being longer when the cutting surface was parallel to the long axis of the rods. However, the removal rate and the force applied to the tissue during cutting appeared to have no significant influence. These findings are of particular importance when considering the marginal seal and longevity of restorations, since the presence of these cracks at the CRI may influence the adaptability of the restorative material; in their discussion, Xu *et al* described the cracked enamel surface as being damaged, thereby implying that such an appearance was not desirable. They found that the damage induced by the use of coarse diamond burs was reduced effectively when finer diamond burs were used to finish cavity preparation, but etching with 33% phosphoric acid gel failed to either remove or improve the damaged surface. As a result, the authors concluded that these findings supported the use of fine diamond burs to complete cavity preparation. However, the clinical significance of the appearance of the cut surface on both the strength of the enamel and the adaptabity of restorative materials needs further investigation.

The appearance of the dentine surface following conventional cavity preparation has also been investigated. With SEM analysis following conventional caries removal and cavity preparation at x50 magnification, the dentine surface featured clear grooved marks because of the rotary action of the burs (Aoki *et al.*, 1998). At higher magnification (x3000) the surface appeared flat and a smear layer (Section 2.7.2.2) was visible. Within the same experiment, Aoki *et al* compared this appearance with the dentine surface arising as a result of cavity preparation with an Er:YAG laser. These findings are of relevance to this study and are described in Section 2.10.6.3.

In addition, to the morphology of the cut enamel and dentine surfaces, use of rotary instruments also produces frictional heat and vibration, giving rise to pain and a hyperaemic increase in pulpal blood flow (Närhi *et al.*, 1982). Heat production and its sequelae are limited with the use of water coolants (Stanley & Swerdlow, 1959). However, these side effects, combined with the noise of the motor, may cause apprehension for the patient and damage to the pulp. In addition, the instruments are not selective in their tissue removal, although tactile assessment with a slow speed bur in particular does assist in the differentiation of healthy and carious dentine and enamel. Despite these limitations, the use of high and slow speed handpieces in cavity preparation remains the commonest method of caries removal and provides the standard by which all other methods are compared.

However, as noted in Section 1.3. the dental drill is one of the commonest fear-provoking stressors for the anxious patient. Alternatives to conventional methods of cavity preparation have been investigated in the attempt to find a technique that can prepare the cavity within a reasonable length of time without causing pain or affecting the CRI adversely.

2.9.2 Alternative techniques for cavity preparation

To date, four alternative techniques have been investigated; air abrasive techniques, ultrasonic instruments, chemomechanical caries removal and lasers. All have been reported to provide a means of cavity preparation or caries removal without pain or vibration for the patient (Black, 1955; Oman, 1955; Brännström *et al.*, 1980; Keller & Hibst, 1997). However, the air abrasive

technique is limited to the teeth and surfaces in the direct vision of the operator and conventional rotary instruments are required to complete cavity preparation. Conventional instruments are also required for the removal of hard caries and the completion of cavity preparation with the chemomechanical and ultrasonic techniques (Oman, 1955; Brännström *et al.*, 1980).

The success of lasers as a replacement for the conventional drill has varied depending on the lasing medium employed. The Er:YAG laser is used in this study as an alternative to conventional cavity preparation and it is therefore pertinent to consider this area in greater detail.

2.10 - Lasers in dentistry

2.10.1 Introduction

The word 'Laser' is an acronym for Light Amplification by the Stimulated Emission of Radiation. The light is produced in a closed system and is a coherent, monochromatic, collimated beam of photons. The beam may be continuous, pulsed or gated and the size of the focal point can be adjusted to create a beam of electromagnetic radiation of tremendous energy which is significantly more intense than conventional light sources. Lasers are named according to the laser medium employed and to date, more than 600 have been identified, each operating at a different wavelength.

Since its conception by Maiman in 1960 , the laser has been considered for use in many areas of medicine and surgery. Two main categories of laser have been developed for use in these fields; 'soft' and 'hard' lasers. 'Soft' lasers provide low energy at wavelengths which activate the circulation and cellular activity (Midda & Renton-Harper, 1991; Miller & Truhe, 1993). They are used to promote healing and to reduce the pain and oedema produced by inflammation. 'Hard' lasers are used widely for surgical applications. All further references to lasers in this thesis will refer to this latter type of laser.

Research into the application of lasers in dentistry has been ongoing over the last 30 years and is almost as old as the laser itself, a reflection of the inherent difficulties of producing a clinical laser system that both interacts effectively with

the hard dental tissues and is easy to use, while complying with health and safety requirements. Several hard and soft tissue applications for hard lasers in dentistry have been reported (Table 2.6). However, it is the ability of lasers to cut enamel and dentine that is of interest in this study.

2.10.2 Lasers as optical 'drills'

When they were first developed, it was hoped that lasers would provide an alternative to the dental drill (Goldman *et al.*, 1964; Gordon, 1967; Stern *et al.*, 1972). The first report of the use of a laser on a vital tooth was by Goldman *et al* (1965). Two pulses of a ruby laser were applied to a vital tooth. With sufficient energy densities, the laser beam was able to penetrate sound, normal enamel, and the enamel surrounding the impact area showed no macroscopic evidence of change. Furthermore, there was no sensation of pain. As noted in Section 2.9.1, the pain experienced during conventional cavity preparation is usually caused by the vibration of the bur and the heat produced from friction. It was hoped therefore that, in addition to cutting enamel and dentine, the use of a contactless operating laser would provide a more accurate and painless means of tooth preparation. In so doing, the need for local analgesia would be reduced and would provide a welcome alternative for tooth preparation for anxious individuals.

For the laser to replace or support, conventional means of cavity preparation, it must fulfil certain criteria. Laser irradiation of the tooth surface should result in:

- the removal of enamel, dentine, caries and restorations without damage to the surrounding hard tissues and pulp or to other oral tissues
- the production of minimal temperature change in the irradiated tissue
- a consistent and predictable effect on a defined area or tissue
- an ablation rate equivalent to the cutting rate of conventional handpieces
- the production of a cavity surface that does not influence the marginal sealing ability of restorative materials or the bonding of adhesive materials adversely.

In addition, desirable properties are that the tool should be selective for caries to minimise hard tissue removal and damage, and should not cause pain sensation during cavity preparation.

Table 2.6 Potential soft and hard tissue applications of lasers in dentistry

Soft tissue applications

- incise, excise, remove or biopsy lesions such as papillomas, fibromas, and epulides
- vaporise excess tissues, for example, frenectomy, gingivoplasty and ginigivectomy
- remove or reduce hyperplastic tissue, for example epanutin hyperplasia
- remove and control haemorrhaging of vascular lesions such as haemangiomas, and in patients with hemorrhagic disorders such as haemophilia
- symptomatic pain relief of aphthous ulcers

Hard tissue applications

- vaporise carious lesions
- desensitise exposed root surfaces
- endodontic: vaporise organic tissue, glaze canal wall surfaces and fuse an apical plug with the potential to resist fluid leakage, root canal sterilisation
- roughen tooth surfaces *in lieu* of acid etching
- preventive effect on enamel: arrest demineralisation, promote remineralisation and increase acid resistance
- debond ceramic orthodontic brackets
- cure composite resin (reduces polymerisation shrinkage)
- cut enamel and dentine
- scaling and root planing
- increase acid resistance of enamel

Contrary to the high hopes arising as a result of the first reports, further studies using the early lasers reported that the high energy densities required to cut through the enamel and dentine led to overheating. This caused cracking and shattering of the enamel surface which led to irreversible pulp damage (Stern *et al.*, 1969; Adrian *et al.*, 1971). Furthermore, reflected energy produced visible, albeit less severe, changes in the enamel of adjacent teeth (Taylor *et al.*, 1965). When used at lower energies to minimise these side effects, the lasers failed to ablate enamel and dentine. These studies involved the use of continuous wave ruby, carbon dioxide and Nd:YAG lasers.

The significant limitations in the use of the early lasers for the 'cutting' of enamel and dentine led some workers to conclude that they had no role in this area. However, over the last thirty years, there have been continued technological developments in the field. As this has happened, interest in the application of lasers to dentistry has been rekindled to the extent that, at the end of the twentieth century, the clinician is faced with an array of laser types all of which purport to cut enamel and dentine. In order to understand which of these may satisfy the requirements of an optical drill, an understanding of the way in which laser light interacts with enamel and dentine is necessary.

2.10.3 Mechanism of laser–tissue interactions

2.10.3.1 Introduction

On impinging a tissue surface, the laser light can be reflected, scattered, absorbed and/or transmitted. The absorbed light is responsible for the tissue effects of the laser, and the quantity of light absorbed is influenced by the proportion in which the other three effects occur. For instance, reflection limits or reduces the quantity of energy which enters the tissue and light that is reflected is dissipated effectively resulting in very little damage to the other oral tissues. Scattering occurs within the tissue and effectively distributes the energy over a larger volume of tissue than the laser beam entering the tissue. In so doing, it dissipates thermal energy. However, this may also result in an increase in collateral damage where the scattered radiation is absorbed. After a characteristic amount of scattering has occurred in the tissue, light energy is absorbed. Transmission

occurs when the light passes beyond a given tissue boundary and may result in damage to surrounding tissues such as the pulp.

2.10.3.2 *Interaction of absorbed light with the dental hard tissues*

The interaction of the absorbed electromagnetic radiation with tissues involves the interaction of photons with the atoms or molecules of the target tissue. These interactions are followed by very complex reactions, many of which are still not understood fully. Four mechanisms are currently recognised: photochemical interactions, thermal interactions, non-linear processes and thermomechanical processes. The first of these, photochemical processes, are not involved in the reaction of laser light with the dental hard tissues and will therefore not be considered further.

2.10.3.3 *Thermal interactions*

Thermal effects occur when the absorbed electromagnetic radiation is converted to heat energy; absorption leads to an increase in internal lattice vibrations which in turn is converted to thermal energy. While vaporisation of the irradiated tissue may occur, several side effects in teeth have been noted. The direct effect of excessive heat results in the formation of cracks, zones of necrosis, carbonisation (charring) and melting in enamel and dentine, and irreversible damage to the pulp. The ability of some ruby, carbon dioxide and Nd:YAG lasers to melt enamel has been proposed as a means to prevent carious attack because of the increased acid-resistance seen in the tissue (Stern, 1972; Yamamoto & Ooya, 1974; Meurman *et al.*, 1992). However, with this exception, these thermal side effects are less than desirable, and the laser-induced alterations of the tooth surface may have a deleterious affect on the successful bonding of restorative materials. In most clinical situations therefore, it is desirable to minimise these thermal changes.

2.10.3.4 *Non-linear processes*

When pulse energies lie above a certain threshold, and the pulse duration is shorter than 1ms, the laser energy is used to break bonds non-thermally. Heat conduction can therefore be disregarded. In the removal of enamel and dentine,

two main types of non-thermal effects are known: photoablation by either multi-photon stimulation or direct electron dissociation, and photo-disruption.

2.10.3.4.1 Photoablation

In contrast to the thermal effects, molecules can be directly dissociated with laser light of high photon energies (single photon dissociation), or with high energy densities and short pulse duration (multi-photon processes). Only the excimer laser emits radiation with photon energies high enough for direct electron dissociation. The molecular bonds are broken with minimal thermal side effects. Photoablation is a tissue-specific process and promotes selective caries removal. In contrast to healthy dentine, the demineralised zones of a carious defect are very easy to remove, resulting in retentive areas in the enamel and dentine (Frentzen & Koort, 1990).

2.10.3.4.2 Photodisruption

Very high energy and short pulsed laser light can ionise material by building up a plasma, a sea of electrons and ions with temperatures between 6,000–10,000 °C where the laser light focuses on the tooth. If this occurs, several effects may be seen, depending on where the plasma is generated. By absorbing some of the incident radiation, the presence of the plasma may result in a reduction in laser energy reaching the tooth surface. However, this is in part compensated for by the direct action of the plasma on the tooth surface; thermal energy is conducted to the surface, which results in ablation and heating of the dental hard tissues. If uncontrolled, the formation of a plasma at the tooth surface may result in an unacceptable degree of thermal damage. If the plasma is generated beneath the tooth surface, pressure builds up and dissipates explosively inducing acoustic shock waves. These result in the mechanical detachment of various sized particles of enamel and dentine. This effect of the plasma is independent of absorption and is dictated in part by the type of laser. For some lasers, the development of high pressure waves has the potential to produce cracks, microcracks and zones of debris at the cavity surface. Others, notably some of the later Nd:YAG lasers, attempt to use the plasma to cut enamel and dentine by controlling the plasma with a water coolant (Pick, 1993). This poses some concerns because the superhot plasma can heat areas beyond the desired target

area, causing significant iatrogenic thermal damage. In addition, the plasma is generally difficult to control, varying rapidly in intensity, width and location.

2.10.3.5 Thermomechanical processes

The major absorption band of water is at 3.0 μm. Some of the newer infra-red lasers that have wavelengths in this region, for example, the Er:YAG laser, are able to ablate the dental hard tissues via an indirect thermomechanical mechanism: on impinging the dental hard tissues, the incident laser energy is absorbed by water in the tissues. The water heats to boiling producing water vapour which in turn causes a build up in pressure resulting in a microexplosion and the ablation of a small proportion of the tissue. The majority of the energy is expended in the process of ablation and therefore only a small fraction is available to heat the tissues, thus thermal changes are minimal.

The laser-induced effects seen on enamel and dentine are the result of a combination of one or more of the interactions described above. The balance between these is controlled by the characteristics of the laser radiation and the irradiated tissue. The laser parameters of concern are the wavelength, energy density, waveform and irradiation time, while the relevant tissue factors are its optical, thermal and mechanical properties. These parameters will be considered further in the following two sections.

2.10.3.6 Laser parameters

The depth of penetration and absorption of radiation impinging on a tissue is dictated by the balance that occurs between the absorption, transmission, scattering, and reflection of the light. This balance is in turn dependent on both the wavelength of the radiation, and the optical properties of the irradiated tissues. The latter are considered further in Section 2.10.3.7.

Considering the laser parameters further; in addition to the wavelength, the energy density (fluence) of the laser light is important. This is defined as the quantity of energy that is distributed over a surface area. The overall energy deposited on the tissue surface depends also on the waveform and the irradiation

time and this will influence the type of interaction that is seen. The waveform is the way in which the power output varies with time i.e. continuous, gated or pulsed. In general, long pulse durations are not desirable because thermal energy develops, thereby increasing the possibility of adverse thermal changes in the irradiated tissue. Pulse shortening, on the other hand, results in a reduced volume of tissue that is heated because of the reduced deposition time, and also a decreased threshold energy for ablation (Wilder-Smith *et al.*, 1997). The pulse frequency is expressed in Hertz (Hz) and is also known as the pulse repetition rate (PRR) or the pulses per second (PPS).

2.10.3.7 Optical and tissue parameters

As was seen in Section 2.2, teeth are markedly heterogenous structures. Absorption, the key to laser interaction is wavelength dependent, as indicated by the absorption spectra of the tissue components. It takes place at single atoms or molecules which have resonant absorption levels for the wavelength of the light applied. As noted in Section 2.2.1, water and hydroxyapatite, components of both enamel and dentine, have strong absorption spectra at both UV and mid- to far-IR wavelengths. Ruby and Nd:YAG laser radiations (visible and near-IR respectively) are therefore not absorbed well in either enamel or dentine, whereas light from the carbon dioxide (far-IR) and Er:YAG (mid-IR) lasers are well absorbed by both tissues.

However, absorption is not the only tissue factor dictating the characteristics of the laser-tissue interaction. The thermal properties and the vaporisation temperatures of the dental hard tissues also play an important role in determining the ability of a laser to ablate the tissue with minimal adverse thermal effects. Both enamel and dentine have low thermal coefficients of thermal expansion ($11.4,10^{-6}/°C$ and $8.3,10^{-6}/°C$ respectively) and low thermal conductivities and therefore any heat generated in the tissue, while creating minimal expansion, will diffuse slowly from the impact point of the laser beam. If of sufficient intensity, the resulting production and retention of thermal energy will lead to damage, the nature of which was described in Section 2.10.3.3. In addition, the vaporisation temperature of enamel is of sufficient size that high energy densities are necessary for ablation. For wavelengths that ablate enamel

and dentine via thermal interactions, such an increase in energy density will increase the potential for thermal damage.

Indirect irreversible pulpal changes may be seen by the direct heating effect of dentine close to the pulp. However, in addition to this, the 'system' of optical fibres provided by the dentinal tubules (Section 2.2.2.) permits transmission of electromagnetic energy to the pulp and direct pulpal damage may arise from the absorption of the transmitted light by the pulp tissue.

The influence of the tissue parameters on the laser-tissue interaction explains the poor performance of the early dental lasers.

2.10.4 The early hard tissue dental lasers

These early lasers, carbon dioxide, ruby and Nd-YAG, were continuous-wave or pulsed, with pulse durations in the microsecond range, and thermal changes played an important role in their interaction with the dental hard tissues.

The carbon dioxide wavelength is well absorbed by hydroxyapatite and as a result the early prototypes thermally ablated enamel. However, because of the shape of the laser beam (Gaussian) with reduced intensity towards the outer limits of the beam, the heat generated in the tissue at the periphery was insufficient to cause vaporisation. This led to the production of adverse thermal changes (Stern *et al.*, 1972). Laser irradiation of dentine with the early carbon dioxide laser had similar effects.

In contrast, the wavelengths emitted by the ruby and Nd:YAG lasers are not well absorbed by hydroxyapatite. From this it may be anticipated that thermal side effects would not be seen following irradiation of enamel or dentine. However, as noted in Section 2.10.2, this was not the case and the early models exhibited thermal change, with minimal ablation (Goldman *et al.*, 1964; Stern & Soggnaes, 1964; Yamamoto & Ooya, 1974). This was because large energy densities were used in an attempt to increase absorption and resulted in a two fold effect; the energy density was sufficient to cause thermal damage of the enamel with minimal vaporisation, and the quantity of transmitted light increased, resulting in increased direct pulp damage. Enamel ablation was increased following the application of a dye to the enamel surface (Yamomoto & Sato, 1980). This

phenomenon (initiation) reflects the increased absorption of the Nd:YAG and ruby laser wavelengths in pigmented tissue and resulted also in greater absorption of these wavelengths for non-sclerotic dentine, sclerotic dentine and caries (Dederich & Zakariasen, 1984). However, while enhancing the ablative properties of the lasers, initiation also had adverse clinical implications. During ablation the bulk of the energy was still converted to heat, which in turn produced charring of the dental hard tissues. This acted as an initiator, increasing the absorption of the laser and resulted in the production of a laser beam which was difficult to control (Dederich, 1991).

Further developments in the field of lasers has led to the development of laser parameters which ablate via the non-thermal mechanisms outlined in sections 2.10.3.4 and 2.10.3.5, thus limiting the development of adverse thermal interactions. This has led to a generation of hard lasers which appear to have great potential as optical drills.

2.10.5 The new generation of lasers

Experience gained with the early 'hard' lasers has indicated that there are essentially two requirements for laser ablation of the dental hard tissues: the wavelength must be efficiently absorbed and the laser energy must be delivered in short bursts with high peak powers. The two trains of development in the manufacture of lasers for ablating dental hard tissues have been to use wavelengths in either the UV or mid- to far-IR spectral regions, and to reduce the pulse duration and size of the impact point of the beam, thereby increasing the peak power density, although the overall energy reaching the tissue may be relatively low. Table 2.7 lists some of the lasers used on the dental hard tissues to date.

The newer laser systems have given promising results. Arima and Matsumoto (1993) demonstrated that both sound and carious enamel and dentine could be cut by the ArF:Excimer laser with a pulse duration of 10–12 nsec without thermal injury and with minimum temperature rise. However, the ablation rate (i.e. ablated volume per pulse) of this laser was very low. This, and the general risks of UV radiation to the patient are major disadvantages to its use in cavity preparation. Furthermore, the high cost of these lasers limit their clinical use.

