In Vitro

Microleakage and Adaptation of Tunnel Restorations©

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ABSTRACT

Microleakage and marginal adaptation of proximal cavosurface margins was studied in tunnel preparations restored with Ketac Silver (Espe), Fuji II (GC), Fuji IX (GC), Fuji II LC (GC) and Dyract (Dentsply). Artificial caries was induced in a defined area on the mesial and distal surfaces of 50 extracted sound, intact lower third molars suspended in a 10% gelatin solution with a pH of 3.5. Once small lesions were identified radiographically, the teeth were mounted in plaster blocks to establish proximal contacts and cavities were prepared from the occlusal surface. The cavities restored with glass ionomer cement were conditioned with polyacrylic acid, washed, then restored from the occlusal surface. The teeth restored with Dyract were primed with PSA Prime. Control teeth had no artificial caries and were prepared from both the occlusal and the proximal surfaces, conditioned with polyacrylic acid, then restored with Ketac Silver. Impressions were taken of the proximal surfaces of all restorations before and after they were load cycled with 90 N for 2000 cycles at 37°C and thermal cycled with 200 one minute cycles between 5°C and 55°C. The teeth were sealed with varnish within one millimetre of the restoration and immersed in 0.5% basic fuchsin dye for 24 hours. They were then mounted in epoxy resin, sectioned and examined at X40 magnification to score the depth of leakage. Resin replicas were fabricated from the proximal impressions and examined in the scanning electron microscope at X60 and X200 magnification to determine the amount of cavosurface perimeter with visible adaptation defects. A comparison was then made between the microleakage and adaptation results of each material tested. The degree of leakage was analysed using the Kruskall Wallis Non-parametric test. Results indicated that those cavities restored with Dyract demonstrated significantly greater leakage than the other materials ($p = 0.002$). Ketac Silver, Fuji II and Fuji II LC all showed similar leakage, while Fuji IX demonstrated the least leakage ($p = 0.05$). Adaptation results were performed using the Kruskall Wallis Non-parametric test. Results of pre-cycled specimens indicated that there were no significant differences between the adaptation of Ketac Silver, Fuji II, Fuji IX and Fuji II LC ($p = 0.185$). Dyract

demonstrated the poorest adaptation ($p = 0.008$). Post-cycled specimen results indicated significant differences between the six restorative materials ($p = 0.001$). No differences were noted between the control, Ketac Silver and Dyract ($p = 0.657$) and no differences existed between Fuji II, Fuji II LC and Fuji IX ($p = 0.085$). No change occurred between pre-cycled and post-cycled specimens. Analysis of pre-cycled and post-cycled specimens showed an increase in marginal defects of the control and Ketac Silver ($p = 0.749$) after load and thermal cycling. Less deterioration occurred in specimens of Fuji II, Fuji II LC, Dyract and Fuji IX ($p = 0.853$). Using the Spearman rank correlation coefficient, comparison of microleakage with adaptation found no correlation with Fuji II and Fuji IX, while a significant correlation was found with control, Ketac Silver, Fuji II LC and Dyract ($p > 0.05$). The glass ionomer cement materials, particularly Fuji IX, provided a more reliable seal and better adaptation in tunnel restorations than the compomer material Dyract under the conditions of this study. Of all the materials tested, Fuji IX was the only restorative material capable of providing ideal adaptation of cavosurface margins in some specimens, however, microleakage did not always occur where the marginal deficiencies existed.

TABLE OF CONTENTS

ORIGINAL STUDY

LIST OF TABLES

LIST OF FIGURES

LIST OF SUPERSCRIPTS

1 Protect Varnish (Kuraray Co., Osaka, Japan)

2 Curved probe (HF-EXD11) (Hu-Friedy, USA)

3 #1 Tofflemire matrix band (NY, USA)

4 Tofflemire matrix band holder (NY, USA)

5 Wizard wedge (Slim Jim) (Teledyne Water Pik. Co, USA)

6 Amalgamator (SDI, Australia)

7 Ball burnisher (HF-BB18) (Hu-Friedy, USA)

8 Microbrush disposable applicator (Microbrush Corp. WI, USA)

9 Dental tape (Oral B Laboratories, Australia)

10 Interproximal carver (GF-EC1445) (American Dental, USA)

11 Lucifix matrix band (Hawe Neos Dental, Switzerland)

12 Luciwedge (Hawe Neos Dental, Switzerland)

13 Demetron curing light (Kerr, Germany)

14 Buehler 1" reusable rubber mounting cups (Buehler, Lake Bluff, USA)

15 Epirez 2-part low viscosity casting resin (Epirez, Australia)

16 Isomet saw (Buehler Ltd, Evanston, USA)

17 Extrude automix (polyvinylsiloxane elastomeric impression material) (Kerr, Germany)

18 Clear cervical matrix (Hawe Neos Dental, Switzerland)

19 Kerr Adhesive (Kerr, Germany)

20 Blue Star pre-measured resin die material (Girrbach Dental, Germany)

INTRODUCTION

Cavity design for the treatment of proximal caries in posterior teeth has for a long time been influenced by the principles established by G. V. Black (1904) and the restorative materials available. Preparation techniques included the removal of non-carious tooth structure which subsequently created weaknesses in the remaining cusps (McLean, 1980), while correct anatomical form was difficult to reproduce during material placement.

With the development of adhesive materials such as glass ionomer cement (GIC) came the evolution of new conservative cavity designs. Prior to this, restorations of a "tunnel" type had initially been placed in the distal surface of deciduous second molars by Jinks (1963), as a preventive technique for the adjacent permanent molars. The first technique where tunnel restorations were proposed to restore proximal caries was reported 21 years later by Hunt (1984) and Knight (1984) as an alternative to the conventional Class II restoration. The rationale for this type of restoration was that by tunnelling from the occlusal towards the proximal caries, the marginal ridge could be left intact, thus avoiding the creation of anatomically inadequate proximal restorations.

Wilson and Prosser (1982) stated that the ideal restorative material should adhere and perfectly adapt to the cavity wall, be free of irritant substances, have the appearance of the tooth, and match it in both mechanical and thermal properties. Although no material has yet been able to fulfil all these criteria, glass ionomer cement does bond chemically to tooth structure. It has therefore been used routinely for tunnel restorations.

Later development of glass ionomer cement produced the cermet cement which had the advantage of increased radiopacity, which is essential for radiographic analysis. Further development has seen the introduction of resin-modified glass ionomer cements (RMGIC) and polyacid-modified resin composites (PAMRC) utilising different bonding mechanisms. More recently, however, new generation auto-cure glass ionomer cements have been developed.

Although the ideal assessment of new techniques and materials involves the use of clinical studies, these are expensive and slow to produce results. *In vitro* testing can be accomplished more rapidly and with lower costs involved. A number of *in vitro* tests have been performed on tunnel restorations, including microleakage and marginal ridge fracture studies. However, these have not been a true representation of the clinical situation. Microleakage studies are often carried out on sound teeth and restored using a hand held technique and these studies have produced conflicting microleakage results for various materials. Fatigue loading tests often use excessive, static forces applied to marginal ridges that would not occur clinically, to determine the strength of the prepared tooth and the effectiveness of the restorative material to reinforce the marginal ridge.

There have been no *in vitro* tests performed on tunnel restorations utilising both sub-fracture load cycling and thermal cycling in the assessment of microleakage. There have also been no studies performed on the effectiveness of adaptation of the restorative material at the cavosurface margins. The results of these tests would be more clinically significant and would be a more valid representation of a newly developed material's ability to prevent microleakage.

The purpose of this investigation was to compare the microleakage and adaptation of various materials in teeth with small proximal lesions restored with tunnel restorations conducted in a laboratory model that closely resembled the clinical environment.

Chapter 1

HISTORY OF TUNNEL RESTORATIONS

1.1 Introduction

It has long been recognised that the removal of proximal caries in posterior teeth is a destructive process requiring removal of the marginal ridge when an adjacent tooth is in contact. Conventional Class II restorations, as described by Black (1904), require removal of sound tooth structure, including the fissure system, to prevent recurrent caries and achieve retention and resistance form. Markley (1951) was one of the first to propose alternatives to the idea of 'extension for prevention' with designs not involving the fissure system. This, however, did not prevent removal of the marginal ridge and despite refinement of the original concept with rounding of axial margins and reduction of isthmus widths (Larson *et al*, 1981; Sigurjons, 1983; O'Hara & Clark, 1984), the need to remove unsupported enamel and to clear isthmus margins in Class II restorations ultimately results in weak cusps (Hood, 1991). McLean (1980) found that slightly undercutting cusps to gain retention effectively increased the height of cusp tips which could predispose to cusp fracture, while Healy & Phillips (1949) found that 50 per cent of amalgam Class II restorations fail due to faulty cavity design.

Studies have drawn attention to various deficiencies in conventional Class II cavity preparations. One study by Cardwell and Roberts (1972), showed that damage may be inflicted on adjacent teeth during removal of proximal enamel, and this was supported in a later study by Qvist and co-workers (1992). Hunt (1984) proposed that greater postoperative sensitivity may be experienced in conventional Class II restorations due to excessive removal of unaffected dentine during cavity preparation. Because there was no opportunity for the dentine to undergo sclerotic changes, the possibility existed for a more rapid progression of secondary caries.

Observations have also been made of the deficiencies associated with restoration placement. Elderton (1976) reported that ditching of amalgam at the cavity margins could result from unsatisfactory marginal adaptation of amalgam against the highly corrugated tooth surface, acute amalgam margin angles and overcarving. In a study by Gilmore and Sheiham (1971) it was shown that due to the difficulty of contouring proximal restorations, up to one-third of conventional class II restorations displayed overhangs with the potential to affect periodontal health, while Pack *et al* (1990) showed that Class II restorations restored with amalgam suffer from poor marginal and interproximal adaptation. The original anatomical form of the marginal ridge and isthmus area is difficult to reproduce and consequently the restoration may encourage greater food retention, food impaction, gingival inflammation and development of periodontal defects.

It has also been shown that conventional Class II amalgam restorations are prone to failure, with one study by Mjör *et al* (1990) finding that one quarter of restorations placed had failed after five years and, as a consequence, many restorations are replaced due to recurrent caries or fractures of the amalgam (Qvist *et al*, 1990). These restorative deficiencies, together with the development of adhesive materials, the demand for aesthetic alternatives and an understanding of the need for a more rational, biological approach has led to the development of more conservative options. This is despite suggestions by Hunter & Hunter (1989) that the familiarity of old techniques allowed limited re-evaluation.

1.2 Development of the tunnel restoration

In 1963, Jinks first introduced the idea of preparing tunnels in non-carious second primary molars as a preventive rather than restorative procedure. The purpose of that study was to provide a fluoride-rich environment for the erupting first permanent molar. This was achieved by preparing a tunnel from the occlusal surface, angled towards and penetrating the proximal surface of the non-carious second primary molar, beneath and maintaining the marginal ridge. This tunnel was subsequently restored with a fluoride-containing restorative material consisting of silicate cement, silver amalgam alloy powder and sodium silicofluoride. It was hoped that the adjacent enamel surface of the erupting first permanent molar would become impregnated with fluoride ions and therefore rendered caries-resistant. Although this technique was not considered conservative for the deciduous molar, Jinks showed that the incidence of carious involvement was considerably reduced in the permanent first molars. He was also able to demonstrate that fluoride could be incorporated into cements without causing damage to the restored tooth

With the development of glass ionomer cement (GIC) and its use in Class V and paediatric restorations, alternative techniques were slowly developed for its use. It has been shown that glass ionomer cement is biologically compatible with tooth structure and has a low thermal conductivity, while its adhesion to tooth structure gave hope for a biological seal (McLean, 1979). Welk & Laswel (1976) showed that the scientific understanding of plaque and its effect on caries enabled further development of preventive techniques using glass ionomer cement which would encourage the preservation of tooth structure. McLean (1980) predicted that the use of magnification would enable the development of micropreparations for early approximal carious lesions with intact enamel marginal ridges. Elderton (1985) felt that the changing attitude towards caries diagnosis and treatment would lead the way to more conservative restorative approaches, while Thylstrup (1986) noted that decisions on restorative techniques were becoming increasingly difficult due to a decreasing amount of enamel cavitation associated with carious lesions.

In separate studies in 1984, Hunt and Knight first described the restoration of proximal carious lesions using a tunnel approach. Both authors had performed clinical trials and achieved good success. It was recognised that access to proximal caries was difficult to achieve and therefore the occlusal entry point should be within the occlusal fossa, using a conservative outline form which needed to be large enough to allow access to the caries. Knight described this technique as a Class VI type restoration, while Wilson and McLean (1988) later classified it as the "internal occlusal fossa preparation". As a result of changes in attitude to the role of fluoride in the demineralisation/remineralisation process and the long-term adhesion of restorative materials, more recent cavity classifications by Mount and Hume (1998) have placed the site and size of the lesion suitable for a tunnel restoration as "Site 2, Size 1". The site referred to the proximal surface, just beneath the contact area, and the size was described as "minimal" where there has been minimal involvement of dentine, yet beyond remineralisation treatment.

Initial studies suggested that cavity preparation begin with a round entry point made in the fossa closest to the caries, at least two millimetres from the intact enamel marginal ridge (McLean, 1987). Knight (1992) suggested a 'T' shape occlusal outline form, which was more extensive buccolingually, for the detection and instrumentation of laterally spreading caries. It has been shown, however, that there is a correlation between the size and position of the access cavity in relation to the marginal ridge and the strength of the restored tooth (Strand *et al*, 1995b). Although smaller access cavities produce stronger restored teeth, there is an increased likelihood of leaving residual caries (Strand and Tveit, 1993; Strand, 1995b). It had been suggested by McLean (1986) and Hunt (1987), that a caries-disclosing solution and fibreoptic lighting be adopted to aid in the detection of caries, because of its lateral spread within the proximal dentine.

Two methods exist for handling the enamel section of the proximal lesion. While most authors advocate removing demineralised or broken down enamel (Knight, 1984a; McLean, 1985; Knight, 1984b; Albers, 1985; McLean, 1986; Kidd & Joysten-Bechel, 1986; Clinical Research Associates, 1987; Hunt, 1987a; Ehrlich & Yaffe, 1987; McLean, 1987; Croll, 1988b; McLean, 1988), it is sometimes possible to retain

proximal enamel, as long as no cavitation exists. The incomplete removal of the proximal enamel has been described as a 'Class I tunnel restoration' (Hasselrot, 1990), 'Blind-tunnel' (Forsten, 1990), 'internal preparation' (Hunt, 1990), and 'partial tunnel restoration' (Svärdström, 1991). Removal of the proximal enamel is known as a Class II tunnel restoration (Hasselrot, 1993). Hickel & Voβ (1987) and Hasselrot (1993) have both reported a higher incidence of marginal ridge fracture when perforation of the proximal enamel has been performed. After preparation is complete and demineralised, intact enamel exists, the presence of the glass ionomer cement should promote remineralisation of the proximal enamel. If some enamel should dislodge later, there may be the development of plaque traps and recurrent caries.

Kidd and Joyston-Bechel (1986) have suggested that rotary instruments should not be used to remove all demineralised proximal enamel when there has been breakthrough of the enamel, because white spot lesions become more resistant to further demineralisation after fluoride exposure from glass ionomer cement. Although most authors utilise rotary instruments during preparation to prevent pressure on the marginal ridge, McLean (1986) suggested that hand instruments be used to avoid damaging the adjacent tooth. Ehrlich & Yaffe (1987) and Christensen & Christensen (1987) overcame this problem by placing a metal strip proximally and using rotary instruments to finish the proximal margins. Knight (1984) used small excavators and light hand pressure for caries detection but, like Hunt (1984), he used rotary instruments for preparation. Croll (1988b) used a loose metal matrix strip to delineate when proximal enamel was broken, while Hunt (1984) applied light pressure to proximal margins with a probe to detect fragile enamel.

After completion of the preparation in a molar tooth, ideally three millimetres of enamel should exist between the cemento-enamel junction and the gingival extent of the cavosurface margin, and 2.5 millimetres from the top of the marginal ridge to the occlusal portion of the cavosurface margin (McLean, 1987). Van Waes *et al* (1988) emphasised the importance of understanding the necessity to leave the completed preparation in a form that was ultimately difficult to restore and may have enamel deficiencies. This was the compromise for preserving the contour of the tooth, allowing remineralisation and avoiding a larger occlusal cavosurface margin.

While little consideration has been given to the primary dentition due to the variation in anatomy of deciduous teeth and the difficulty of performing these technically difficult procedures on children, two studies have suggested the use of tunnel restorations in deciduous teeth (Croll, 1988a; de Freitas *et al*, 1994).

1.3 Restorative materials used in tunnel preparations

A variety of materials including amalgam (Ehrlich & Yaffe, 1987; Hill & Halaseh, 1988; Covey *et al*, 1989) and composite resin (Bausch *et al*, 1986; Ehrlich & Yaffe, 1987; Covey *et al*, 1989; Purk *et al*, 1995) have been used to restore tunnel preparations. Most authors, however, advocate the use of glass ionomer cement, particularly the radiopaque varieties.

In Hunt's initial studies (1984), a non-radiopaque glass ionomer cement was used, with a calcium hydroxide base placed to delineate cavity walls on radiographs and to reduce postoperative sensitivity. Ketac Silver was recognised for its radiopaque characteristics and was first used in tunnel restorations by McLean in 1985 and later in studies by Croll (1988a), Croll (1988b), Robbins & Cooley (1988), Fasbinder *et al* (1991), Hasselrot (1993), Elmnford (1994), Strand *et al* (1995a), Shetty & Munshi (1996), Strand *et al* (1996) and Hasselrot (1998). In 1989, Garcia-Godoy and co-workers first described the condensation of Ketac Silver with a dampened cotton pellet. They also found that composite resin placed over the occlusal portion resulted in better wear resistance, as previously suggested by Hunt (1987a), Hunt (1987b), McLean (1987), Croll (1988b) and McLean (1988).

Encapsulated glass ionomer cements are favoured by most authors, however Christensen (1990) preferred hand-mixed glass ionomer cement that can be rolled into a 'sausage' shape and condensed into the tunnel preparation. It was suggested by Croll 1988(b) that a centrix syringe be used when the syringe tip is too large to enter the full depth of the cavity preparation. He found that because of the wide nozzle tip, small air bubbles were often incorporated into the mix upon injection of the restorative

material. Because of the thin lumen of the centrix syringe tip, a high pressure is produced during placement of the cement, preventing air bubbles being incorporated into the restorative material. The reduced diameter of the tip also allowed greater access into the depths of the cavity preparation. More recent studies have restored tunnel preparations with new generation auto-cure glass ionomer cements such as Fuji IX, as well as Hi-Dense, an admix of spherical high-copper amalgam alloy particles and a glass-ionomer (Jones, 1999).

Finishing of the proximal cavosurface margins is difficult because of limited access but is not required if these margins are conservative and do not encroach into the embrasure area. Any attempt to remove excess from the proximal margins is best left until after the initial set (Pearson, 1983). Wedging of the matrix minimises the amount of excess material and McLean (1986) suggested that once the matrix band was removed, excess restorative material can be removed from the margins with sharp excavators and water-cooled diamond burs. Croll (1988a) preferred to use fine abrasive strips to smooth and polish the axial segments, while Hunt (1984) suggested that flossing was adequate to remove excess interproximal material. It has been suggested, however, that material may be lost from the proximal surface after placement (Forsten *et al*, 1994), due to the acidic environment (Crisp *et al*, 1996) and the risk of early moisture contamination because of limited proximal access in which to place a protective coating (Um and Oilo, 1992).

1.4 Case selection for tunnel restorations

The aim of a tunnel restoration is to remove proximal caries from a posterior tooth via an entry point in the occlusal fossa close to the carious lesion, while maintaining the integrity of the marginal ridge. The most important consideration in case selection is the extent of the proximal caries. This can only be achieved by accurate diagnosis using bitewing radiographs. It must be said, however, that accurate interpretation of the radiographs is often difficult.

When a lesion is detected radiographically to have slightly invaded enamel, histological evidence shows that this lesion is larger than it appears on the radiograph (Gwinnett, 1971; Purdell-Lewis *et al*, 1974), suggesting that the radiolucency may underestimate the extent of the caries. It has also been reported that the decay process associated with proximal lesions can take two to four years to progress through the enamel (Bracker Dirks, 1961; Berman & Slack, 1973; Marthalar & Wiesner, 1973; Zamir *et al*, 1976; Granath *et al*, 1980). Therefore, a radiolucency discovered radiographically could have been present for a number of years.

Berman and Slack (1973) reported that 50 per cent of proximal lesions in dentine did not progress over three years, while Backer Dirks (1961) showed that 50 per cent of proximal dentine lesions did not progress over a four year period, and after six years 33 per cent had not continued to develop. All these studies emphasise the importance of accurate, standardised, reproducible radiographs which are interpreted correctly. In addition, other variables such as oral hygiene and diet of the patient, the condition of surrounding teeth, caries prevalence, condition of the tooth to be restored and the ability to perform tunnel restoration procedures must all be taken into account.

Notwithstanding these factors, the operator's judgement in diagnosis must be seen as a critical part of treatment planning for these restorations. Despite the known mechanism of caries progression in enamel, there appears to be little information reporting the process of caries progression in dentine. Some authors, however, have shown that dentine caries may not enlarge radiographically over many years, with

Berman and Slack (1973) and Backer Dirks (1961) questioning the correct time to debride caries using invasive techniques. It is also possible that enamel cavitation is not present when a radiolucency exists in the dentine radiographically. In a study by Bille and Thylstrup (1982), it was shown that 50 per cent of radiographic radiolucencies extending minimally into dentine did not show enamel cavitation. This contrasted with studies by Marthalar and Germann (1970) and Rugg-Gunn (1972), where all radiographic dentine lesions showed evidence of enamel cavitation at the time of cavity preparation. It has been shown by Gröndahl (1982), however, that the higher the caries prevalence, the more likely these lesions will show cavitation. Méjàre *et al* (1985) and Espelid and Tveit (1986) found that diagnosis of cavitation by clinical or radiographic means was difficult and not entirely accurate unless the enamel cavitation was clearly visible. Therefore, it can be concluded that bitewing radiographs are essential for diagnosis despite interpretation difficulties (Kidd, 1984).

Fibreoptic transillumination has been suggested as a useful adjunct in the diagnosis of a carious lesion. However, it may not be particularly useful for smaller lesions as it has been shown by Purdell-Lewis and Pot (1974) and Mitropoulos (1980) that this technique is less sensitive than bitewing radiographs. Nyvad *et al* (1980) reported that once caries has progressed to the dentine-enamel junction and beyond on radiographs, fibreoptic transillumination may become almost as reliable as the bitewing radiograph.

The philosophy of treatment modalities must continue to change with the focus on prevention and remineralisation where possible, in order to prevent eventual replacement restorations becoming larger and more complex. When demineralised enamel has been identified via the various diagnostic procedures, fluoride has been demonstrated to control levels of bacteria at infected sites and promote remineralisation (Wei *et al*, 1968; Silverstone *et al*, 1988a; Johansen *et al*, 1988). If, however, the dentine is invaded and the operator makes a judgement to remove the caries, the main aim must be to conserve as much tooth structure as possible without compromising the end result and therefore encouraging premature failure. Ideally, the resultant size and shape of the cavity preparation should be largely based on the extent of the carious lesion (Dawson and Makinson, 1992). Forsten (1993) suggested that

many dentists expect tunnel restorations to become a general alternative to traditional Class II amalgam restorations.

When the proximal caries is extensive, cracks might be present in the marginal ridge and caries removal via a tunnel access could lead to premature failure of the marginal ridge, particularly if it was greatly undermined (Ehrnford and Frannson, 1994). These teeth would be better restored with a conservative class II restoration. Patient compliance also plays a major role in the case selection and, if access is difficult, a tunnel restoration would be an arduous procedure to perform.

Hunt (1994) suggested that there existed a need to develop a modern, biologically based rationale that was a guide for the operator in removal of proximal caries. He felt that a thorough knowledge was required on the spread of caries, the structural integrity of the tooth, the effects of microleakage, as well as the performance of the different materials used for restoration. Therefore, case selection for a tunnel restoration is dependent on many variables and may be ideal for the treatment of a small carious lesion that has just invaded the proximal dentine, in a compliant patient with low caries susceptibility and good oral hygiene, when this type of lesion is considered to require restoration.

Chapter 2

GLASS IONOMER CEMENT

2.1 Development of glass ionomer cement

Glass ionomer or aluminosilicate polyacrylate (ASPA) cement was developed in 1969 at the laboratory of the Government Chemist in England and was first reported by Wilson and Kent in 1971. Its development was borne from a logical progression of the dental silicates in an attempt to eliminate some of their deficiencies and in 1972 ASPA was unveiled by Wilson and Kent. It was four years later before it became commercially available, with McLean and Kent outlining their use of ASPA in clinical situations in 1977.

Despite the shortcomings of the dental silicates, such as deterioration of the metal phosphate binder in the presence of acid produced from fermented sugars in the oral environment and poor adhesion to tooth structure, Wilson and Kent (1972) favoured them for the development of other materials because of the superior strength of the glass particles and the effective bond between the filler and matrix. They also found that the dental silicates displayed superior abrasion resistance when compared to composite resin, and a closer match in the modulus of elasticity and thermal expansion between the filler and matrix. Wilson and Kent (1972) observed during the development, however, that there needed to be a greater proportion of alumina to silica in the powder because of the weaker polyacrylic acid. It was found that the set glass ionomer cement obtained a comparable compressive strength to the dental silicates (218 MPa) and exhibited a superior tensile strength (17 MPa) compared to the dental silicates (13 MPa). Other advantages found by Wilson and Kent (1972), were a greater resistance to acid attack, resistance to certain stains and adhesion to base metals which would be useful for orthodontic brackets. Theoretically it was also expected that there would be less irritation to the dental pulp because of the large polyelectrolyte chain and polyacrylic acid molecules, which show less tendency to diffuse along the dentine tubules.