Table 2.7 Hard lasers which ablate enamel and dentine

Laser type	Waveband	Wavelength λ (nm)	Waveform	Power (W)
Ar-F excimer	UV	193	Pulsed	0-50
XeCl-excimer	UV	308	Pulsed	
Nd/YAG	Near-IR	1,064	Pulsed/continuous	0-100
Ho/YAG	Near-IR	2,100	Pulsed/continuous	0-100
Er/YAG	Mid-IR	2,790	Pulsed/continuous	0-100
Er/Cr/YAG	Near-IR	2,690	Pulsed	
CO_2	Far-IR	10,600	Pulsed/continuous	0-100

Niemz (1995) reported the removal of enamel and dentine by a picosecond laser system, a solid-state Nd:YLF laser. Very precise cavities were obtained, without severe thermal or mechanical damage, in the enamel and dentine of extracted human molar teeth, the quality of which was superior to that achieved by other laser systems. Moreover, the laser exhibited caries-selective properties; when applied to carious enamel, the ablation rate was ten times higher than that for sound enamel. However, these lasers are not yet commercially available and are also likely to be comparatively expensive.

Another laser which has shown great promise is the Er:YAG laser. Lasers of this type have been in clinical use in Germany for approximately five years. Furthermore, the Centauri Er:YAG laser (Premier Laser Systems) was cleared for marketing in the United States of America by the Food and Drug Administration (FDA) on May 7 1997 for 'caries removal, cavity preparation, and modification of dentine and enamel before acid etching for increased bond strength' (Cozean *et al.*, 1997). The laser used in this study was an Er:YAG laser, the Twinlight Dental laser (Fotona, Ljublijana, Slovenia). Therefore this group of lasers will be considered in greater detail in the following section.

2.10.6 The Erbium:YAG laser

2.10.6.1 Introduction

Erbium is a metallic element in the rare-earth group. The Er:YAG laser is a solid state, pulsed laser that has a maximum emission in the mid-infra-red region. At 2.94 μm, the wavelength of this laser coincides with the major absorption band of water (~3.0 μm) and is therefore strongly absorbed in this region; the water absorption coefficient for radiation produced by the Er:YAG laser is ten times that of the radiation of the CO_2 laser. In addition , the wavelength is also well absorbed by hydroxyapatite.

The first description of the effects of the Er:YAG laser on the dental hard tissues was reported in 1988 and indicated that effective ablation of healthy and carious tissue was possible without thermal injury and with minimal temperature changes to the surrounding hard tissues (Hibst *et al.*, 1988; Hibst & Keller, 1989;

Keller & Hibst, 1989). The results of these studies led to the conclusion that ablation was achieved via thermomechanical interactions (Section 2.10.3.5) and that the majority of the incident radiation was consumed in the ablative process, leaving very little residual energy for thermal interactions to occur. However, it is worth noting that, with increasing pulse energies, small cracks surrounding the crater were seen. These were thought to be artefacts arising during specimen preparation rather than a direct effect of the incident radiation (Keller & Hibst, 1989).

The results of these early reports suggested that the Er:YAG laser had great promise as a replacement for the dental drill, and since the late 1980's several workers have investigated the use of the laser system in an attempt to assess how far it fulfils the properties of the ideal optical drill. A résumé of these criteria was given in Section 2.10.2.

Close inter-study comparisons are difficult because of the range of different laser parameters that have been chosen (Table 2.8). The following review of the literature attempts to summarise the major findings reported.

2.10.6.2 Ablation

Early crater measurements indicated that ablation depths of more than 30 μm per pulse could be achieved for healthy enamel and dentine, with greater depth measurements being recorded for carious lesions (Keller & Hibst, 1995a). The ablation threshold for enamel is higher than that of dentine and when the threshold is exceeded, mass loss increases linearly with pulse energy (Hibst & Keller, 1989) providing the tissue does not become desiccated (Hoke *et al.*, 1990). Crater depths and widths increase with increasing pulse energies in both enamel and dentine, those in dentine being larger than the craters found in enamel for the same pulse conditions (Hibst & Keller, 1989). Keller and Hibst (1995a) calculated that with a total pulse duration of 250 μs at 300 mJ, 73 and 25 pulses were required to ablate 1 mm^3 area of enamel and dentine respectively and that this would be achieved in 20 seconds with a repetition rate of 4 Hz.

The speed in which enamel and dentine is removed is clearly of clinical importance. The ablation rate of the laser has been compared to both high and

Table 2.8 The range of Er:YAG laser parameters used in referenced reports

Report	Energy density (Jcm^{-2})	Energy per pulse (mJ)	Power (W)	Individual pulse duration (μs)	Pulse repetition rate (Hz)	Total pulse duration (μs)	Pulse cycle time (μs)	Pulse no.
Hibst & Keller, 1989		30–360		1	1, single	250		
Keller & Hibst, 1989		30–360		1	1, single	250		
Hoke *et al*, 1990		56–118		2.5		250	14	
Hibst & Keller, 1991		50–350			1	300		10
Kayano *et al*, 1991	15.9	39–500		200,000	1, 3,10			3–100
Keller *et al*, 1991		100–300			1–3	200		2–10
Burkes *et al*, 1992		56–95		2.5		250	14	
Haller *et al*, 1992		250			2			300–500
Keller *et al*, 1992		150–300			0.5–3	250		50–250
Koort & Frentzen, 1992		150–300			1.5, 5	200		
Li *et al*, 1992		25–365			2, 5	200		
Hofmann *et al*, 1992		300/200			2			
Wigdor *et al*, 1993		500			3	250		
Hibst & Keller, 1994		350			1.5			
Keller & Hibst, 1995b		500			1.5-4	250		
Wright *et al*, 1993		0.2–0.3			2			
Frentzen *et al*, 1996		75–200			1.5	200		
Visuri *et al*, 1996	up to 110	ablation threshold–400			2-10	230		
Chao *et al*, 1996			0.5-2		3, 5, 10			
Matsumoto *et al*, *1996*		250–500			8			
Cozean *et al*, 1997		25–120			5–10			
Keller & Hibst, 1997		150–350			2	250		
Tanji *et al*, 1997	8.64–14.11	60–100						
Aoki *et al*, 1998		180			10			
Keller *et al* 1998		250–400, 150–300			2–4, 1–3	250		

slow speed burs in conventional dental handpieces (Wigdor *et al.*, 1993; Chao *et al.*, 1996; Keller *et al.*, 1998). For the laser parameters used (Table 2.8), the laser ablated both enamel and dentine faster than the slow-speed bur, but was less efficient than the high-speed bur. Furthermore, the laser appeared to cause less damage to the pulp and surrounding dental hard tissues than the slow speed bur (Wigdor *et al.*, 1993), a property that is desirable *in vivo*.

Hibst and Keller's (1989) proposal that thermomechanical interactions were responsible for enamel and dentine ablation were confirmed in subsequent studies (Hoke *et al.*, 1990; Li *et al.*, 1992). To achieve ablation when the laser beam is applied over an area as opposed to a single spot and, or when, high energy densities are used, water is required. In the absence of water, ablation occurs to a lesser extent (Hoke *et al.*, 1990; Burkes *et al.*, 1992) and the dental hard tissues become desiccated, exhibiting areas of charring, melting and crack formation. The simultaneous application of a water mist during lasing prevents this. However, there is evidence to suggest that the presence of excess water in deep cavities can have an adverse affect on dentine ablation when laser energies approaching the threshold value for dentine are used. This is because a significant proportion of the laser energy is absorbed by the excess water leaving insufficient energy for dentine ablation (Visuri *et al.*, 1996).

For clinical use, it is not only essential to be able to remove enamel, dentine and caries with the laser, it is also necessary to remove restorative materials. Hibst and Keller (1991) found that the ablation efficiency of phosphate cement, carboxylate cement, glass-ionomer cement and composites was only slightly lower than that for enamel and dentine for laser parameters of 10 pulses at 1 Hz and pulse energies of 50–350 mJ. The ablation of silver amalgam was only possible with energies exceeding 150 mJ. However, high temperatures were generated during amalgam ablation and, because of the high concentration of mercury in the plume, Keller and Hibst (1995a) recommended that the Er:YAG laser should not be used for the removal of these restorations. This has obvious implications when considering the possibility of replacing the dental drill with a laser.

2.10.6.3 Morphology

Several workers have investigated the morphology of lased enamel and dentine using light microscopic and SEM analysis (Keller & Hibst, 1989; Hoke *et al.*, 1990). Examination of lased tooth sections under light microscopy revealed slightly rough cavosurface angles in enamel, smooth dentinal cavity walls, and an irregular topography of peaks and valleys on the pulpal floor. SEM analysis found that enamel ablation produced an irregular surface of grooves, flakes, shelves and pits. In addition, at numerous sites on the enamel wall there were cone-shaped craters extending irregularly into the surface. The surface configuration of the dentine was smoother and more rounded than that of enamel with smaller pits and grooves. At high magnifications (x3,000) the lased dentine surface was found to lack a smear layer and the dentinal tubules were prominent because of selective ablation of the peritubular dentine. In addition, the orifices of many of the tubules were exposed, though some were occluded with crystalline deposits (Aoki *et al.*, 1998).

As noted in Section 2.10.6.1, one early study reported the absence of thermal damage to the ablated surface and the surrounding hard dental tissue, despite the presence of cracks in the surrounding enamel with high pulse energies (Keller & Hibst, 1989). In this study, a single spot was lased without additional water. Subsequent investigations using similar laser parameters for cavity preparation reported evidence of adverse thermal changes. This was prevented with the application of a water mist during lasing (Hoke *et al.*, 1990; Burkes *et al.*, 1992). However, even with the additional water, some changes in the surrounding 10 μm of both enamel and dentine were noted; enamel exhibited shelves with small flakes and grooves and the dentinal tubules were not intact (Hoke *et al.*, 1990). In a further study, evidence of acid resistance of lased enamel without crack formation, and a thin mineralising zone in the subsurface area of lased dentine have been reported with pulse energies of 500 mJ suggesting the presence of some thermal change, albeit minimal (Kayano *et al.*, 1991).

However, in contrast to the lack of, or minimal thermal change found in the studies so far noted, other workers have reported evidence of crack formation in the dental hard tissues irrespective of the laser parameters used (Koort & Frentzen, 1992; Frentzen *et al.*, 1996). It would appear therefore that while laser

parameters are important for successful ablation, the morphology of the tooth tissue is also significant (Frentzen *et al.*, 1996; Visuri *et al.*, 1996). While the complete absence of thermal changes would appear to be unlikely, the Er:YAG laser produces less damage than comparable carbon dioxide , Nd:YAG, Ho:YAG, Th:YAG and ArF excimer lasers (Keller & Hibst, 1989; Koort & Frentzen, 1992; Wigdor *et al.*, 1993; Frentzen *et al.*, 1996).

This resumé has focused on the morphological effects of the laser radiation on the dental hard tissues. Of equal importance is the response of the pulpal tissues to heat produced during ablation of the dental hard tissues.

2.10.6.4 Temperature

The pulp's sensitivity to changes in temperature were noted in Section 2.2.3. It is therefore essential that any changes in pulp temperature during lasing do not exceed 5.5°C, since an increase beyond this is likely to produce irreversible pulpal damage (Zach & Cohen, 1965).

Reference has already been made to the effect of applying the Er:YAG laser beam to an enamel surface without water coolant (Section 2.10.6.3). This was accompanied by an increase in temperature of at least 20°C at the pulpodentinal junction. When a water mist was used simultaneously with the laser, the average rise in temperature was only 2.2°C (Hoke *et al.*, 1990). This finding is in agreement with other workers (Burkes *et al.*, 1992; Visuri *et al.*, 1996). The measurements were made *in vitro* which may be assumed to provide more stringent conditions than *in vivo* where blood flow accelerates the dissipation of thermal energy. It can therefore be assumed that the simultaneous application of a water mist while using the Er:YAG laser is sufficient to maintain the pulp temperature within safe limits for the laser parameters investigated. Indirect confirmation of this has been achieved with the use of a laser Doppler flowmeter to measure changes in the micro-circulation of the pulp of vital teeth (Keller *et al.*, 1991).

To minimise the thermal effects on both the dental hard tissues (Section 2.10.3.3) and the pulp, the use of maximum energy densities of less than 80 and 74 Jcm^{-2} for enamel and dentine respectively (Li *et al.*, 1992) with a water mist for pulse

repetition rates greater than 2 Hz (Keller & Hibst, 1995b) have been recommended.

2.10.6.5 *Long-term pulp reaction*

Keller *et al* (1992) investigated the effect of irradiation with the Er:YAG laser on the histology of the dental pulp in dogs. The laser energies ranged from 150–300 mJ with pulse repetition rates of 0.5–3 Hz. No pulp reaction occurred for any of the laser parameters when the cavity preparation stopped in enamel or in dentine that did not approximate the pulp. For deep cavities, an increase in the number of blood vessels was seen within two weeks, and when the pulp was exposed with the laser radiation, there was evidence of necrosis near the lased area. However, the odontoblasts adjacent to the laser defect were unchanged and two weeks later, a layer of secondary dentine was seen in this region which continued to increase in thickness over the next four weeks. These findings were in agreement with subsequent *in vivo* studies reported by Wigdor *et al* (1993) using laser parameters within the same range, and by Cozean *et al* (1997) using energies of 25–120 mJ with a PRR of 5–10 Hz. In the latter study, a group of lased teeth were followed up for up to 36 months during which time radiographs and routine sensitivity tests confirmed the continued vitality of the pulps.

While these studies found a favourable pulpodentinal response to Er:YAG laser irradiation, an inflammatory reaction followed by necrosis has been reported with pulse energies of 500 mJ for pulse repetition rates of more than 2 Hz in the absence of additional water (Keller & Hibst, 1995b).

Thus, these findings suggest that with the use of suitable laser parameters and a water cooling system, irreversible pulp damage can be avoided even with deep cavity preparations.

2.10.6.6 *Patient acceptance*

The mechanical preparation of a cavity with a bur in both a slow- or high-speed dental handpiece can result in pain because of vibration, pressure, heat and noise. For the patient's comfort, pain-free cavity preparation without local analgesia would be ideal. The absence of significant temperature and pulpal

changes noted in sections 2.10.6.4 and 2.10.6.5 led workers to suggest that this may be possible for the Er:YAG laser.

In their *in vivo* study investigating the use of the Er:YAG laser for the preparation of small to moderate wedge-shaped defects, Matsumoto *et al* (1996) found that 80% (49) of patients felt no pain or discomfort. Overall, the clinical efficacy of the laser, taking into account pain, patient perception, and the results of sensibility and radiographic investigations, was felt to be good in 82% of cases. Two more recent *in vivo* studies (Cozean *et al.*, 1997; Keller & Hibst, 1997) reported that patients experienced minimal pain during cavity preparation even with deep cavities, and that less than 2% of the cavities required the administration of local analgesia for completion. In the latter study, laser preparation was found to be comparable to the use of high-speed drill when pulpal changes were compared. However, the routine use of local analgesia for the control group of patients was inferred and therefore it was not possible to compare patient comfort for the two procedures. In a later study, 6% of patients undergoing laser preparation required local analgesia compared to 11% of patients with conventionally-prepared cavities (Keller *et al.*, 1998). This latter value is lower than would be expected from anecdotal clinical experience. For 80% of patients, the bur was judged to be more uncomfortable, and 82% of patients stated a preference for Er:YAG therapy in the future.

From this review, it can be seen that the Er:YAG laser has several advantageous properties for cavity preparation. With the correct choice of laser parameters and the use of a water coolant, ablation of both enamel and dentine is possible with minimal damage to the hard dental tissues and pulp and with very little pain for the patient. However, in addition to these qualities, it is also essential that the quality of the marginal integrity of restorations is not affected adversely.

2.10.6.7 Microleakage

While the morphological changes seen in enamel and dentine after irradiation with the Er:YAG laser have been extensively reported (Section 2.10.6.3), less information is available on the effect of the laser on microleakage. Some assumptions may be made by considering the ultrastructural features of lased enamel and dentine. The roughness of the lased surface, while increasing

porosity, may increase the wettability of the surface and therefore have a positive effect on micromechanical retention, effectively producing an 'etched surface' without the use of etchant. On the other hand, the converse is possible and the rougher surface may result in increased spacing and therefore greater microleakage. In addition, other structural features may have an adverse effect on marginal adaptability. A momentary temperature rise in enamel of 800–1,100 °C is sufficient for the fusing and melting of the apatite crystals (Featherstone & Nelson, 1987). As noted in Section 2.10.3.3, by sealing pits and fissures and reducing the potential for acid demineralisation of the enamel surface, this property has been used with carbon dioxide and Nd:YAG lasers to advantage in caries prevention (Yamamoto & Ooya, 1974; Nammour *et al.*, 1992). However, these structural changes serve to reduce the wettability and etchability of the enamel surface and thus could have an adverse effect on the seal at the CRI. In addition, the formation of cracks may increase the permeability of the surrounding tissue (Lobene & Ferreira, 1966; Koort & Frentzen, 1992). Thus while the thermal side effects of the Er:YAG laser are minimal, when they do occur it may be assumed that cracks and fusing of crystals may influence the CRI adversely. These features are not limited to enamel: in a recent study, it was concluded that the Er:YAG laser promoted acid resistance of the remaining dentine, and that a pulse energy of 100 mJ would provide a better pattern of micromechanical retention when compared with smaller values (Tanji *et al.*, 1997).

Studies investigating the influence of the Er:YAG laser on the quality of the marginal seal of restorations have investigated three areas: cavity preparation and enamel conditioning with the laser, cavity preparation with the laser and conventional enamel etching with phosphoric acid, and finally conventional cavity preparation with a high-speed diamond bur in an air-rotor handpiece and laser conditioning. The apparent contradictions in the results of these studies is perhaps a reflection of differences in the choice of laser parameters, restorative material and cavity shape. This review will be limited to the studies using composite resins, glass-ionomer cements and related materials in Class V cavities.

Hofmann *et al* (1992) compared the leakage of bevelled enamel margins of box-shaped cavities prepared with the conventional high-speed diamond bur with

both bevelled and non-bevelled cavities prepared by the Er:YAG laser. In addition, they also investigated the effect of omitting the acid-etching process in the restoration of these three cavity types. Pulse energies of 300 mJ and 200 mJ for enamel and dentine respectively, at a PRR of 2 Hz, were used for the lased cavities. After seven days storage and thermocycling, the conventionally-prepared, bevelled and etched margins exhibited significantly less leakage when compared to enamel margins that had been prepared and bevelled with the laser prior to acid-etching. When acid etching was omitted, an increase in leakage was observed, though the differences were only significant for the conventionally-prepared cavities. This led the authors to conclude that the acid etching technique had very little influence on microleakage in the laser-prepared cavities, with or without a bevel. As would be predicted, of the lased cavities, those with the higher C-factor (non-bevelled) exhibited the worst leakage.

In a similar study using 350 mJ at 1.5 Hz for cavity preparation, 120 mJ for bevelling, and an undefined storage period, Hibst and Keller (1994) investigated the efficacy of the enamel/composite bond using laser etching instead of conventional acid preparation, with and without thermocycling. Irrespective of the method of cavity preparation, thermocycling resulted in a significant increase in microleakage. After thermocycling and immersion in fuchsin dye, they found that bevelling and acid etching significantly reduced microleakage in the lased cavities. Furthermore, for the laser-prepared margins, when acid-etching was omitted, the box-shaped cavities exhibited significantly more microleakage than those that had been bevelled with the laser. This, and the influence of acid-etching on microleakage were in contrast to the findings of Hofmann *et al* (1992). However, in agreement with Hofmann *et al* (1992), with the exception of the lased cavities where bevelling had been achieved with the laser, the etched cavities that had been conventionally prepared and bevelled exhibited the least dye penetration. In addition, the sealing quality of laser-etched enamel margins improved and approximated to that of acid-etched margins, when, prior to laser etching, the enamel was roughened by a defocused Er:YAG laser application. Hibst and Keller (1994) suggested that this was because cavity preparation with a single laser energy led to a surface consisting of small, but separated craters when compared to the two stage procedure, and the relatively large area of untreated enamel led to a reduced micromechanical attachment. These findings

led them to suggest that etching with phosphoric acid could be replaced by laser conditioning with conventionally-prepared bevelled enamel margins.

Wright *et al* (1993) compared the efficacy of the enamel/composite seal obtained after acid-etching with that achieved with laser etching. They reported no significant difference in leakage after 90 days storage between conventionally-prepared cavities with enamel etching achieved by conventional phosphoric acid-etching or laser-etching, and lased cavity preparation with laser-etched enamel margins. However, very low pulse energies were used in this study; 300 μJ at 2 Hz with a 200 μJ etch.

To summarise, from these studies, there would appear to be agreement that the conventionally-prepared, bevelled and etched enamel margins, on the whole, produce a better composite/enamel seal when compared to margins prepared by the laser. However, while the leakage seen at the lased margins was influenced by the margin preparation, there did not appear to be any clear cut trends. It would appear, therefore, that both the macro- and micro-structure of the enamel is important when considering microleakage (Hibst & Keller, 1994). In addition, differences in experimental protocol and material variables may also contribute to these apparent discrepancies. Investigations on the sealing quality of composite restorations in dentine has highlighted the importance of the choice of dentine bonding agent (Haller *et al.*, 1993b). Using the same microfilled composite resin, and laser parameters of 250 mJ at 2 Hz, two of the seven dentine bonding agents exhibited significantly lower microleakage scores for lased cavities when compared to conventional preparation. A further two showed no difference and the efficacy of the remaining three agents, one of which was Scotchbond Multi-Purpose, was reduced when the cavities were prepared with the Er:YAG laser. It would appear therefore that in addition to the need for optimal laser variables, the choice of composite resin and dentine bonding agent is also essential.

In addition to investigating the efficacy of the tooth/composite restoration interface, Hofmann *et al* (1992) and Haller *et al* (1993b) also found that the marginal seal of glass-ionomer cement materials and resin-modified glass-ionomer cements was superior in the conventionally-prepared cavities when compared to those prepared with the laser.

2.11 General summary

This review of the literature has indicated that, of the lasers developed to date, the Er:YAG laser shows promise as an optical drill and therefore may have a role to play in the dental management of anxious individuals. It is essential that the use of the laser does not damage the marginal integrity of the resulting restoration. However, when using the laser, the dentist is faced with a broad range of operating parameters. While it is desirable to be able to remove caries, enamel and dentine at rates that are at least comparable to the conventional high-speed drill and bur, it is important that the selected operating conditions do not adversely affect microleakage at the dentine and enamel margins for the restorative material being used. This study seeks to address this issue for three pulse energies and two currently used direct adhesive materials.

2.12 Aims and objectives

The aim of this *in vitro* study was to investigate whether cavity preparation with an Er:YAG laser influenced the seal of Class V composite resin and compomer restorations at the enamel and dentine margins.

The objectives were to:

- evaluate the effect of three different laser energy densities on microleakage
- compare the microleakage of cavities prepared with the Er:YAG laser with those prepared conventionally with a diamond bur in a high-speed air-rotor handpiece
- compare the microleakage of the two materials
- assess the influence of storage on composite restorations

This work tests the null hypothesis that the use of the Er:YAG laser in cavity preparation does not have a deleterious effect on the microleakage of Class V restorations when compared to cavity preparation with a diamond bur used in a conventional high-speed handpiece.

3 *Materials and method*

3.1 Materials

Two restorative systems, each with their respective bonding agents, were used in this study. They were:

- Z100 MP (Z100) (3M Dental Products, St Paul, MN, USA) with Scotchbond Multi-Purpose (SMP) (Figure 3.1) and
- Compoglass (Vivadent, Schaan, Leichtenstein) with Compoglass Single Component Adhesive (SCA) (Figure 3.2).

3.1.1 Z100

Z100 is a dense, ultrafine compact-filled hybrid composite (Willems *et al.*, 1993) with an inorganic filler loading of 84.5% by weight and 71% by volume (3M, 1997) and is dispensed in pre-dosed compules. The fillers are rounded zirconia fillers produced by the sol-gel process (Ferracane, 1995) and have a mean size of 0.6–1.0 μm. However, there is a wide distribution of sizes up to a maximum of 4 μm which obviates the need for the addition of amorphous silica to improve the handling properties. The major component of the resin is Bis-GMA with a diluent resin of TEGDMA. This organic phase comprises 15.5% by weight of the total material (3M, 1997). The material has good strength and handling properties, and the abrasion resistance and polishability are excellent, due in part to the spherical nature of the fillers. The resin is also fast-setting and relatively rigid (de Gee & Pallav, 1994).

3.1.2 Scotchbond Multi-Purpose

SMP is a fourth generation dentine bonding agent and is composed of three components: an acid, a primer and an adhesive. The etchant in the original SMP agent was 10% maleic acid, and bond strengths to enamel and dentine of

Figure 3.1 Z100 composite resin and Scotchbond Multi-Purpose bonding agent

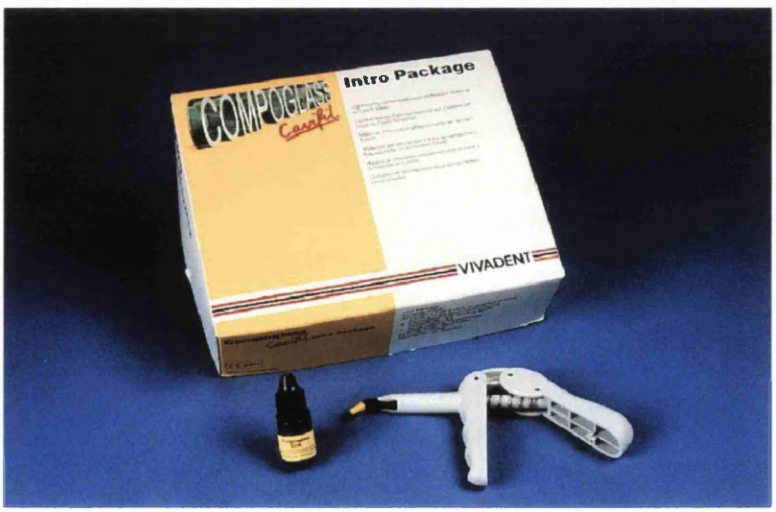

Figure 3.2 Compoglass compomer resin and Compoglass Single Component Adhesive

17.0 MPa and 21.8MPa respectively were achieved (Swift & Triolo, 1992). Moreover, these values increased when 35% phosphoric acid was substituted as the etchant with bond strengths of 24.5 MPa (Swift & Cloe, 1993) and 24.0 MPa (3M, 1994) being reported for enamel and dentine respectively. The more recent materials in the UK, and therefore in this study have used a phosphoric acid etchant.

The primer is composed of the hydrophilic monomer HEMA and an acid copolymer, while the adhesive is based on Bis–GMA and HEMA and also contains an initiator. In common with other fourth generation materials, SMP employs total etch and moist bonding techniques. Successful moist bonding is dependent on the presence of the acid co-polymer (Gwinnett, 1992). Bonding is achieved by the alteration of the smear layer and subsequent hybridisation (Section 2.7.2.2.1). *In vitro* microleakage does not appear to be affected adversely when the dentine is left visibly moist (Saunders & Saunders, 1996), an advantage when bonding to deeper, highly permeable dentine. The viscous adhesive results in a relatively thick intermediate resin layer with an identical stress-relaxation buffer capacity as a low viscosity resin (Van Meerbeek *et al.*, 1994).

3.1.3 Compoglass

Compoglass is a single-component, light-cured, fluoride-releasing compomer resin and is dispensed in pre-dosed plastic compules known as Cavifils. Composite resin makes up 70% of the material, the remainder is glass-ionomer. The resin is based on Bis–GMA and urethane dimethacrylate in a ratio of 1:2.3 by weight, and the monomer has been modified by adding a cycloaliphatic dicarboxylic acid dimethacrylate (DCMA) (Vivadent, 1996). Compoglass has a filler loading of 55.9% by weight and 79% by volume. The fillers, sialinised barium fluorosilicate glass and ytterbium trifluoride fillers, have a mean particle size of 1.6 μm and are responsible for the fluoride release of the resin.

The manufacturers claim that the resin sets via radical polymerisation and that an auxiliary acid-base setting reaction occurs when the material is placed in water. However, no increase in compressive strength was found after storage in water, and this secondary reaction has been questioned (Burgess *et al.*, 1996).

Bonding to enamel and dentine is purely reliant on micromechanical attachment via a resin-reinforced hybrid layer formed by the application of Compoglass SCA.

3.1.4 Compoglass Single Component Adhesive

Compoglass SCA is a single-component, light-curing, self-priming bonding agent. It consists of a methacrylate-modified polyacrylic acid, HEMA, water, maleic acid, ammonium fluoride, photoinitiators and stabilisers. Acid-etching is not required and the material bonds effectively to the dentinal smear layer via the formation of a hybrid layer. Bond strengths to enamel and dentine of 18 MPa and 19 MPa respectively have been reported (Vivadent, 1996). In addition, the presence of the fluoride ion results in fluoride release.

3.2 Method

3.2.1 Tooth selection

Caries- and restoration-free extracted permanent human premolar teeth, which had been stored in 0.12% thymol solution, were examined macroscopically for defects in the enamel and dentine. One hundred and eighty four were selected and cleaned of superficial debris with a scalpel. They were then lightly pumiced before being randomly allocated to three equal sized groups, A, B and C.

3.2.2 Cavity preparation

A butt-joint Class V cavity was prepared on both the buccal and lingual surfaces of each tooth. Each tooth hosted a test and control cavity. The former was cut with a pulsed Er:YAG laser (Twinlight Dental Laser, Fotona d.d, Ljublijana, Slovenia) (Figure 3.3) and the control cavity was cut with a diamond fissure bur (#FG108008, Horico, Berlin, Germany) in a high-speed air-rotor handpiece. In both cases an air/water coolant was used and the tooth and handpiece were held by hand (Figure 3.4). The bur was changed after 20 cavities. Allocation of the test and control surfaces was random. The cavities were prepared at the cervical margin of the tooth (Figure 3.5), with the coronal and gingival margins in cervical

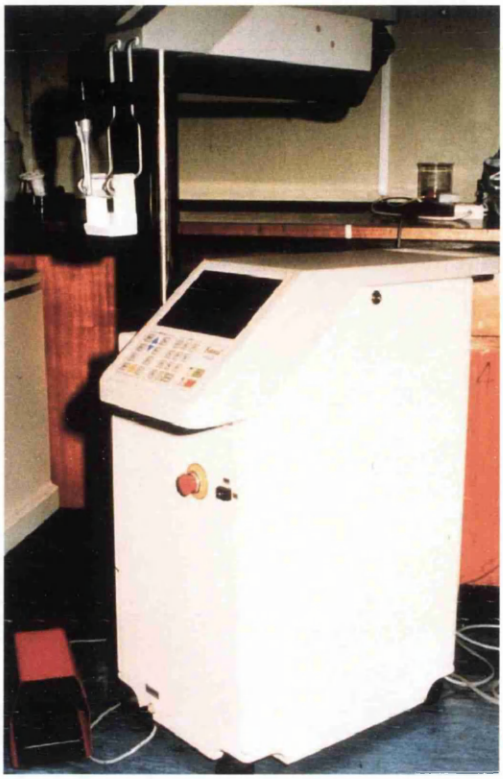

Figure 3.3 The Erbium:YAG Twinlight Dental Laser

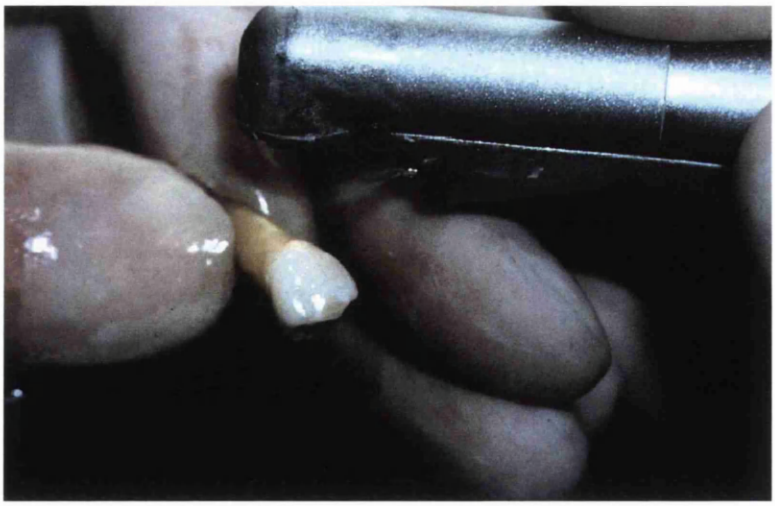

Figure 3.4 Cavity preparation using the Erbium:YAG laser

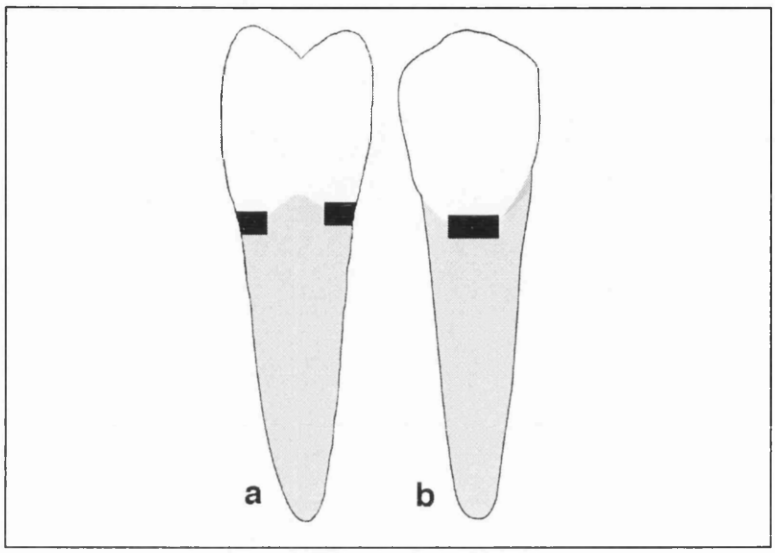

Figure 3.5 Line drawing showing the position of the cavity at the cervical margin of the tooth; a) approximal surface b) buccal surface

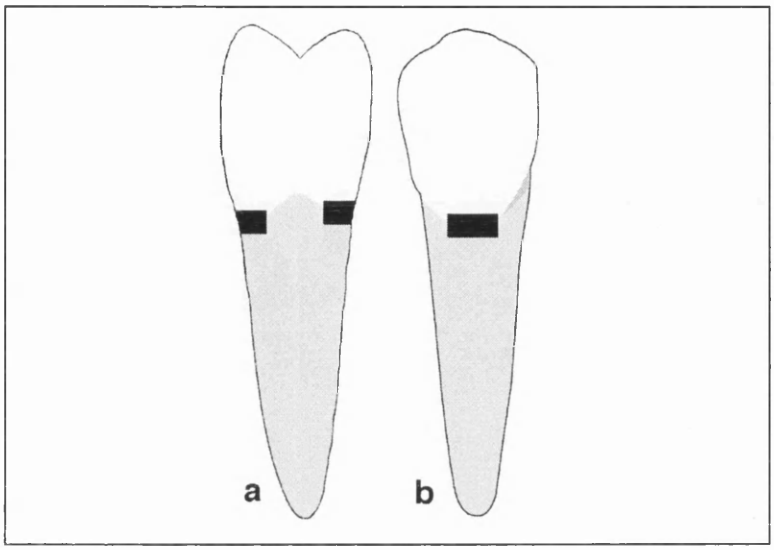

Figure 3.5 Line drawing showing the position of the cavity at the cervical margin of the tooth; a) approximal surface b) buccal surface

enamel and dentine or cementum respectively. The cavity size was made as uniform as possible, 1.5 mm deep, 3 mm in width and 2 mm in height, using metal strip templates (Figure 3.6). A two stage impression of each cavity was then taken using Extrude addition cured silicone elastomeric impression material (Kerr, Romulus, MI, USA) in a purpose-made tray. These were stored for SEM analysis in another study. On completion the teeth were returned to the thymol solution.

3.2.2.1 Laser parameters

Local laser protection guidelines were followed during lasing. The operating parameters were selected on the control panel (Figure 3.7). A pulse repetition rate of 5 Hz was used. This is known to ablate enamel and dentine with minimal thermal damage (Li *et al.*, 1992). The teeth in each of the three groups (A, B and C) were randomly divided into three subgroups, so enabling three different laser energies to be tested on each group; one on each subgroup within a group. The three laser energies selected were 200 mJ, 240 mJ and 300 mJ. Charring of the dentine was seen at the latter pulse energy (Figure 3.8) and therefore a 100 mJ dentine finish was used for the 300 mJ cavities only. For clarity, the subgroups were identified using the suffixes 200, 240 and 300. The air pressure was maintained at a constant 20 PSI, and the water mist was provided from a hand-pumped plastic container. The maximum pressure for this was selected by qualitative assessment of the resistance felt during hand-pumping.

3.2.3 Cavity restoration

The teeth in groups A and B were restored with SMP and Z100 resin (shade A3.5) according to the manufacturer's instructions: each cavity was lightly cleaned with a pumice and water slurry in a rubber cup. They were then washed and dried with compressed, oil-free water and air from a 3-in-1 syringe. Total etching was performed with the 35% phosphoric acid gel for 15 seconds, then each cavity was washed copiously with water for 15 seconds before being dried gently with compressed air for 5 seconds. The priming agent was applied and was lightly dried immediately with air for 2 seconds. Following this, the adhesive was applied with a brush and light-cured for 10 seconds with a visible light activating

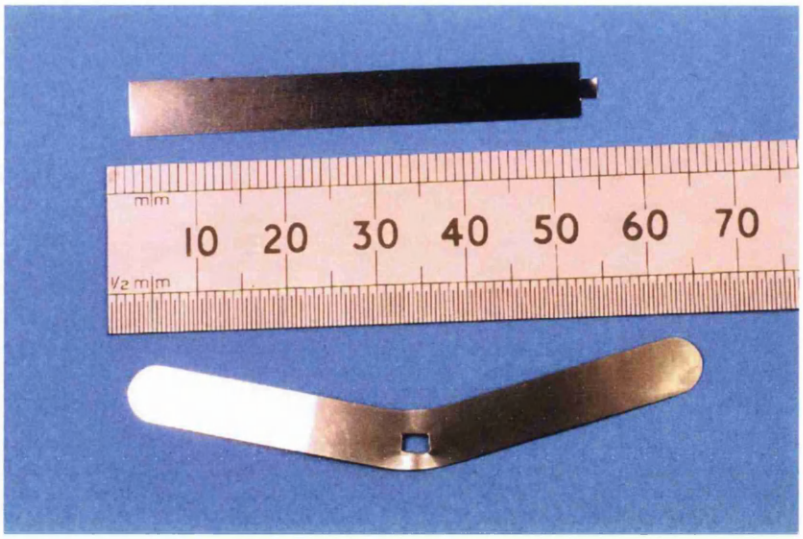

Figure 3.6 The metal templates used during cavity preparation

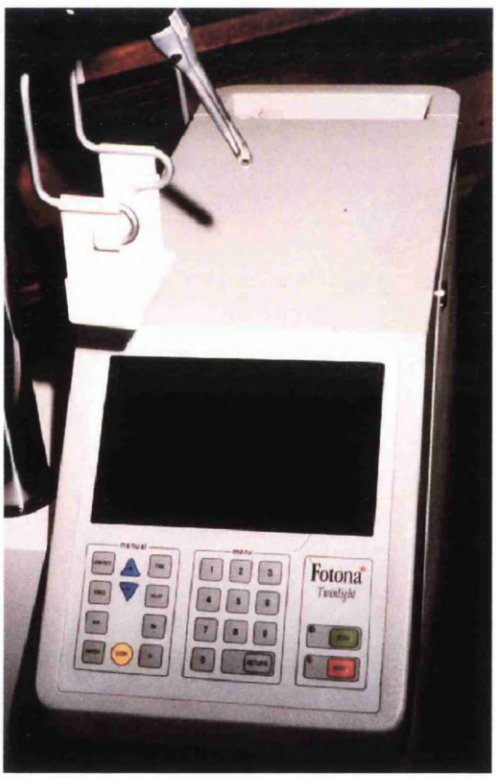

Figure 3.7 The control panel of the Erbium:YAG Twinlight Dental Laser

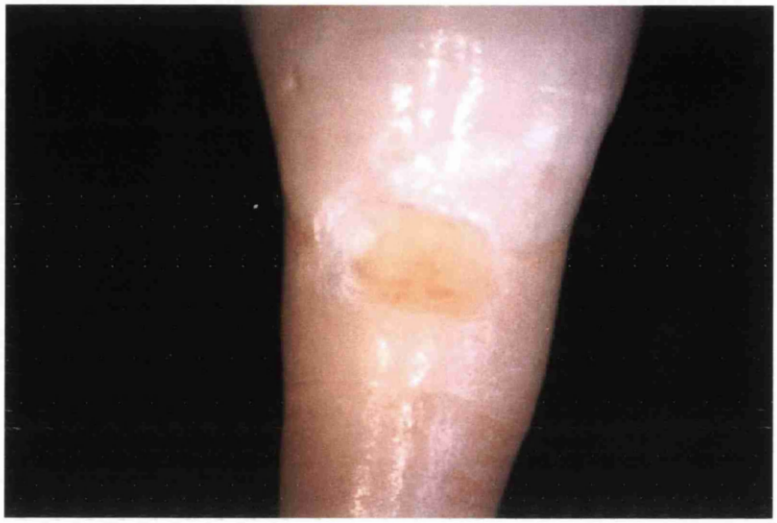

Figure 3.8 Dentine charring during cavity preparation with the 300 mJ pulse energy

unit (Luxor, ICI Macclesfield, UK). The composite resin was applied in three increments. The first two were applied obliquely against the occlusal and the gingival walls respectively. The final increment was placed flush with the contour of the tooth and covered with a transparent cellulose acetate matrix strip to both assist in packing and contouring, and reduce oxygen inhibition during polymerisation. Each increment was light-cured for 40 seconds. Finishing was carried out immediately after polymerisation using graded Soflex discs (3M Dental Products, St Paul, MN, USA) according to the manufacturer's instructions.