Polyacrylic acid was investigated because it had previously been shown to possess binding properties of cations to polyanionic chains (Miller, 1966). The breakthrough, however, came when Smith (1968) suggested the use of polyacrylic acid to replace phosphoric acid in dental cements. Initial investigations using dental silicate powders and various organic acids produced unfavourable findings, with the resultant polyacrylic cement pastes setting slowly and being not hydrolytically stable (Wilson, 1968). Wilson and Kent (1971) established that the setting mechanism was an acid-base reaction and that clinical success would depend on the development of new glasses (Wilson *et al*, 1972). After extensive experimentation, Kent *et al* (1973) found a glass (G-200) that was high in fluoride and produced a workable cement called ASPA I. The resultant mixture was still slow to set (20 minutes) and due to the fluoride content was very opaque. It was noted, however, that carving was easily carried out with a sharp scaler and it possessed excellent adhesive properties.

Commercial development was enhanced when Crisp (1975) introduced tartaric acid to modify the cement-forming reaction, which produced improved manipulation, extended working time and a faster setting rate (Wilson *et al*, 1976). This refined version, known as ASPA II, was the first glass ionomer cement used for practical applications. Setting times, however, were still considered too long and the liquid shelf life too short. This was overcome by Crisp and Wilson (1973) when they synthesised a copolymer of acrylic and itaconic acid that was stable in a 50 per cent aqueous solution. This development was used in ASPA IV and formed the basis of the first commercially available glass ionomer cement (De Trey ASPA) produced in Europe in 1975 and later released in Australia and the USA in 1976 and 1977. With the use of tartaric acid in later development, the resultant faster setting times allowed reduced levels of fluoride thereby producing more aesthetic cements. In early clinical studies, dislodgment of these restorations was reported (Smales, 1981; Vlietstra *et al*, 1978). A survey into the longevity of glass ionomer cement by Mount (1986) found, however, that the main cause of this early clinical failure was due to improper manipulation of the material resulting from a lack of understanding of the chemical adhesion and the setting reaction, despite earlier work by Mount (1981) to simplify clinical procedures.

Further development of glass ionomer cement occurred as a result of unfavourable abrasion resistance and fracture toughness. Initially, the addition of silver-tin alloy fibres or flakes improved the flexural strength of glass ionomer cements (Sced and Wilson, 1980; Simmons, 1983). McLean and Gasser (1985) found that optimal results were achieved using pure silver powder with an average particle size of 3.4 micrometres, while the inclusion of titanium dioxide improved aesthetics. In studies carried out at the Laboratory of the Government Chemist in England, Wilson (1984) reported that the inclusion of silver sintered particles improved mechanical properties of the glass ionomer cement. He reported the main advantage was the increased plastic strain and energy to fracture, while enhancing abrasion resistance, reducing setting time and increasing resistance to early water contamination. Wilson (1984) attributed the improved fracture resistance to the soft silver particles acting as stress absorbers and the good wear characteristics to the low coefficient of friction of the polished metal surface.

Nakajima *et al* (1989) found that like conventional glass ionomers these cermet cements released fluoride and bonded to tooth structure while having a much higher compressive strength. Arcoria *et al* (1988) had previously been using cermet cement for core build-ups as an alternative to amalgam. It was postulated that it could be used as a lining beneath amalgam (Scherer *et al*, 1989a and 1989b) because it could reduce the potential for amalgam to deteriorate under heavy load. Arcoria *et al* (1991) found that as a lining beneath amalgam restorations it dramatically reduced microleakage, while McLean and Gasser (1985) described a technique of restoring the cervical two millimetres of the box of a conventional Class II restoration providing an adhesive, cariostatic material in an area of high caries risk (Mjör, 1985). Placement of varnish over the material was shown to also reduce microleakage (Powis *et al*, 1982; Welsh and Hembree, 1985; Garcia-Godoy *et al*,1988).

The first commercially available cermet cement was Ketac Silver (Espe, Germany), which displayed mechanical strength lower than that of amalgam and posterior composite resin and comparable to conventional glass ionomer cements. Despite their fluoride release being less than conventional glass ionomer cement (Swift, 1989;

Hasselrot, 1993), clinically it was suggested by Croll (1991) in a six-year clinical trial that glass-ionomer-silver-cermet Class I restorations could routinely last six years or more.

More recently, it was recognised that despite the clinical success of glass ionomer cement, particularly for cervical restorations (Tyas, 1994; Van Dijken, 1996), disadvantages existed, including sensitivity to moisture contact and increased opacity over time (Mount, 1994). Research was directed towards combining the characteristics of resin composites with conventional glass ionomer cements, with Antonucci *et al* (1988) and Mitra (1989) first reporting the resin-modified glass ionomer cements. They contained components of both visible-light cured resins, mostly hydroxyethyl methacrylate (HEMA) and conventional chemical-cured glass ionomer cements (Croll and Killian, 1992; Christensen, 1993). Not only did they bond to tooth structure, release fluoride, achieve biocompatability and thermally insulate, but they exhibited greater early compressive and diametral tensile strength and were more resistant to moisture.

Resin-modified glass ionomer cements (RMGIC) were popularised by the liner Vitrebond (3M, Mn, USA), with the first restorative material released by GC (Fuji II LC), an evolution of Fuji II (a chemically-cured glass ionomer cement). These materials were relatively sticky initially, but became popular after their introduction because they were easier to use than conventional glass ionomer cements, the visible-light curing allowed earlier finishing (Christensen, 1997) and resulted in better aesthetics than conventional glass ionomer cements (Burgess *et al* 1994). Although surface finish was dull and deteriorated after placement due to abrasion by mechanical contact and corrosion by chemical interaction with food (Christensen, 1996; Sidhu *et al*, 1996), it has been suggested that a smoother surface could be obtained when an application of unfilled resin was applied after the material was placed and cured (Burgess *et al*, 1994). However, it was considered that this might prevent normal fluoride release and subsequent uptake (Castro *et al*, 1994; Burgess *et al*, 1994).

Despite improved physical properties (Huget and Murray, 1994), surface staining was found to occur due to their lower surface hardness (Papageorgiou and Mount, 1992;

De Gee *et al*, 1994), while residual HEMA, present for up to 24 hours after polymerisation (Yoshikawa *et al*, 1994), may be susceptible to hydrolytic breakdown and contribute to surface staining. It has also been suggested that HEMA causes increased water sorption (Nicholson *et al*, 1992), while Mount (1993) observed slow dehydration in a moist environment which would affect the colour stability if not coated with a protective resin. The resistance to abrasion and wear of resin-modified glass ionomer cement was found to be less than for conventional glass ionomer cement (Creo and Vivattine, 1994; Schreyger *et al*, 1994; Koutsikas, 1995). Using Rockwell hardness and three-body *in vitro* wear tests, Peutzfeldt *et al* (1997) published data which supported these findings. In a clinical study by Smales and Koutsikas (1995), occlusal Class I preparations restored with Fuji II LC showed up to 300 micrometres of wear at the cavity margins after 12 months. This contrasted with findings by Croll (1993), where the surface of Class I restorations restored with Fuji II LC was reported to be as hard as composite resin several days after placement and equally as sound after 12 months. Another study by Maki *et al* (1994), also found no obvious wear after 12 months on the occlusal surface of immature permanent teeth restored with the same material. It was found that wear could be minimised by using a thicker mix and applying a thin layer of resin sealant over the restoration (Croll and Killian, 1993).

Burgess *et al* (1994) reported that resin-modified glass ionomer cements such as Fuji II LC displayed a higher coefficient of thermal expansion than conventional glass ionomer cements which more closely approximated tooth structure. This has been supported in other studies by Cardenas and Burgess (1994) and Mitra and Conway (1994).

More recently, however, glass ionomer cement development has produced a new generation of conventional glass ionomer cements such as Fuji IX (GC, Japan) and Ketac Molar (Espe, Germany). These materials have been shown to have greater compressive strengths than resin-modified glass ionomer cements (Ewoldsen *et al*, 1997), suggesting they are stronger than earlier conventional glass ionomer cements. Peutzfeldt *et al* (1997) also found that the surface hardness was greater and *in vitro* wear was less than resin-modified glass ionomer cements. An *in vitro* study by

Virmani *et al* (1997) restoring non-retentive Class II preparations with Fuji IX, amalgam and Fuji II LC, found that Fuji IX produced a higher cuspal fracture resistance than amalgam and resin-modified glass ionomer cement. In another *in vitro* study, Sanders-Tavares *et al* (1997) investigating polymerization shrinkage stresses during setting and after load cycling in Class II restorations, found no leakage in any preparations restored with Fuji IX. However, in a similar study by Ferrari *et al* (1997) 80 per cent of *in vitro* specimens displayed microleakage while only 20 per cent of clinical specimens showed leakage. The authors, therefore, questioned the effectiveness of *in vitro* studies in predicting clinical performance. It was suggested that the high wettability of the powder particles of the Fuji IX was the main reason for the presence of overcontoured cervical margins of the specimens, yet helped in the material's sealing ability. As with the earlier glass ionomer cements, an ion-enriched zone was found to exist between the glass ionomer cement and the dentine.

2.2 Composition and setting reactions

Glass ionomer cement is supplied as a powder and liquid either for hand-mixing or in an encapsulated form. If the polyalkenoic acid is dehydrated and incorporated into the powder, then the liquid is usually water, with or without tartaric acid. Although components of the powder and liquid vary among different materials and therefore cannot be interchanged, the setting reaction is essentially the same.

Glass powder

The range of size of the powder particles can be up to 50 micrometres for restorative glass ionomer cements and as small as 4 micrometres in the luting cements. The temperature of glass fusion of the powder particles is affected by the addition of fluoride. This subsequently influences the working characteristics and hence the properties of the glass ionomer cement. Radiopacity is achieved by the incorporation of barium, strontium, lanthanum or silver. In cermet cements, metal such as silver is sintered, or fused to the glass particles and titanium oxide is added to produce a more acceptable clinical colour.

Liquid

Initially, polyacrylic acid was used as the liquid for glass ionomer cements, however modern materials contain a 40-55 per cent copolymer solution of two parts acrylic acid to one part itaconic acid. A 10 per cent tartaric acid is often incorporated into the liquid to control the setting reaction (Wilson *et al*, 1976).

Resin-modified glass ionomer cements contain hydrophilic resin components such as hydroxyethyl methacrylate (HEMA) or bisphenol-A diglycidyl dimethacrylate (Bis-GMA) in the liquid (Mathis and Ferracane, 1989). Wilson (1990) used a water/HEMA mixture to replace water in the conventional glass ionomer cement. Two variations in liquid content exist for use in resin-modified glass ionomer cements. Materials such as Fuji II LC contain HEMA blended with polyalkenoic acid, while other manufacturers have modified the polyalkenoic acid by the attachment of polymerizable methacrylate side groups. The initial set of the resin component after

visible-light curing offers protection to the ongoing acid-base reaction, with around five per cent hydrophilic resin in the final set resin-modified glass ionomer cement (Mount, 1994; Sidhu and Watson, 1995). Therefore the monomer cross-links when polymerized while the acid-base reaction continues as water is absorbed.

Setting reaction

A glass ionomer (polyalkenoate) cement forms from the acid-base reaction between ion leachable calcium aluminosilicate glass particles and a polyalkenoic acid. Wilson (1977), represented the acid-base reaction as:

Glass (base)	+	Polyacid	=	Polysalt gel	+	Silica gel
POWDER		LIQUID		MATRIX		PARTICLE COATING

The setting reaction takes place in three overlapping stages (Crisp and Wilson, 1974a). Stage one occurs when the polyacid attacks the surface of the glass particles (Crisp and Wilson, 1974b). Approximately 20-30 per cent of the glass is decomposed with calcium, aluminium and fluoride anions released. Stage two involves precipitation, gelation and hardening of the material. With the increase in pH, cations and anions precipitate as calcium polysalts followed by aluminium polysalts (Crisp and Wilson, 1974a; Crisp *et al* 1974). The third stage is the maturation phase involving the hydration of salts which develops the improved physical characteristics (Wilson *et al*, 1979). The final structure consists of original glass particles within a siliceous hydrogel, bonded by a matrix of hydrated, fluoridated, calcium and aluminium polyacrylates (Smith, 1990; Hatton and Brook, 1992). It is critical that in the first hour after placement of the glass ionomer cement, no water movement occurs in or out of the material, to avoid contamination or dehydration. However, it has been suggested by Earl and co-workers (1985) that varnishes as well as other non-proprietary products are often ineffective.

During setting of the resin-modified glass ionomer cement, Wilson (1990) described a dual mechanism, where the normal glass ionomer acid-base reaction occurred upon

mixing, in addition to a free radical polymerisation reaction which was produced by either photoinitiators, chemical initiators, or both. Wilson (1990) found that due to the presence of HEMA, which replaced some of the water, the acid-base reaction was slowed down upon mixing. This was supported by Mitra (1991a) and Bourke *et al* (1992) when they found that these dual-cure materials continue to undergo chemical reactions for some days after the initial curing. A true resin-modified glass ionomer cement will set fully without being visible-light cured, that is, in a dark environment (McLean *et al*, 1994; Mount, 1994a). This has been suggested to be the result of the continued acid-base reaction. At the completion of setting, a metal polyacrylate salt hydrogel and a polymer are formed. This was confirmed in a shear punch test by Mount and co-workers (1996), where strength measured over five days was shown to increase in the same manner as auto-cure glass ionomer cements, suggesting a continuing acid-base reaction.

Attin *et al* (1995) suggested that the continued setting reactions were responsible for the continued curing shrinkage after polymerisation. They found that the curing shrinkage of resin-modified glass ionomer cements was greater than for conventional glass ionomer cements. It has been proposed that this shrinkage could create marginal deficiencies if the material did not sufficiently adhere to tooth structure (Bausch *et al*, 1982), and also create stresses within the material with the potential to produce cohesive fracture within the restoration (Bowen and Marjenhoff, 1992). It has been shown, however, that the resin-modified glass ionomer cements behave as a hydrogel (Anstice and Nicholson, 1992), with initial swelling due to the hydrophilic HEMA chains taking up water (Meyer *et al*, 1998). This swelling is greater than that of conventional glass ionomer cement.

The powder : liquid ratio of new generation auto-cure glass ionomer cements is greater than earlier materials, with more aluminosilicate powder providing enhanced physical properties (Hickel *et al*, 1998; Jones, 1999). In order to control the speed of the setting reaction, the powder particles of a glass ionomer cement such as Fuji IX are treated so that there is sufficient working time (Hirota, 1999). The setting reaction, however, is the same as for the original glass ionomer cements.

2.3 Physical characteristics

Adhesion to enamel

An important characteristic of glass ionomer cement is its ability to bond chemically to tooth structure. It was thought that the highly ionic nature of the cement allowed it to compete with water to form hydrogen bonds with enamel apatite (Hotz *et al*, 1977; McLean and Wilson, 1977; Wilson and Prosser, 1982). Hotz *et al* (1977) suggested metal ion bridges were formed and this was supported by Powis *et al* in 1982. Wilson *et al* (1983), however, showed in SEM studies, the displacement of calcium and phosphate ions due to the bond between polyacrylates and hydroxylapatite. Adhesion is initiated by polyalkenoic acid when the unset glass ionomer cement comes in contact with the tooth surface, developing an ion-enriched layer between the tooth and material to create a firm bond without microleakage (Mount, 1991). Upon separation of the glass ionomer cement from the tooth structure, this ion-enriched layer is left behind, indicating a cohesive failure in the material and not an adhesive failure at the interface. Studies on the bond strength to enamel have found that this adhesive strength is greater than the cohesive strength of the material (Coury *et al*, 1981; Eakle, 1985). Furthermore, a study by Weerheijm *et al* (1993) found that the enamel seal with glass ionomer cement when placed over dentine caries is good enough to encourage a fall of bacterial counts by 100 times over several months.

Mechanisms of bonding to enamel for resin-modified glass ionomer cements are the same as for conventional glass ionomer cements. However, it has been suggested that their composition allows the possibility of an acid-etch bonding mechanism similar to resin systems (Phijaisanit and Tyas, 1996). Cortes (1993) and Erickson and Glasspoole (1994) found that the bond of resin-modified glass ionomer cement was improved after etching of the enamel due to the infiltration of various monomers.

Adhesion to dentine

The mechanisms already described in bonding between glass ionomer cement and enamel also occur within dentine. However, additional bonding takes place through either hydrogen bonding or metallic ion bridging between the carboxyl groups on the polyacid and the collagen molecules of the dentine (Hotz *et al*, 1977; McLean and Wilson, 1977). Adhesive strength has not yet been precisely measured because the ion-exchange layer always exists upon separation, suggesting cohesive failure within the glass ionomer cement (Watson *et al*, 1991).

Most of the early clinical trials on glass ionomer cement were carried out on cervical abrasion lesions which measured the material's effectiveness in bonding to dentine. McLean and Wilson (1977) reported a nine per cent loss after three years, while Tyas and Beech (1985) using Fuji II reported an eight per cent loss after two years. Horsted-Bindslev *et al* (1988), however, using Fuji II to restore 22 cervical restorations, reported 100 per cent success after three years. This was despite 50 per cent of the restorations displaying marginal fracture and 30 per cent marginal staining.
These studies together with results of other clinical studies (Knibbs, 1987; Tyas *et al*, 1986; Matis *et al*, 1988; Powell *et al*, 1991) supported glass ionomer cement's ability to adhere to dentine.

New generation auto-cure glass ionomer cements have been shown to develop an acid resistant interdiffusion zone at the dentine interface of approximately six micrometres under *in-vitro* and clinical conditions (Ferrari and Davidson, 1997). Hosoya and Garcia-Godoy (1998) also described in their study an intimate adaptation of these materials to enamel and no gap formation at the dentine/restoration interface. This was evident in a study by Virmani *et al* (1997) where Fuji IX displayed the best adaptation and least microleakage when compared with amalgam and resin-modified glass ionomer cements. This study also revealed that Fuji IX most successfully prevented cusp fracture in Class II restorations compared with amalgam and resin-modified glass ionomer cements. Smales *et al* (1997) studied the seal of these new generation auto-curing glass ionomer cements in fissures and compared them to resin sealants. They found that there was no statistically significant difference between the materials

tested, with the glass ionomer cement showing minimal microleakage and better fissure penetration despite the greater viscosity.

Resin-modified glass ionomer cements demonstrate greater adhesion than conventional glass ionomer cements (Holtan *et al*, 1990). An effective adsorbed layer forms on the dentine, as a result of an increased ion-exchange process occurring, due to the production of acid once the material is visible-light cured (Lin *et al*, 1992). Lin *et al* (1992), Desai and Tyas (1996) and Uno *et al* (1996) have suggested this increased bond strength, which is typically 4-6 MPa (Burgess *et al*, 1994), was due to the material's higher strength and improved physical properties. Mitra (1991a) and Burgess *et al* (1993) also found that the bond to dentine was higher than that of conventional glass ionomer cement due to the additional bond between HEMA and dentine. Friedl et al (1995) suggested that this component provided superior wetting abilities. Compton *et al* (1992) found that resin-modified glass ionomer cements had higher initial and sustained bond strengths than conventional glass ionomer cements. This was further supported in later studies by Bell and Barkmeier (1994b), Triana *et al* (1994), Sidhu and Watson (1995) and Peutzfeldt (1996). *In vitro* studies have shown that resin-modified glass ionomer cements produce a good marginal seal (Crim, 1993; Hallet and Garcia-Godoy, 1993; Chandwani *et al*, 1993).

Resin modifications to glass ionomer cement have not been shown to affect the short-term bond to dentine (Pawlus *et al*, 1994; Triana *et al*, 1994; Bell and Barkmeier, 1994b; Yu *et al*, 1995). In a one-year clinical study, Maneenut and Tyas (1995) reported 100 per cent retention of cervical restorations restored with Fuji II LC, Photac-Fil (Espe, Germany) and Vitremer (3M, Mn, USA). However, it was noted that marginal staining was evident around most restorations. A long-term study by Fritz *et al* (1996) found that like auto-cure glass ionomer cement, resin-modified glass ionomer cements failed cohesively rather than at the restoration/tooth interface. The shear bond strength of Fuji II LC to dentine has been reported between 11 and 15 MPa and to enamel between 9-14 MPa (Triana *et al*, 1994; Bell and Barkmeier, 1994a; Charlton and Havemann, 1994; Kato *et al*, 1995; Chain *et al*, 1995; Scott *et al*, 1995; Fritz *et al*, 1996a).These figures are thought to be a guide only to the bonding capabilities of the material and do not necessarily infer better clinical performance

(Fritz *et al*, 1996b). It has been suggested by some authors that the improved adhesion of resin-modified glass ionomer cement reduces microleakage at the tooth/restoration interface compared with conventional glass ionomer cements (Burgess *et al*, 1993; Crim, 1993; Hallet and Garcia-Gardoy, 1993; Sidhu, 1994).

Factors affecting adhesion

Adhesion is the attraction between two molecules of different materials at their interface and is affected by a clean tooth structure, wetting of the surface and effectiveness of the adhesive. Chemical variation of the substrate, differences in the coefficient of thermal expansion and wetting changes on solidification will affect the final adhesion (Lin *et al*, 1992). *In vitro* testing of adhesion of glass ionomer cement to tooth structure has involved microleakage investigations. Early studies by Alperstein *et al* (1983) and Baez *et al* (1984) found significant leakage in Class III and Class V preparations restored with ASPA and other early glass ionomer cements, while Hembree and Andrews (1984) reported more encouraging results. This was supported by the results of a study by Welsh and Hembree (1985) where Fuji II glass ionomer produced similar positive results at six months.

With the ability of glass ionomer cement to bond chemically to tooth structure, less mechanical retention is required (McLean and Wilson, 1977). However, an intimate contact must be created at the interface of the tooth and glass ionomer cement in order to optimise adhesion. Brännström and Johnson (1974) suggested the removal of any material such as hard tissue particles, blood, saliva and microorganisms that would inhibit this bond. Several techniques have been suggested, such as pumice on a rubber cup (Dahl, 1978 ; Duke *et al*, 1985, Aboush and Jenkins, 1986) and use of a Prophy-jet (Dentsply Int, PA, USA) (Aboush and Jenkins, 1986), as well as various chemical agents. Although initial studies found that 50 per cent citric acid was effective in clinical use (Hotz *et al*, 1977; Prodger and Symonds, 1977), later studies by Powis *et al* (1982) and Aboush and Jenkins (1986) found that it did not promote adhesion to tooth structure and was not particularly biocompatible. In 1982, Powis *et al* reported that 25 per cent polyacrylic acid was effective in removing debris from dentine surfaces and produced significantly increased bond strengths between dentine and

glass ionomer cement. Hewlett *et al* (1991), however, found in a laboratory study that there was no difference in bond strength when the concentration of polyacrylic acid was varied for conditioning. Bond strength, however, was not found to be increased in later studies by White *et al* (1989), Tyas (1993) and Bell and Barkmeier (1994b). Aboush and Jenkins (1986) showed that an application of 25 per cent polyacrylic acid for 30 seconds was equally effective as using pumice and water for 10 seconds in removing a saliva contaminated dentine surface layer. Different results were obtained in a clinical study by Van Dijken (1992), where cervical abrasion lesions prepared with 40 per cent polyacrylic acid accounted for a greater number of failures (17.9 per cent) than those prepared with pumice and water (11.6 per cent) when restored with glass ionomer cement.

Importantly though, using polyacrylic acid to prepare the cavity surface will not interfere with the setting reaction as it is present in the glass ionomer cement. The polyacrylic acid acts by lowering the surface energy of the tooth which increases the wettability, encouraging adaptation. Excessive conditioning, however, may cause demineralisation of the tooth surface and diminish the adhesive ability of the glass ionomer cement. Application of a mild polyacrylic acid does not remove dentine smear plugs, but rather renders the tooth surface clean and inhibits fluid flow within the dentine tubules during restoration placement. Causten and Johnson (1982) have suggested that the application of a mineralising solution such as 25 per cent tannic acid for 1-2 minutes before washing thoroughly in order to include the smear layer within the ion-exchange layer. A study on Class V restorations by Tyas (1994), found that there was no difference in retention or marginal staining after three years between groups of restorations treated with 25 per cent polyacrylic acid and those prepared with a pumice and water slurry. It was suggested that removal of the saliva pellicle which existed over the smear layer was necessary for effective adhesion. This had previously been shown in a study by White *et al* (1989), where the smear layer was thought to be dissolved by the free acid from the glass ionomer cement during placement and did not require prior removal.

With resin-modified glass ionomer cements, greater adhesion has been shown after dentine conditioning and prior to placement of the restorative material (Hinoura *et al*,

1991; Bell and Barkmeier, 1994b; Burgess *et al*, 1994). However, McLean (1992) suggested it was not critical to condition the tooth surface because the presence of the HEMA component produced improved adhesion. In studies by Prati *et al* (1992) and Garcia-Godoy (1992), the effect of polyacrylic acid for conditioning produced different results. Sim and Sidhu (1994) found no significant differences between pretreatment methods on gap formation at the tooth interface with the restoration. This was supported in a study by Pachuta and Meiers (1995). Cortes *et al* (1993), however, found that etching of enamel prior to placement of resin-modified glass ionomer cement can increase its adhesion. This was also found in a study by Desai and Tyas (1996), where Fuji II LC showed significantly better tensile bond strength compared to conventional glass ionomer cement after the application of 10 per cent polyacrylic acid, and an even higher bond strength with the use of 35 per cent phosphoric acid. However, the use of phosphoric acid was not recommended because its placement was difficult to control.

Biocompatability

Early testing of glass ionomer cement by a number of researchers (Tobias, 1978; Kawahara *et al*, 1979; Pameijer *et al*, 1981) showed it to be well tolerated by the dental pulp. McLean (1984) promoted it for clinical use because of its low pulpal toxicity. In a study by Langeland and Pascon (1986), however, early pulpal inflammation was shown after glass ionomer cement was applied to dentine of premolars and molars of *Macaca cynomulgus*. Polyacrylic acids used in glass ionomer cements are weak acids with a high molecular mass and a chain entanglement that prevents them from penetrating dentinal tubules (McLean, 1988). Dentine is also an excellent buffer (Wang and Hume, 1988), therefore, despite the pH of freshly mixed glass ionomer cement being between 0.9 and 1.6, the thin layer of dentine separating the restoration and the pulp should be sufficient to prevent pulpal cytoxicity. This could be due to the polyacids being precipitated by calcium ions within the tubules (Hume and Mount, 1988). Conclusions drawn from these more recent studies indicate that glass ionomer can be safely applied to dentine where there is 0.5 millimetres of dentine separating the pulp.