The initial stages of the protocol for the restoration of group C was identical to that described for groups A and B (i.e. cleaning with pumice and water slurry and washing and drying with compressed water and air). The cavities were then restored with Compoglass SCA and Compoglass resin (shade A3.5) following the manufacturer's instructions. The bonding agent was applied to the cavity for 20 seconds, following which it was distributed with air and light-cured for 20 seconds. A second layer of Compoglass SCA was applied and immediately distributed with blown air before being light-cured for 20 seconds. The resin was applied incrementally and cured as for groups A and B and then the restoration was finished and polished with graded Soflex discs.

3.2.4 Storage and thermocycling

Following restoration, group A was stored for 24 hours and groups B and C were stored for 3 months in 0.12% thymol solution at a constant temperature of 37 °C. Each tooth was then thermocycled through water baths at 5 °C, 37 °C, 55 °C and 37 °C, with a 10 seconds dwell time in each bath for 240 cycles (Figure 3.9) before being returned to the thymol solution at 37 °C for 12 hours. Care was taken to avoid dehydration at any stage of restoration and during the subsequent preparation for microleakage.

3.2.5 Microleakage assessment

Microleakage was assessed using a dye penetration technique with *in vitro* immersion (Section 2.5.2). The teeth were dried, the root apices sealed with sticky wax and coated with two layers of nail varnish (Max Factor Diamond Hard, Procter and Gamble, Surrey, UK) to within 1 mm of the restoration. Once

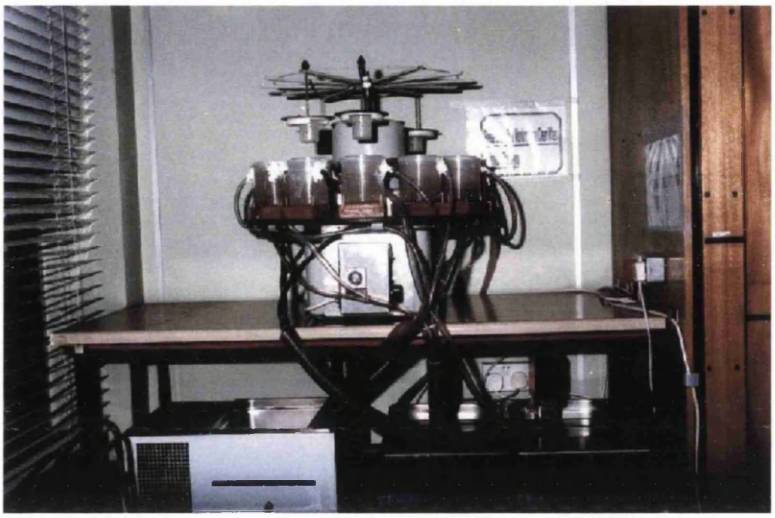

Figure 3.9 The thermocycling unit

the nail varnish was dry, the teeth were returned to the thymol solution for a further 12 hours. Following this, each tooth was placed in a 2% aqueous solution of methylene blue, buffered to pH 7.00, for 24 hours at 37 °C. The teeth were then rinsed thoroughly in tap water and the varnish removed with a wax knife. Each tooth was sectioned longitudinally in a bucco-lingual plane through the mid-point of the restorations with a water-cooled diamond disc on a microtome, Labcut (Agar Scientific Ltd, Stansted, UK) (Figure 3.10). Microleakage was assessed by two calibrated examiners who were unaware of the groupings of the teeth. Differences were reconciled by agreement. For each tooth, both sections were examined under x6 magnification and the extent of the leakage was scored at both the enamel and dentine margins using the following rank order system (Saunders *et al.*, 1991) (Figures 3.11–3.15).

0: no dye penetration;
1: dye penetration up to one-third cavity depth;
2: dye penetration up to two-thirds cavity depth;
3: dye penetration to full cavity depth;
4: extensive dye penetration to and into pulpal floor/axial wall.

The scores for both sections were compared and the worst score for each margin was chosen to represent the specimen for statistical analysis.

3.2.6 Statistical analysis

The data were analysed on a PC using Minitab (Minitab inc. State College, PA, USA). The effect on leakage of the type of restorative material used was assessed by comparing the results for group B (Z100 restorative stored for 3 months) with those for group C (Compoglass stored for 3 months). To assess the effect of storage time on leakage the results from group B were compared with those from group A (Z100 stored for 24 hours). These comparisons were made for the enamel and dentine margins separately. For both margin types the conventionally-prepared and lased cavities were considered separately and were then compared.

In addition, the extent of leakage in each of the subgroups (200, 240 and 300) within each group (A, B and C) was compared for both types of cavity

Figure 3.10 The Labcut microtome used for sectioning

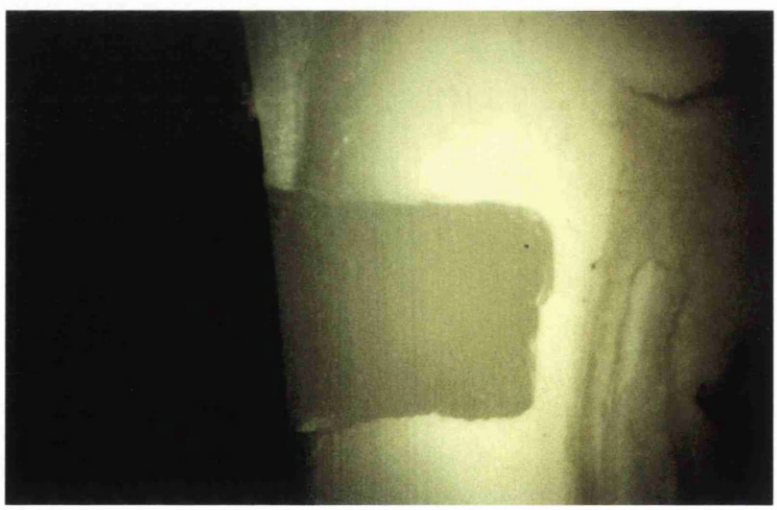

Figure 3.11 Microleakage scoring: enamel margin = 0, dentine margin = 0

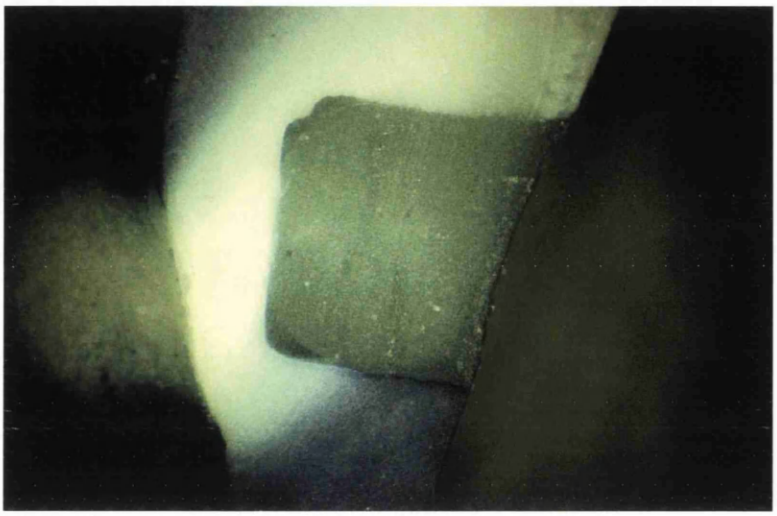

Figure 3.12 Microleakage scoring: enamel margin = 1, dentine margin = 3 with extensive dye penetration in the dentinal tubules

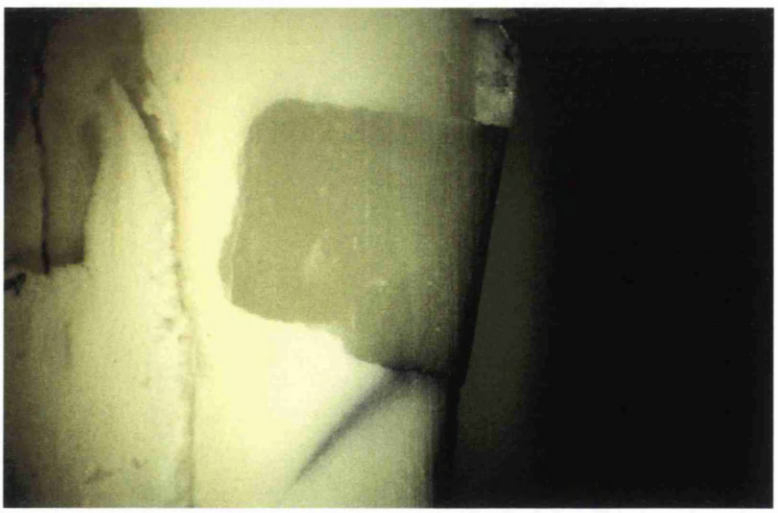

Figure 3.13 Microleakage scoring: enamel margin = 1, dentine margin = 2 with minimal dye penetration in the dentinal tubules

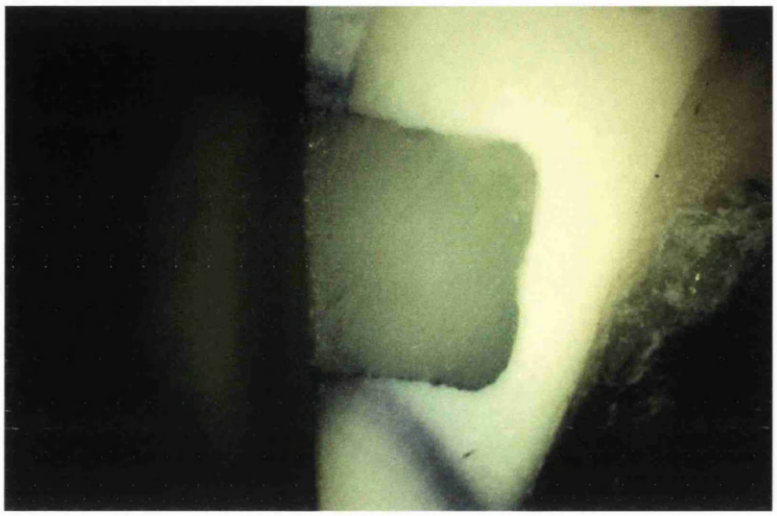

Figure 3.14 Microleakage scoring: enamel margin = 2, dentine margin = 4 with minimal dye penetration in the dentinal tubules

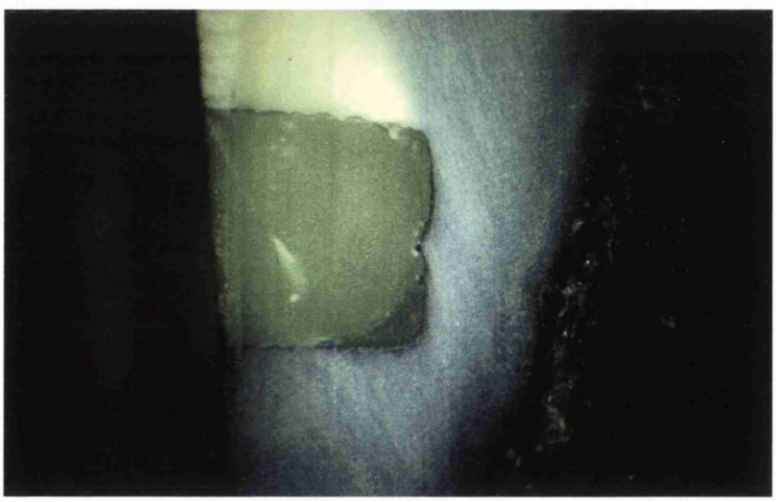

Figure 3.15 Microleakage scoring: enamel margin = 2, dentine margin = 4 with extensive dye penetration in the dentinal tubules

preparation. Since these subgroup divisions were based on the different laser energies used, no significant difference in microleakage was expected for the conventionally-prepared cavities i.e. the control cavities. Statistical comparison of the subgroup data for the conventionally-prepared cavities therefore provided a means of checking the integrity of the methodology used.

The Kruskal-Wallis test was used to determine the statistical difference among the groups. The comparison of paired groups was made using the non-parametric Mann-Whitney U-test. Both tests were corrected for ties and a 0.05 level of significance was applied.

4 Results

4.1 Introduction

There was evidence of dye penetration, and therefore microleakage, to a greater or lesser extent, in teeth from each of the groups (Table 4.1). As indicated in Section 3.2.6, ranking the degree of microleakage enabled the data to be analysed statistically. The results of these analyses are reported below for the two margin types following the framework described in Section 3.2.6. Where appropriate, the results have been illustrated using graphs annotated with the levels of significance.

4.2 Enamel margins

4.2.1 Conventionally-prepared enamel margins

4.2.1.1 Within-group analyses

For the conventionally-prepared enamel margins, the Kruskal-Wallis test showed no significant difference in leakage at the 95% significance level between subgroups 200, 240 and 300 for each of the three groups, A, B and C ($p = 0.21$, $p = 0.53$ and $p = 0.86$ respectively). As indicated in Section 3.2.6, this provided an indication of the integrity of the methodology used. It also meant that these subgroup leakage scores could be combined for further comparisons involving only the conventionally-prepared cavities (i.e. the intergroup analysis in Section 4.2.1.2 and the enamel *versus* dentine analysis in Section 4.4).

4.2.1.2 Intergroup analyses

As discussed in Section 3.2.6, to assess the effect of storage time on the degree of leakage, the group A scores were compared to those from group B. The effect of the restorative material on the degree of leakage was assessed by comparing the

Table 4.1 Microleakage scores for all cavities

Restoration	Group	N	Margin	Conventionally-prepared scores					Lased scores				
				0	1	2	3	4	0	1	2	3	4
Group A	A200	20	Enamel	3	13	3	1	0	3	11	6	0	0
Z100 and	A200	20	Dentine	0	12	0	0	8	0	7	1	0	12
SMP stored	A240	23	Enamel	3	7	11	1	1	4	1	16	2	0
for 24 hours	A240	23	Dentine	4	11	3	0	5	1	4	4	2	12
	A300	20	Enamel	5	6	6	2	1	4	5	9	1	1
	A300	20	Dentine	1	8	5	1	5	0	7	6	1	6
Group B	B200	20	Enamel	11	7	1	1	0	5	12	1	2	0
Z100 and	B200	20	Dentine	2	4	6	2	6	0	1	1	2	16
SMP stored	B240	20	Enamel	15	2	2	0	1	12	7	1	0	0
for 3 months	B240	20	Dentine	1	4	3	2	10	0	1	0	0	19
	B300	20	Enamel	11	7	2	0	0	13	6	1	0	0
	B300	20	Dentine	8	1	4	0	7	3	3	1	1	12
Group C	C200	20	Enamel	8	9	2	1	0	12	6	2	0	0
Compoglass	C200	20	Dentine	7	4	7	1	1	6	7	7	0	0
and SCA	C240	20	Enamel	8	8	4	0	0	18	2	0	0	0
stored	C240	20	Dentine	5	7	6	1	1	9	5	3	2	1
for 3 months	C300	21	Enamel	9	10	1	0	1	11	8	1	0	1
	C300	21	Dentine	7	7	6	0	1	11	3	4	0	3

group B scores with those of group C. The results of these intergroup analyses are presented in Figure 4.1. This shows that the enamel margins of the teeth in group B exhibited significantly less leakage than those in either group A or group C ($p < 0.001$ and $p = 0.04$ respectively).

4.2.2 Lased enamel margins

4.2.2.1 Within-group analyses

Leakage was observed at the lased enamel margins in teeth from all three groups (Figure 4.2a–c). However, the severest level of leakage (score 4) was confined to one specimen in each of the subgroups A300 and C300 which was similar to the conventionally-prepared margins (Section 4.2.1.1).

Within each group the difference in the extent of leakage was compared between the subgroups (200, 240 and 300). In group A (Figure 4.2a) at least 80% (16) of specimens in each subgroup exhibited some degree of leakage. However, the difference was only significant between the A200 and A240 margins ($p = 0.02$) with the former showing less leakage.

Conversely, in group B (Figure 4.2b), the B200 margins showed significantly more leakage than those of B240 and B300 ($p = 0.02$ and $p = 0.01$ respectively). The patterns of leakage recorded for the B240 and B300 margins were almost identical ($p = 0.77$).

For group C (Figure 4.2c), there was no leakage in 90% (18) of cavities in C240. This was significantly better than the degree of leakage observed in either the C200 ($p = 0.03$) or C300 ($p = 0.01$) subgroups, where only 60% (12) and 55% (11) respectively of the enamel margins were completely sealed. There was no significant difference in leakage between margins in the C200 and C300 subgroups.

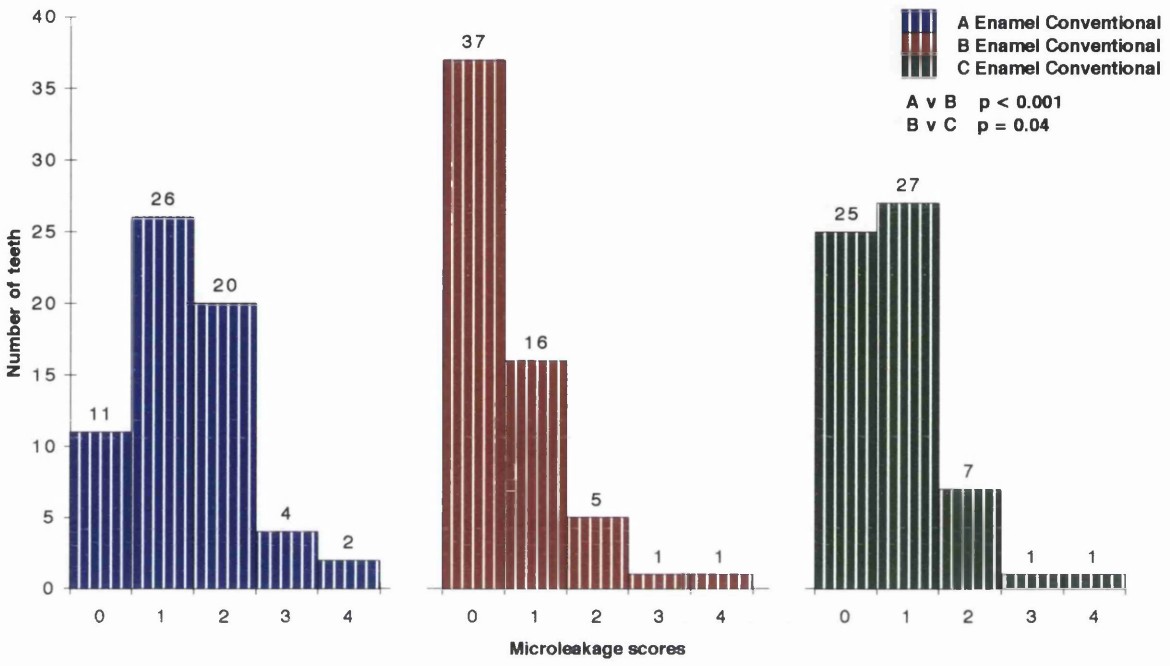

Figure 4.1 Microleakage seen at the enamel margins of conventionally-prepared cavities

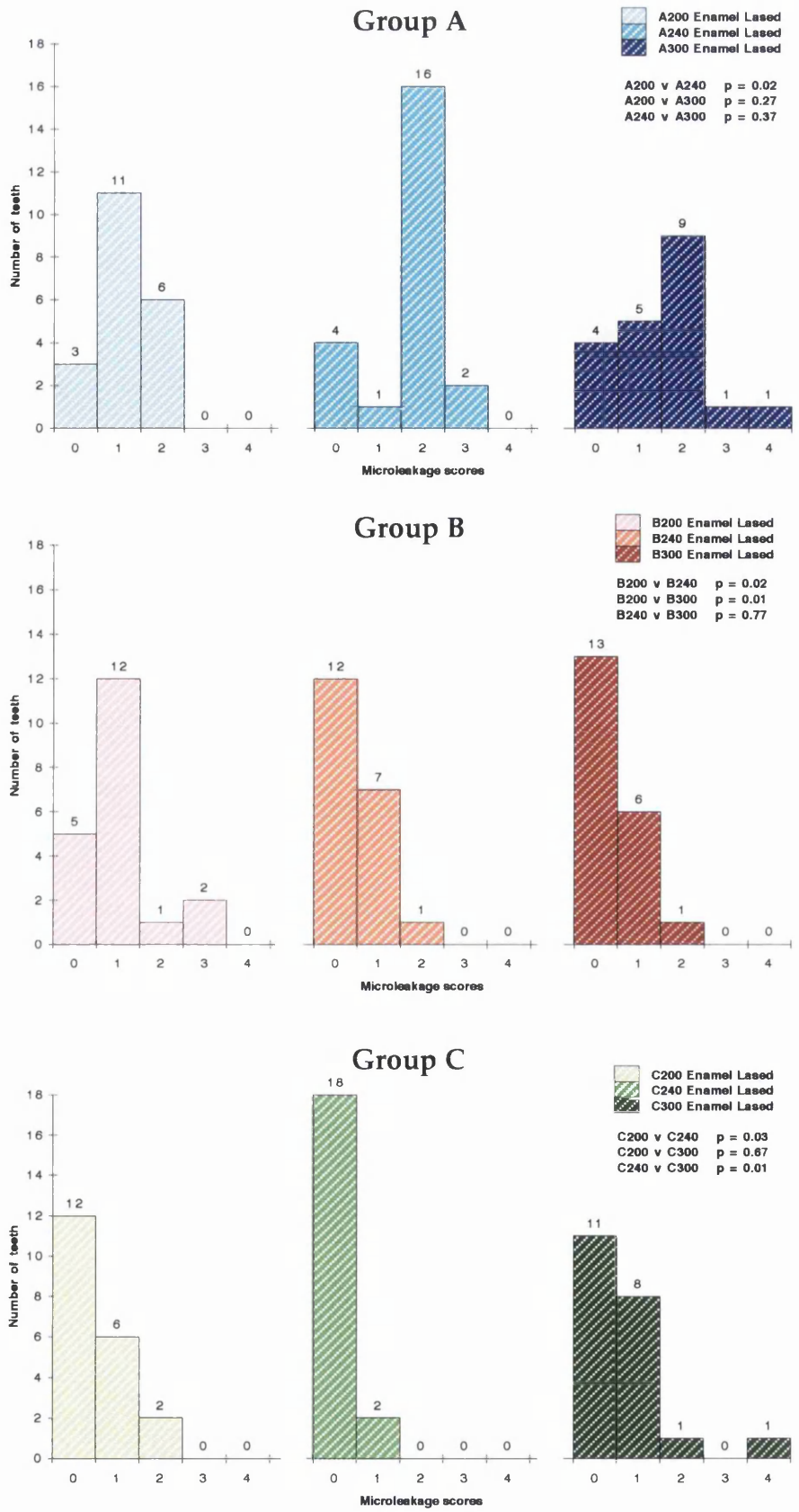

Figure 4.2a–c Microleakage seen at the enamel margins of lased cavities in groups A, B and C

4.2.2.2 *Intergroup analyses*

As with the conventionally-prepared cavities (Section 4.2.1.2), the group B results were compared with the leakage seen at the enamel margins of teeth in groups A (Figure 4.3) and C (Figure 4.4).

For all three subgroups (200, 240 and 300), the group B cavities exhibited less extensive microleakage than those of group A. However, the difference was only significant for subgroups A240 compared to B240 ($p < 0.001$) and A300 compared to B300 ($p < 0.001$). This pattern of leakage was similar to that reported for the conventionally-prepared margins in enamel (Section 4.2.1.2).

Comparison of the results from group B with those from group C showed significantly less leakage at the enamel margins in subgroups C200 ($p = 0.04$) and C240 ($p = 0.03$) compared to subgroups B200 and B240 respectively (Figure 4.4). In contrast, the difference in leakage between subgroups B300 and C300 was insignificant ($p = 0.39$).

4.2.3 Conventionally-prepared *versus* lased enamel margins

The extent of dye penetration at the conventionally-prepared enamel margins was compared to that at the enamel margins prepared with the Er:YAG laser (Figure 4.5a–c).

For group A (Figure 4.5a), the lased margins in subgroups A200 and A240 showed evidence of greater leakage than those in the same conventionally-prepared subgroups. However, the extent of leakage in the A300 lased margins was less than that observed in the A300 conventionally-prepared margins. None of the differences described above was significant ($p > 0.05$).

Comparison of the results from the group B lased margins with those from the group B conventionally-prepared margins (Figure 4.5b) showed a similar pattern to group A, i.e. greater leakage along the lased B200 and B240 margins and less leakage along the lased B300 margins compared to their respective conventionally-prepared margins. Again the differences were not significant ($p > 0.05$).

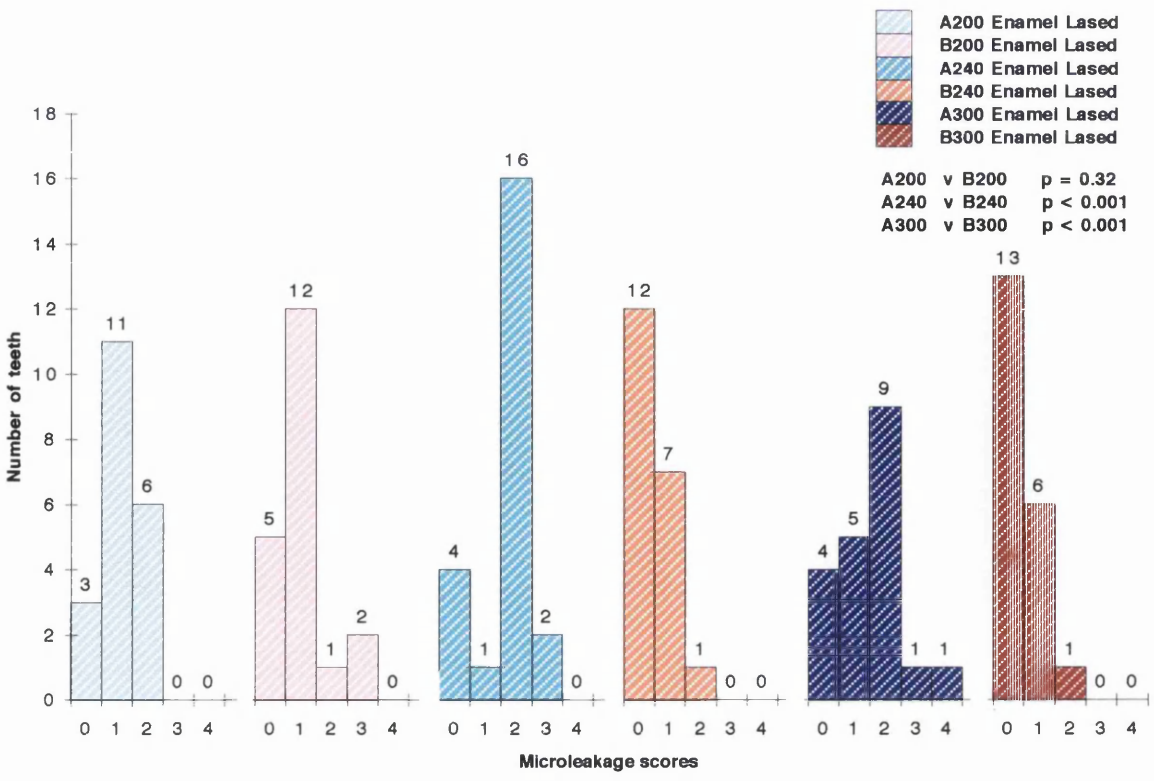

Figure 4.4 Intergroup analysis of microleakage seen at the enamel margins of lased cavities in groups A and B

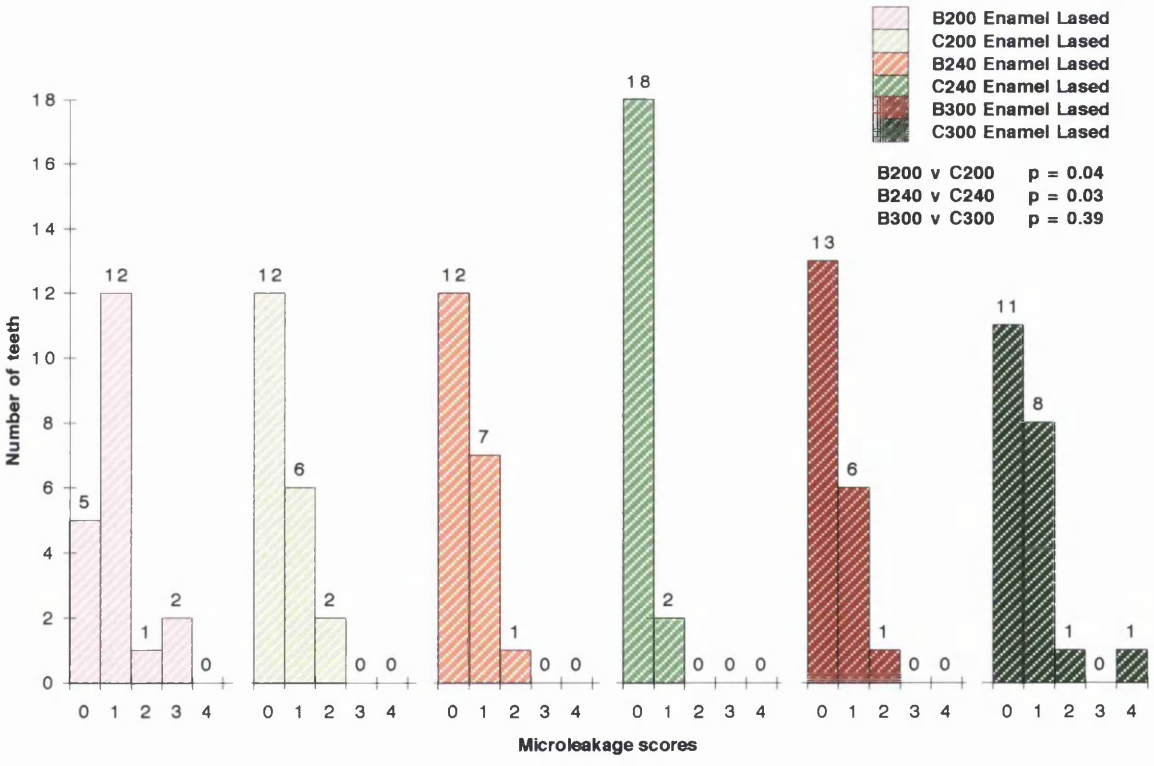

Figure 4.4 Intergroup analysis of microleakage seen at the enamel margins of lased cavities in groups B and C

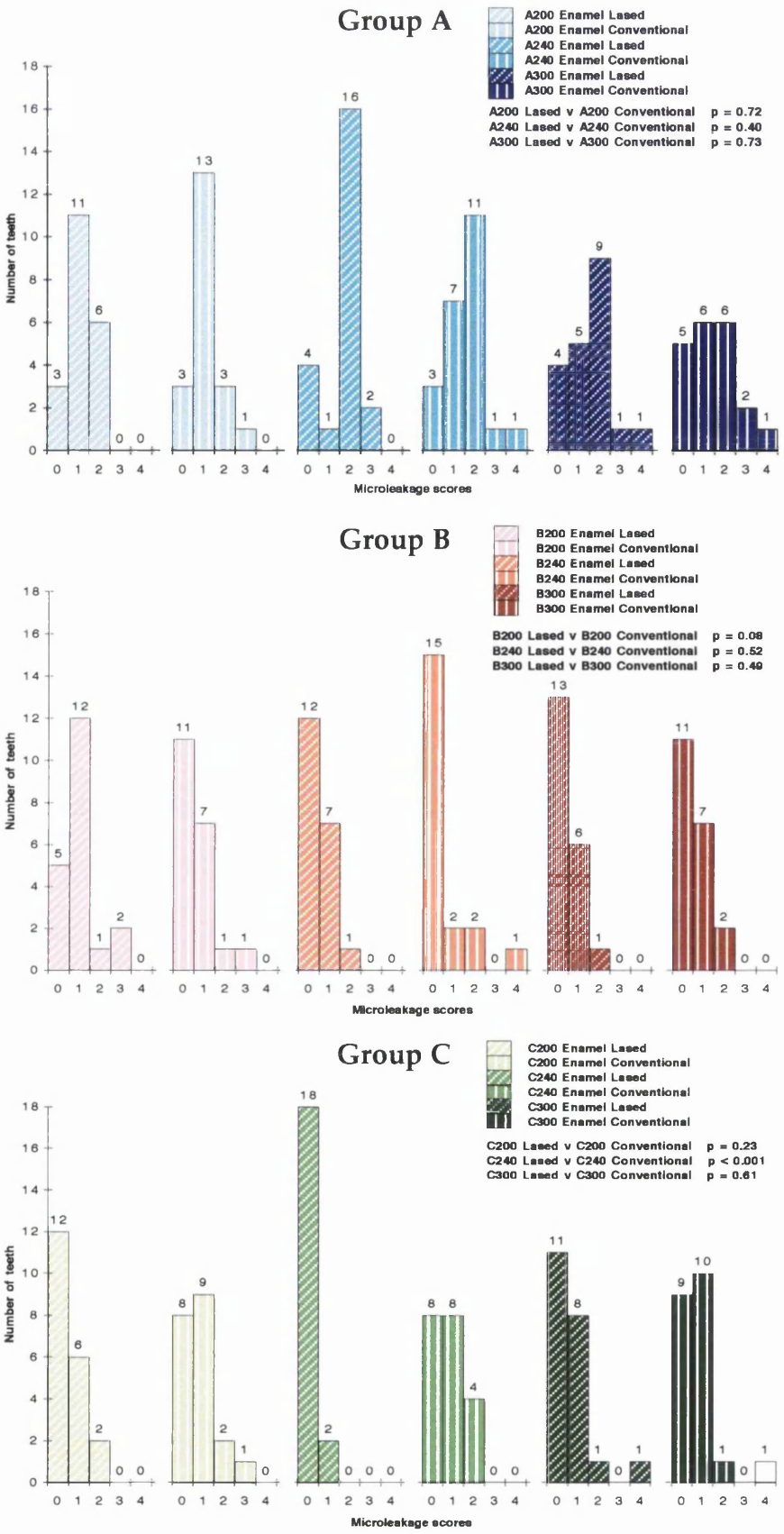

Figure 4.5a–c Analysis of the microleakage seen at the lased and conventionally-prepared enamel margins in groups A, B and C

In contrast to groups A and B, the group C lased enamel margins showed evidence of less leakage in subgroups C200 and C240 and more leakage in C300 than those prepared conventionally (Figure 4.5c). However, the differences were only significant for the C240 subgroups ($p < 0.001$).

4.3 Dentine margins

4.3.1 Conventionally-prepared dentine margins

4.3.1.1 Within-group analyses

There were examples in all three groups of scores for maximum leakage at the dentine margins (Figure 4.6). In group C this amounted to 5% (3) of the specimens but rose to 29%(18) and 38% (23) for groups A and B respectively. The Kruskal-Wallis test again (see Section 3.2.6) found no statistical difference between the subgroups in each of the three groups A, B and C ($p = 0.37$, $p = 0.18$ and $p = 0.76$ respectively), and therefore the subgroup leakage scores were again combined for further statistical analyses involving only the conventionally-prepared cavities.

4.3.1.2 Intergroup analyses

In contrast to the leakage seen at the enamel margins (Section 4.2.1.2), the dentine margins in group C demonstrated a significantly better seal than those of group B ($p < 0.001$; Figure 4.6). No significant difference was seen between groups A and B at the dentine margin.

4.3.2 Lased dentine margins

4.3.2.1 Within-group analyses

The leakage observed at the dentine margins in the three lased cavity groups is compared in Figure 4.7a-c. With the exception of C200, all subgroups in each group had at least one tooth which exhibited maximum dye penetration at the dentine margin. In group A, there was no significant difference in microleakage between the three pulse energies ($p > 0.05$; Figure 4.7a).