Mechanical Strength

Conventional glass ionomer cements are weak and very brittle, lacking significant resistance to fracture (Prosser *et al*, 1984). Although they are adversely affected by moisture contamination, dehydration of the material causes surface crazing (Mount and Makinson, 1982; McLean, 1992). Maximum mechanical strength can only be achieved through the application of a protective coating during the setting phase of the glass ionomer cement. Cermet cements are not stronger than conventional glass ionomer cements, but rather are more resistant to abrasion (McLean, 1985). This was supported in a study by Mount *et al* (1996). In this study the shear punch test was used to measure the cohesion within a material and its resistance to deformation, as initially proposed by Roydhouse (1970).

Resin-modified glass ionomer cements are stronger than conventional materials, with the inclusion of the resin resulting in a faster set with increased strength development. Various authors have found improvement in compressive and tensile strength, modulus of elasticity and decreased brittleness compared to conventional glass ionomer cements, and their susceptibility to early moisture contamination greatly reduced (Mathis and Ferracane, 1989; Wilson, 1990; Burgess *et al*, 1993; Cho *et al*, 1995; Li *et al*, 1995; Uno *et al*, 1996).

The cohesive strength within these materials has also been studied. Conventional glass ionomer cement has been reported to be between 3-5 MPa (Hotz *et al*, 1977; Powis *et al*, 1982; Aboush and Jenkins, 1986), while Fuji II LC was shown to have a cohesive strength of between 9-13 MPa (Burgess and Burkett, 1993). Although other studies gave varied results, greater cohesive strengths than for auto-cured materials have generally been reported (Pawlus *et al*, 1994 ; Bell and Barkmeier, 1994a; Cortes *et al*, 1993; Friedl and Powers, 1994).

Fluoride Release

Fluoride release from glass ionomer cements can be influenced by the specimen shape, method of mixing, medium in which it is placed and the material type. It may also be influenced by factors such as the material's solubility, solution acidity and the presence of surface coatings (Fukazawa *et al*, 1987; Muzynski *et al*, 1988; Castro *et al*, 1994). Water plays a role in the release of fluoride ions. Water must diffuse from the environment before the process of glass dissolution and fluoride release can begin (Wilson *et al*, 1979; Wasson and Nicholson, 1993). When fluoride ions are released from glass ionomer cement after placement they are taken up by the surrounding tooth structure (Maldonado *et al*, 1978 ; Swartz *et al*, 1980 ; Derkson *et al*, 1982). It was suggested by Retief *et al* (1984) that the fluoride acquired by the enamel became firmly bound to the apatite structure, possibly in the form of fluorapatite or hydroxyfluorapatite, while that taken up by the cementum was not firmly bound. Calcium fluoride has been found to be deposited on dentine surfaces after exposure to high levels of fluoride (Saxegaard *et al*, 1987). Therefore, Featherstone (1994) suggested that higher concentrations of fluoride would be required to inhibit demineralisation of dentine and cementum. Studies by Swartz *et al* (1984), Retief *et al* (1984), Forss and Seppa (1990) and Skarlveit *et al* (1990) demonstrated that the level of fluoride can be increased in the enamel and dentine after placement of the restoration. This was demonstrated in a laboratory study by Tyas (1991) where the zone of acid resistance was found to be approximately three millimetres around the glass ionomer restoration.

The release of fluoride from glass ionomer cement has been measured in studies by Thornton *et al* (1986), McCourt *et al* (1990) and Mitra (1991). Glass powder particles contain up to 23 per cent fluoride which is initially released in large quantities (Forsten, 1991), followed by a rapid decline in release over the first week after placement and a levelling off over the next 2-3 months. Wilson and McLean (1988) found that, after the initial high release, fluoride release was constant throughout a period of at least 18 months and that the total release was dependent on the sodium and calcium content of the glass rather than the amount of fluoride. This was considered important since sodium fluoride is not involved in the matrix formation

during the setting reaction and therefore the glass ionomer cement would not be weakened during the release of fluoride.

The release and subsequent uptake of fluoride has been suggested to enhance the cariostatic effect of glass ionomer cement (Forss and Seppa, 1990; Hicks *et al*, 1986; Hattab *et al*, 1989; Tyas, 1991; Campos Serra and Cury, 1992; Varpio and Noren, 1994; Souto & Donly, 1994). This has been supported clinically by Mount (1986) in a nine-year study of Class III restorations where there were no reported cases of recurrent caries. A five-year clinical study by Tyas (1991) found that 11 per cent of Class V composite resin restorations exhibited recurrent caries as opposed to two per cent of glass ionomer cement restorations. These results were similar to those of Levy *et al* (1988), who had previously found that three per cent of Class V restorations restored with glass ionomer cement displayed recurrent caries, compared to six per cent of restorations restored with composite resin. In this study, glass ionomer cement restorations displayed twice the amount of microleakage compared to composite resin restorations. This conflicted with findings by Triadan (1987), who suggested that recurrent caries was the end result of marginal leakage. However, it did highlight the effect of the fluoride on secondary caries formation. Mount and Makinson (1978) and Garcia-Godoy *et al* (1988) found in the laboratory that the capacity of the glass ionomer cement to release fluoride into adjacent tooth structure reduced the incidence of secondary caries and helped reduce the degree of microleakage. Valk and Davidson (1987) also found that orthodontic brackets cemented with glass ionomer cement showed cariostatic effects, while Hallgren *et al* (1992) showed that *Streptococcus mutans* levels beside brackets retained with glass ionomer cement were lower than those retained with composite resin.

In vitro studies have also shown that the release of fluoride enhances the antimicrobial action of the glass ionomer cement against *Streptococcus mutans* in plaque (Forss *et al*, 1991; Loyola-Rodriguez, 1994; Svanberg *et al*, 1990) as well as the antimicrobial action of resin-modified glass ionomer cement (Meier and Miller, 1996). Glass ionomer cement restorations have also been reported to remineralise incipient enamel lesions *in vitro* (Campos Sera and Cury, 1992), while a study by Arends *et al* (1989) found that fluoride from glass ionomer cement can lead to dentine

hypermineralisation. This was later supported in a study by Ten Cate and Van Duinen (1995). Walls (1986) found that fluoride was not only released from glass ionomer cement, but was taken up and stored after fluoride applications from toothpastes and topical solutions, with the glass ionomer cement acting as a reservoir for fluoride. He suggested, however, that acidified fluoride preparations such as acidulated phosphate fluoride should be avoided because they alter the surface of conventional glass ionomer cements. Jones and co-workers (1988), however, did not find this to be the case during their *in vitro* studies.

In contrast, a study by Mjör (1996) has suggested the cariostatic effect of glass ionomer cement is not as effective as previously reported. He presented a retrospective study carried out amongst Swedish practitioners who reported that nearly half the glass ionomer cement restorations that required replacement did so as a result of secondary caries. Although he questioned the cariostatic properties of glass ionomer cement, it must be noted that not only were most of the practitioners surveyed new graduates, but the criteria for replacement and the diagnosis of recurrent caries were not standardised. Further retrospective studies were performed by Wilson *et al* (1997) and Burke (1999) in the United Kingdom with similar results obtained. Because the restorations were placed by unknown operators in these studies, the techniques employed and the conditions under which the restorations were placed initially were not considered. There was also no significance placed on the caries activity of the patients or the oral hygiene.

Some authors have also questioned the effectiveness of fluoride uptake in the presence of intermediary microgaps at the restoration/tooth interface (Geiger and Weiner, 1993; Sidhu and Watson, 1994). Despite an ion-exchange layer forming during the setting reaction of the glass ionomer cement, Eliades and Palaghias (1993) reported the presence of gaps between the glass ionomer cement and dentine, yet it is unclear whether the presence of fluid in these gaps would encourage or suppress fluoride transfer between the material and the tooth structure.

The release of fluoride has also been shown to occur from resin-modified glass ionomer cements (Hatibovic-Kofman and Koch, 1991; Tam *et al*, 1991; Kato *et al*, 1993; Takahashi *et al*, 1993; Kupietzky *et al*, 1994) and it has been suggested that this release is greater than from current conventional glass ionomers such as Fuji IX (Rothwell *et al*, 1998). A study by Mogkolnam and Tyas (1994) showed fluoride release from resin-modified lining materials was greater than that from conventional glass ionomer materials. In laboratory studies, Glasspoole and Erickson (1994), Nagamine et al (1994) and Tam *et al* (1997) all reported the ability of resin-modified glass ionomer cement to inhibit demineralisation. It was proposed that this was due to fluoride release, which like that from conventional glass ionomer cement has been shown by Mitra (1991) to penetrate up to 100 μm and even up to 300 μm into dentine (Tam *et al*, 1997). Mitra (1991b) has also shown that the uptake of fluoride by resin-modified glass ionomer cement to be comparable, if not greater than, conventional glass ionomer cement. This has been supported in studies by Forss (1993), Momoi and McCabe (1993), Burgess *et al* (1994) and Forsten (1995). Hatibovic-Kofman *et al* (1994) and Alvarez *et al* (1994) showed that fluoride-containing toothpastes, together with topical fluoride solutions, replenished the fluoride in resin-modified glass ionomer cements, which is then available for subsequent release. These materials have also been found to be more resistant to surface degradation after application of acidified fluoride solutions, compared to conventional glass ionomer cements (Burgess *et al*, 1994). This was thought to be due to the different matrix found in the resin-modified glass ionomer cements.

Chapter 3

POLYACID-MODIFIED RESIN COMPOSITES (COMPOMERS)

3.1 Description

This group of materials, classified as polyacid-modified resin composites (PAMRC) (McLean *et al*, 1994; Burgess *et al*, 1994; Mitra, 1994), was introduced in the early nineties, claiming to be from the glass ionomer cement family with the advantages of fluoride release and improved physical characteristics. Although these materials are also known as 'compomers', which suggests they possess the characteristics of both composite resin and glass ionomer cement, the glass ionomer attributes are minimal.

3.2 Composition and setting reactions

Most polyacid-modified resin composites consist of a single paste which requires light-activation to initiate the setting reaction. They are made up of fluoride-containing glass filler particles, typical of glass ionomer cements, together with resins such as urethane dimethacrylate (UDMA) or bis-glycidyl dimethacrylate (BIS-GMA) which comprise the matrix. These resins contain carboxylic acid and methacrylates together in the one molecule, allowing cross-linking of the monomer, when initiated, through free-radical polymerisation. An acid-base reaction also occurs with the reactive glass particles through the presence of carboxyl groups. The process of polymerisation occurs in two stages. Initially, light activation of the resin creates a resin network enclosing the filler particles and clinically the material hardens. The second stage is a slow process whereby water is absorbed over a period of two to three months and the carboxyl groups from the polyacid and the metal ions initiate a very slow and limited acid-base reaction, creating hydrogels within the resin structure. Essentially, a polyacid-modified resin composite contains either or both of the

components of a glass ionomer cement, but cannot produce an acid-base reaction without the presence of water; neither can they polymerise without light-activation (McLean et al, 1994).

With different compositions available, two subgroups have been suggested by Burgess *et al* (1994) and Hammesfahr (1994): two-component and single-component systems. Some polyacid-modified resin composites, such as Geristore (Den-Mat, Santa Maria, CA), are two-component and contain an ion-leachable glass which has been pre-reacted with a polyalkenoic acid and ground into small filler particles. Variglass (Dentsply, York, PA), however, contains unreacted glass added to the resin.

Dyract (De-Trey Dentsply, Konstanz, Germany) is an example of a single-component polyacid-modified resin composite containing a newly developed tetracarboxyl butane (TCB) resin. This resin is formed from the reaction of a bifunctional butane tetracarboxylic acid and a polymerizable hydroxyethylmethacrylate (HEMA) side chain. As previously described, the methacrylate groups of the monomer can cross-link with other methacrylate resins when light-activated, while the carboxyl groups of the monomer can undergo an acid-base reaction to form a salt with the metal ions and water. Dyract contains reactive glass fillers containing fluoride with a mean size of 2.5 μm, while a more recent development of Dyract AP has seen the addition of a highly cross-linked monomer to increase the hardness and strength of the material and the incorporation of strontium-fluoro-silicate glass filler particles reduced in size to 0.8 μm.

More recently released materials include Compoglass F (Vivadent, Liechtenstein), F2000 (3M, USA) and Hytac Aplitip (Espe, Germany) which show great variation in their formulation, particle size and filler content. Compoglass F contains barium-aluminium-fluoro-silicate glass filler particles with a mean size of 1 μm, while F2000 contains fluoro-aluminosilicate glass filler with particle sizes ranging from 3-10 μm. Hytac Aplitip contains calcium-aluminium-zinc-fluoroglass with a mean particle size of 5 μm. In addition, new monomers have been developed to react with the various filler particles.

Physical characteristics

Adhesion

All polyacid-modified resin composites utilise their own bonding and conditioning systems to suit the unique components of the material. Unlike etching with phosphoric acid which is routinely used for composite resin and polyacrylic acid conditioning for glass ionomer cements, adhesion for compomers is gained through the application of different bonding systems for each material. The objective of the single-application bonding systems was to avoid the additional steps of acid etching and washing.

In the Dyract system, the primer/adhesive (Dyract-PSA Prime) contains three resins. The first component, dipentaerythritolpentacrylate phosphoric acid (PENTA), is a patented material containing an acidic monomer made up of phosphoric acid with a light-curable methacrylate group attached. This component is responsible for the formation of ionic bonds to the enamel. The second part of the adhesive system is tetraglycerol dimethacrylate (TGDMA) which controls the level of cross-linking among the different monomers and the elasticity of the cured primer/adhesive. The third part of the adhesive/primer is acetone which acts as a solvent to wet the tooth surface and carry resin into the micropores, assisting penetration of the resin into the dentine surface. This bonding system has been further developed in the new Dyract AP, with the addition of cetylamine hydrofluoride which delivers additional fluoride to the tooth.

Other materials utilise their own bonding systems. Compoglass F uses Syntac Single-component, F2000 uses F2000 compomer adhesive/primer, while Hytac Aplitip uses Hytac OSB. F2000 primer/adhesive and Syntac Single-component bonding adhesive are different from previous compomer bonding systems because they are hydrophilic and more suitable for use on moist dentine surfaces. They contain a resin monomer, 2-hydroxyethyl methacrylate (HEMA) consisting of a methacrylate modified polyacrylic acid and maleic acid in a solution of water. The bonding systems of other compomers use acetone. All these bonding systems require some amount of visible light activation.

Within the Dyract restorative system, the adhesion process that occurs after priming of the enamel and dentine takes place through two different mechanisms. The hydrophilic carboxyl groups of the TCB monomer are reportedly able to bond to tooth structure without acid-etching, because they are claimed to form ionic bonds with calcium ions on the tooth surface. The second mechanism takes place through the phosphate group of the PENTA resin in the adhesive, when it forms ionic bonds with calcium ions of the hydroxyapatite. The manufacturers suggest that when the adhesive is light-cured, the three methacrylate-based resins undergo cross-linking to form a reinforced zone on the surface of the tooth allowing bonding to the restorative composite resin. Further reactions between the methacrylate groups of the adhesive and the restorative resin are then thought to take place after material placement.

The effectiveness of the dentine bond with PSA Prime is dependent on its ability to bond chemically to hydroxyapatite. It has been suggested in a study by Heymann *et al* (1991), where Prisma Universal Bond 2 (DeTrey) was tested, that dentine-bonded systems are affected by occlusal stresses which can cause tooth flexure, particularly at the cervical region. It was suggested that the elastic modulus of a material at the cervical region should be as close as possible to dentine, which has been cited by Heymann and co-workers (1991) as ≥18 GPa. A study by Braem *et al* (1995), however, reported that the elastic modulus of Dyract was only 11.6 GPa, while another study by Attin *et al* (1996) found it to be 8.39 GPa. The performance of Dyract at the cervical region cannot be established from these data because dentine is well known to be anisotropic; that is, the mechanical properties are dependent on the specimen orientation. Clinically, however, Dyract has been shown to have excellent one year retention rates in Class V restorations: Van Dijken (1995), 97.6 per cent; Elderton et al (1996), 100 per cent; Jedynakiewicz et al (1996), >98 per cent; Barnes et al (1996), 100 per cent; Tyas (1998), 97 per cent.

It has been found that Dyract has a higher bond strength to dentine than resin-modified glass ionomer cements and conventional glass ionomer cements (Triana *et al*, 1994; Aboush and Torabzadeh, 1994; Kielbassa *et al*, 1997). Bonding to enamel is not as effective, however, and has been reported to be more effective if acid etching is

performed prior to the placement of the PSA Prime (Cortes *et al*, 1993; Triolo *et al*, 1995; Desai and Tyas, 1996; Abate *et al*, 1997). This was suggested by Tyas in 1997, who noted staining around the enamel margins of class V restorations after one year. This had previously been noted by Elderton *et al* (1996) and van Dijken (1995), while a more recent clinical trial by Loher *et al* (1997) looked at the marginal discolouration of Dyract Class V restorations, thought to be caused by swelling of the material and found that polishing of the Dyract restorations at either 6 or 15 months after placement eliminated the marginal discolouration, and no further staining was noted at the two-year follow up. Ferrari *et al* (1998) also found that the bonding systems for compomers did not prevent leakage at either the enamel or dentine margins, and therefore recommended the use of enamel-dentine bonding systems. Tyas (1998) felt it was reasonable to expect a higher bond strength to etched enamel because Dyract was essentially a resin composite. This was supported from studies that reported values to unetched enamel of 8.26 MPa (Cortes *et al*, 1993) and 4.21 MPa (Desai and Tyas, 1996) compared to bond strength values to etched enamel of 22.04 MPa (Cortes *et al*, 1993) and 14.3 MPa (Desai and Tyas, 1996). Morabito and Defabianis (1997) showed that compared to conventional and resin-modified glass ionomer cements, compomers exhibited the best mechanical properties and marginal seal.

Cortes *et al* (1998b) found that Dyract produced significantly greater bond strength after enamel etching compared to Compoglass, while the Compoglass displayed a greater bond strength when no acid etching of enamel was performed. Also in this study, no difference was found between various dentine treatments. The reported shear bond strength, however, lies between that of the resin-modified glass ionomer cements and composite resin materials (El Kalla and Garcia-Godoy, 1998).

As with other light-cured restorative systems, polymerisation shrinkage occurs. Attin *et al* (1995) found no significant difference in shrinkage between polyacid-modified resin composite and hybrid composite resin. Therefore, it was proposed that compomer restorative materials must be placed in increments, with a recommended curing time of 40 seconds for each increment.

Strength and Wear Resistance

Compressive, diametral tensile and transverse strengths of Dyract have been shown to be greater than resin-modified and conventional glass ionomer cements (Kielbassa *et al*, 1997; Uno *et al*, 1996; Irie and Nakai, 1998). Attin *et al* (1996) found that Dyract had compressive strength values close to that of a hybrid composite resin.

Wear resistance has been shown to be greater than that of conventional and resin-modified glass ionomer cements (De Gee *et al*, 1997). This differs from the findings of Peutzfeldt *et al* (1997), where resistance to wear of polyacid-modified composite resin was found to be less than conventional glass ionomer cement and composite resin, yet greater than resin-modified glass ionomer cements. The lower wear resistance of compomers was thought by Eliades *et al* (1998) to be due to the development of a carboxylate-rich surface layer resulting from the acid-base reaction. This reaction was found to take four weeks to reach saturation point following storage in water. Newer compomers, however, have demonstrated wear values similar to composite resin in laboratory studies (De Gee *et al*, 1997).

Although clinical studies should provide a more reliable source of wear resistance data, those that have been published report a broad range of values. Peters *et al* (1996) found an average of 100 μm of wear in primary molars after 6 months and 190 μm after 12 months. Another study reported only 43.3 μm of wear after 6 months and 72.7 μm in 12 months (Hse and Wei, 1997), while Leung *et al* (1998) found 113 μm of wear after two years, which was considered by the author to be clinically acceptable.

Fluoride release and uptake

Many studies have shown that fluoride release from compomers takes place (Suljak *et al*, 1996; Nunez *et al*, 1997; Rasmussen *et al*, 1997; Bala *et al*, 1997; Shaw *et al*, 1998). This release, however, is significantly less than for resin-modified or conventional glass ionomer cements (Forsten, 1995; Aboush *et al*, 1995; Suljak *et al*, 1996; Cardenas *et al*, 1995; Lavis *et al*, 1997; Stassinakis *et al*, 1995; Bala *et al*, 1997; Shaw *et al*, 1998). Although a study by Forsten (1998) found there to be no initial 'burst' period of fluoride release immediately after material placement, Eliades *et al* (1998) found that the release of fluoride was greater immediately after placement followed by a lessening and stabilisation of fluoride release after one week. It has been shown that compomers can take up fluoride from topical applications and toothpaste dentrifices and then release the fluoride once the source is removed (Suljak *et al*, 1996; Nunez *et al*, 1997; Rasmussen *et al*, 1997). However, Forsten (1998) found that polyacid-modified resin composites did not 'recharge' after being exposed to a 50 ppm fluoride solution. Although a study by Friedl *et al* (1997) showed that Dyract had an inhibitory effect on *Streptococcus mutans* growth, Millar *et al* (1998) found that the anticariogenic effect was significantly less than for conventional glass ionomer cements. In an earlier laboratory study, Erlenbaugh and Donly (1995) found that compomers displayed a greater caries inhibitory effect than composite resin materials. Therefore, although limited fluoride release may exist, opinions are divided as to whether these levels are significant enough to provide effective anticariogenicity.

Chapter 4

TUNNEL RESTORATION STUDIES

4.1 Microleakage and adaptation investigations

Introduction

Concern has been raised by critics of the tunnel restoration over the ability to effectively seal and prevent microleakage at the proximal margin. Reasons for the presence of microleakage might include the failure to remove all caries and unsupported enamel, the inability to finish margins and the deficiency of bonding systems to effectively seal. These factors are complicated by difficulties with material placement and the possibility of crack propagation in the overlying marginal ridge. Numerous *in-vitro* studies have been conducted to assess the performance of various restorative materials in tunnel preparations. However, the different techniques and protocols used for these studies have produced varied results, which in most cases do not enable a direct comparison between results.

Thermal Cycling Studies

Thermal cycling is an artificial method of simulating temperature fluctuations that exist within a clinical environment. Observations of marginal percolation as a result of temperature change were first made by Nelson *et al* (1952). It has been suggested that the differences in coefficient of thermal expansion of the tooth and restorative material are responsible for this fluid exchange (Going, 1972; Kidd, 1976; Bauer and Henson, 1984). There are conflicting reports, however, regarding the effectiveness of thermal cycling, particularly in microleakage assessment.

It has been shown that studies using thermocycling techniques have been more potent in demonstrating leakage than non-cycled techniques (Crim *et al*, 1981; Williams and Hedge, 1983; Crim *et al*, 1985; Crim and Garcia-Godoy, 1987). However, some researchers have suggested thermal cycling may not play such a significant role in

microleakage studies (Guzman *et al*, 1969; Maldonado *et al*, 1978; Glyn Jones *et al*, 1979; Lacefield *et al*, 1982).

Since the early studies of thermal cycling, little agreement exists among researchers regarding details such as the number of cycles, temperature ranges used and the immersion time within the different temperatures to accurately reproduce the clinical situation. Lloyd *et al* (1978) suggested that a "few thousand thermal cycles" could represent several years in the oral environment.

Nelson *et al* (1952) showed that the mouth had a thermal tolerance of 4-60°C which produced temperature ranges under acrylic restorations of 9-52°C. Later studies found ice water (0°C) actually gave a temperature within the oral environment of 10-15°C (Peterson *et al*, 1966) and the upper limit of thermal tolerance was 45-55°C (Peterson *et al*, 1966; Plant *et al*, 1974). Brown and co-workers (1972) postulated temperature fluctuations of repeated low and high temperatures within the mouth over a range of 45°C. Ernst *et al* (1997) therefore suggested a range of temperatures for thermocycling of 5-55°C as appropriate for simulating clinical temperature stresses.

Although immersion time has varied between studies, it has been found that the maximum thermal gradient develops within the first second of exposure to the temperature (Lloyd *et al*, 1978). Therefore, 25 second exposure times are deemed more than adequate for clinical simulation. This was supported by Crim *et al* (1985), who found no difference in microleakage using dwell times of 4 and 30 seconds.

Load Cycling Studies

Load cycling has not been used routinely in the study of marginal adaptation. This is despite Jorgensen (1970) showing that mechanical components within the oral environment were responsible for fluid percolation at restoration margins. A study by Raadal (1979) found an increase in microleakage of fissure sealants when load cycling was combined with thermal cycling. A similar finding was also reported in an investigation studying cervical restorations (Erickson *et al*, 1986), where margins finished on cementum exhibited greater leakage after load cycling. In contrast, however,

Stewart *et al* (1986) found that similar restorations finished within enamel did not produce greater leakage after load cycling. The contrasting results of these latter two studies reflect the different leakage patterns as a result of finishing margins in enamel and cementum/dentine. However, the clinical relevance of load cycling has never been established.

Different opinions exist regarding the effects on microleakage of the force applied, the duration of loading, the number of cycles and the position of force application during load cycling. The forces exerted and the duration of application vary considerably in a clinical environment, depending on the type of food being chewed or the parafunctional activity of the patient (Neill *et al*, 1989). These authors found that dentate male patients produced forces ranging from 28-181 N. DeLong and Douglas (1983) described a range of 9-180 N for a duration of 0.25-0.33 seconds as an estimated magnitude of masticatory force. These authors developed a complicated model to simulate the grinding or gliding phase of the chewing cycle. This is the phase believed to be dictated by the anatomy of the teeth (Gibbs *et al*, 1981).

Although variables exist between load cycling techniques, it has been suggested that the difference in the visco-elastic properties between the restoration and the surrounding tooth could result in marginal gap formation and subsequent microleakage when load cycling is performed (Munksgaard, 1988). This was supported in a study by Kubo *et al* (1997) where flexural loading impaired the bond of cervical restorations and microleakage was observed.

4.2 Microleakage investigations of tunnel restorations

Early studies examining the microleakage of tunnel restorations used a glass ionomer cement restorative material because it had been claimed to provide an effective seal (Gordon *et al*, 1985). Later studies showed that another advantage of these materials was the inhibitory effect of further demineralisation through fluoride release from the glass ionomer cement and subsequent incorporation into adjacent enamel (Eickolz *et al*, 1997). McLean *et al* (1985) suggested using cermet glass ionomers and Ketac Silver was investigated because of its increased abrasion resistance (McLean, 1986). More recently it has been shown that the traditional glass ionomer cements provide improved marginal seal compared to Ketac Silver (Shetty *et al*, 1996).