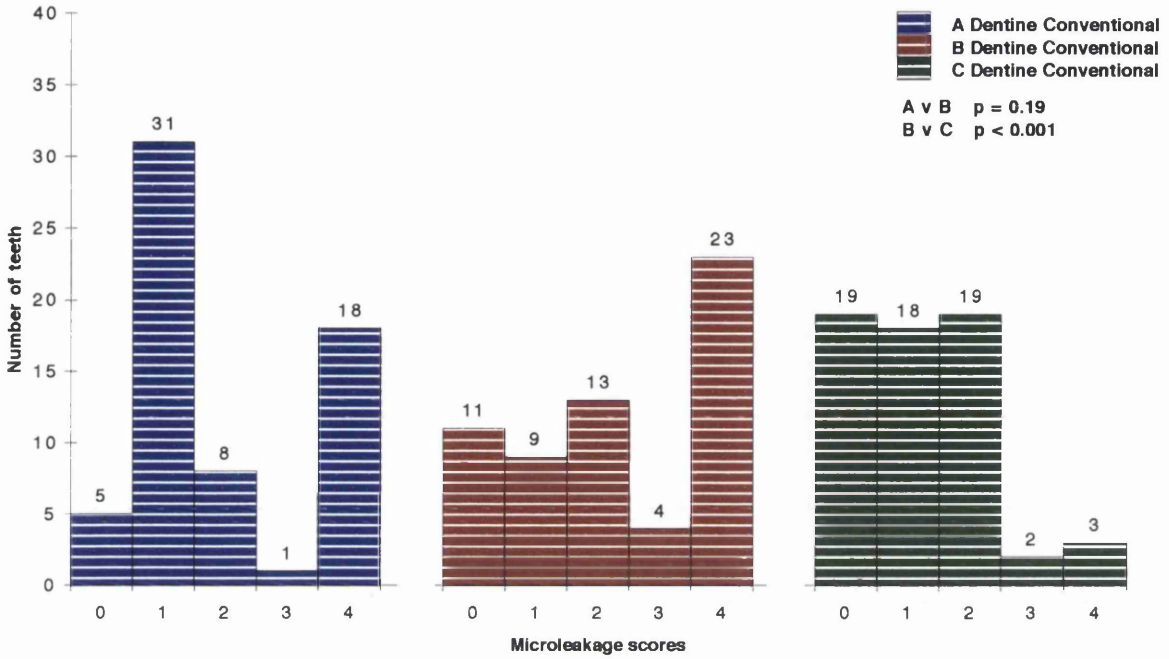

Figure 4.6 Microleakage seen at the conventionally-prepared dentine margins

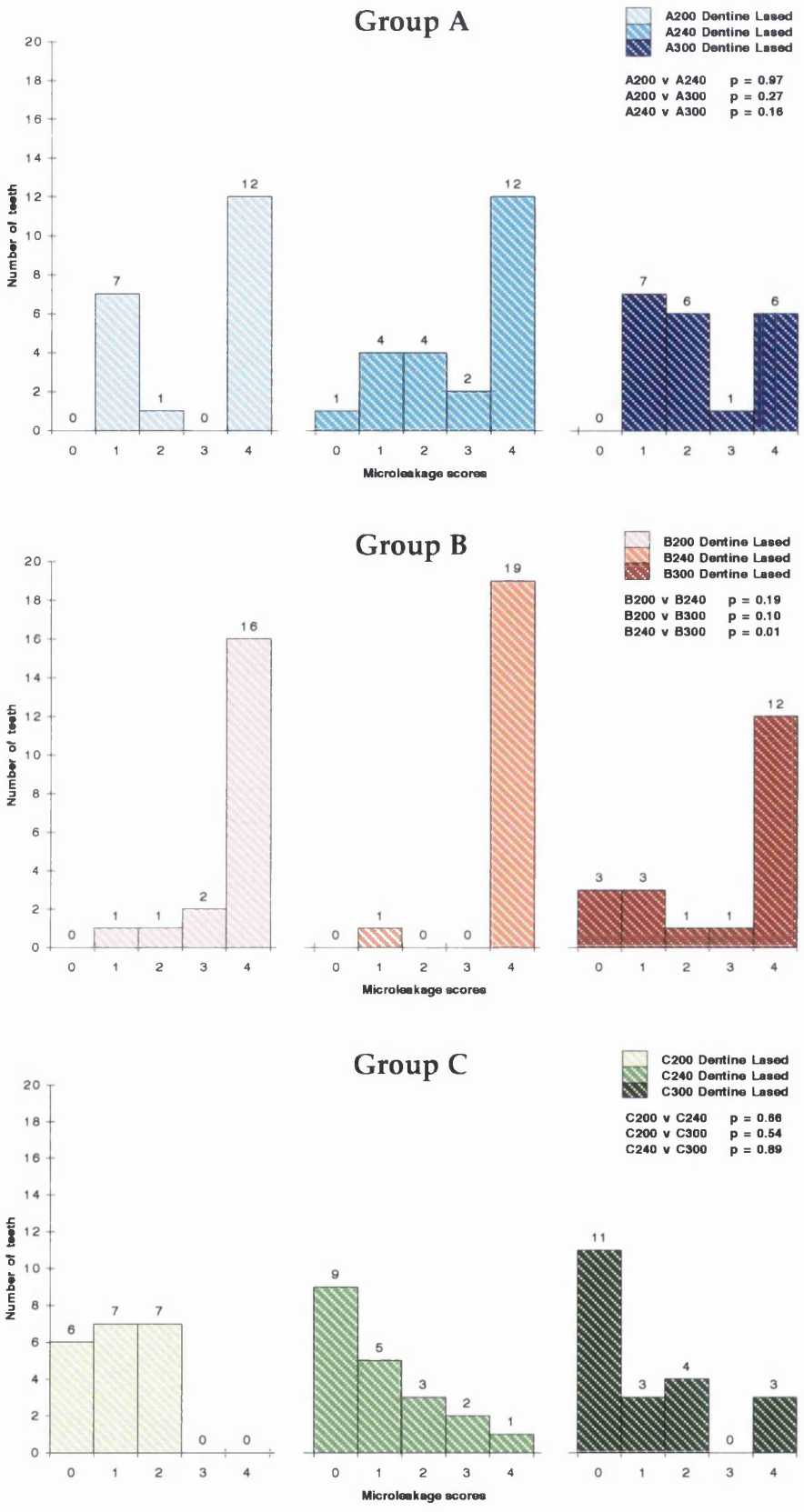

Figure 4.7a–c Microleakage seen at the dentine margins of lased cavities in groups A, B and C

There was very close correlation between the degree of leakage exhibited at the dentine margins of the A200 and A240 subgroups ($p = 0.97$).

Group B showed similar patterns of leakage to group A (Figure 4.7b). However, the dye penetration was more severe across all subgroups. The B300 margins exhibited less microleakage than both the B200 and B240 dentine margins but the difference was only significant for the latter ($p = 0.01$). Again no significant difference was found in leakage between the B200 and B240 subgroups ($p > 0.05$).

Comparison of the dentine margins within the subgroups of group C (Figure 4.7c) showed no statistical difference in leakage between the three pulse energies.

4.3.2.2 *Intergroup analyses*

Intergroup analysis between the subgroups of A and B (Figure 4.8) revealed that the leakage at the dentine margins was more severe for all subgroups of B compared to their respective subgroups in group A. This is in contrast to the leakage found at the enamel margins (Section 4.2.2.2). However, the difference was only significant between A240 and B240 ($p = 0.003$). This pattern of leakage was similar to that reported for the conventionally-prepared dentine margins (Section 4.3.1.2).

Comparison of the results for groups B and C (Figure 4.9) showed significantly worse leakage for B200, B240 and B300 compared to the respective subgroups in C ($p < 0.001$, $p < 0.001$ and $p = 0.002$ respectively).

4.3.3 Conventionally-prepared *versus* lased dentine margins

As for the enamel margins, the extent of dye penetration in the conventionally-prepared groups was compared to that of the lased cavities (Figure 4.10a–c).

Comparison of the dentine margins in group A (Figure 4.10a), indicated that the extent of microleakage was less for the conventionally-prepared cavities than it was for the lased cavities. However, the difference was only significant for the A240 subgroup ($p = 0.005$).

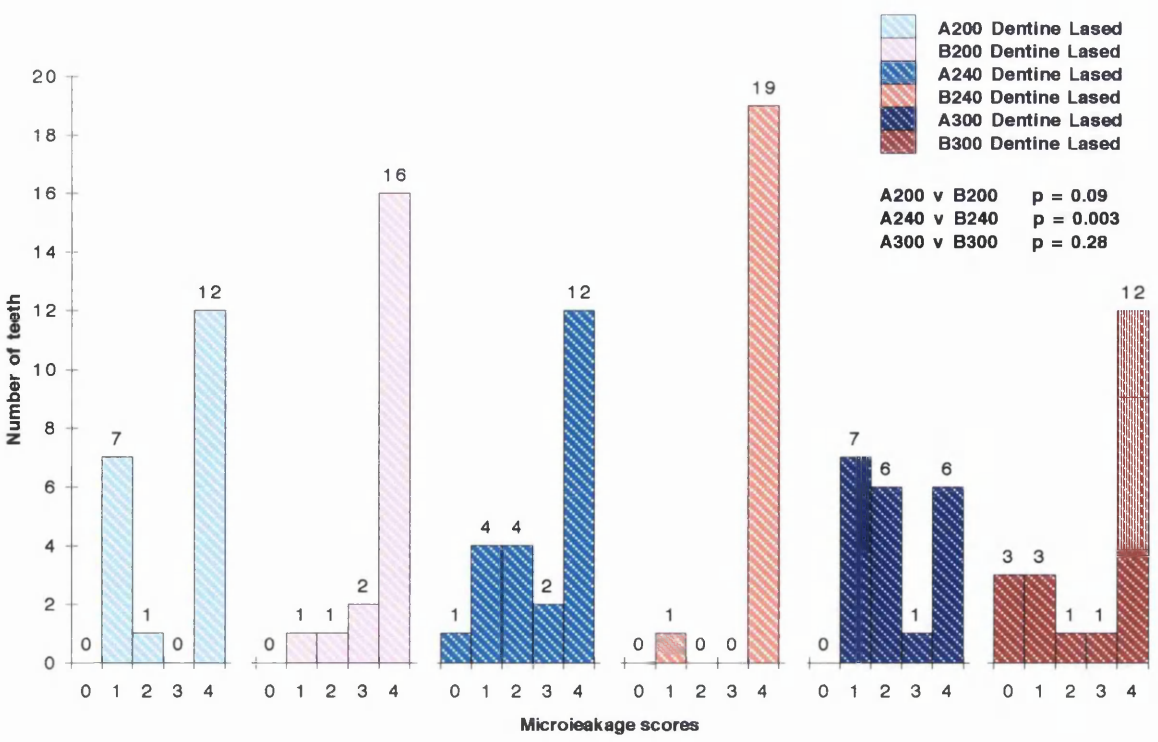

Figure 4.8 Intergroup analysis of microleakage seen at the dentine margins of lased cavities in groups A and B

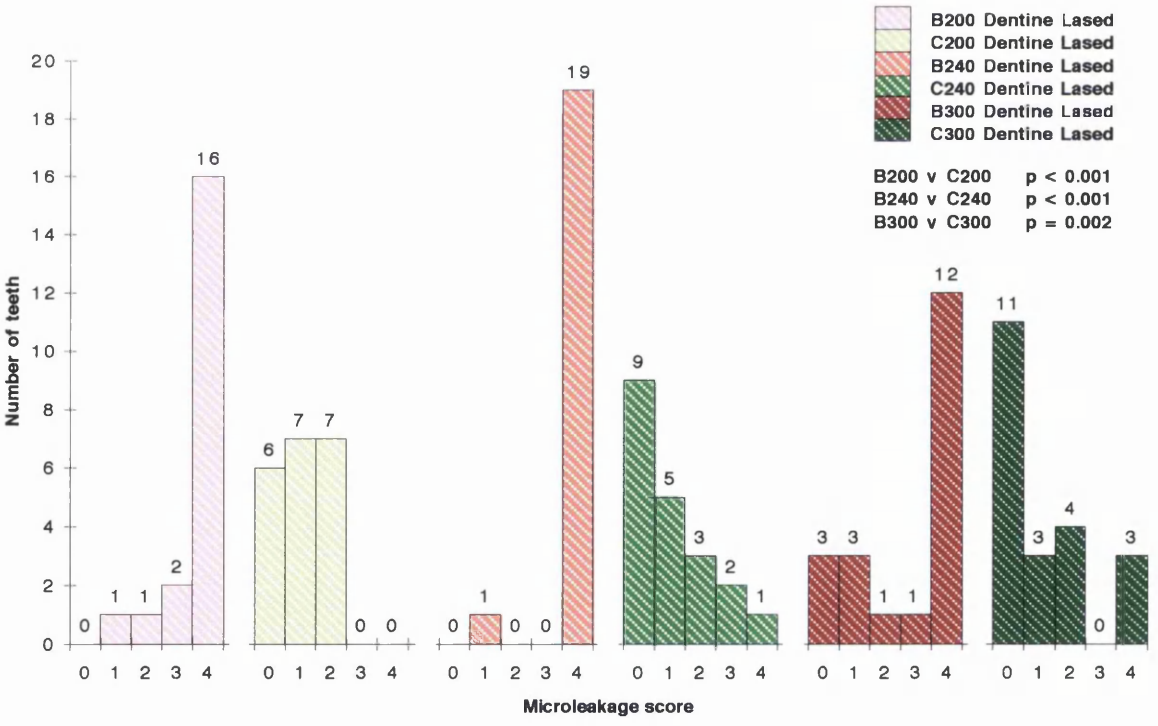

Figure 4.9 Intergroup analysis of microleakage seen at the dentine margins of lased cavities in groups B and C

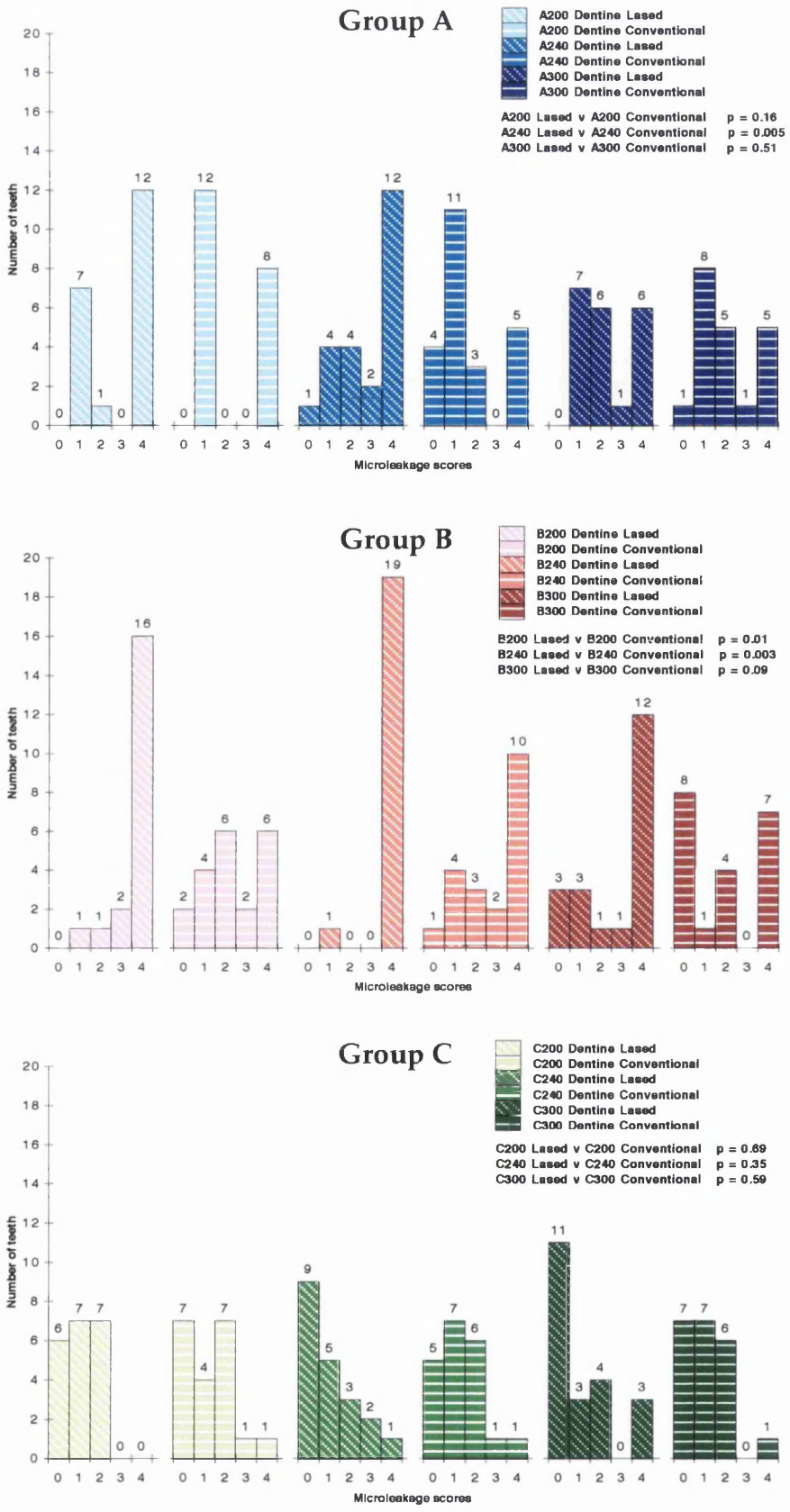

Figure 4.10a–c Analysis of the microleakage seen at the lased and conventionally-prepared dentine margins in groups A, B and C

A similar pattern was observed for the group B cavities where the extent of leakage at the dentine margins was less for the conventionally-prepared cavities compared to the lased cavities for all three subgroups. However, the difference was only significant for the B200 and B240 subgroups ($p = 0.01$ and $p = 0.003$ respectively; Figure 4.10 b).

In contrast to groups A and B, in group C the lased margins showed less leakage than those that had been conventionally prepared. However, the differences were not significant for any of the three subgroups ($p < 0.05$; Figure 4.10c).

4.4 Enamel *versus* dentine

4.4.1 Conventionally-prepared margins

Because of the lack of statistical significance between the subgroups of each group, the subgroup leakage scores were combined for the analysis of the difference between leakage at the enamel and dentine margins of the conventionally-prepared cavities for groups A, B and C (see Section 4.2.1.1) In all three groups (Figure 4.11), the enamel margins demonstrated less leakage than the dentine margins. However, despite 29% (18) of the dentine margins in group A scoring the maximum of 4, the differences in microleakage were only significant for groups B ($p < 0.001$) and C ($p = 0.02$).

4.4.2 Lased margins

Figure 4.12 illustrates the extent of microleakage observed in the lased cavities. For all groups, the seal at the enamel margins was better than the dentine margin seal. Indeed, with the exception of the A300 subgroup, more than half the dentine margins for groups A (Figure 4.12a) and B (Figure 4.12b) exhibited extensive dye penetration beyond the full cavity depth (i.e. score 4). This was in marked contrast to group C where leakage at the dentine margin was limited to the outer third of the cavity depth (i.e. score 0 or 1) in at least 65% (13) of the samples, with many showing no leakage (Figure 4.12c). The difference in leakage between the enamel and dentine margins was not significant for the A300 ($p = 0.08$) and C300 ($p = 0.51$) cavities. Analysis of the other subgroups revealed

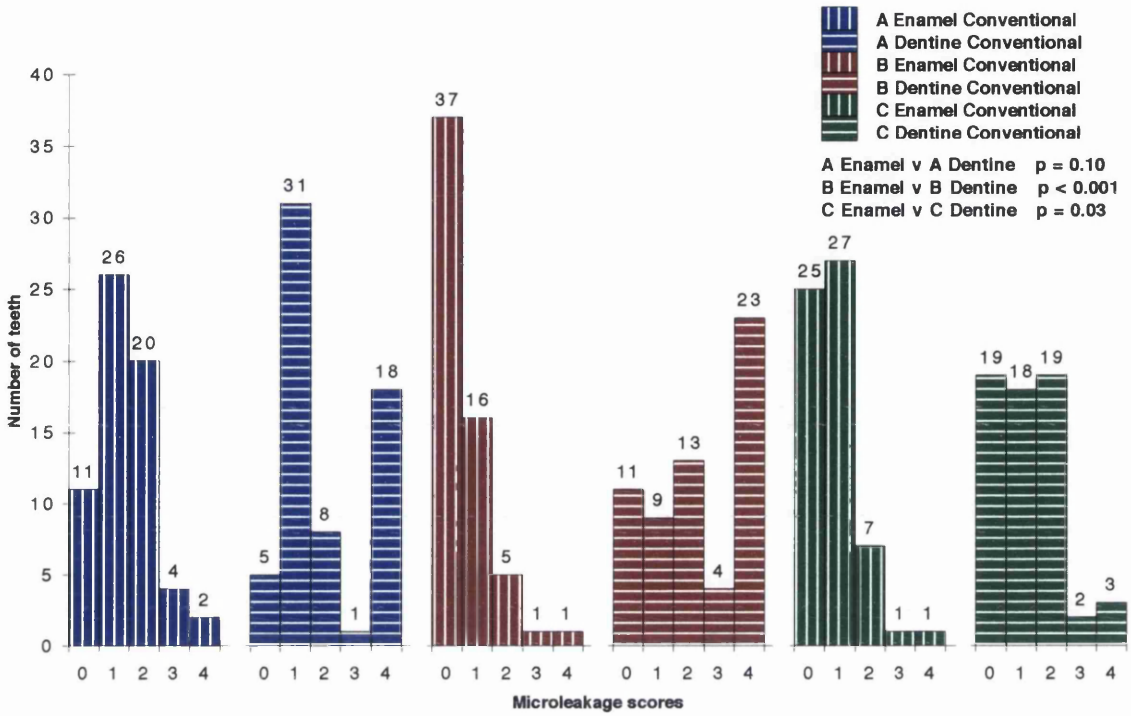

Figure 4.11 Analysis of the microleakage seen at the enamel and dentine margins of conventionally-prepared cavities

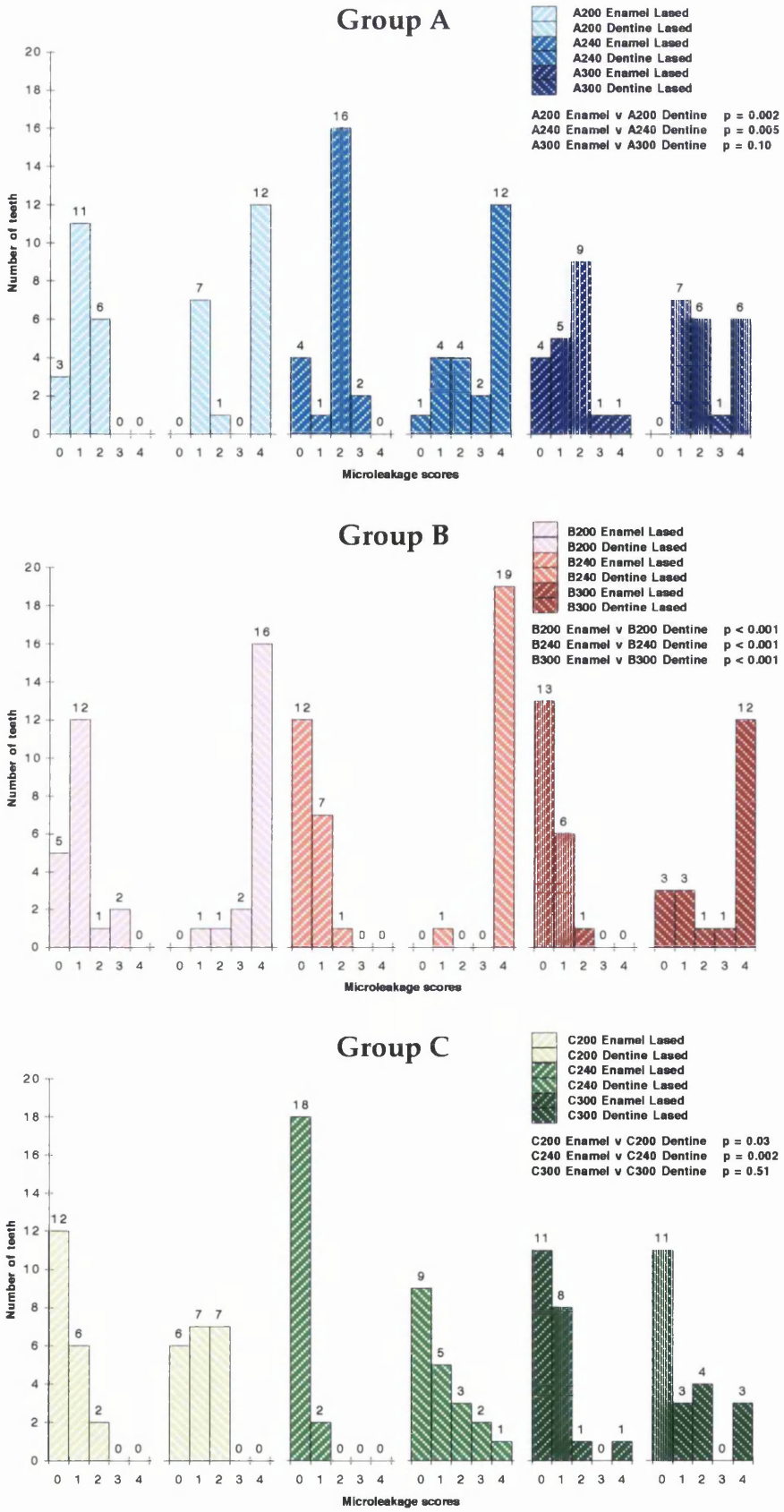

Figure 4.12a–c Analysis of the microleakage seen at the enamel and dentine margins in the lased cavities of groups A, B and C

that the dentine margins exhibited significantly more leakage than the equivalent enamel margins ($p < 0.05$).