Most *in vitro* studies have been carried out on sound extracted teeth. The study by Hickel *et al* (1987) was an exception where extracted teeth containing small proximal carious lesions were mounted adjacent to each other, then prepared and restored in a simulated clinical model. Findings from this investigation showed a failure to remove all proximal caries due to inadequate access and convenience form, yet none of the Ketac Silver restorations displayed leakage. It was also noted after sectioning that thin demineralised edges of enamel were not removed during cavity preparation and that residual caries remained at the dentino-enamel junction on the occlusal section of the preparations. Difficulties were encountered directing the bur toward the carious lesion, which also complicated the finishing of proximal cavosurface margins. Other findings included the creation of bubbles during material placement and the presence of overhangs in the final restoration. Another study using teeth with small carious lesions (Wenzel *et al*, 1998) revealed that nearly half the restored teeth were still carious after restoration placement; this was not easily detected on post-operative radiographs. Incomplete caries removal was also reported for 20 per cent of teeth prepared with partial tunnel restorations, where the proximal enamel remained intact (Strand *et al*, 1993).

All other *in vitro* tunnel restoration studies were performed using sound, intact, extracted teeth. In a study by Robbins and Cooley (1988), sound extracted teeth mounted adjacent to each other were restored with Ketac Silver and all except one exhibited leakage. It was speculated that the leakage may have been the result of an inadequate bond along the cavosurface margin, mishandling of the restorative material or the harsh thermocycling regimen (24 hours at 6 - 60°C). A further study by (Garcia-Godoy, 1988), found that 80 per cent of tunnel restorations restored with Chelon-Silver (Espe, Germany), a hand-mixed cermet, exhibited no leakage after 100 thermocycles. In both of these studies, #330 carbide burs were used and the cavities were prepared from the occlusal aspect. Although the restorative materials of these studies were not the same, the main difference was the number of thermal cycles.

Later studies using Ketac Silver to restore tunnel preparations found that all restorations leaked when subjected to 1500 thermocycles between 5 and 55°C (Hotz and Holzer, 1989), whereas very little leakage was shown when only 40 thermocycles were performed using a similar regimen of temperature fluctuations (Bassiouny *et al*, 1989). Again the difference appeared to be the degree of thermal cycling. In contrast, it has been revealed in a study by Crim *et al* (1987) that the number of cycles did not affect the microleakage of resin bonded class V restorations. Thermal changes after restoration placement are capable of producing flexural stresses, at the tooth/restoration interface, which may affect the bond. However, other factors may also contribute to microleakage, such as preparation of the cavity walls and inadequate adaptation.

Thorough cleaning of the cavity walls is generally considered to play a critical role in the ability of glass ionomer cements to adhere to tooth structure. Nordbo *et al* (1996) found that polyacrylic acid conditioning alone was not as effective as a combination of conditioning with solutions such as "Pronase" or sodium hypochlorite in minimising microleakage. In a study by Hickel *et al* (1987), cavities irrigated with hydrogen peroxide and alcohol produced restorations with no marginal leakage. Most of the tunnel restoration microleakage studies, however, used polyacrylic acid for periods of 10-15 seconds except for one study where 25 per cent polyacrylic acid was used for 60 seconds (Hotz and Holzer, 1989). This investigation resulted in all restorations showing leakage, although as described previously, a large number of thermocycles was utilised.

Robbins and Cooley (1988) conditioned their preparations for only five seconds and found greater leakage than Garcia-Godoy (1988) who conditioned for 10 seconds.

Conditioning agents are thought to increase the capacity of the glass ionomer cement to adhere to tooth structure. Lin *et al* (1992) examined the mechanical interlocking of glass ionomer cement to dentine through SEM studies and suggested the viscosity of the restorative material may play a role in the enhancement of mechanical adhesion. It was suggested from these studies that the increased flow of less viscous materials into irregularities created in the pores of the dentinal tubules after conditioning would create a greater surface area for chemical interaction between the material and the tooth surface.

Adaptation of the restorative material after condensation within a tunnel restoration has not been investigated, although a study by Blagojevic *et al* (1988) examined the effectiveness of Ketac Silver placement in tunnel restorations. It was recognised that the material did not flow far from the tip of the syringe and it was suggested that incremental placement be used with gentle tamping to exclude voids within the material and possibly encourage adaptation. This technique had been previously suggested by Hunt (1984), but there have been no studies reporting its effectiveness.

Microleakage occurs as a result of gap formation at the interface between the restorative material and tooth structure. Cavity preparation at the proximal margin may influence the marginal finish and therefore the ability of the material to bond. Irregular cavosurface margins also make adaptation and finishing difficult and encourage plaque accumulation. One study using different methods of finishing cavity margins showed that a round steel bur in a low speed handpiece gave the best enamel finish (Chalker *et al*, 1993). Because ideal proximal cavity margins are difficult to achieve and removal of carious dentine is impossible to guarantee in tunnel preparations, Chalker *et al* (1993) recommended the use of glass ionomer cement with its fluoride releasing properties as the preferred restorative material.

The proximal surfaces of most tunnel restorations are not polished because of difficult access and the effect of early interference on the setting reaction of glass ionomer

cement in disturbing the adaptation and bonding process. A study by Robbins and Cooley (1988) used interproximal carvers and fine polishing strips to finish the accessible proximal margins of tunnel restorations, but these teeth demonstrated leakage. Clinically, proximal finishing may discourage plaque formation, but is unlikely to improve adaptation or prevent microleakage.

An important aspect of tunnel restorations not previously studied is the effect of subfracture loading on microleakage. Most microleakage studies have examined the effects of thermocycling, yet overlooked the possibility of crack propagation within marginal ridges or associated breakdown of the interproximal margins that could occur with functional loading. The proximal portion of the restoration is not unlike a cervical restoration, and it has been shown that when cervical restorations of posterior teeth are finished in enamel and loaded from the occlusal aspect, the marginal seal can be impaired (Kubo *et al*, 1997). Laboratory tests have been used to study the load required to fracture marginal ridges of tunnel restorations. It has been suggested that tooth fracture is more likely to be caused by the progression of small cracks during dynamic, repeated loading (Bell *et al*, 1982). The ability of a restorative material to reinforce the marginal ridge in a clinical situation is influenced not only by the extent of cavity preparation and the type of restorative material, but also by the functional pattern of the occluding teeth, the rate of loading and the magnitude of the forces applied.

4.3 Marginal ridge fracture investigations of tunnel restorations

Introduction

By virtue of the technique, preparation of a tunnel restoration leaves the marginal ridge undermined, often with little supporting dentine. It does, however, preserve the marginal ridge and this contributes to tooth strength (Mondelli *et al*, 1980). *In vitro* load studies performed on tunnel restorations have reported the fracture resistance of these preparations, and their marginal ridge strength has been compared to unrestored teeth and conventional class II restorations. The fracture resistance of teeth restored with tunnel restorations is influenced by the materials used. Although no sub-fracture loading investigations have been reported, the following discussion involves studies where restored teeth have been loaded to fracture.

To overcome the problems of incomplete caries removal and possible fracture of the undermined marginal ridge, it has been proposed that glass ionomer cement be used to restore tunnel preparations (McLean *et al*, 1980; McLean *et al*, 1985; Hunt, 1984; Knight, 1984a; Knight, 1984b). Although the bond achieved between glass ionomer cement and dentine or enamel is not particularly strong (Levine *et al*, 1977; Hotz *et al*, 1977; Powis *et al*, 1982), most tests have focused on this material for the restoration of tunnel preparations because it contains leachable fluoride (Maldonado *et al*, 1978; Cranfield *et al*, 1982; Wilson *et al*, 1985) with the potential to be taken up by adjacent teeth (Swartz *et al*, 1980; Retief *et al*, 1984) and inhibit recurrent caries formation (Hicks *et al*, 1986).

Investigations

Hill and Halaseh (1988) recognised the need to evaluate the inherent weakness produced by tunnel preparations and found that the marginal ridge strength was reduced to 61 per cent of a sound tooth. This was increased to 92 per cent once restored with glass ionomer cement. The same study found that amalgam did not produce a significant increase in fracture resistance, and justified the use of glass ionomer cement on this basis. The loss of fracture resistance resulting from cavity preparation is consistent with

data from previous studies. Vale (1956) found that mesiocclusodistal preparations reduced fracture resistance of premolars under compressive loads by 35 per cent. Other studies produced similar results (Modelli *et al*, 1980 ; Larson *et al*, 1981). In the study by Hill and Halaseh (1988), it was found that the mean compressive load required to fracture a sound premolar was 574.9 N, while a tunnel preparation restored with glass ionomer cement required 527.8 N and 420.8 N when restored with amalgam. This result was noteworthy, particularly when it was found that the compressive strength of glass ionomer cement has been reported as 215 MPa (Brune and Smith, 1982) and 115 MPa (Negm *et al*, 1982), while amalgam recorded 300 MPa (Combe 1986).

A study by Covey *et al* (1989) found that amalgam and bonded composite resin provided fracture resistance to the marginal ridge of approximately 84 per cent of the original tooth strength in tunnel restorations. It was noted during examination of the teeth in this study that fracture patterns existed at the dentino-enamel junction of both intact and tunnel-restored teeth following loading. This suggested that the mechanism of fracture progression was not affected by the amount of dentine removed during cavity preparation. The fracture resistance data from Covey are in contrast to those from Joynt *et al* (1987) and Stampalia *et al* (1986), who after restoring conventional Class II preparations, found that there was a significant decrease in fracture resistance produced when amalgam and composite resin were used to restore mesio-occlusal-distal cavities.

Fasbinder *et al* (1991) investigated the resistance to fracture of tunnel restorations when they were prepared with different sized burs. It was found that, if the preparation was conservative in relation to the size of the ridge (that is, #2 (012) bur for a premolar and #4 (014) or #6 (016) bur for a molar), the marginal ridge strength once restored was similar to that of an unprepared tooth. They also proposed that the bond of Ketac Silver to tooth structure was responsible for the inhibition of crack propagation. This has been supported in a study by Halverson and Hamilton (1987), where a two millimetre base of Ketac Silver in a conventional Class II restoration significantly increased cuspal fracture strength compared to an unrestored preparation. The modulus of elasticity of glass ionomer cement has also been shown to be similar to dentine (Walls *et al*, 1987) and could therefore discourage marginal ridge flexure and crack propagation. Shetty and

Munshi (1996) also noted that Ketac Silver was slightly more effective than glass ionomer cement in its ability to prevent ridge fracture.

Ehrnford and Frannson (1994) also studied the ability of Ketac Silver, a hybrid composite (Superlux, DMG) and an experimental composite to support the marginal ridge in large tunnel restorations where the remaining marginal ridge width was 1.5 millimetres. Against the recommendations of Fasbinder (1991), these restorations were prepared with a #6 (016) bur. Although results showed no significant reinforcement of the marginal ridge in those teeth restored with Ketac Silver, 62 per cent of ridge strength was retained with both composite resins. It was the recommendation of these authors to use composite resin in large tunnel restorations.

A further study using composite resin compared the fracture resistance of conservative class II restorations with tunnel restorations (Papa *et al*, 1993b). It was found that class II restorations lost only 10 per cent of their original fracture resistance compared to a 56 per cent reduction for tunnel restorations restored with Ketac Silver. These results differed from those of Purk *et al* (1995), who reported that tunnel preparations restored with glass ionomer cement and conservative class II composite restorations exhibited similar fracture resistance. Their fracture strength, however, was only 67 per cent of the original unprepared teeth. This variation in results between studies could be due to different preparation methods and material placement techniques, in addition to the varied methods of achieving fracture (Reeh *et al*, 1989) and the influence of tooth anatomy which can affect the direction of load application (Hood, 1991).

Most results indicate a favourable fracture resistance for tunnel preparations restored with glass ionomer cement. However, the amount of remaining marginal ridge and the strength required to maintain clinical success is unknown. The most clinically significant finding from the study by Fasbinder (1991) was that a conservative tunnel preparation does not significantly weaken an otherwise intact tooth.

4.4 Clinical studies of tunnel restorations

As with any innovative restorative procedure, the effectiveness of tunnel restorations will be determined by their long-term clinical success. When the clinical complications encountered during preparation and restoration are considered, together with the combined processes of plaque formation and parafunctional activity, a true indication of the viability of the tunnel restoration will be known. Despite their slow acceptance, there have been clinical studies reported that support the positive findings of some *in vitro* tests. It must be noted, however, that many of these studies are retrospective and in some cases cannot be directly compared because the methods of cavity preparation and restoration placement are quite different.

In the first reported clinical study, Knight (1984) found that, of 22 tunnel preparations restored with Fuji II and Ketac Fil (Espe, Germany) glass ionomer cements placed over a period of 30 months, no failures were recorded and only three showed signs of significant occlusal wear. Hunt (1984) reported the results of a clinical trial involving 13 restorations placed in molars and seven in premolars where no failures were found after 23.3 months. The criteria used by Hunt (1984) for assessing failure were more stringent than for the Knight (1984) study and involved probing of margins, passing floss through contacts, assessing colour changes and the examination of bitewing radiographs.

In a clinical trial (Ehrlich and Yaffe, 1987) where 154 tunnel preparations were restored with amalgam, it was found after 2.5 years that 6 restorations had failed. Four occurred in premolars and 2 in molars, with 5 failing within 6 months as a result of marginal ridge fracture. This was the first clinical trial using amalgam as the restorative material.

The first long-term clinical study was presented by Knight (1992); a 9-year follow up of 51 restorations with an average age of 5.25 years, ranging from 3 years to 9 years 7 months. Using visual inspection with no magnification, 92 per cent of restorations exhibited no evidence of marginal breakdown and marginal ridge failure was noticed in only 2 restorations. Svärdström (1991) also reported no marginal ridge failures in 80 restorations. Svanberg (1992), conducted a study in 18 caries-active adolescent patients

where a conventional class II amalgam and a tunnel restoration were placed on contralateral sides and an assessment made after three years. Three of the 18 amalgam restorations failed due to recurrent caries, while only one of the 18 tunnel restorations failed as a result of marginal ridge failure. The author concluded that fluoride release from the Ketac Silver had prevented any recurrence of caries.

Hasselrot (1993) evaluated 318 tunnel restorations placed in 224 patients over a 2-year period. Of these, only 35 were in permanent teeth and cavity preparation involved penetration of the proximal enamel to create an interproximal cavosurface margin. After 3.5 years, 34.3 per cent of restorations had failed. An interesting finding was the higher failure rate of teeth prepared during the first year of the study. Failure modes included marginal ridge collapse, cavitation of proximal enamel of the internal tunnel restoration and recurrent caries. Despite a greater failure rate than in earlier studies, a most significant finding was the improvement in the success of tunnel restorations once the clinician had become more experienced. Hasselrot (1993) also found that, on occasions, clinical inspection of the proximal surface of teeth with tunnel restorations was possible following extraction of the adjacent tooth for orthodontic reasons, and noted that a restoration often presented with less than ideal adaptation, yet was usually free of caries. He noted that the presence of poor adaptation was not necessarily a reason for clinical failure, and concluded that the seal provided by a glass ionomer cement restoration prevented microleakage and that enamel dissolution could be arrested by adequate preventive measures. In another study there was evidence of small defects, surface voids and occlusal wear in tunnel restorations restored with Ketac Silver (Wilkie *et al*, 1993).

In order to evaluate the effectiveness of glass ionomer cement, Forsten (1993) conducted a survey amongst 630 dentists at continuing education courses and reported that 60 per cent performed tunnel restorations as part of routine restorative procedures. One hundred and seventy dentists had been placing tunnel restorations for greater than two years and 75 per cent of these practitioners observed no pulpal symptoms, 45 per cent observed no residual caries, 60 per cent found no development of secondary caries, yet 25 per cent noted marginal ridge fractures. Only five dentists had observed incomplete filling of the tunnel at the cavosurface margin. The survey results did not confirm any problems due to technical difficulties and Forsten (1993)reported that

students doing their first tunnel restorations on extracted teeth did not find the technique difficult to master as long as instructions were followed accurately.

Concern has been raised over the conservative nature of tunnel restorations and whether it would be simpler to perform small amalgam restorations. Strand *et al* (1995b) considered the tunnel restoration to be more difficult to perform than conventional Class II restorations. Lumley and Fisher (1995) examined the success rates over a minimum of five years and up to ten years for 33 restorations. Small conservative class II amalgam restorations were used as controls and after three years all restorations were regarded as satisfactory. A failure was recorded when recurrent caries, marginal ridge fracture or gross loss of restorative material was noted. It was felt that studies of less than five years duration were of limited benefit because in this study less than 20 per cent of the tunnel restorations failed during this period of time, yet after 8-10 years of service, 63.6 per cent of restorations had failed. It was concluded that small amalgam restorations were more effective because no failures were recorded after 10 years.

Some recent studies have been carried out by a number of dentists with varying levels of proficiency. Strand *et al* (1996) investigated the performance of 161 partial tunnel restorations placed by four inexperienced dentists. Restoration replacement was required in 30 per cent of restored teeth after three years. Evaluation was carried out using radiographs and clinical examination with 16 per cent of failures due to recurrent caries and 14 per cent due to marginal ridge fracture. It was also found that 34 per cent of the remaining restorations exhibited signs of increased radiolucency of the remaining approximal enamel. Clinically significant was the greater failure rate of tunnel-restored teeth in patients with a high caries activity and where the initial lesion was large. In this study the use of Ketac Silver to restore the preparations was unable to prevent a recurrence of caries. These results are similar to those of Hasselrot (1993) and follow reports by Swift (1989), who suggested that fluoride release from Ketac Silver was less than that from conventional glass ionomer cements. The authors felt, however, that some small proximal cavitations may have existed in the enamel prior to preparation of the partial tunnel restorations, a suggestion also reported by Lunder and von der Fehr (1996). Forsten (1991) suggested that in caries-active patients the absence of a direct contact between Ketac Silver and the demineralised enamel lesion may have prevented

effective remineralisation and led to further enamel cavitation. Prabhu and co-workers (1997) also restored partial tunnel restorations in teeth indicated for orthodontic extraction and tested them *in vitro* once extracted. They reported that glass ionomer cement and cermet cement contributed to marginal ridge fracture resistance, exhibited minimal microleakage and were biologically compatible.

Survival time and failure modes were recorded in a long-term clinical study conducted in a general dental practice (Hasselrot, 1998). Only 13 per cent of 267 restorations involved preparation of proximal enamel and failure rates were the same as those not involving proximal preparation. However, recurrent caries was found more frequently when proximal enamel was preserved. This study reported a yearly failure rate of seven per cent with 50 per cent of restorations failing after six years. It was also found that restorations placed in the second year were more successful, which highlights the importance of experience in overcoming technical difficulties.

A recent clinical study by Pilebro *et al* (1999), where tunnel restorations were performed by 12 dentists over a three-year period, produced similar results to previous studies. Three hundred and seventy four tunnel preparations were restored with Ketac Silver, where demineralised proximal enamel was left intact. After one year a failure rate of 3.5 per cent was reported. Two-thirds of these failed as a result of marginal ridge fracture. After two years, 13 per cent of restorations had failed, while 20 per cent failed after three years. Marginal ridge fracture after three years was responsible for 89 per cent of failures. It was suggested that a material, that released higher levels of fluoride and provided greater protection for the marginal ridge than Ketac Silver, may be beneficial, but that it was essential that the carious dentine lesions be small.

In a prospective study by Jones (1999), 60 tunnel restorations were placed in 48 patients over eight years with a failure rate of 15 per cent. Restorative materials used were Ketac Silver (14), Hi-Dense (25) and Fuji IX (21). Three of the Ketac Silver restorations failed (two from marginal ridge fracture and one from recurrent caries) over a mean survival time of 58 months. Four Hi-Dense restorations failed over a mean survival time of 48 months, while one Fuji IX restoration failed over a 16-month period. A significant clinical observation was made by Holst and Brännström (1998), evaluating 302

restorations performed by 17 dentists in public dental clinics over a 3-year period. A success rate of 92.7 per cent after 1 year, 89.5 per cent after 2 years and 84.3 per cent after 3 years was obtained. Only 8 per cent failed due to recurrent caries and 6 per cent due to marginal ridge failure. The broad base of practitioners surveyed in this study may indicate that tunnel restorations are an increasingly reliable restorative technique.

From the clinical studies reported, most confirm that tunnel restorations are clinically successful. However, the performance of Ketac Silver has varied, with the studies that have compared different restorative techniques and materials to Ketac Silver producing the more favourable results. Although most studies maintain the ability of Ketac Silver to support the marginal ridge and help prevent recurrent caries, marginal ridge fracture has accounted for the majority of clinical failures. The success of the tunnel restoration, however, was considered to be dependent on the technical experience of the operator, the careful choice of the small carious lesion and the caries activity of the patient.

Chapter 5

PURPOSE OF THE INVESTIGATION

It has long been suggested that when caries is removed from the proximal region of a tooth, a more conservative approach, than the conventional two surface, Class II restoration, should be used to avoid destruction of the marginal ridge. Although the tunnel restoration fulfils this criterion, it is technically difficult to perform and opinions vary regarding the effectiveness of caries removal through a limited access. Other areas of concern include the strength of the remaining marginal ridge after restoration and the ability to adapt the restorative material to the interproximal cavosurface margin which will influence the marginal seal. If an effective seal is not provided, microleakage will follow and could result in post-operative sensitivity, the development of recurrent caries and ultimately adverse pulp responses.

The introduction of glass ionomer cement and the subsequent development of resin-modified glass ionomer cement and polyacid-modified resin composite (compomer) restorative materials have enhanced conservative attitudes to restorative techniques. Not only can glass ionomer cement adhere to dentine and enamel and release fluoride to be incorporated into adjacent teeth, but it is able to absorb fluoride from external fluoride supplements, thus providing ongoing cariostatic properties. This suggests that glass ionomer cement would be a useful restorative material for tunnel restorations.

A review of the literature for tunnel restorations has revealed that *in vitro* microleakage tests do not adequately represent the clinical situation, where carious teeth are prepared and restored under conditions of limited access. No studies have investigated microleakage using accelerated ageing techniques involving both sub-fracture load cycling and thermal cycling. There have also been no investigations reporting the adaptation of restorative materials at the cavosurface margins of tunnel restorations and no correlation has been made between microleakage and adaptation at the proximal cavosurface margins.

The aim of this investigation was to compare the microleakage and adaptation of various materials in teeth with small proximal lesions restored with tunnel restorations, conducted in a laboratory model that closely resembled the clinical environment.

Chapter 6

MATERIALS AND METHODS

6.1 Microleakage Study

1. Artificial Caries Development

Teeth

Sixty, extracted, sound mandibular third molars were collected after atraumatic removal and stored at 4°C in formal saline until required for the study. Storage time was no longer than 4 months from the time of extraction and all teeth were closely examined using fibre-optic illumination before inclusion in the study to confirm the absence of cracks following extraction. Teeth that showed any staining or caries were also discarded. All periodontal ligament and soft tissue remnants were removed prior to preparation of the teeth. Care was taken to select teeth with marginal ridges of similar shape and form. Teeth with unusual enamel anatomy or incomplete formation were discarded.

Acid Gel

A suspension of 10 per cent gelatin and lactic acid with a pH of 3.5 was prepared. Fifty of the selected teeth were cleaned and dried before being painted with protective varnish[1] to leave a uniform area of 1 mm diameter unprotected on both the mesial and distal surfaces of the teeth *(Figure 6.1),* just beneath the point of most convexity (contact point). This corresponded to the natural position where caries would form *in situ*. Once the varnish had dried, teeth were placed into the gelatin solution for five weeks.

At the end of five weeks, all teeth were radiographed to confirm the presence of a small radiolucency no more than 1 mm into the dentine on the proximal surface where enamel was free of varnish. The purpose was to create a small decalcified area within the

dentine closely resembling a small interproximal lesion *(Figure 6.2)*. Teeth displaying an adequate degree of radiolucency in dentine were immediately included in the study and those lacking sufficient radiolucency were returned to the gelatin solution. No teeth were left in the solution for more than six weeks. When artificial caries formation was complete, all teeth were cleaned with varnish remover and stored in formal saline at 37°C.

Figure 6.1 : Proximal view of area of tooth not coated with protective varnish prior to artificial caries induction

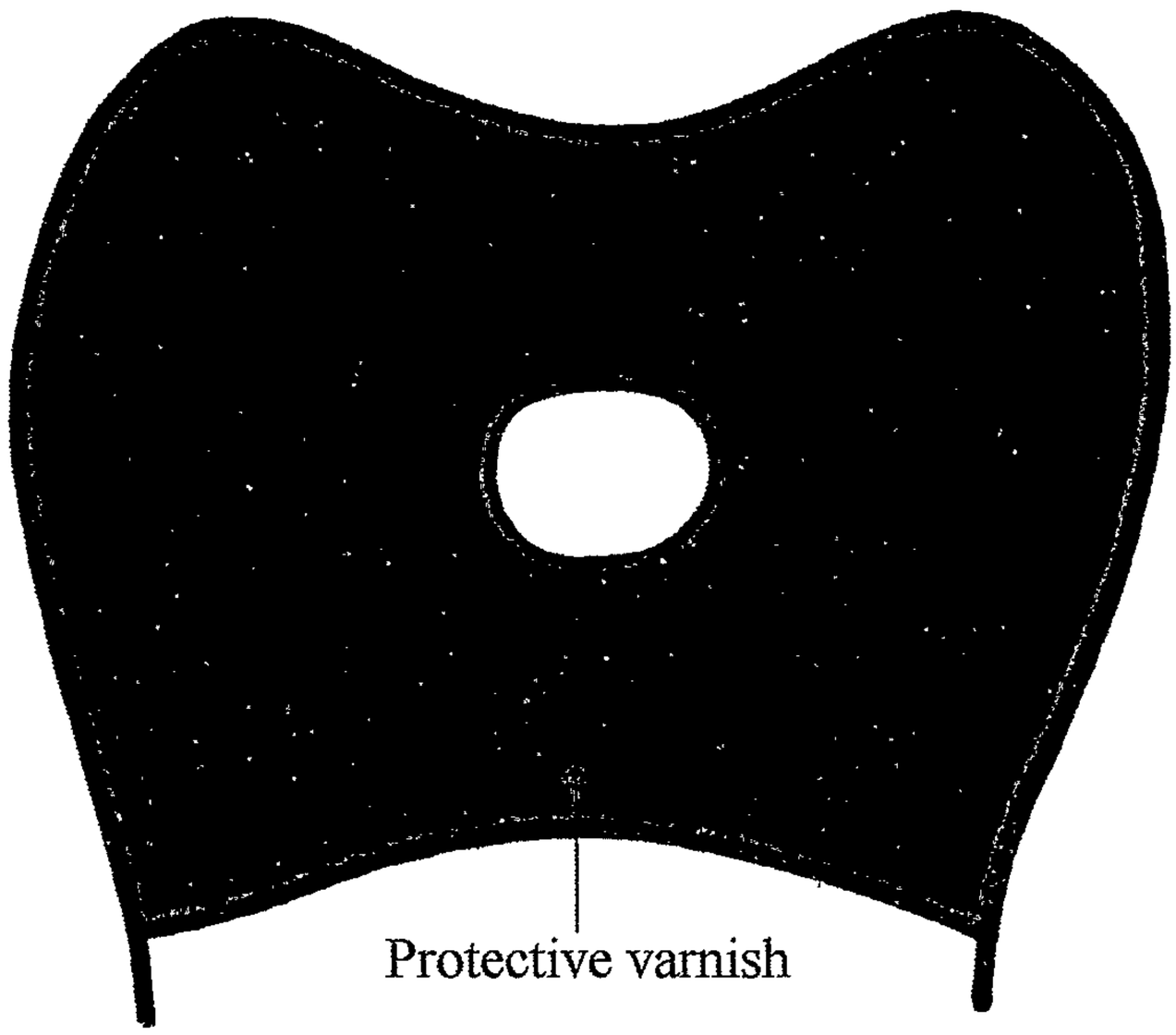
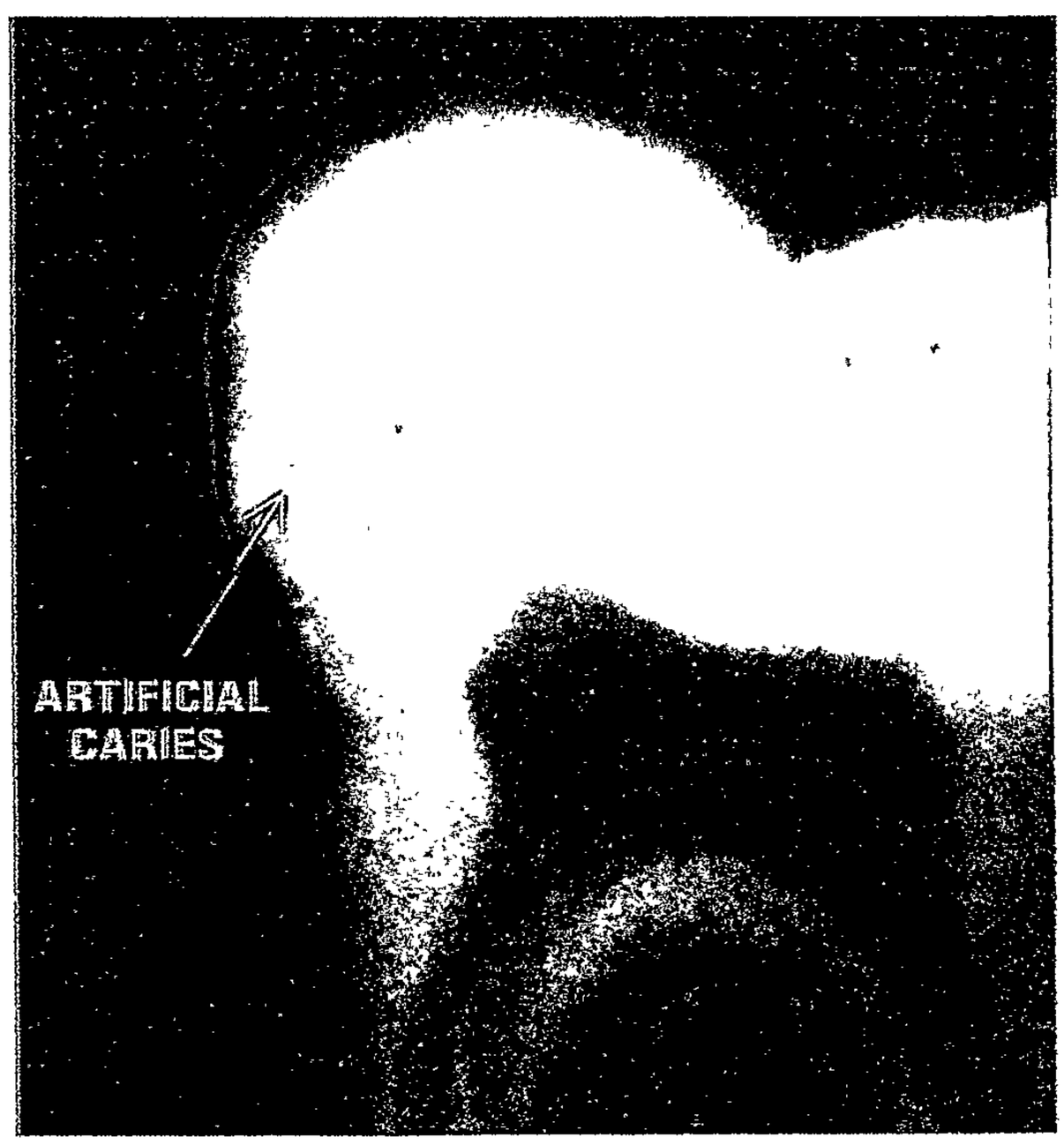


Figure 6.2 : Radiograph showing interproximal decalcification produced from artificial caries induction



2. Cavity Preparation

The experimental teeth were randomly selected and placed into groups of ten. Each tooth was prepared on the distal and mesial surfaces, enabling two restorations to be tested and individually assessed on each tooth. All preparations were carried out by a single operator and burs were changed every ten preparations (ie. two burs for every group of ten teeth).

Control group

The control group consisted of ten sound teeth, with no proximal artificial caries.

Preparation of the control teeth was carried out using two stages of preparation and direct visual inspection *(Figure 6.4)*. Holding each tooth by hand, access was made through the fossa on the occlusal surface with a water-cooled #1 (010) round diamond bur. After penetration of enamel, the bur was angled approximately 45° towards the proximal surface. Entry into the dentine was limited to approximately 1 mm from the occlusal surface. Preparation was then continued from the proximal region, just beneath the contact point. This corresponded to the area where artificial caries was produced for the experimental teeth. Bur angulation was initially directed perpendicular to the long axis of the tooth, but once entry into dentine was gained, bur angulation was slightly altered towards the occlusal surface. Once the occlusal portion of the preparation was reached, internal finishing of the preparation was performed from both occlusal and proximal surfaces. This allowed the most 'ideal' preparation of the cavity walls and enabled cavosurface margins to be free of unsupported enamel. Preparation procedures were repeated for the other proximal surface of each tooth. Hand instruments were not used and pressure on the marginal ridge was avoided during preparation of the cavities.

Experimental group

Five groups of ten teeth were aligned and mounted in plaster to create contact points resembling the clinical situation. A sound molar was mounted at both ends of each

group to provide two contacts for each tooth. Care was taken to keep all teeth moist until prepared. Mounted blocks of teeth were secured to the bench top with a vice. Uniform occlusal access cavities approximately 1 mm in diameter were created with a water cooled #1 (010) round diamond bur in the distal and mesial fossae of each tooth. The handpiece was angled at 45° towards the proximal region of the tooth *(Figure 6.3).* Once soft dentine was reached, the cavity was completed with a #2 (012) stainless steel round bur at low speed and, for the purpose of this study, cavosurface margins were created by extending the cavity preparation completely through the proximal enamel with the low speed bur.

Assessment of the cavity after the removal of softened dentine was made using clinical judgement through visual inspection and with the use of a curved probe[2]. Finishing of the occlusal margins was performed using round high-speed diamond burs, and care was taken not to place stress on the marginal ridge during cavity preparation. No hand excavators were used for the removal of softened dentine or finishing of enamel margins.

Figure 6.3 : Bur angulation towards artificial caries

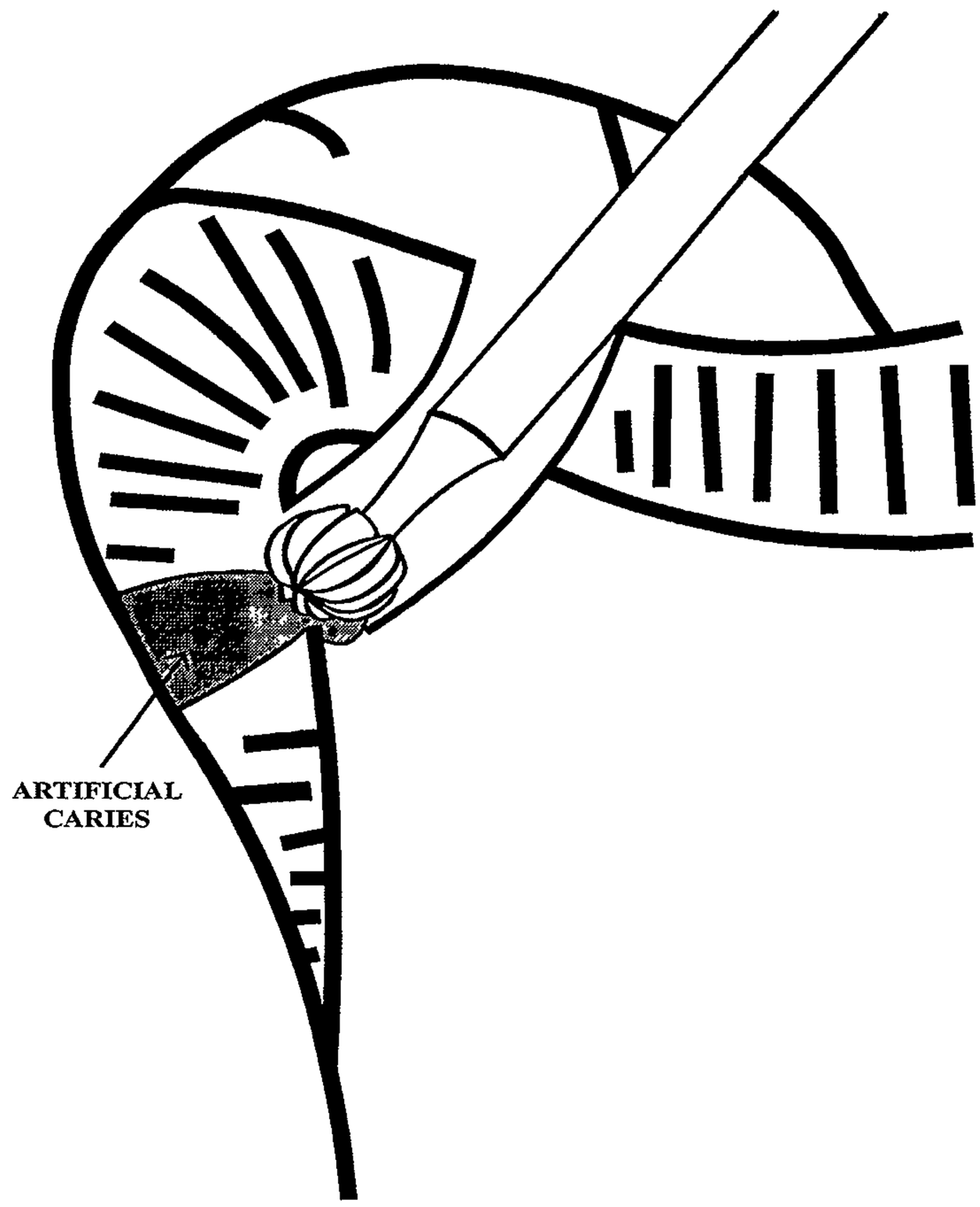
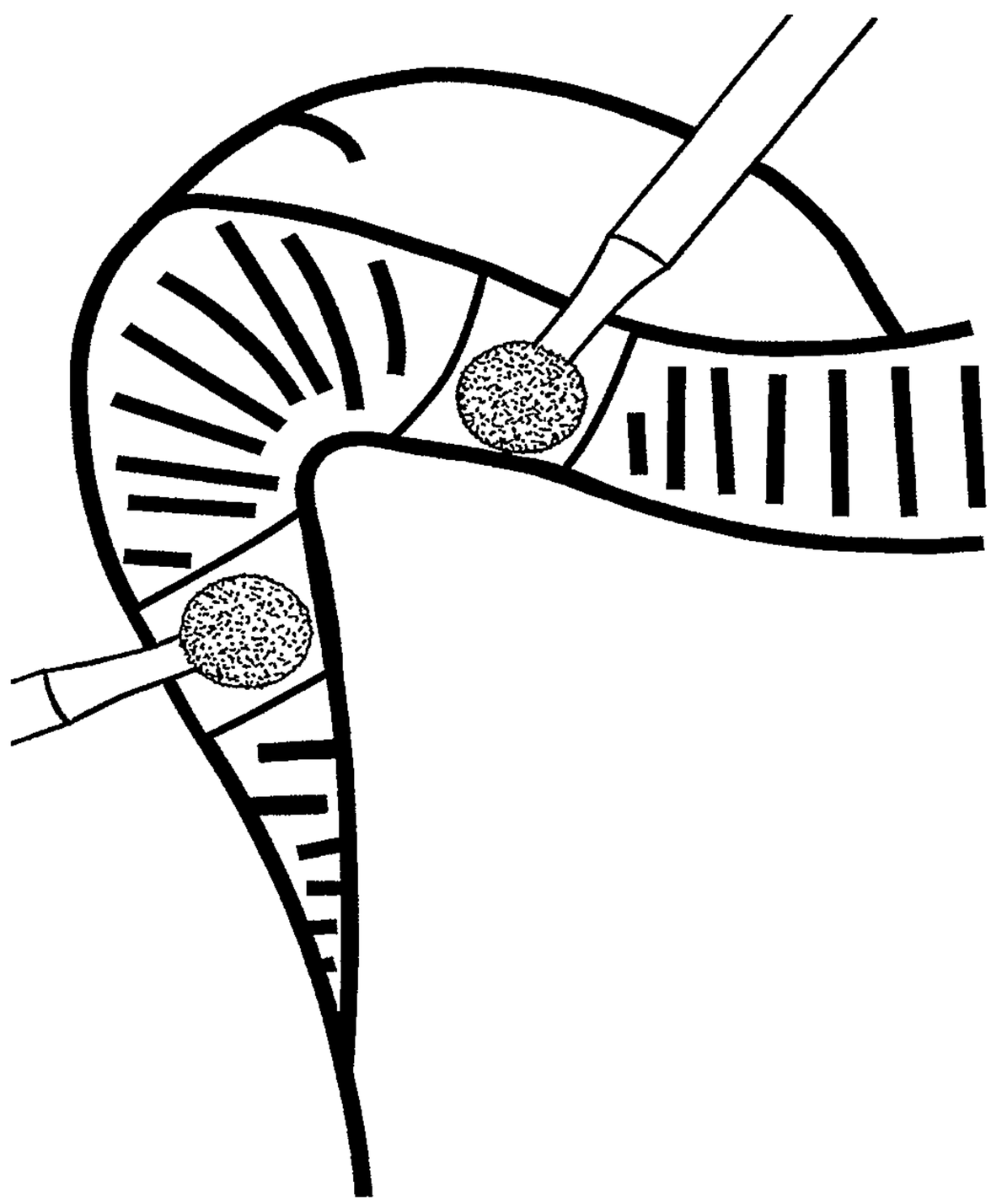


Figure 6.4 : Preparation of control teeth



3. Cavity Restoration

Restorative technique

After preparation, each tooth was immediately restored and placed in distilled water at 37°C before load and thermal cycling. Five restorative materials *(Table 6.1)* were selected to restore those teeth with artificially induced caries (experimental groups); the control teeth were restored with Ketac Silver.

A vice was used to secure blocks of teeth to the bench top for restoration of the caries-induced teeth under simulated clinical conditions. Care was taken to restore teeth from the front of the mounted blocks and material placement was directed from the occlusal.

Table 6.1 : Restorative Materials used in this study

Material	Category	Manufacturer
Ketac Silver	Cermet cement	ESPE GmbH, Seefeld, Germany
Fuji II	Glass ionomer cement	GC International, Tokyo, Japan
Fuji IX	Glass ionomer cement	GC International, Tokyo, Japan
Fuji II LC	Resin-modified glass ionomer cement	GC International, Tokyo, Japan
Dyract	Polyacid-modified resin composite (Compomer)	Dentsply De Trey, Konstanz, Germany

Restoration Placement

Control group

Each tooth in the control group was hand-held during preparation and restoration. Following cavity preparation, Ketac Conditioner (25% polyacrylic acid) was applied to the internal walls of the cavity preparation for 10 seconds, washed for 10 seconds and dried with a steady flow of uncontaminated compressed air for 10 seconds. A metal matrix band[3] in a matrix holder[4] was placed around the tooth and tightened to prevent overhangs. A capsule of Ketac Silver was activated and triturated in an

amalgamator[6] for 10 seconds. The capsule was placed into an Espe applicator and the material injected with force into the mesial and distal tunnel preparations of one tooth. A new capsule was used for each tooth. As the preparation filled with material, the nozzle was slowly removed. Excess material was wiped from the occlusal surface and the Ketac Silver was vertically condensed with a ball burnisher[7] when the 'glossy' appearance had disappeared from the surface. Care was taken to ensure condensation did not push material below the occlusal cavosurface margin. After placement, the material was allowed to set for 10 minutes before removal of the matrix band. Ketac Glaze (Espe, Germany) was applied with a microbrush[8] to the occlusal and proximal surfaces and visible-light cured for 20 seconds.

Experimental group

Restoration of the cavities prepared in the caries-induced teeth was carried out with the teeth mounted in plaster blocks, and with each preparation contacting an adjacent tooth surface as described for the preparation.

Ketac Silver

The experimental teeth to be restored with Ketac Silver were coated internally with Ketac Conditioner, rinsed and then dried, as previously described. A matrix band was placed around one tooth at a time and a wedge[5] placed to minimise overhangs. After activation of the Ketac Silver capsule, the nozzle tip was located within the occlusal access of the preparation *(Figure 6.5)* and injected with force. The nozzle tip was withdrawn from the cavity as it filled and material placement was repeated with the same capsule for the other preparation in the tooth. No condensation of material was performed and all excess was immediately removed from the occlusal surface. Ten minutes was allowed for material setting before removal of the matrix band. Overhangs were identified with dental tape[9] and the excess removed with an interproximal carver[10] Ketac Glaze was then applied, spread interproximally with dental tape, and visible-light cured for 20 seconds.

Fuji II

The internal cavity walls were coated with GC Dentine Conditioner (20% polyacrylic acid) for 15 seconds, washed with water for 10 seconds then dried with uncontaminated air for 10 seconds. The Fuji II capsule was activated by twisting the body of the capsule, followed by trituration in an amalgamator for 10 seconds. A slight bend of the nozzle tip was required to allow easier and more efficient placement of the nozzle tip into the preparation. The nozzle was slowly removed from the preparation as the Fuji II was injected. One capsule was used to restore two preparations for each tooth. Placement of the material, setting time and finishing of the proximal cavosurface margins were performed as described for Ketac Silver. GC Fuji Coat (a varnish) was then applied to all restored surfaces and flossed proximally.

Fuji IX

The prepared tunnel cavities were conditioned with GC Dentine Conditioner as previously described for Fuji II, then restored with Fuji IX. Activation of the Fuji IX capsule was carried out as specified by the manufacturer, followed by trituration for 10 seconds. Ten minutes after placement the proximal area was finished and GC Fuji Coat applied as previously described.

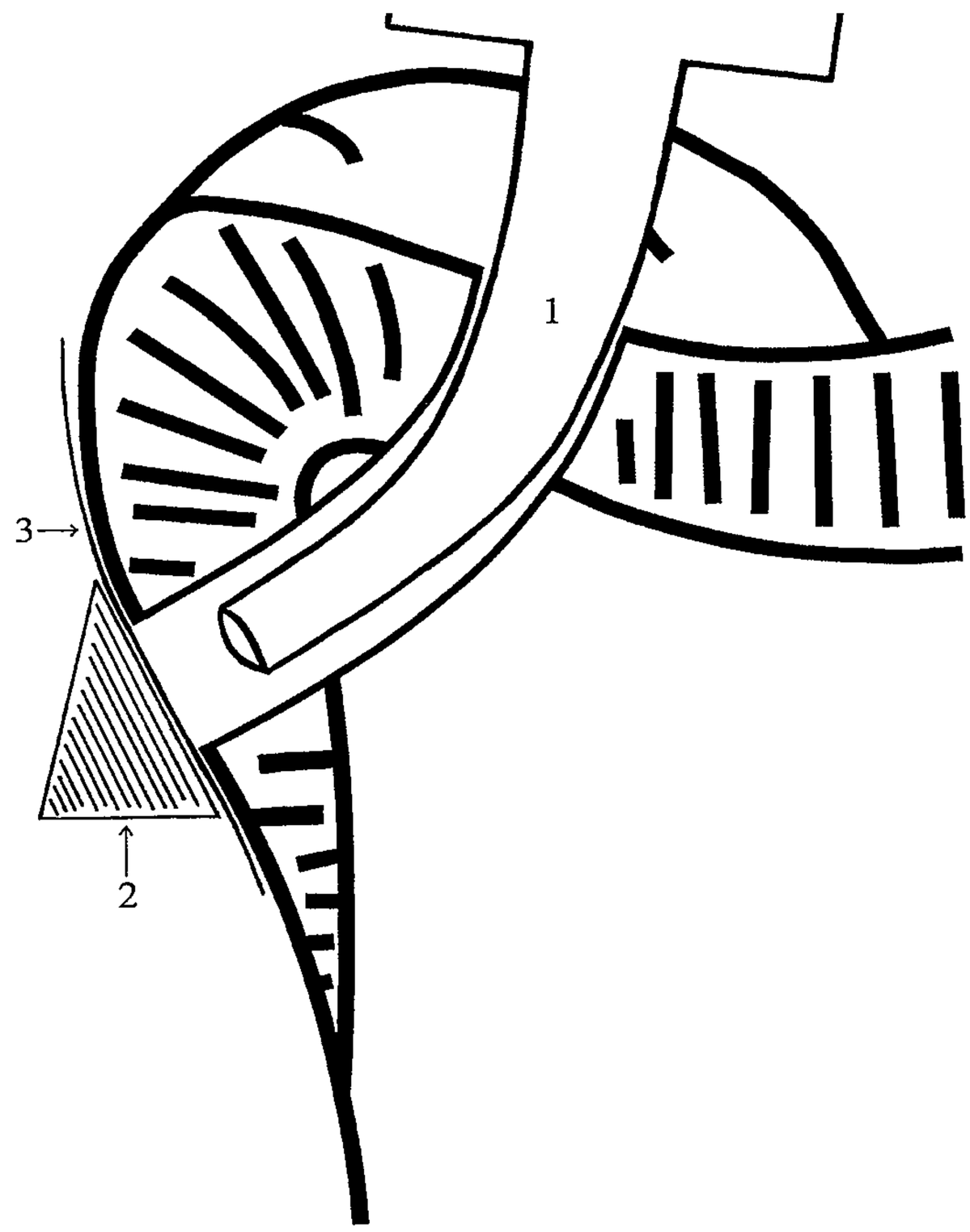
Fuji II LC

The preparations were conditioned, washed and dried as described for Fuji II. A clear matrix band[11] was placed and secured with a light reflecting wedge[12]. Fuji II LC capsules were activated as directed by the manufacturer and triturated for 10 seconds. The nozzle tip was slightly angled and withdrawn as the material was injected into the cavity preparation. Following immediate removal of the excess, the material was cured for 40 seconds with a visible-light source[13] directed from occlusal surface, followed by 20 seconds from the buccal and lingual surfaces of both the mesial and distal restorations (making use of the light-reflecting wedge, where appropriate). After removal of gross excess with an interproximal carver, GC Fuji Coat was applied and flossed.

Dyract

PSA Prime was applied with a microbrush to the cavity walls of each preparation for one minute, dried with a gentle stream of uncontaminated air and cured for 10 seconds with a visible-light source. PSA Prime was then reapplied, left for 10 seconds, dried and light curing repeated for 10 seconds. A clear matrix band and wedge were placed as previously described. Dyract was injected from the occlusal access to fill the proximal portion of the preparation, before condensation with a ball burnisher. This first increment was visible-light cured for 40 seconds from the occlusal surface and 40 seconds from the proximal surface, before a second increment was placed to overfill the cavity. Condensation was then repeated, and excess material removed before curing for 40 seconds from the occlusal surface. Although no finishing of the restoration was performed on the occlusal surface, normal finishing was carried out on the proximal surfaces.