4.5 Summary

Statistically significant differences in the extent of leakage observed between the groups and subgroups are summarised below.

1. Enamel margins:
   - conventionally-prepared enamel margins:
     - A > B ($p < 0.001$);
     - C > B ($p = 0.04$);
   - lased enamel margins:
     - A240 > A200 ($p = 0.02$);
     - B200 > B240 ($p = 0.02$);
     - B200 > B300 ($p = 0.01$);
     - C200 > C240 ($p = 0.03$);
     - C300 > C240 ($p = 0.01$);
     - A240 > B240 ($p < 0.001$);
     - A300 > B300 ($p < 0.001$);
     - B200 > C200 ($p = 0.04$);
     - B240 > C240 ($p = 0.03$);
   - conventionally-prepared v lased enamel margins:
     - C240 conventionally-prepared > C240 lased ($p < 0.001$);

2. Dentine margins:
   - conventionally-prepared dentine margins:
     - B > C ($p < 0.001$);
   - lased dentine margins:
     - B240 > B300 ($p = 0.01$);
     - B240 > A240 ($p = 0.003$);
     - B200 > C200 ($p < 0.001$);
     - B240 > C240 ($p < 0.001$);
     - B300 > C300 ($p = 0.002$)

- conventionally-prepared v lased dentine margins:
  - A240 lased > A240 conventionally-prepared ($p = 0.005$);
  - B200 lased > B200 conventionally-prepared ($p = 0.01$);
  - B240 lased > B240 conventionally-prepared ($p = 0.003$).

3. Enamel v dentine margins
   - conventionally-prepared margins:
     - B dentine > B enamel ($p < 0.001$);
     - C dentine > C enamel ($p = 0.03$);
   - lased margins:
     - A200 dentine > A200 enamel ($p = 0.002$)
     - A240 dentine > A240 enamel ($p = 0.005$)
     - B200 dentine > B200 enamel ($p < 0.001$)
     - B240 dentine > B240 enamel ($p < 0.001$)
     - B300 dentine > B300 enamel ($p < 0.001$)
     - C200 dentine > C200 enamel ($p = 0.03$)
     - C240 dentine > C240 enamel ($p = 0.002$)

5 *Discussion*

5.1 Introduction

The main purposes of restoring carious cavities are to arrest the disease process, and to restore the form and function of the teeth in such a way that the health of the dental tissues is maintained. Adequate marginal integrity of a restoration is therefore essential for the achievement of these goals. As noted in Section 2.10.6.7, failure of the seal may contribute to staining, post-operative sensitivity, an inflammatory pulpal response and secondary caries, and as a result, may necessitate the replacement of the restoration.

The control of microleakage in composite resins was discussed in Section 2.7. From this review of the literature, it was evident that, while factors integral to the material itself were of relevance, of equal importance were the restorative techniques used, and the interplay between these and the choice of material. Underlying these factors, is the importance of good adaptation of the resin to the cavity surface. For resin based materials, this is influenced by the surface morphology of the cavity following preparation, and the quality of the pattern achieved following cavity etching or conditioning. The use of the Er:YAG laser for cavity preparation results in a cavity with a significantly different morphology to that achieved by conventional means (Aoki *et al.*, 1998). Prior to the introduction of the laser to routine clinical dentistry, it is essential to ensure that its use does not affect the efficacy of the cavity seal at the enamel and dentine margins adversely. This study therefore sought to clarify this situation for three laser pulse energies.

5.2 Methodology

The study was carried out *in vitro* and therefore some aspects of the experimental work varied from that which would be expected clinically. Nevertheless,

measures were taken to ensure as close a representation as possible was achieved.

The laser was held by hand for the preparation of the cavities, and while care was taken in positioning the handpiece so that the laser beam was focused, this relied on clinical judgement and was more arbitrary than if the laser had been clamped in a fixed position. Other aspects of the experimental set up were carefully controlled. The water mist was provided under pressure from a hand-pumped plastic container. The effects of excess and insufficient water during the ablative process were described in Section 2.10.6.4 and care was taken to ensure the water pressure was monitored and adjusted at regular intervals. However, the lack of standardisation of this may have introduced confounding factors.

As noted in Section 2.2.2, variables in the composition and structure of dentine occur with time because of ageing and environmental influences. In addition, with *in vitro* studies, the storage period and media may influence dentine permeability (Goodis *et al.*, 1991), dentine bonding (Sidhu *et al.*, 1991) and microleakage (Haller *et al.*, 1993a). In this study, because of the method of random allocation, no account was taken of either the age of the tooth, or the storage time, when the teeth were placed in their groupings. In an attempt to limit any errors this may have introduced, the teeth were stored in thymol solution. This is known to have limited affect on microleakage when compared to teeth that are processed immediately post-extraction (Haller *et al.*, 1993a).

The oral cavity presents a rapidly changing environment to any restoration. Thermocycling was therefore included in the sample processing method to provide a measure of thermal challenge to the restorations. The temperatures used were within the clinical range (Barclay, 1998) and the shortest dwell time possible for the thermocycling unit was used.

The marginal integrity at the CRI in enamel and dentine was assessed by scoring the depth of dye penetration of a single section in the mid-buccal plane, perpendicular to the long axis of the tooth. This method is one of the commonest used but, as with all *in vitro* tests, it does have its limitations. These were discussed fully in Section 2.5.2 and so will not be considered further, other than to note that, whilst this method gives neither a direct measurement of the

likelihood, nor the degree of microleakage that could be expected clinically, it does indicate a potential for leakage. Furthermore, as the significance of the leakage seen in any one particular group can be related to the dye penetration seen in the other treatment groups of teeth valid conclusions can be drawn.

Since Buonocore (1955) first reported the use of acid etching to produce a suitable enamel surface for the mechanical bonding of composite resin materials, a succession of composite materials and bonding agents have been developed. These have shown an increasing improvement in the seal at both the enamel/restoration and dentine/restoration interfaces. Adequate sealing of the enamel margin has been easier to achieve than of dentine, and historically, microleakage has been greater at the dentine margin than that found at enamel.

In this study, microleakage was evident in some specimens at the enamel and/or dentine margins in all groups of teeth (Table 4.1). This is in agreement with previous studies reporting the microleakage of cavities restored with Z100 and SMP (Vargas & Swift, 1994; Saunders & Saunders, 1996). However, the leakage found at both the enamel and dentine margins in this study was greater than that reported in these earlier studies. Reports in the literature describing microleakage in Class V cavities at the cervical margin which were restored with the original composition of Compoglass, the compomer used in this study, are limited. However, in agreement with this study, *in vitro* studies employing this material have reported leakage at both the dentine and enamel margins (Cortes *et al.*, 1998; Ferrari *et al.*, 1998).

5.3 Outline of discussion

The following discussion will first consider the results of the enamel/restoration interface, looking initially at the conventionally-prepared margins before considering those prepared by the laser. Following this, the leakage seen at the dentine/restoration interface is evaluated for both methods of cavity preparation.

5.4 The enamel/restoration interface

When considering the extent of dye penetration found at the enamel margin, it is pertinent to note that, because of the width of the enamel in the cervical region and the criteria for scoring, a score of '1' is likely to indicate complete failure of the enamel/restoration bond. Scores greater than this therefore represent failure of both the enamel/restoration and dentine/restoration bonds. Thus the severity of leakage seen at the enamel CRI is, in some part, due to dentine leakage. The stresses at the dentine/restoration bond at the coronal margin are likely to have differed to those at the cervical margin because of the method of incremental packing used. However, all other factors contributing towards microleakage will have been similar. Therefore, for clarity, discussion on the possible reasons for the leakage seen at the coronal margin is confined to the consideration of the enamel/restoration interface only. Leakage at the cervical dentine margin is discussed in Section 5.5 and this section is confined to issues relating to the enamel/restoration bond only.

5.4.1 Conventionally-prepared enamel margins

Despite the lack of uniformity in the morphology of enamel found at the cervical margin, conventionally-prepared bevelled enamel margins which have been etched with 35% phosphoric acid (Saunders & Muirhead, 1992; Vargas & Swift, 1994) or primed with an acidic primer (Saunders *et al.*, 1991) have resulted in an absence of leakage. However, in this study, leakage was found at the enamel CRI in all groups of teeth with conventionally-prepared enamel margins (Figure 4.1). Several factors may account for this apparent reduction in the efficacy of the enamel seal. A box-shaped cavity was used in an attempt to standardise cavity shape, since a uniform bevel preparation with the laser could not be guaranteed for all samples. However, such a cavity has a high C-factor (Feilzer *et al.*, 1987) and therefore it provided an unfavourable cavity shape for the control of microleakage. As noted in Section 2.7.2.2, the stress generated by polymerisation contraction in a cavity of this shape has been calculated to be of the order of 13–17 MPa (Davidson *et al.*, 1984). The enamel/SMP bond strength using 35% phosphoric acid as etchant is has been reported as being 24.5 MPa (Swift & Cloe, 1993) and for Compoglass as 18.0 MPa (Vivadent, 1996). At first glance, it would seem reasonable to assume that these were of sufficient size to resist

polymerisation stresses. However, these values were measured on a flat surface i.e. low C-factor, after 24 hours and are therefore higher than would be expected at the time of curing in an unfavourable cavity shape. The development of significant polymerisation stresses arising as a result of this factor may therefore mean that the enamel/composite bond could not survive the polymerisation stresses. The use of incremental packing, in reducing the C-factor, will have reduced the stresses that developed during curing, but it is unlikely that this would have completely compensated for the effect of the 90° cavosurface angle and the cavity shape for the materials tested.

Material factors may also have played a role in the leakage seen at the enamel margin. Looking first at the factors relating to Z100/SMP, the high filler content of Z100 has resulted in a material with a polymerisation shrinkage of 6% after one hour (McConnell *et al.*, 1994). While this is an improvement on the earlier materials, the resulting rigidity of the material combined with its rapid curing reaction, results in a reduction in the compensatory flow of the material during curing and will therefore influence the incidence of microleakage. The positive effect of hygroscopic expansion on storage in reducing microleakage was noted in Section 2.7.1.2. and would account for the significant improvement in microleakage seen at the enamel margins in group B, after 3 months storage compared to group A.

In addition to the effect the composition of the Z100 resin may have had on microleakage, three aspects of the application technique may have influenced the results. Firstly, while the manufacturer's instructions were carefully followed, Saunders and Saunders (1996) postulated that the 'total etch' technique using acids of either lower concentration, or of normal concentration for shorter periods may result in inadequate etching of the enamel. Traditionally, the adequacy of the enamel etch has been assessed visually. However, this was not possible in this study because a wet-bonding technique was used. Modification of the manufacturer's technique to permit visual examination of the enamel prior to re-wetting the surface to re-expand the decalcified dentine network may have served to improve the enamel seal without detriment to the dentine margin (Gwinnett, 1994). Secondly, the application of SMP primer to enamel can have an adverse influence on the bond with enamel etched with phosphoric acid (Barkmeier & Erickson, 1994). The relationship of bond strength measured on a

flat surface 24 hours after polymerisation and microleakage has already been discussed (Section 2.7.2.2). However, the effect on bond strength suggests that the primer may influence the adaptation of the resin to the etched enamel surface, and this, combined with the amorphous structure of the cervical enamel, would not have enhanced the enamel seal. Finally, it has been suggested that the bond to dentine using this combination of bonding agent and composite resin is of such magnitude to cause disruption of the enamel bond during polymerisation (Saunders & Saunders, 1996). The likelihood of this being a significant factor in this study is questionable in view of the extensive leakage seen at the dentine margins. However, if it were, an improvement in the leakage found at the enamel margins would be expected by reversing the order in which the first two increments were applied i.e. placing and polymerising the cervical increment before the occlusal.

Material factors are also relevant to the degree of leakage seen at the enamel margins restored with the compomer material (Figure 4.1). Compoglass has a high filler content and exhibits a polymerisation shrinkage of 2–3% on curing (personal communication with Vivadent). It achieves maximum hygroscopic expansion within one week. However, because of the poor propensity of urethane dimethacrylate for water, this does not fully compensate for polymerisation shrinkage and will result in residual marginal gaps, particularly with the stringent cavity conditions used in this study.

As noted in Section 2.3.6, compomers were developed to provide a material that incorporated the positive qualities of composite resins with those of the glass-ionomer cements. Polymerisation shrinkage was one of the less desirable properties of composites which was hoped would be reduced with the addition of glass-ionomer to the material. It is therefore of interest to note that there was significantly greater leakage at the enamel margins of the Compoglass restorations (Group C) compared to the Z100 stored for a similar period (Group B) (Figure 4.1). This trend is in agreement with the results of earlier studies (Uno *et al.*, 1997; Owens *et al.*, 1998). In addition to the differences in hygroscopic expansion, these differences can be accounted for by the method of priming and cavity preparation. The enamel seal is dependent on the micromechanical retention achieved by the resin tags. Compoglass SCA is a fifth generation bonding agent and as such, etching is achieved by the acidic components in the

primer (methacrylate-modified polyacrylic and maleic acids). These weaker acids produce a shallower etch pattern when compared to phosphoric acid (Meryon *et al.*, 1987; Glasspoole & Erickson, 1994), and in addition the acid salts produced during etching are not washed away. These factors lead to a reduction in resin tag formation and would account for the increase in leakage found for the drill margins. The use of phosphoric acid, applied and washed away, prior to primer application has been shown to improve the marginal sealing ability of Compoglass restorations after two to three months storage (Vichi *et al.*, 1997). This is presumably because of the increased wettability and area for micromechanical retention afforded by the etched enamel surface and suggests that the use of SCA alone, does not provide the optimum etch pattern for micromechanical retention at conventionally-prepared enamel margins. This combined with the material factors could account for the greater incidence of dye penetration seen at the Compoglass/enamel interface when compared to the enamel margins in group B. The use of phosphoric acid prior to SCA application in this study may have improved the marginal integrity of the Compoglass/enamel margins.

This discussion has so far been confined to the leakage seen at the conventionally-prepared enamel margins. The factors discussed are of relevance to the lased groups also. However, the aim of this study was to evaluate the influence that cavity preparation using the Er:YAG laser has on the cavity/restoration interface. This will be considered for the enamel margins in the following section.

5.4.2 The influence of the Er:YAG laser on the enamel cavity/restoration interface

Before considering the results in detail, it is pertinent to note that, because of the experimental design, it was likely that the enamel margin in the 300 mJ lased group would have been influenced by the 100 mJ during dentine finishing. Enamel ablation is harder than dentine ablation for the same laser parameters (Section 2.10.6.2) and therefore the 100 mJ will not have affected the surface morphology to the same degree when compared to dentine. However, it could be speculated that the resultant crater pattern will have been shallower and

possibly more regular than that seen when the enamel was ablated with 300 mJ only.

Looking first at the results for the composite/enamel interface (groups A and B), there was a tendency for the conventionally-prepared margins to exhibit less leakage than those prepared with the laser. However, the differences were not statistically significant. Thus it can be concluded that all the laser parameters used in this study produced an enamel surface that, when acid-etched, provided bonding characteristics that were comparable to those achieved with conventional preparation and etching. This finding is not in agreement with the previous studies using similar pulse energies (Hofmann *et al.*, 1992; Hibst & Keller, 1994) reviewed in section 2.10.6.7. However, the studies differ in the choice of cavosurface angle and cavity position relative to cervical margin, and in the restorative material and pulse repetition rate used. All these factors influence the distribution and size of the stresses that could be expected to develop within the resin material during polymerisation and may account for the differences in leakage performance.

The laser can be operated at one of a range of pulse energies, all of which influence the morphology of the cavity surface and the ablation rate. Clinically, a fast ablation rate without detrimental effects on the hard tissues and pulp is desirable. In this study, three pulse energies were used to assess whether the choice of pulse energy influenced microleakage. While all three resulted in levels of microleakage that were comparable to conventionally-prepared margins, statistical differences were seen between the different subgroups. After twenty four hours storage (group A; Figure 4.2a), the marginal adaptation at the enamel margins prepared by the 200 mJ energy was better than both the 240 mJ and 300 mJ. However, after three months storage (Figure 4.2b), the seal of the 200 mJ margins had not improved and, while the seal had not degraded, the margins exhibited significantly more microleakage than the other two laser subgroups. It would therefore appear that the deeper crater patterns produced by the higher pulse energies in combination with acid-etching provided a more favourable surface for long-term adaptation of this particular combination of composite resin and bonding agent. The lack of improvement with the 200 mJ subgroup after three months is difficult to explain on the basis of this theory.

For the Compoglass restorations (Figure 4.5c), laser preparation did not have an adverse affect on microleakage when compared to the seal provided by conventionally-prepared enamel margins. However, in contrast to Z100 where there was no significant difference between the two methods of cavity preparation for any of the pulse energies used, the margins prepared by the 240 mJ pulse energy showed statistically less leakage than the equivalent conventionally-prepared subgroup. The use of this laser energy also resulted in significantly less microleakage than the other two laser subgroups (Figure 4.4c). Thus, of the parameters investigated, a pulse energy of 240 mJ would appear to provide the best surface for sealing the enamel margin with Compoglass.

When the microleakage at the conventionally-prepared enamel margins in groups B and C was analysed (Figure 4.1), leakage was greater for the margins restored with Compoglass (group C) than those restored with Z100 (group B). An explanation for this difference was given in Section 5.4.1. However, when the lased enamel margins were considered the reverse was found for margins prepared with the 200 mJ or 240 mJ pulse energies i.e. Compoglass exhibited significantly less microleakage than Z100 for these energies but there was no statistically significant difference between the two materials when the 300 mJ energy was used. These differences are difficult to explain and perhaps merely reflect the poor performance of the enamel margins prepared by the 200 mJ laser energy and restored with Z100 and the low leakage seen with the Compoglass/240 mJ group.