Figure 6.5 : Nozzle placement within cavity preparation



1 Nozzle

2 Wedge

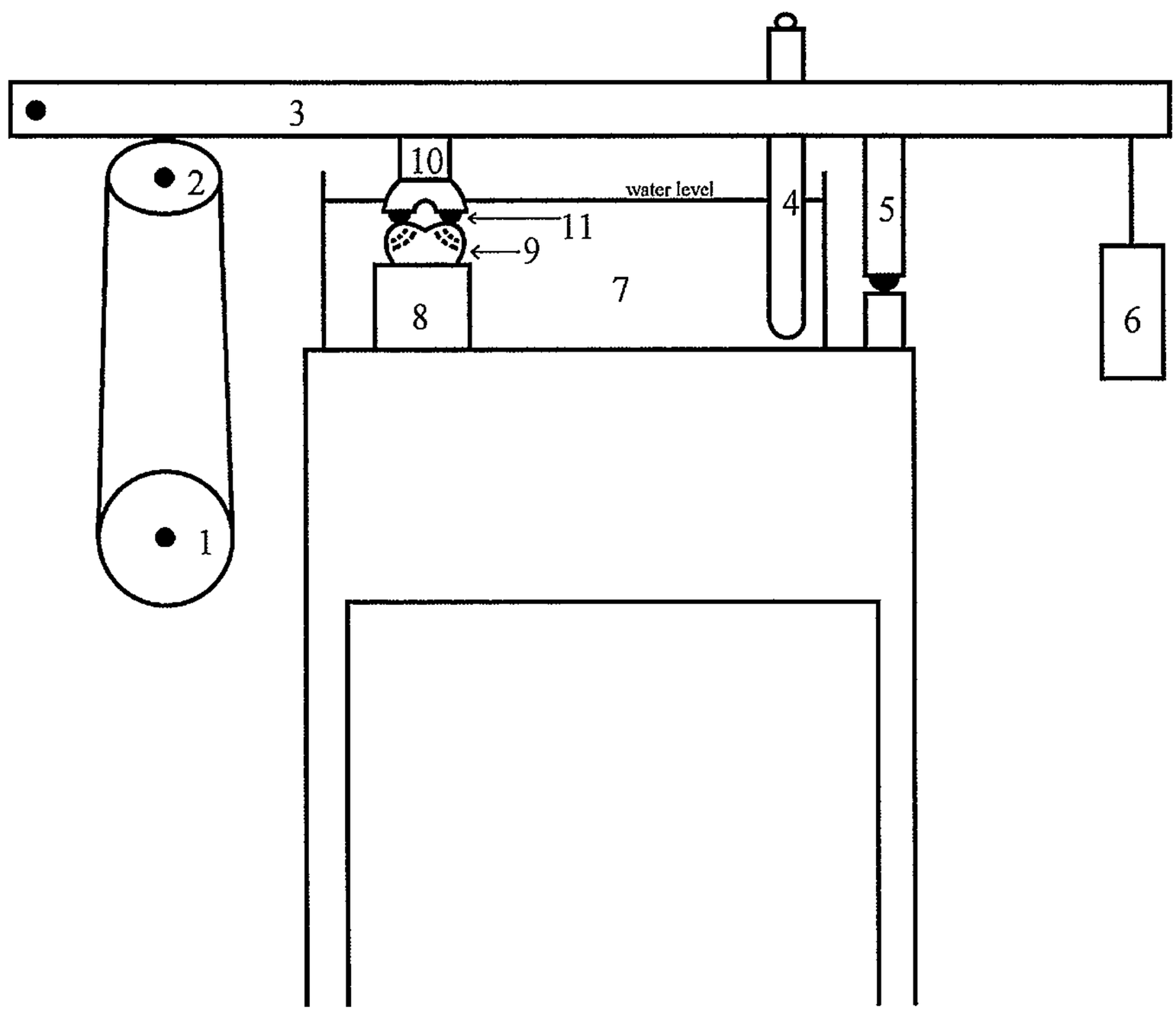
3 Matrix band

4. Subfracture Loading

Following restoration, the teeth were removed from their plaster mounts and stored for no longer than 24 hours in distilled water at 37°C before load cycling. Using a rubber mould[14], 25 mm in diameter, each tooth was remounted in an individual plaster cylinder with mesial and distal marginal ridges kept at similar heights. Using a load cycling machine *(Figure 6.6)* the teeth were loaded through a metal ball aligned to contact the marginal ridge. Loading was directed down the long axis of each tooth with a uniform application of 90 N for 2000 cycles at 2 cycles per second. Using the formula (force = mass x gravity), the load force of 90 N was calibrated by using a 9.2 kg weight on the end of the lever of the load cycling machine. Load cycling was performed in a water bath kept at a constant temperature of 37°C by a thermostatically controlled fish tank heater. At the completion of load cycling, teeth were removed from their plaster cylinders, cleaned and stored in distilled water at 37°C.

Figure 6.6 : Load cycle machine

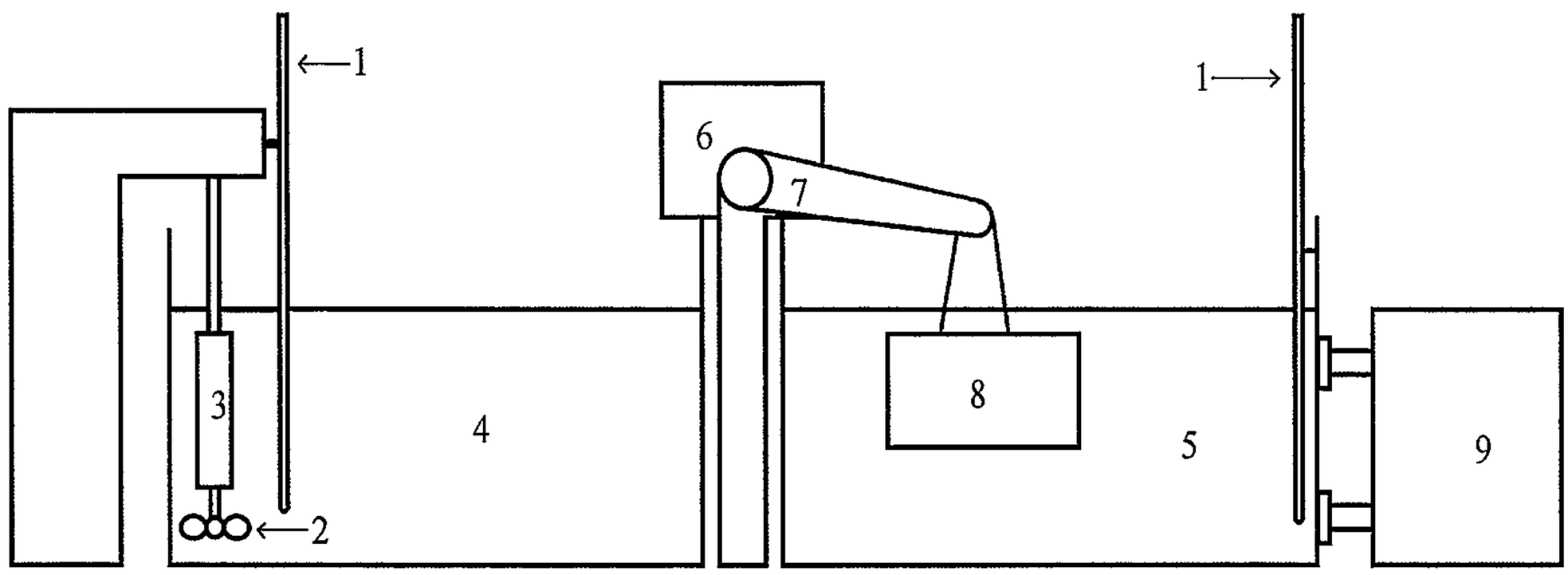
1 Flywheel
2 Cam
3 Hinged beam
4 Heater
5 Stopper
6 Calibrated weight providing 90 N at loading point
7 Water bath
8 Plaster mount
9 Restored tooth
10 Load applier
11 Loading point



5. Thermal Cycling

The restored teeth were subjected to thermal cycling within 24 hours of completion of load cycling. To simulate extremes of temperature within the mouth, two water baths were set up. One contained hot water at (55 ± 2)°C, thermostatically controlled by a water heater and circulator and the other contained cold water kept at (5 ± 2)°C by ice and water circulated through a refrigerated coil *(Figure 6.7)*. Teeth were subjected to 200 thermocycles. One cycle consisted of 25 seconds in the cold water bath, 5 seconds transfer, 25 seconds in the hot water bath and 5 seconds transfer.

Figure 6.7 : Thermal cycle machine



1 Thermometers
2 Water circulator
3 Heating element
4 Hot water bath
5 Cold water bath
6 Timer and motor
7 Transferring arm (driven by motor)
8 Basket holding teeth
9 Refrigerated coil with pump

6. Dye Penetration

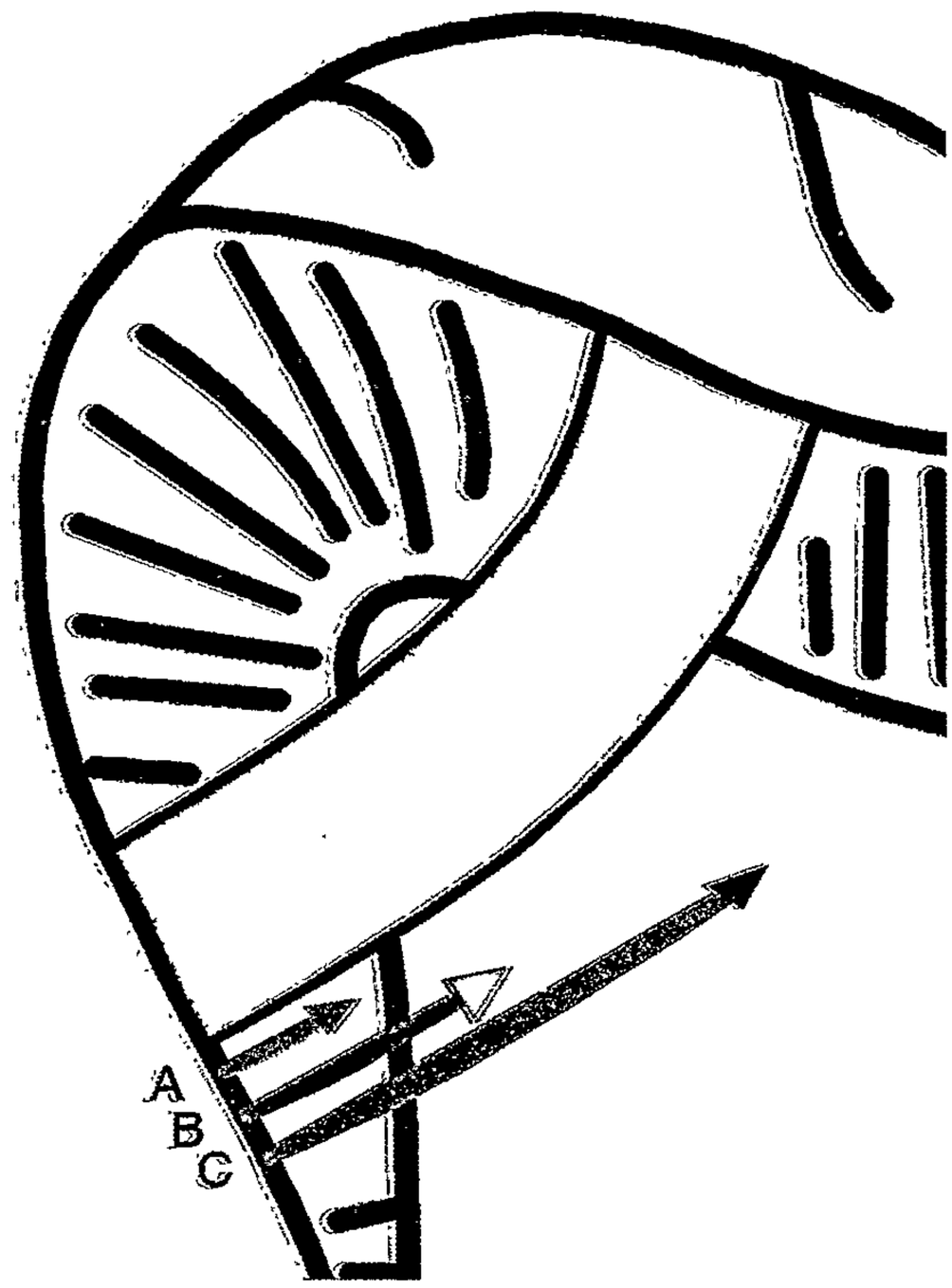
At the completion of thermal cycling, teeth were coated with a protective varnish to within 1 mm of the occlusal and proximal cavosurface margins of the restorations and placed in a solution of 0.5 % basic fuschin at 37°C for 24 hours. The solution was changed after each group of 10 teeth.

7. Resin Mounts and Sectioning

The teeth were removed from the 0.5 % basic fuschin dye, rinsed, dried, and mounted in epoxy resin[15] within cylindrical rubber moulds. Care was taken to mount each tooth on its buccal surface to enable sectioning through the restoration in a mesio-distal direction. Specimens were then stored until sectioning. An Isomet saw[16] fitted with a diamond blade was used at slow speed to cut 0.75 mm thick sections. Water was used during the sectioning of the specimens to prevent burning of the epoxy resin or blade breakage. At least two 0.75 mm sections were obtained from each restoration, resulting in a total of four surfaces for examination. Sections of each tooth were placed in a labelled container and stored in a dry, dark environment for subsequent analysis.

Using a reflected light source and a binocular microscope at X40 magnification, four surfaces from each restoration were examined and leakage at the tooth/restoration interface of the proximal surfaces was graded by the depth of dye penetration *(Figure 6.8)*, using a millimetre rule. When the degree of leakage of the various surfaces of the same restorations differed, the grade representing the most leakage was recorded. From a clinical point of view, the selection of the grade with the worst leakage represented the worst "case scenario", with the potential for the most serious clinical consequences.

Figure 6.8 : Depth of dye penetration and grades of leakage



Grade N = no leakage

Grade A = leakage into enamel along the restoration/tooth interface

Grade B = leakage < 1 mm into dentine along the restoration/tooth interface

Grade C = leakage ≥ 1 mm into dentine along the restoration/tooth interface

Examples of the grades of dye penetration are shown in *Figure 6.9 to 6.12.*

Figure 6.9 : Grade N leakage

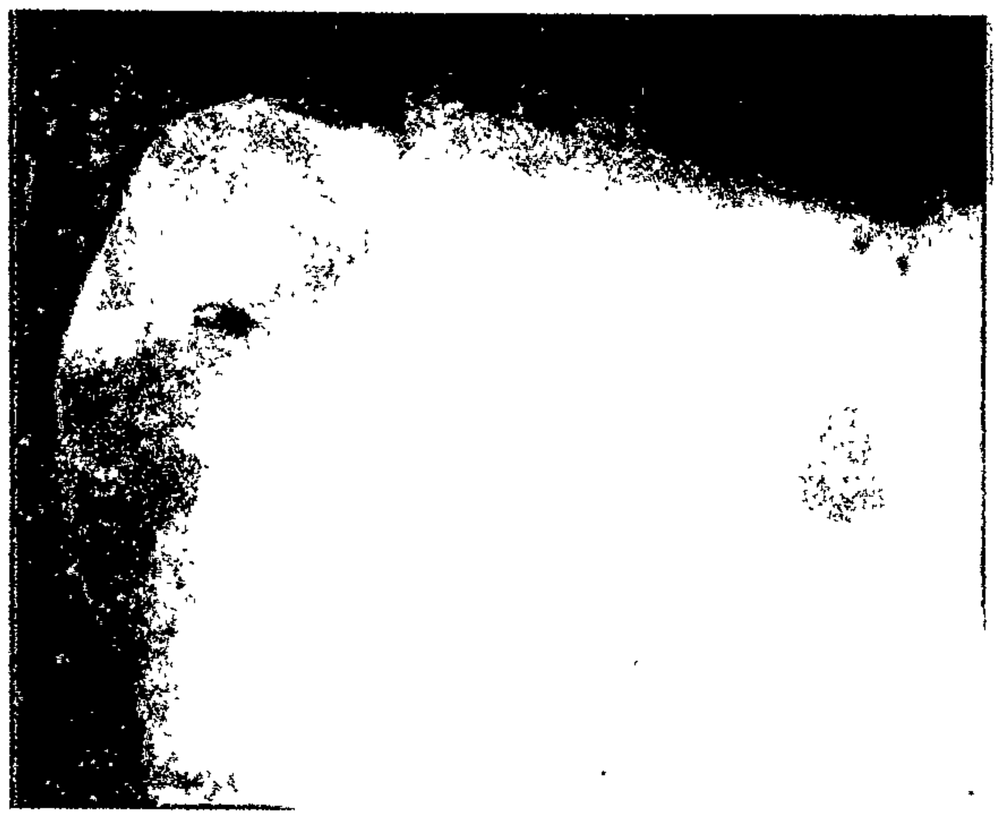


Figure 6.10 : Grade A leakage

Figure 6.11 : Grade B leakage

Figure 6.12 : Grade C leakage

6.2 Adaptation Study

1. Resin Replicas

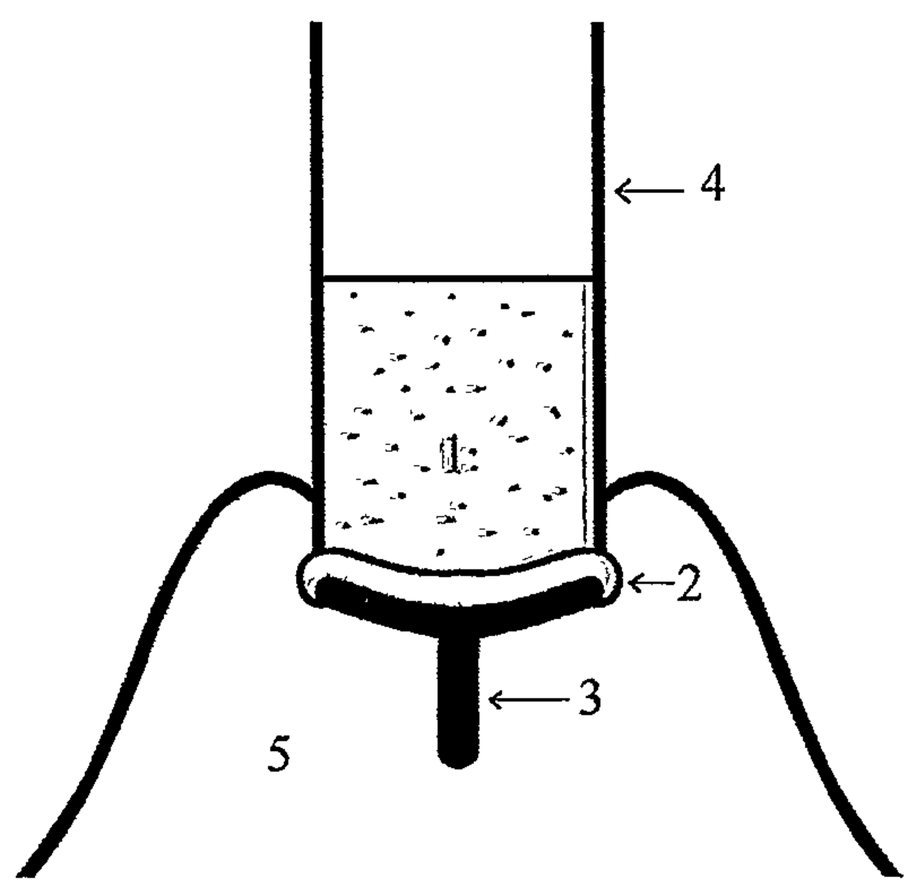
To study the adaptation of restorative materials to the cavity margins, impressions were taken of the proximal surfaces of each tooth with a polyvinylsiloxane impression material[17] supported by a clear matrix[18], which had been coated with an adhesive[19]. Impressions were taken both prior to and after load and thermal cycling.

The polyvinylsiloxane impression material was injected over the proximal surfaces of each restoration, extending the material beyond the margins by approximately 1 mm. A clear cervical matrix coated with adhesive was immediately applied to the body of the material, which was left to set for 6 minutes at room temperature. Forty impressions were taken for each group of 10 teeth; ie. 20 restorations before load cycling and 20 after thermal cycling.

All impressions were labelled and stored in containers for later correlation between adaptation and microleakage. To enable replication of the tooth/restoration surfaces, impressions were placed face up into modelling clay. Five millimetre lengths of drinking straw with an internal diameter of 4 mm were placed over the impressions and modelling clay was adapted round the sides of the straw *(Figure 6.13)*. Care was taken to contain the restoration margins within the internal section of the straw. Epoxy resin[20] was poured into the straw to a uniform height of 5 mm. Resin replicas were allowed to set for 24 hours before being labelled and stored for later analysis.

Figure 6.13 : Impression mounting for replication

1 Epoxy Resin
2 Impression material
3 Clear matrix
4 Straw
5 Modelling clay



2. Analysis of Replicas

The replicas were arranged and mounted with double-sided adhesive tape onto aluminium discs cleaned with 70% alcohol. Carbon dag was applied to the sides of each replica prior to gold-plating for examination in the scanning electron microscope (SEM).

The specimen replicas were examined in the SEM using an accelerating voltage of 15 kV, secondary electron detection, a spot size of 200 nm and a tilt range of 35° to 55°. For the purpose of this study, all replicas were examined initially under X60 magnification for grading of the perimeter of the cavosurface margins and later under magnification of X200 for specific areas. By visual assessment, any breach in the interface between the restorative material and the tooth cavosurface margin was considered to be a defect, even though some areas under higher magnification showed adhesion to the dentine beneath the cavity margin. Overfilled restorations were not classed as defective unless separation at the tooth/restoration interface was apparent. Margins of the replicas were not sufficiently accurate to allow high magnification analysis for microscopic evaluation of adhesion to enamel and dentine.

Photographs were taken using black and white film and incorporating a camera factor of 0.5.

Grades were recorded for the total percentage of cavosurface margin displaying adaptation with no value given for the severity of the defect. Scores were recorded for both pre-cycled and post-cycled replicas and examples are shown in *Figures 6.14* to *6.17*.

Grade N = no visible gaps around the perimeter

Grade X = < ¼ of the circumference exhibited marginal defects

Grade Y = ≥ ¼ and < ½ of the circumference exhibited marginal defects

Grade Z = ≥ ½ of the circumference exhibited marginal defects

Figure 6.14 : Grade N adaptation

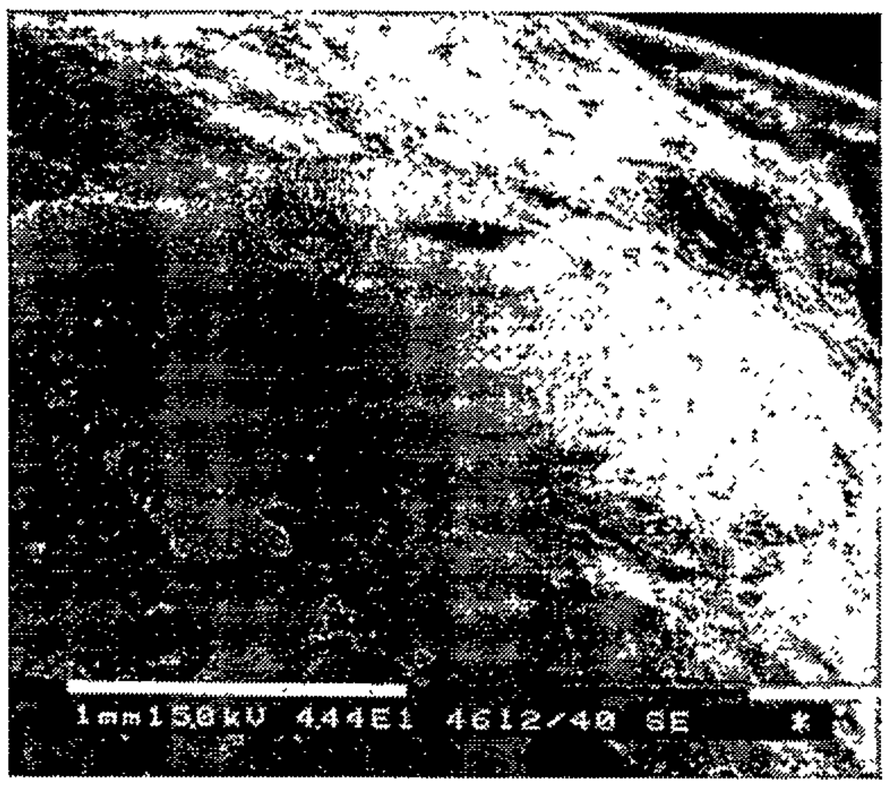


Figure 6.15 : Grade X adaptation

Figure 6.16 : Grade Y adaptation

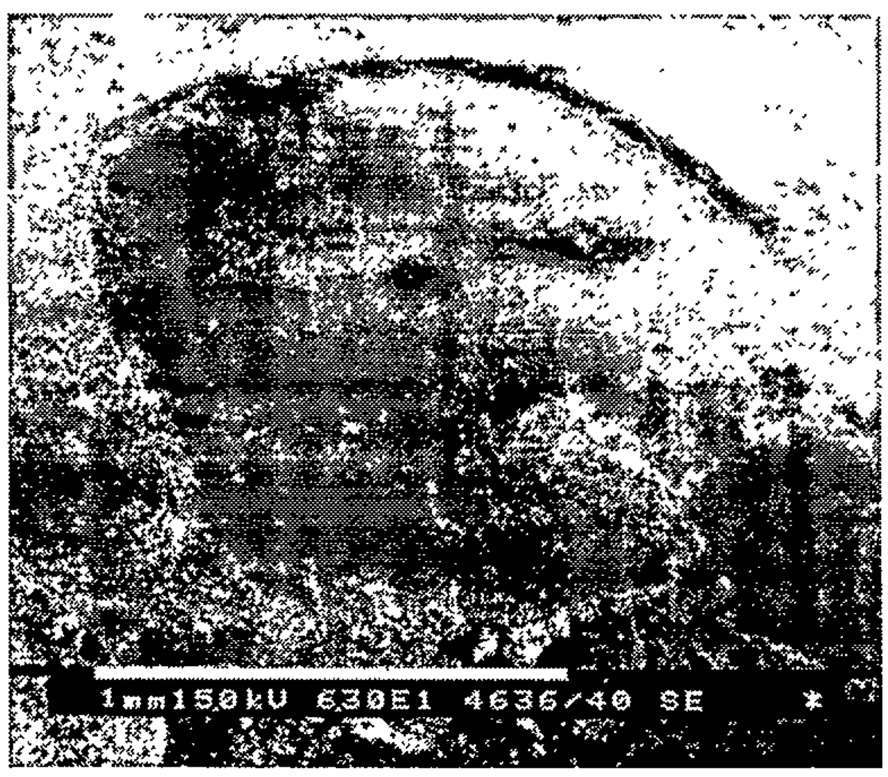
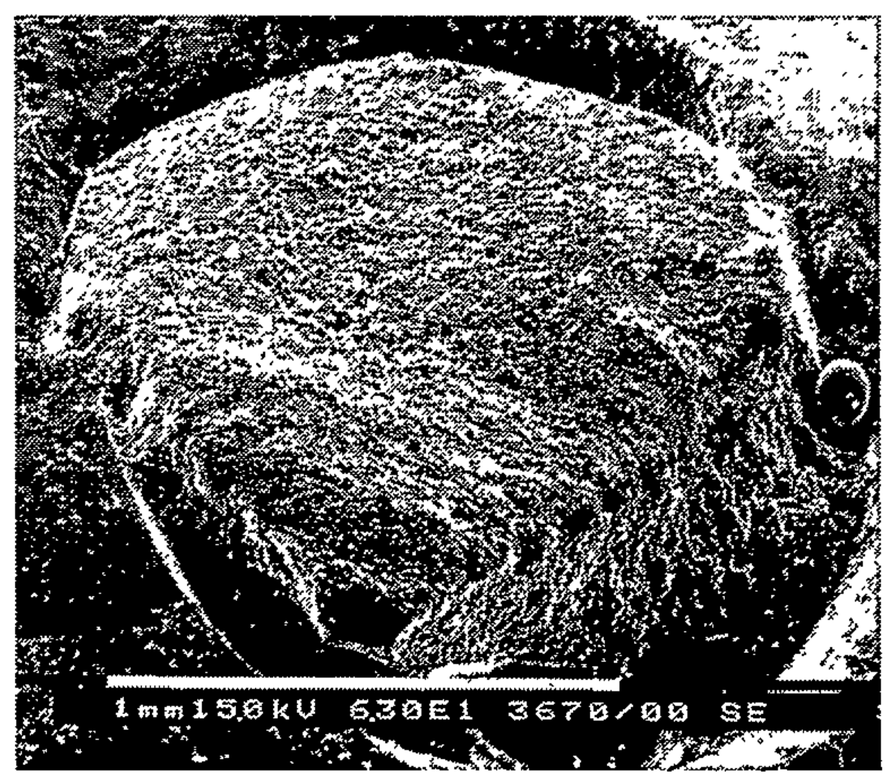


Figure 6.17 : Grade Z adaptation



Chapter 7

RESULTS

7.1 Microleakage

Microleakage results (obtained from sectioned specimens, after load and thermal cycling) are shown in *Table 7.1*. Analysis of the four sections from each restoration produced varying results, so, for the purpose of this study, the grade representing the most leakage was recorded for each restoration. The number of restorations for each grade together with the percentages of specimens are recorded in *Table 7.2* and a bar chart combining the results for each material is shown in *Figure 7.1*. No teeth showed evidence of marginal ridge fracture during the load and thermal cycling.