In summary, the use of the laser at the three pulse energies did not adversely influence microleakage at the enamel margin for either material tested. Indeed, the performance of Compoglass was improved with the use of the laser at 240 mJ. Furthermore, pulse energies of at least 240 mJ enhanced the long-term marginal seal of the composite resin tested. These results suggest that laser energies below 240 mJ do not provide the optimum surface for adaptation of either material to the enamel margin.

5.5 The dentine/restoration interface

The cavity and material factors described for the enamel margins (Section 5.4.1) apply equally well to the CRI in dentine and therefore will not be discussed further in this section.

5.5.1 Conventionally-prepared dentine margins

For the conventionally-prepared cavities, dye penetration was more severe at the dentine margin than at the enamel margin in all three groups (Figure 4.11). However, these differences were only significant for the two groups stored for three months, groups B and C. This is in agreement with previous studies using Z100 and SMP (Vargas & Swift, 1994; Saunders & Saunders, 1996), but is in contrast to the findings of Crim (1993). These apparent discrepancies could be because of material and cavity factors outlined in Section 5.4.1.

Considering first the dentine leakage at margins restored with Z100 and SMP (groups A and B), the severity of the leakage seen in this study, when compared to similar reports, is of concern. As noted in Section 2.7.2.2, dentine bonding with SMP is achieved by the removal of the smear layer prior to the formation of both the resin-reinforced hybrid layer and the resin tags in the widened dentinal tubules. Leakage at the dentine CRI can occur in a variety of planes; below or within the hybrid layer, between the hybrid layer and the composite resin, or within the restorative material itself. The dye penetration and magnification techniques used in this study did not differentiate between the layers, or between adhesive and cohesive failure and therefore it was impossible to locate the exact plane of leakage for the specimens with minimum leakage. The use of silver nitrate staining techniques with SEM analysis described by Sano *et al* (1994) would be necessary to achieve this level of resolution. However, with a knowledge of the structure and function of the hybrid layer (Section 2.7.2.2.1) some assumptions can be made by analysing the pattern of dye penetration seen in the specimens: where leakage occurred, dye penetration was seen along the CRI, and in some cases this appeared to be confined to the CRI. Examples of this can be seen at the dentine portion of the enamel margins in Figures 3.14 and 3.15. However, in a proportion of specimens, dye penetration appeared to follow the path of the dentinal tubules. Where this occurred, there appeared to be two

patterns of leakage. The distinction between the two was in the proportion of tubules involved. In 2% (1) and 13% (8) of specimens in groups A and B respectively, the area of tubule penetration did not correspond to the leakage at the CRI (Figures 3.13 and 3.14). Whereas in 27% (17) of group A specimens and 58% (35) group B, tubule penetration appeared to match the extent of the dye penetration along the CRI (Figures 3.12 and 3.15). Where the dye was confined to the CRI, it can be assumed that the dentinal tubules had been adequately occluded by the formation of the resin-reinforced hybrid layer. The leakage seen therefore represented cohesive failure within the restoration, most likely at the hybrid layer/resin interface. However, the presence of dye in the dentinal tubules would suggest that the hybrid layer was not intact in these areas. The two patterns of tubule penetration indicating partial or complete failure of the hybrid layer. This could arise because of inadequate formation of and/or, poor stability of the hybrid layer during storage. It is not possible to differentiate between the two mechanisms with the methodology used in this study, but the proportion of specimens exhibiting the two patterns of leakage in both groups A and B would suggest that both were involved.

There are several factors which may have contributed to the microleakage and failure of the hybrid layer seen at the dentine CRI: firstly, after phosphoric acid conditioning, the dentine surface has been shown to be completely demineralised with exposure of the collagen fibrils to a depth of 4 μm (Prati *et al.*, 1993). Secondly, SEM examination of the hybrid layer formed by SMP found that the resin tags are conical in shape. This may be because of physical characteristics of the bonding resin such as viscosity and surface tension which serve to reduce penetration along the tubule before polymerisation. Thirdly, the hybrid layer has been found to be more porous than several other dentine bonding agents (Sano *et al.*, 1994). These factors suggest that physical properties of SMP may provide a constraining influence on optimum wetting of the denatured dentine surface and subsequent micromechanical retention.

The role of water in hybridisation with fourth generation bonding agents was discussed in Section 2.7.2.2.1. The manufacturers of SMP claim that it can produce strong bonds to dentine under conditions of 95% humidity (3M, 1994). Optimum adaptation of SMP to a dentine surface is seen when the surface is left visibly moist after the etch has been rinsed off (Swift & Triolo, 1992), presumably

because the collagen network is maintained in an expanded state. The manufacturers of SMP state that, after the acid etch has been rinsed off the tooth surface, the tooth should be either lightly dried with compressed air, or 'blot dried', for 2 seconds. In this study, the former technique was used. Although care was taken to avoid excessive drying, the possibility of such an occurrence cannot be ignored because of the drying method employed. This would result in inadequate resin infiltration of the demineralised collagen and increased susceptibility to hydrolytic degradation with poor sealing of the tubules. The influence of excessive drying has been investigated in previous studies. Swift and Triolo (1992) reported a reduction in bond strength to dry dentine when compared to that achieved when the surface was left visibly moist, although their results were not statistically significant. However, other workers could detect no significant difference in microleakage when the surface was left wet or dry (Saunders & Saunders, 1996). These studies would suggest that with SMP, excessive drying was not a risk factor for microleakage. However, in this study, the stringent cavity factors may have increased the polymerisation stresses experienced within the restoration resulting in disruption of a weakened, porous hybrid layer. This sensitivity to water is partly overcome by the use of self-priming agents such as Compoglass SCA. The use of an intermediate bonding resin with Z100/SMP has also been shown to reduce the microleakage at the dentine/restoration interface (Swift *et al.*, 1996) and if used, may have served to reduce the extent of dye penetration seen in this study.

Earlier work, using maleic acid conditioning, has shown that a storage period of ninety days did not affect the bond strength of SMP (Miears *et al.*, 1995) or microleakage (Crim, 1993) adversely. Indeed, as seen with the enamel margins (Section 5.4.1), it would be reasonable to expect hygroscopic expansion of the resin to result in a reduction in microleakage with time. However, where inadequacies of the hybrid layer are implicated in microleakage, this increase may be balanced by an increase in leakage over time because of further hydrolytic breakdown of the layer. In this study, although more specimens exhibited maximum dye penetration in group B when compared to group A, the differences in leakage were not found to be significant at the conventionally-prepared dentine margins (Figure 4.8). This may purely be a reflection in the high levels of leakage seen in group A. However, as noted earlier, the incidence

of tubule penetration by the dye was higher in group B when compared to group A (72% and 29% respectively). This would suggest that there was greater failure of the hybrid layer in group B when compared to group A. The role of hydrolytic breakdown has already been referred to in this context. Conversely hygroscopic expansion may also have had an adverse effect on the hybrid layer: although this has been reported to compensate, in part, for polymerisation shrinkage (Section 2.7.1.2), it is essential to remember that this does not occur immediately, but rather develops slowly over a period. Furthermore, by the very process of water sorption, the resin exposed to the oral cavity will absorb water in advance of the bulk of the material. This in itself adds new stresses to the restoration (Davidson & Feilzer, 1997) which would result in greater strain on an already weakened hybrid layer. Thus, while only speculation, several factors may account for the lack of statistical difference three months storage appeared to have on the dentine bond when compared to that seen at the enamel margin.

The application of SMP involves a number of sequential steps which is both time consuming and, from the results of this study, technique sensitive. The use of the single primer/bonding system of Compoglass led to a significant improvement in dentine leakage at conventionally-prepared margins when compared to the margins restored with Z100 and stored for a similar period (group B; Figure 4.6). In contrast to the leakage seen in group B, only 36% (22) exhibited evidence of dye penetration down the tubules and, of these, 64% (14) were similar in appearance to Figures 3.13 and 3.14 rather than Figures 3.12 and 3.15. Fifth generation bonding agents such as SCA incorporate a modified smear layer into the hybrid layer (Section 2.7.2.2). In addition, the application of the acidic primer produces a demineralised surface to a depth of 5μm with partially opened dentinal tubules and a porous collagen network covering the surface of the intertubular and peritubular dentine (Northeast & Della Bonna, 1998). This is similar in appearance and depth to the hybrid layer formed with SMP (Prati *et al.*, 1993). The incidence of microleakage and the pattern of dye penetration seen in this study would therefore suggest that the hybrid layer with SCA was more homogenous than that achieved with SMP.

The factors outlined in this section are also of relevance when considering the lased dentine margins.

5.5.2 The influence of the Er:YAG laser on the dentine cavity restoration/interface

Looking first at the leakage seen with the different laser energies in groups A and B, in the former, Z100/SMP stored for 24 hours, the absence of significant differences in microleakage between the different laser energies (Figure 4.7a) suggests that all three pulse energies produced surfaces that, when etched, were comparable to each other. However, in group B, Z100/SMP stored for three months, the use of 240 mJ appeared to result in greater levels of microleakage, although the differences were only significant when compared with the 300 mJ group (Figure 4.7b). From these results, it would appear that, when considering long-term performance, the use of laser parameters of 200 mJ and, in particular, 300 mJ would be preferable to 240 mJ. These findings were reinforced when the results of the intergroup comparisons were reviewed (Figure 4.8). The differences can be explained by postulating on the shape of the crater patterns that are likely to be produced by the different pulse energies. The crater patterns in dentine, while deeper and wider than those found in enamel, will tend towards a shallower, less rough pattern with reducing laser energies (Hibst & Keller, 1989). As noted in the previous paragraph, etching of the surface increases the depth of the crater pattern significantly, because of the absence of the smear layer. Thus with deeper crater patterns, the likelihood of incomplete penetration of the viscous SMP resin occurring will increase, resulting in the formation of a poorer hybrid layer. This explains the slight trend in leakage seen with the 200 mJ and 240 mJ energies in group B, althought the differences were not statistically significant. As such, the 300 mJ group would be expected to exhibit the worst levels of microleakage, but this was not seen. The 100 mJ finish with the 300 mJ pulse energy was an important factor in this study. Dentine ablation using the 300 mJ energy was completed with 100 mJ to remove charred tissue on the dentine surface. By doing this, the lower energy would have also had the effect of 'smoothing' the dentine surface and in so doing would provide a surface that allowed closer adaptation of the resin than the higher energy of 240 mJ.

In this study, the performance of the laser in relation to that of the conventional technique is of interest. When the composite/dentine interface in groups A and B are considered, the laser-prepared dentine margins tended to exhibit more

microleakage than those prepared conventionally. However, the differences were only significant for the margins prepared with a pulse energy of 240 mJ in group A and 200mJ and 240mJ in group B. This is in agreement with an earlier report using Scotchbond Multi-Purpose and pulse energies of 250 mJ with a storage time of 24 hours (Haller *et al.*, 1993b). Therefore, in contrast to the findings at the enamel/composite margin, it would appear that the performance of the laser is not satisfactory for all the pulse energies investigated in this study. Speculation as to the reason for this can be made by considering the morphology of the dentinal surface produced by lasing. This was described in Section 2.10.6.3. In addition to the scaly, cratered surface, SEM analysis of the dentine surface following laser preparation with pulse energies of 100 mJ and 180 mJ found it to be devoid of a smear layer, the dentine tubules were protruding and the tubule orifices were exposed (Tanji *et al.*, 1997; Aoki *et al.*, 1998). With the higher pulse energies used in this study, similar appearances of the dentine surface would be expected, but with deeper crater patterns. The absence of the smear layer may result in excessive demineralisation of the dentine and widening of the tubules following the application of phosphoric acid in the total etch procedure. Considering the viscous nature of the SMP bonding resin noted in the previous section, this pattern of demineralisation could result in inadequate infiltration of the demineralised tissue and therefore a more porous hybrid layer. This may account for the increase in microleakage seen with the laser and, if true, would suggest that conditioning with either a less dissociated acid, or the laser only may be indicated for this material with cavity preparation by the laser. SEM analysis of the morphology of the lased surface before and after application of the phosphoric acid is required to support these conclusions.

Thus while both the 200 mJ and 300 mJ with 100 mJ finish appeared to give the more favourable long-term microleakage results when compared to a 240 mJ pulse energy, of the three energies tested, the 300 mJ lased dentine margins in group B were the only subgroup that did not exhibit significantly worse dye penetration than the equivalent conventional margins.

In group C (Compoglass), the dentine margins prepared by the three laser energies performed equally well (Figure 4.7c). Furthermore, all three pulse energies appeared to provide favourable surfaces for wetting and penetration of Compoglass SCA when compared to conventionally-prepared margins (Figure

4.10c). Thus it would appear that the hybrid layer formed with Compoglass SCA is of a similar quality irrespective of the presence of the smear layer for the three pulse energies. From this, it can be postulated that dentine conditioning with the weak organic acids in Compoglass SCA does not cause excessive demineralisation in the absence of a smear layer. In addition, it would appear that the penetration and adapatability of Compoglass SCA was not influenced by the different surface morphologies produced by the three pulse energies.

These factors are of relevance when the performance of the two materials is compared. Like the conventionally-prepared cavities, Compoglass gave a better long-term seal at the dentine margins than Z100. This difference was significant for all three pulse energies (Figure 4.9). As noted in section 5.5.1, it would appear that Compoglass SCA resulted in a more homogenous hybrid layer than SMP, with or without the presence of the smear layer. Wettability and adaptability characteristics of the two materials and the cavity surface are of relevance here. Furthermore, when applied to lased dentine surfaces, it is unlikely that the weak organic acids found in Compoglass would produce the extent of demineralisation seen with more dissociated acids such as phosphoric.

In summary, laser ablation of dentine had a varied effect on microleakage when Z100/SMP were used to restore the cavities, with the 300 mJ energy with a 100 mJ finish providing the more favourable results. However, all three laser parameters were equally effective for Compoglass.

5.6 Conclusions

The effects the acid-etching of dentine has on the pulp have been controversial (Kanca, 1990; Retief *et al.*, 1992) though recent consensus has agreed that the procedure is biologically safe where adequate dentine hybridisation is achieved. Indeed, it has been suggested that the current hybridisation adhesive systems could replace conventional liners and bases for pulp protection (Cox & Suzuki, 1994). However, in this study, sealing of the dentine tubules was not guaranteed with either material, but particularly so with the combination of SMP/Z100. This is of concern, especially in situations where the adhesive system is the only

means of pulp protection. On the basis of the results of this study it is concluded that further measures are necessary if pulp protection is to be guaranteed.

In conclusion, the results of this study suggest that for the laser parameters used, the Er:YAG laser can vary in its effect on the efficacy of the marginal seal at both the enamel and dentine margins. It would appear that, within the limitations of the range of parameters investigated in this study, optimum cavity sealing is achieved with different laser energies for dentine and enamel. For both Z100/SMP and Compoglass/SCA, laser energies of at least 240 mJ are preferable to lower ones for enamel ablation. While lower energies of 200 mJ or more particularly, higher but with a lower energy for finishing (300 mJ–100 mJ), appear to provide a better long-term marginal seal for dentine with Z100/SMP. All three laser energies are equally effective at the dentine margin for Compoglass.

Thus it would appear that with care in the choice of laser parameters, tailored to the choice of restorative material, the Er:YAG laser does not have an adverse effect on microleakage at enamel and dentine margins and therefore this could be considered as a potential tool to replace the use of the conventional drill for anxious individuals. Within the constraints of this study, and for the two materials used, the null hypothesis was therefore found to be true for certain pulse energies.

6 *Future research*

This study has concentrated on one aspect of the use of the Er:YAG laser, namely that of microleakage. As with all studies, the results of this study have led to further questions which should be answered before the laser can be accepted for routine use in the UK.

As noted in Section 2.11, the clinician is faced with a broad choice of combinations of operating variables when using the Er:YAG laser. While this study investigated the influence on microleakage of three pulse energies at the same pulse repetition rate, it may be that a higher energy or a different pulse repetition rate would result in at least as good a seal with the additional benefit of operating at a faster ablation rate. Further work is necessary in this area. In addition, the results of this study have indicated that satisfactory enamel and dentine ablation may require different laser parameters, and that this may further be dependent on the restorative material to be used.

In addition to finding the optimum combination of laser parameters for ablation with respect to microleakage, it is essential that the choice gives a clinically acceptable ablation rate with minimal thermal damage to the dental hard tissues or pulp. These areas need further evaluation. In this study, impressions of the cavities were taken prior to restoring the teeth. SEM examination of these is to be carried out to evaluate the resulting surface morphology for all three laser energies. Such examination will give an indication as to the incidence of thermal changes that occurred during the lasing process. In addition, comparison of the morphology with the leakage patterns will give information on the adhesion characteristics of the surface for optimum sealing for the two materials investigated. This, and the extent of the leakage seen, particularly at the dentine margins with Z100 also raises the question as to whether, for the correct combination of variables, laser etching and conditioning may obviate the need for acid etching and conditioning.

Satisfactory ablation with the Er:YAG laser requires an adequate water supply. In the *in vitro* conditions of this study, this was obtained from the water mist produced by the laser and from residual moisture in the tooth from storage. However, *in vivo*, cavity preparation results in an increased outflow of dentinal fluid from the opened dentinal tubules. Theoretically, this, and the moist environment of the oral cavity should reduce the potential for tissue desiccation during lasing and may also influence microleakage. As with all new techniques, the acceptability of the use of the Er:YAG laser requires further *in vivo* assessment.

Finally, clinical acceptability of the laser for the optimal parameters should be assessed. Lasers are expensive items of equipment and it is therefore essential that they are fully evaluated from both the patient's and the clinician's perspective. To date, *in vivo* studies to assess patient comfort during cavity preparation with the laser have reported favourable results, particularly when compared to conventional preparation (Section 2.10.6.6) However, in their *in vivo* assessment of an Er:YAG laser, Evans *et al* (1998) found that the clinicians themselves preferred conventional rotary handpieces. The reasons for this were not evaluated, but can be speculated from recent work by Aoki *et al* (1998) and the experience gained during this *in vitro* study. The Erbium:YAG laser operates at a wavelength which is readily reflected by the intra-oral mirrors in current clinical use and if absorbed by the eye, permanent damage may ensue. To limit the possibility of this, the use of intra-oral mirrors is contra-indicated and the clinician must wear tinted protective glasses, specific for this wavelength. Both affect visibility in the oral cavity, although a high intensity operating light would be of help in minimising this effect. Intra-oral access can also be problematic; the anterior teeth, and buccal surfaces of the posterior teeth are readily accessible to the laser, but lasing other surfaces can be difficult. This has implications when considering the laser as an alternative to the conventional handpiece and bur when managing the anxious individual.

Finally, ablation with the Er:YAG laser is not tissue specific and thus may result in excessive tissue removal during cavity preparation. When using conventional methods of cavity preparation, the experienced clinician relies on tactile sensation and visual examination, often with reflected or transilluminated light to assess the cavity. As noted in the previous paragraph, the use of reflected or

transilluminated light while lasing is contra-indicated. In addition, the lack of tactile sensation associated with a non-contact laser such as the one used in this study could be perceived as a disadvantage to the experienced clinician. The introduction of all new techniques into clinical dentistry requires a period of training and adjustment. The introduction of the Er:YAG laser into clinical practice is no exception. Experienced operators of the Er:YAG laser report a difference in the quality of the sound produced when ablating dentine, enamel or caries and suggest that this is a useful aid for cavity preparation. Furthermore, there are reports in the literature of the use of Er:YAG lasers that operate in the contact mode (Chao *et al.*, 1996; Aoki *et al.*, 1998). This would be expected to provide a measure of tactile sensation. However, Aoki *et al* reported that there was insufficient feedback with the contact laser to enable differentiation to be made between enamel, dentine and caries. They relied on tactile examination with the probe and caries disclosing procedures to assess the caries-status of the cavity. The latter was not without its difficulties; because of staining differences between the lased and conventionally-prepared surfaces, the clinician was not able to judge complete caries removal with laser treatment. It would therefore appear that cavity assessment may be problematic and should be considered further.

In conclusion, while there are an increasing number of reports being published on the effectiveness of the Erbium:YAG laser as an optical drill, the advantages and limitations of the laser for clinical treatment have yet to be fully evaluated. A reliable procedure for the clinical use of the laser must be established. To achieve this, the further studies outlined above should be completed.

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