Table 7.1 : Microleakage results

Specimen	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
1	A	C	A	A	C	A
2	C	C	A	N	B	C
3	A	C	B	A	A	C
4	C	A	B	N	A	A
5	N	B	B	A	B	C
6	C	A	B	A	A	C
7	A	A	A	A	B	B
8	A	A	B	C	B	B
9	A	A	N	A	A	B
10	N	A	A	N	B	A
11	N	N	C	A	C	C
12	C	N	A	A	B	A
13	C	B	A	B	A	C
14	A	N	A	A	B	B
15	B	A	A	A	C	C
16	A	B	A	A	B	C
17	C	B	C	B	A	C
18	A	A	A	A	A	C
19	B	B	B	N	N	A
20	A	A	A	A	N	B

Grade N - no leakage

Grade A - leakage into enamel along the restoration/tooth interface

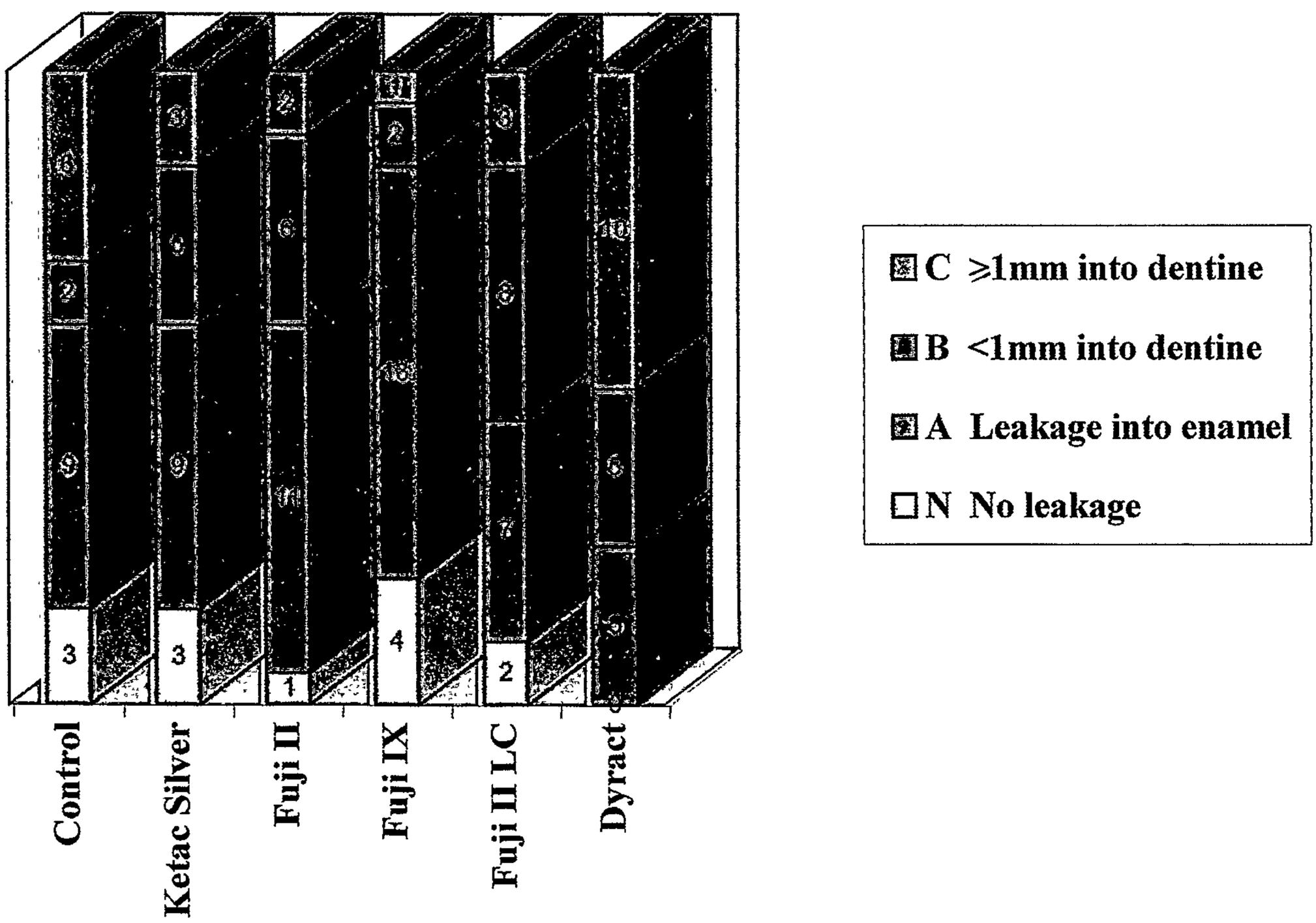
Grade B - < 1mm leakage into dentine along the restoration/tooth interface

Grade C - > 1mm leakage into dentine along the restoration/tooth interface

Table 7.2 : Number (percentage) of specimens for each grade of microleakage

Grade	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
N	3 (15%)	3 (15%)	1 (5%)	4 (20%)	2 (10%)	0
A	9 (45%)	9 (45%)	11 (55%)	13 (65%)	7 (35%)	5 (25%)
B	2 (10%)	5 (25%)	6 (30%)	2 (10%)	8 (40%)	5 (25%)
C	6 (30%)	3 (15%)	2 (10%)	1 (5%)	3 (15%)	10 (50%)

Figure 7.1 : Bar chart displaying the amount of microleakage



From the bar chart, *Figure 7.1,* yellow indicates 'no leakage' while other colours represent varying degrees of microleakage. The data show that no restorative material was able to prevent microleakage at the restoration/tooth interface. Blue areas represent restorations with leakage confined to the enamel. Restorations showing leakage into dentine are represented by purple and green. Distinct differences can be seen in the histogram between Dyract and Fuji IX.

For the control restorations, three showed no leakage, nine exhibited grade A, two grade B and six displayed the deepest leakage into dentine (grade C). Twelve restorations of the 20 prepared (60 per cent), showed minimal or no leakage and a total of eight restorations (40 per cent) showed leakage within dentine.

Analysis of Ketac Silver results found three restorations with no leakage, nine with grade A, five grade B and three displayed grade C leakage. As with the control results 12 of the 20 restorations (60 per cent) demonstrated minimal or no leakage, while eight restorations (40 per cent) exhibited leakage within dentine.

Only one Fuji II restoration demonstrated no leakage, while eleven displayed grade A leakage, six grade B and two exhibited grade C leakage. As with the control and Ketac Silver restorations, 12 of the 20 restorations (60 per cent) exhibited minimal or no leakage, while eight Fuji II restorations (40 per cent) displayed leakage into dentine.

The results showed that four Fuji IX restorations displayed no leakage, with 13 exhibiting grade A, two grade B and only one displayed grade C leakage. Therefore, 17 of the 20 restorations (85 per cent) displayed minimal or no microleakage and only three restorations (15 per cent) exhibited leakage within the dentine.

In the analysis of Fuji II LC results, two restorations showed no leakage, seven grade A, eight grade B and three displayed grade C leakage. Nine restorations (45 per cent) showed minimal or no leakage while 11 restorations (55 per cent) exhibited leakage into dentine.

No Dyract restorations were able to prevent microleakage. Five, however, showed grade A, five grade B and ten exhibited grade C leakage. Only five of the 20 restorations (25 per cent) exhibited minimal or no leakage whereas fifteen restorations (75 per cent) displayed leakage into dentine.

Statistical Analysis of microleakage

In all the statistical tests applied to the results, a p-value of less than 0.05 was considered to denote a "statistically significant" result where we had strong evidence against the null hypothesis being tested.

By considering the worst values of leakage for each specimen and using the Kruskal Wallis non-parametric test it was found that there were no statistically significant differences between control, Ketac Silver, Fuji II and Fuji II LC ($p = 0.883$). When comparing Fuji IX to these materials there was evidence to support a statistically significant result ($p = 0.05$, exactly). Although this p-value was not less than 0.05, it could be suggested that Fuji IX demonstrated the best marginal seal of all the materials tested. Dyract demonstrated the greatest leakage ($p = 0.002$) when it was compared to all the other materials tested.

7.2 Adaptation

Pre-cycled adaptation

Scanning electron microscope (SEM) analysis of the marginal adaptation was performed and the results of the pre-cycled specimen replicas are reported in *Table 7.3.*

Table 7.3 : SEM pre-cycled adaptation results

Spec #	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
1	X	Y	X	Y	Z	X
2	Y	Z	X	N	Y	Z
3	Y	Z	Y	X	X	Y
4	Z	X	Y	X	X	Y
5	X	Y	X	X	Y	Z
6	Y	Y	Y	Y	Y	Z
7	Y	Y	Y	Y	Y	Y
8	X	Y	Y	Y	X	X
9	Z	Y	X	Y	X	Y
10	Y	X	X	X	Y	Y
11	X	X	Z	X	Z	Z
12	Z	Y	Y	Y	Y	Y
13	Y	Y	Y	X	Z	Z
14	Y	X	Y	X	Y	Z
15	Z	X	Z	X	Y	Z
16	Y	Y	Y	Z	Y	Z
17	Z	Z	Z	X	X	Z
18	X	Y	Y	Y	Y	Z
19	Y	Y	X	N	X	Y
20	X	Y	X	Y	X	X

Grade N - No visible gaps around the perimeter

Grade X - < ¼ of the circumference exhibited marginal defects

Grade Y - ≥ ¼ and < ½ of the circumference exhibited marginal defects

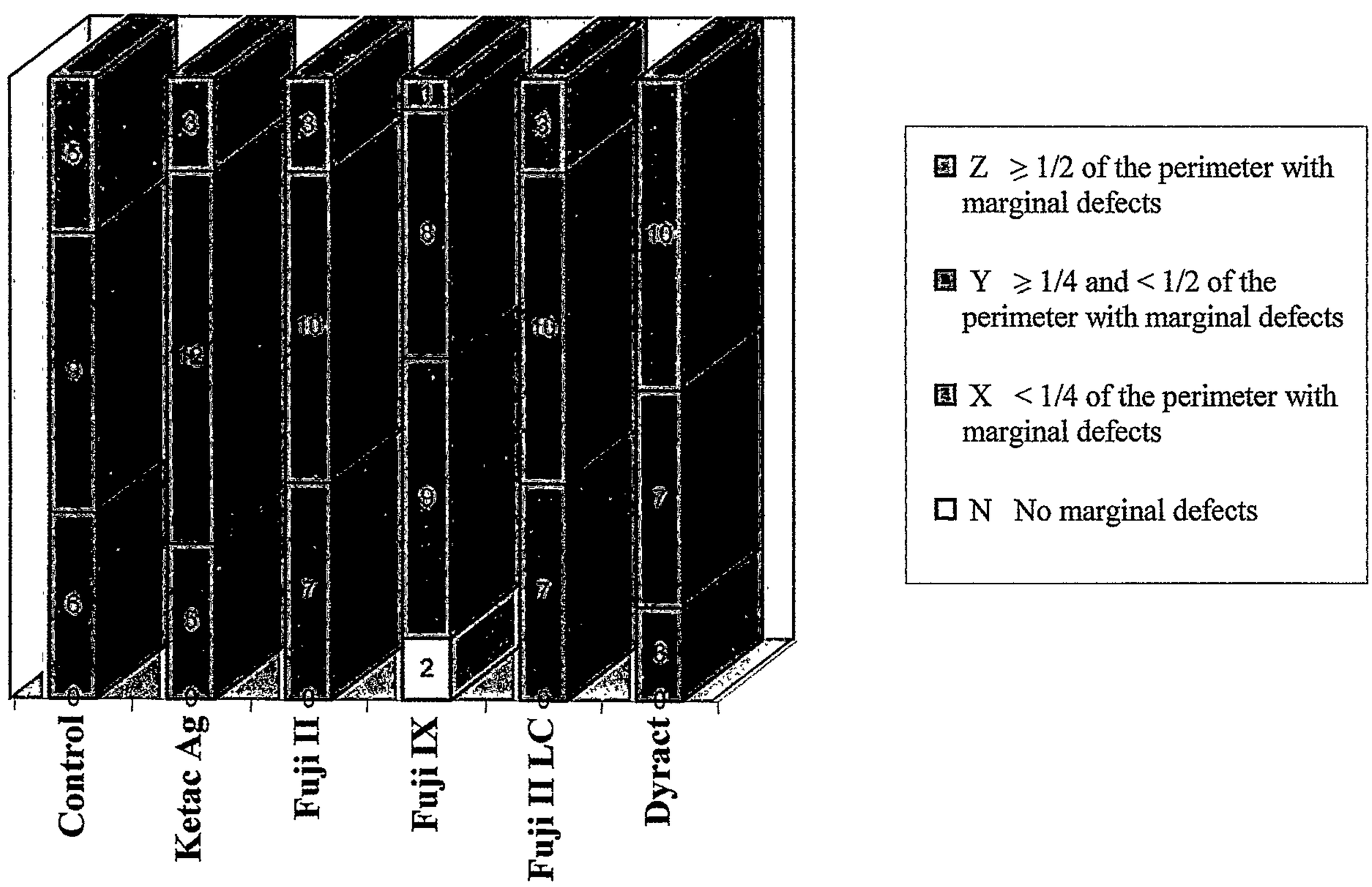
Grade Z - ≥ ½ of the circumference exhibited marginal defects

For each material, the number and percentages of pre-cycled specimens are summarised in *Table7.4* and a bar chart combining the results is shown in *Figure 7.2.*

Table 7.4 : Number (percentage) of pre-cycled specimens for each grade of marginal defects

GRADE	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
N	0	0	0	2 (10%)	0	0
X	6 (30%)	5 (25%)	7 (35%)	9 (45%)	7 (35%)	3 (15%)
Y	9 (45%)	12 (60%)	10 (50%)	8 (40%)	10 (50%)	7 (35%)
Z	5 (25%)	3 (15%)	3 (15%)	1 (5%)	3 (15%)	10 (50%)

Figure 7.2 : Bar chart displaying pre-cycled marginal defects



Two Fuji IX specimens demonstrated perfect proximal margin adaptation, as seen with the SEM, around the entire cavosurface margin, and only one Fuji IX restoration displayed marginal defects around more than half of the perimeter. By contrast, however, 50 per cent of

the Dyract specimens displayed defects around greater than half of the perimeter of the proximal margin.

After SEM analysis of the control specimens, it was found that all cavosurface margins demonstrated marginal defects. Six restorations exhibited marginal deficiencies affecting less than a quarter of the periphery (grade X), while nine specimens showed between one quarter and one half the perimeter with marginal defects (grade Y) and five specimens showed defects affecting more than half the cavosurface margin (grade Z).

Analysis of Ketac Silver specimens found no restorations with perfect marginal adaptation. Five showed defects of grade X, 12 exhibited defects of grade Y and three displayed defects of grade Z.

Fuji II specimens failed to show perfect adaptation in any of the restorations. Seven restorations showed marginal defects of grade X, while 10 restorations displayed cavosurface margin defects of grade Y and three restorations exhibited marginal defects of grade Z.

As previously mentioned, two Fuji IX restorations were the only specimens to exhibit perfect marginal adaptation around the perimeter of the cavosurface margins. Nine restorations displayed marginal defects of grade X, eight specimens showed defects of grade Y and one specimen exhibited defects of grade Z.

Analysis of Fuji II LC found no specimens with perfect marginal adaptation. Seven specimens showed defects of grade X, 10 exhibited defects of grade Y and three specimens displayed marginal defects of grade Z.

All Dyract specimens displayed cavosurface marginal defects. Three specimens exhibited marginal deficiencies of grade X, seven displayed defects of grade Y and 10 restorations showed defects of grade Z.

Statistical Analysis of pre-cycled specimens

The Kruskal Wallis non-parametric test was used to examine differences in adaptation between the six groups of restorations examined in the SEM, with a p-value less than 0.05 denoting a "statistically significant" result. It was found that there were statistically significant differences amongst the various restorative materials ($p = 0.008$). However, after exclusion of Dyract, an analysis of the remaining five materials showed no significant statistical difference ($p = 0.185$). It was concluded, therefore, that Dyract displayed the poorest adaptation, while no significant differences existed between the adaptation of the other restorative materials.

Post-cycled adaptation

SEM analysis of the margins of post-cycled replicas was performed and the results are reported in *Table 7.5*.

Table 7.5 : SEM post-cycled adaptation results

Spec #	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
1	Y	Z	X	Y	Z	Y
2	Z	Z	Y	N	Y	Z
3	Y	Z	Y	Y	X	Z
4	Z	Y	Y	X	Y	Y
5	X	Y	Z	X	Y	Z
6	Z	Y	Y	Y	Y	Z
7	Y	Y	Y	Y	Z	Y
8	Y	Y	Y	Y	Y	X
9	Z	Z	X	Y	X	Y
10	Y	Y	X	X	Y	Y
11	X	X	Z	X	Z	Z
12	Z	Y	Y	Y	Z	Y
13	Z	Z	Y	X	Z	Z
14	Y	Y	Z	X	Y	Z
15	Z	Y	Z	X	Y	Z
16	Z	Z	Y	Z	Y	Z
17	Z	Z	Z	Y	X	Z
18	Y	Y	Y	Y	Y	Z
19	Y	Z	X	N	X	Y
20	Y	Y	X	Y	X	Y

Grade N - No visible gaps around the perimeter

Grade X - < ¼ of the circumference exhibited marginal defects

Grade Y - ≥ ¼ and < ½ of the circumference exhibited marginal defects

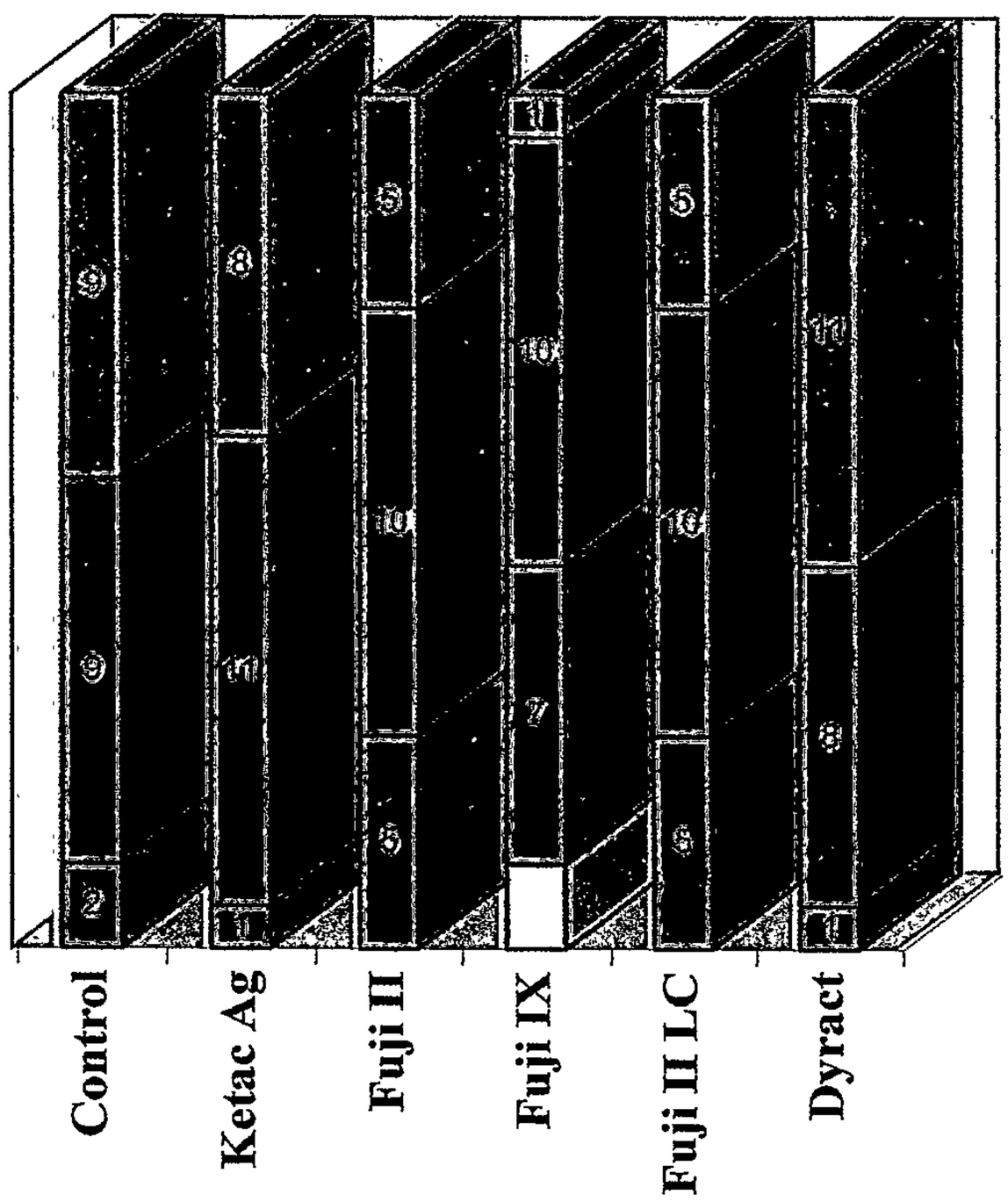
Grade Z - ≥ ½ of the circumference exhibited marginal defects

For each material, the number and percentage of post-cycled specimens are summarised in *Table7.6* and a bar chart combining the results is shown in *Figure7.3*.

Table 7.6 : Number (percentage) of post-cycled specimens for each grade of marginal defects

Grade	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
N	0	0	0	2 (10%)	0	0
X	2 (10%)	1 (5%)	5 (25%)	7 (35%)	5 (25%)	1 (5%)
Y	9 (45%)	11 (55%)	10 (50%)	10 (50%)	10 (50%)	8 (40%)
Z	9 (45%)	8 (40%)	5 (25%)	1 (5%)	5 (25%)	11 (55%)

Figure 7.3 : Bar chart displaying post-cycled marginal defects



The results showed that after load and thermal cycling, Fuji IX was the only material to retain perfect marginal adaptation for any of the restorations. The other materials displayed defects

The results showed that after load and thermal cycling, Fuji IX was the only material to retain perfect marginal adaptation for any of the restorations. The other materials displayed defects around the cavosurface margins with more than 50 per cent of specimens showing deficiencies around more than one quarter of the perimeter (grades Y and Z).

No Control specimens showed perfect adaptation. Two specimens exhibited marginal defects of grade X, while nine displayed defects of grade Y and nine showed defects of grade Z.

Analysis of Ketac Silver results showed that no restorations were free of marginal defects. One specimen displayed defects of grade X, 11 exhibited defects of grade Y and eight specimens showed defects of grade Z.

All Fuji II restorations showed defects around the cavosurface margins. Five restorations exhibited defects of grade X, 10 specimens displayed defects of grade Y and five specimens showed defects of grade Z.

Two Fuji IX specimens showed no defects in the cavosurface margin. Seven displayed defects of grade X, 10 specimens exhibited marginal defects of grade Y and one restoration showed defects of grade Z.

Fuji II LC analysis gave results identical to those of Fuji II post-cycled specimens.

Analysis of the Dyract specimens showed no examples of perfect adaptation at the cavosurface margins. One specimen displayed marginal defects of grade X, eight exhibited defects of grade Y and 11 specimens showed defects of grade Z.

Statistical Analysis of post-cycled specimens

Assuming that a "statistically significant" result would give a p-value of less than 0.05, analysis of post-cycled data using the Kruskal Wallis non-parametric test showed there were statistically significant differences between the six restorative materials ($p = 0.001$). When results were further analysed, two different groupings were identified. No differences existed between the control, Ketac Silver and Dyract ($p = 0.657$) and there were no statistical differences between Fuji II, Fuji II LC and Fuji IX ($p = 0.085$).

Comparison between pre-cycled and post-cycled adaptation

Comparison of pre-cycled and post-cycled results showed that there was no improvement in the adaptation of any material following load and thermal cycling. Adaptation scores from pre- to post-cycled specimens either remained the same or increased one value (became worse), except for one specimen where the degree of change was two grades.

Statistical Analysis of the comparison

To compare pre-cycled and post-cycled results, an analysis on the proportion of specimens changing score was performed using a chi-squared test for proportions, where a p-value less than 0.05 was considered to be "statistically significant". The rating for the proportion of change amongst the control and Ketac Silver was higher than in the other materials tested. The difference was statistically significant ($p = 0.001$). That is, for these two techniques, it was more likely that there was a worsening of adaptation between pre- and post-cycled conditions for each specimen. A comparison of control and Ketac Silver pre- and post-cycled results revealed no statistically significant difference between the results for these two techniques ($p = 0.749$). It was also shown that no statistically significant differences existed between Fuji II, Fuji II LC, Fuji IX and Dyract ($p = 0.853$) in the frequency of change observed for pre- and post-cycled conditions.

Using the Spearman rank correlation test, a positive correlation was found to exist between the pre-cycled and post-cycled results for all materials *(Table7.7)*. The rank correlation z-test was used to test the null hypothesis that the true correlation was zero in each group of materials.

Table 7.7 : Spearman rank correlation coefficients for pre- and post-cycled results

	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
Coefficient	0.771	0.654	0.72	0.886	0.834	0.902

All of these rank correlations were found to be statistically different from zero when tested at the 0.05 significance level.

7.3 Comparison of microleakage to adaptation

A comparison was made of microleakage and adaptation results using the Spearman rank correlation z-test and a null hypothesis of zero correlation. *Table 7.8* represents the Spearman rank correlation coefficients for each of the materials tested. Statistically, the correlation between microleakage and adaptation for Fuji II and Fuji IX was not significantly different from zero ($p > 0.05$). However, a significant correlation was found in the comparison of microleakage and adaptation for control, Ketac Silver, Fuji II LC and Dyract ($p < 0.05$).

Table 7.8 : Spearman rank correlation coefficients for comparison of microleakage and adaptation results

	Control	Ketac Ag	Fuji II	Fuji IX	Fuji II LC	Dyract
Coefficient	0.804	0.8	0.423	0.509	0.65	0.861

Chapter 8

DISCUSSION

Within the limitations of the simulated clinical model used in this study, no restorative material reliably sealed the tunnel restorations, and no material consistently produced ideal adaptation. In addition, a significant and positive correlation between microleakage and adaptation only existed for some of the materials tested. Contrary to expectations, similar microleakage and adaptation results were found for both the experimental and control Ketac Silver restorations.

The simulated clinical model used in this study was designed to overcome the perceived inadequacies of previous studies. A literature review of *in vitro* microleakage in tunnel restorations revealed that only three studies utilised teeth with proximal carious lesions. The study by Hickel and co-workers (1987) used only Ketac Silver as a restorative material, while Wenzel *et al* (1998) examined the effectiveness of caries removal. Work by Strand *et al* (1993) concentrated on the restoration of partial tunnel restorations where the proximal enamel remained intact. All other microleakage and fracture strength studies used sound, intact teeth, and either prepared the tunnels conventionally under simulated clinical conditions, hand-held the teeth during preparation providing unnatural access, or prepared cavities from both the occlusal and proximal directions. To obtain microleakage results more representative of a clinical situation, it was felt necessary to use teeth with small carious lesions, which were mounted and prepared in a more clinically realistic manner.

For the purpose of this study, decalcified lesions were produced using principles from Silverstone (1967) and Lilienthal *et al* (1968), who described techniques of creating artificial caries. These were later modified by Silverstone *et al* (1988a and 1988b), who used lactic acid in a suspension of gelatin to create artificial decalcification. Exposure to this suspension produced small caries-like lesions in an area of exposed enamel. In the present study, tooth surfaces requiring protection from the acidic suspension were

coated with a varnish, 'Protect', developed by Hachiya *et al* (1985). Although artificial caries was induced by acid and not by a bacterial medium, it was considered an intra-study phenomenon and would not influence the results between different materials. The degree of decalcified dentine was monitored by radiographs and it was observed during cavity preparation, that the quantity of softened dentine was consistent. It is thought that no similar model has been used for tunnel restoration analysis.

Most microleakage studies have utilised Ketac Silver as a restorative material because it was among the first radiopaque derivatives of glass ionomer cement. Ketac Silver was chosen as the control material because it had already been established that Class V and tunnel preparations restored with Ketac Silver exhibited similar leakage (Robbins & Cooley, 1988); its use also enabled a comparison of results from this study with those of other studies. In addition to a cermet cement (Ketac Silver), a conventional glass ionomer cement (Fuji II) was used, as well as a high density new generation glass ionomer cement (Fuji IX), a resin-modified glass ionomer cement (Fuji II LC) and a polyacid-modified resin composite (Dyract).

The control teeth, restored with Ketac Silver, were sound and intact and were prepared from both the occlusal and the proximal surfaces. Unlike the Ketac Silver restorations of the experimental teeth, the Ketac Silver in the control teeth was condensed after placement to allow a comparison with other studies. The control method also enabled the material to be assessed without the influence of inadequate caries removal and irregular cavosurface margins. These control teeth (restored with Ketac Silver) were prepared in sound and intact rather than carious teeth (as used in experimental teeth) in order to optimise comparison with other studies, the majority of which have used non-carious teeth. Therefore, a comparison of the results from the carious teeth in this investigation with the results from non-carious teeth in other studies may be made by the means of a comparison between Ketac Silver control and Ketac Silver experimental teeth of this study.

Cavity design of the experimental teeth used preparation principles from the original studies by Hunt (1984) and Knight (1984), together with findings from studies by Fasbinder (1991) and Strand *et al* (1995a). The occlusal opening was placed at least two

millimetres from the marginal ridge (Wilson and McLean, 1988; Leidal and Mjör, 1988) to retain marginal ridge integrity and protect from fracture during load cycling (Strand *et al*, 1995a). This was considered to be clinically important despite better access and visibility being achievable from a more vertical preparation (Strand *et al*, 1994). The proximal exit point of the preparation was beneath the contact area, and was determined by the position of the artificial caries induced on the proximal tooth surface. Despite slight anatomical variations of the experimental teeth, preparations were uniform in design and size.

The use of load cycling as a means of accelerated ageing in the study of tunnel restorations has not been previously published. Studies of microleakage have used thermal cycling to simulate temperature changes in the oral environment (Robbins and Cooley, 1988; Bassiouny *et al*, 1989; Garcia-Godoy *et al*, 1988). Marginal ridge strength and the support given by various materials in tunnel restorations has been studied by fracture loading (Hill and Haleseh, 1988; Covey *et al*, 1989; Fasbinder, 1991; Papa *et al*, 1993b; Ehrnford and Frannson, 1994; Purk *et al*, 1995). One study by Strand *et al* (1995), however, investigated the effect of size and positional placement of the occlusal access on the marginal ridge strength following repeated and progressively increasing sub-fracture loading. It has been recognised that *in vitro* studies need to simulate clinical conditions, and that clinical tooth fracture was more likely to occur due to the progression of small cracks during dynamic, repeated loading (Bell *et al*, 1982). No studies have examined the effect of sub-fracture fatigue loading in tunnel restorations.

There have also been no previously published studies performed on tunnel restorations using the accelerated ageing techniques of both sub-fracture load cycling and thermal cycling, to investigate microleakage and adaptation of the proximal cavosurface margins of tunnel restorations. Although the conditions of this study were chosen to represent the intraoral stresses to which the restoration would be exposed, no *in vitro* tests have been shown to accurately simulate clinical conditions. An *in vitro* study by Ferrari *et al* (1997) using Fuji IX and a composite resin to restore Class II preparations has shown greater leakage (80 per cent of restorations) than clinical studies (20 per cent of restorations) using the same restorative techniques. Loading is extremely varied between

individuals, therefore comparisons can only be valid when made intra-study. In an attempt to simulate clinical conditions, loading parameters included loading under moist conditions, one cycle taking half a second (Ahlgren, 1966), and using a force that was representative of normal chewing (90 N), rather than a maximal biting force of between 300 and 500 N (Bates *et al*, 1975). Strand *et al* (1995a) found that marginal ridge fracture was related to the magnitude of stresses over a period of time, as occurs clinically.

During the load and thermal cycling in this study no marginal ridge failures were observed. The regimen used to age the restorations was harsher than previous microleakage studies, yet few Ketac Silver restorations leaked when compared to studies by Robbins and Cooley (1988) where most restorations exhibited leakage and by Hotz and Holzer (1989) where all restorations leaked. Results, however, were not as good as those obtained in the study by Bassiouny *et al* (1989) and Garcia-Godoy (1988), where only 20 per cent of restorations exhibited leakage. It is possible, therefore, that the microleakage results of this study, with 85 per cent of Ketac Silver restorations displaying some degree of leakage, were influenced by load cycling. Deterioration of the cavosurface marginal integrity of Ketac Silver restorations after age cycling also confirms the effect of this process on the overall performance of the restorative material. During analysis of the specimen sections it was noted that microleakage was greatest at the gingival cavosurface margin.

The materials used in this study produced a range of microleakage values. Although eighty per cent of the Fuji IX restorations displayed leakage, only 15 per cent of all these restorations leaked into the dentine, compared to 75 per cent of all Dyract restorations leaking into dentine. Many possibilities exist to explain the degree of leakage found in this study. One reason could be the failure to completely remove all caries, as reported by Wenzel *et al* (1998). Strand *et al* (1993) had also reported incomplete caries removal in partial tunnel restorations. Within the constraints of the cavity preparation, limited access was thought to be the main reason for between 20-29 per cent residual caries in three different *in vitro* studies (Strand and Tveit, 1993; Strand *et al*, 1994; Strand *et al*, 1995a). Clinically, the presence of residual caries would reduce bonding of the material and encourage recurrent caries formation. During microscopic analysis of the sectioned

specimens in the microleakage studies, however, it was noted that sound dentine was adjacent to the restorative material and no caries was evident. This observation was not confirmed at a histological level. In addition, similar microleakage results were found between Ketac Silver, where artificially induced carious teeth were used, and the control restorations which used sound teeth. Therefore, failure to remove caries was not necessarily a cause of microleakage for the small lesions within this study.

Another possibility for leakage could be the inability to remove demineralised enamel and prepare smooth proximal cavosurface margins in sound enamel. As suggested by Chalker *et al* (1993), round stainless steel burs were used at low speed to finish the interproximal enamel margins of the experimental teeth while the margins of the control teeth were prepared with high speed diamond burs from a direct approach. However, similarity of the Ketac Silver and control microleakage results would suggest that this has not been a factor.

During clinical preparation of tunnel restorations, excessive pressure or removal of sound dentine beneath the marginal ridge could promote crack propagation. By avoiding hand excavators in this study, minimal pressure was applied to the marginal ridge. During sectioning it was noted that dentine beneath the marginal ridges of the teeth was removed on most occasions. This has been suggested as an unsatisfactory restoration for proximal caries (Papa *et al* 1993a) and a reason for their contraindication. During sub-fracture loading of experimental teeth, however, no marginal ridge failures were recorded despite the lack of dentine. Small amounts of dentine remained beneath the marginal ridges in the control teeth, yet similar microleakage results were found between Ketac Silver and the control restorations. This suggests that the amount of dentine remaining beneath the marginal ridge in teeth restored with Ketac Silver did not influence the degree of microleakage.

Material placement techniques could also be responsible for microleakage. Variables influencing the effectiveness of material placement were ease of material placement through capsule design, viscosity of the material and characteristics of bonding systems. Design of the nozzle tips for encapsulated delivery systems varied widely among the materials tested in this study. Fuji IX nozzle tips were narrow and tapered, allowing

deeper placement within the tunnel preparation and therefore a greater ability to deliver the restorative material adjacent to the proximal cavosurface margins, while the Ketac Silver capsule nozzle tips were the broadest. Fuji II and Fuji II LC capsules were designed with straight nozzle tips which were difficult to bend and fit into the cavity without restricting the flow of the material. During clinical handling it was noted that Fuji II and Fuji II LC were the least viscous of the materials tested while Ketac Silver was the most viscous. This may have influenced the flow of the material with some Ketac Silver specimens producing the least favourable adaptation, and condensation of control restorations did not significantly improve the material's adaptability. Condensation of Dyract with a ball burnisher, together with incremental placement, did not prevent cavosurface margin microleakage or assure perfect adaptation. It is possible, therefore, that material placement techniques influenced the microleakage results. In addition, the favourable nozzle shape and viscosity benefited the seal of the Fuji IX restorations.

Under the conditions of this study it was found that Fuji IX restorations showed the least amount of microleakage. These findings agreed with those of a study by Sanders-Tavares *et al* (1997) where the microleakage of conventional, resin-modified and new generation auto-cure glass ionomer cements, and a polyacid-modified resin composite, were compared in Class II cavities. Fuji IX also displayed the least leakage in a study by Virmani *et al* (1997) where Class II preparations were restored with amalgam, resin-modified glass ionomer cement and Fuji IX. The study by Virmani *et al* also showed that Fuji IX provided the greatest cuspal strength in prepared teeth. Ferrari *et al* (1997) found that Fuji IX displayed less leakage than composite resin in Class II restorations. A recent prospective study by Jones (1999) is thought to be the only clinical study using Fuji IX to restore tunnel preparations. Sixty tunnel restorations were performed over an 8-year period; 21 tunnel preparations were restored with Fuji IX and only one failed due to marginal ridge fracture. No recurrent caries was reported, and Fuji IX restorations demonstrated fewer failures than those of Ketac Silver and Hi-Dense (Shofu), although the Fuji IX restorations had been in service for a slightly shorter time.

The improved sealing capacity of the Fuji IX could be due to one or more of a number of properties and characteristics as reported by previous studies. In a comparison with

the earlier auto-cure glass ionomer cements, it was thought that the favourable sealing ability of Fuji IX could be attributed to the higher powder:liquid ratio, (3.6:1 compared to 2.7:1 for Fuji II), producing enhanced physical properties (Hickel *et al*, 1998; Jones, 1999). A comparison of Fuji II and Fuji IX technical data from GC shows improvements in the compressive strength from 202 MPa to 220 MPa, tensile strengths from 16 MPa to 22 MPa and surface hardness from 58 Hv to 74 Hv one day after placement. Glass ionomer cement, particularly the new generation auto-cure materials such as Fuji IX, also display better thermal properties and improved shrinkage compared to resin-modified glass ionomer cements. These factors will minimise gap formation (Bullard *et al*, 1988) and as a result of a higher stiffness will improve stress distribution along the adhesive interface with the surrounding tooth structure (Crim, 1993; Sanders-Tavares *et al*, 1997). The greater number of powder particles in Fuji IX are coated in order to slow the setting reaction and produce a material that flows after mixing and before setting occurs. The higher powder content is thought to contribute to an improved sealing ability, a greater tensile bond strength with enamel and dentine and less solubility in neutral and acidic solutions (Hirota,1999). The greater filler content allows an increased chemical reaction and subsequently a reduced amount of matrix around a greater number of glass particles.

Resin-modified glass ionomer cement was initially considered to have a similar bonding mechanism to conventional glass ionomer cement (Mitra, 1991a). However, it is now reported to have a superior bond strength to dentine (Burrow and Tyas, 1998). This can be explained by the possibility of hybrid layer bonding; HEMA improves the wetting of dentine and the formation of resin tags into the dentine tubules (Friedl *et al*, 1995; Swift *et al*, 1995). Within the parameters of this study, however, conventional glass ionomer cement performed better than the resin-modified glass ionomer cement, Fuji II LC. Perhaps the bond to the enamel cavosurface margins was more effective with Fuji IX.

The extensive microleakage noted around the Dyract restorations in this study is probably the result of lack of seal at the enamel margins. This has been illustrated as staining around margins of Class V restorations after one year (Tyas, 1997; Tyas, 1998). It has been suggested that the PSA Prime cannot adequately seal without prior etching of the enamel margins. This would be difficult to control at the cavosurface

margins of tunnel restorations due to lack of access and visibility of the margins. It is presently unclear what effect etching of the dentine has on the bond strength of Dyract (Desai and Tyas, 1996). However, in a study by Calabrese *et al* (1997) etching of the dentine showed the formation of a hybrid layer under SEM analysis, but did not prevent microleakage. Because PSA Prime is claimed to bond ionically to dentinal calcium, Tyas (1998) felt that etching the dentine could deplete the surface calcium and compromise the bond. No studies, however, have tested this theory. A study using Dyract by Cortes *et al* (1993) found that an increased bond strength could be achieved after enamel etching (22 MPa compared to 8 MPa) and this was later supported by Desai and Tyas (1996) where etching enamel with 35 per cent phosphoric acid increased the bond strength from 4.2 MPa to 14.3 MPa. The bond strength to unetched enamel was found by these authors to be slightly less than that proposed by the manufacturer (9.6 MPa). Interestingly, the manufacturer (Dentsply DeTrey-DeDent, 1994) has published a bond strength to dentine of 14.5 MPa, which is similar to the etched enamel bond strength of 14.3 MPa found by Desai and Tyas (1996).

Three studies using Dyract in Class V restorations, using PSA Prime as the adhesive, have found less leakage than a resin-modified glass ionomer cement (Bravermann and Hatibovic-Kofman, 1997) and a glass ionomer cement (Magalhaes *et al*, 1997; Brackett *et al*, 1997). However, results published by Pettey *et al* (1997), using Class V restorations, showed Dyract to leak significantly more than glass ionomer cement and resin-modified glass ionomer cement. From a review of the literature, it is apparent that no studies have been published using Dyract or other polyacid-modified resin composite in tunnel restorations.

In the adaptation component of the study, scanning electron microscope analysis of the restoration replicas showed deficiencies at the proximal cavosurface margins of all tunnel restorations, except two Fuji IX restorations. Although these two restorations showed evidence of excess contour and overhangs, no marginal deficiencies were noted at high magnification. The excess contour at the cavosurface margins has been thought to occur because of the high wettability of enamel by Fuji IX (Ferrari *et al*, 1997). A number of possibilities might explain the high rate of cavosurface margin deficiencies. Inability of the material to reach all proximal margins could have been influenced by the

shape of the nozzle tips and by the viscosity of the material. Because the material is placed from within the cavity towards the proximal, there is possibly a lack of wetting of the cavity walls, and condensation of the material from the occlusal is not enhancing adaptation. This is evident from the similar results of the control and experimental Ketac Silver restorations. Fuji IX was the only material to produce any restorations with perfect adaptation, and it is possible that this was influenced by the favourable nozzle shape allowing deeper placement within the cavity.

It was also noted during SEM analysis of the replicas that overhangs buccally, lingually and occasionally gingivally were common. This was not apparent until teeth were demounted for replica impressions. The overhangs were undoubtedly the result of an inability of the matrix band to adapt to anatomical variations of the teeth, despite wedges being placed. After material placement, adequate time was allowed for initial setting before matrix removal to minimise "lifting" of material at the cavosurface margins. The use of interproximal carvers ensured visible excess was removed. However, despite removal of gross excess, access to smooth the margins was difficult, because of limited proximal extension of the preparation.

During impression taking of the proximal surfaces of the experimental teeth, care was taken to inject the material over all margins of the restoration surface with the cervical matrix lightly placed over the material to act as support. Care was also taken to minimise distortion resulting from "lifting" the impression material from the matrix. It is unclear whether any distortion occurred during the set up of the plasticine and straw models in the process of replica production. It can be assumed, however, that resin viscosity was ideal because of the clearly identifiable margins of the restoration replicas seen during SEM analysis.

Analysis of the results of adaptation showed no differences between Fuji II, Fuji II LC and Fuji IX. They did however, exhibit superior adaptation when compared to the control, Ketac Silver and Dyract restorations. As expected, the less viscous materials exhibited the best adaptation. Deterioration of the restoration margins between the pre-cycled and post-cycled specimens was more noticeable for the Ketac Silver and control restorations, suggesting that Ketac Silver was more susceptible to the load and thermal

testing, producing further gaps along the proximal cavosurface margins. This was probably due to poorer initial bond strength and adaptation. During placement, it was also observed that Ketac Silver was the most viscous material and required significant effort to inject into the tunnel preparation. There was, however, no difference in adaptation between Ketac Silver and control, despite condensation of the material in the control cavities. In a study by Wilkie *et al* (1993), defects and voids were also present in those tunnel restorations restored with Ketac Silver. Mount (1999) has also noted the presence of ditching and roughened proximal surfaces of tunnel restorations after removal of adjacent teeth, yet no caries was present.

An inability to effectively apply conditioner to tunnel preparations for glass ionomer and primer for Dyract may have caused deficiencies in bonding at the cavosurface margins which were seen in the post-cycled results. The superior adaptation displayed by glass ionomer cement in this study could be due to its lower shrinkage compared to resin-modified glass ionomer cements (Attin *et al* 1995). It is also possible that the bonding mechanisms and chemical adhesion of glass ionomer cement to enamel and dentine, obtained by the formation of an interdiffusion zone, is more effective in tunnel restorations than that of Dyract. Further studies could examine the effectiveness of etching enamel at the cavosurface margins on the adaptation of polyacid-modified resin composites to tooth structure in tunnel restorations.

The results comparing microleakage and adaptation revealed a significant correlation between all materials except Fuji II and Fuji IX. These materials showed poorer adaptation than the microleakage results would suggest. Four Fuji IX restorations presented with no leakage; however, only two restorations displayed ideal adaptation. No other materials showed perfect adaptation, yet every material, except Dyract, exhibited examples of restorations with a perfect seal. These results indicate that restorations with deficient margins do not always leak. This could be explained by the depth of the marginal defects, which if shallow and confined to the enamel could still provide an adequate seal. Clinically, imperfect margins would result in plaque accumulation with the potential for recurrent caries formation. It has been shown, however, that the fluoride release of glass ionomer materials can inhibit this process in the clinical environment (Makinson, 1978; Mount, 1986; Levy *et al*, 1988; Garcia-

Godoy, 1988; Tyas, 1991; Eickholz *et al* 1997), compensating for any slight deficiencies in adaptation. Svanberg (1992) suggested that Ketac Silver was able to prevent recurrent caries with similar fluoride release to glass ionomer cement, while Mogkolnam and Tyas (1994) found that the fluoride release from resin-modified glass ionomer cements was greater than that of conventional glass ionomer cement, particularly the new generation auto-cure glass ionomer cements such as Fuji IX (Rothwell *et al*, 1998). In contrast, Hirota (1999) has stated that the fluoride release of the new glass ionomer cements is as good as other conventional glass ionomer cements and comparable to resin-modified glass ionomer cements.

It has been suggested that the cariostatic nature of glass ionomer cement is not as effective as originally thought (Mjör, 1996). This retrospective study involving a large number of practitioners in Sweden found that almost half of 412 glass ionomer restorations were replaced due to secondary caries. This gave rise to substantial debate (Swift *et al*, 1996; Forsten, 1996; Mount, 1996). It has been suggested that glass ionomer cement will not prevent recurrent caries, but will be more effective if caries activity is under control (Mount, 1999). However, Mjör (1996) gave no indication which type of glass ionomer cement was used, no rationale was given for secondary caries diagnosis and no restoration sites were described. Although this study had the distinction of representing "everyday dentistry", it did recognise the possibility of the false positive and it was noted that one of the subgroups that had a 16 per cent incidence of recurrent caries also reported a lower incidence of restoration replacement. It was noted that a higher incidence of recurrent caries was found around composite resin and amalgam restorations in Mjör's (1996) study, although these had been in place for a longer period. Svanberg (1992) had also found a higher incidence of recurrent caries in Class II amalgam restorations compared to tunnel preparations restored with Ketac Silver, in caries-active patients. Importantly, it was suggested that the literature was unclear what concentration of fluoride release from glass ionomer cement was required to prevent caries recurrence.

Later retrospective studies by Wilson *et al* (1997) and Burke *et al* (1999) in the United Kingdom found similar results to the study by Mjör (1996). Burke *et al* (1999) also commented that in these studies no data were collected on the diagnostic techniques,

caries activity of the patient, the oral hygiene, patient age, diet or the material used. While the data collected showed the rate of recurrent caries to be greater than that of Mjör (1996 and 1997), the median age of a glass ionomer cement restoration replaced by a general practitioner was three years. The results, however, raised doubts over the cariostatic nature of glass ionomer cement as suggested by Randall and Wilson (1997). Fontana (1995) suggested the diagnosis of secondary caries is difficult and, considering that the study by Burke *et al* (1999) involved a high proportion of newly qualified practitioners in a retrospective study, the validity of the data is questionable.

The results of the studies by Mjor (1996), Wilson *et al* (1997) and Burke *et al* (1999), however, are similar to a clinical study using tunnel restorations by Strand (1996). Of 161 partial tunnel restorations performed by four inexperienced dentists and restored with Ketac Silver, 16 per cent failed due to recurrent caries and a further 34 per cent exhibited increased radiolucency on the radiographs where the demineralised proximal enamel was retained. The limited technical expertise of the operators within this study may have influenced the results. However, some authors have found the fluoride release of Ketac Silver and its remineralising potential to be less than that of conventional glass ionomer cement (Swift, 1989; Hasselrot, 1993). Another recent study on partial tunnel restorations by Holst and Brännström (1998) conflicted with findings of Strand (1996). From 302 tunnel preparations restored with Ketac Silver and placed by 17 dentists in public dental clinics, only 8 per cent failed due to recurrent caries. The restorations in this study may have been performed by more experienced clinicians. A more recent study by Pilebro and co-workers (1999) supported the findings of Holst and Brännström (1998). In the study by Pilebro and co-workers (1999), 374 tunnel restorations were placed by 12 dentists and, after 3 years, 20 per cent of the restorations had failed, of which only 11 per cent were due to recurrent caries.

The variation between these studies is possibly due to the caries activity of the patients and the technical skill of the operator. No correlation exists between the recurrent caries activity and the restorative material used. Hasselrot (1993) found that proximal margins of tunnel restorations revealed less than ideal adaptation of the Ketac Silver, yet minimal recurrent caries was present. Hasselrot (1998) also found a higher incidence of recurrent caries when the proximal enamel was not removed.

It was hoped that by introducing a clinically simulated model a difference in leakage and adaptation would be seen between the control and the Ketac Silver restorations. However, comparison of the results of microleakage and adaptation of Ketac Silver and control teeth revealed no difference. This suggests that the technical difficulties, of preparation and material placement of the tunnel restoration in a clinical situation, did not play a significant role in the hands of this investigator. Despite condensation of the Ketac Silver in the control teeth, it is thought that the success of the restoration was more reliant on the properties of the restorative material. It has been shown, within the parameters of this study, that Ketac Silver was not the material of choice, but rather the new generation auto-cure glass ionomer cements, particularly Fuji IX are preferred. Fuji IX exhibited less leakage and improved adaptation when compared to the other materials tested. Polyacid-modified resin composites such as Dyract cannot, at this stage, be recommended for use in tunnel restorations, due to their poor sealing and adaptation. Work by Ehrnford and Frannson (1994) found that Dyract displayed similar bonding characteristics to composite resin, and these authors suggested using glass ionomer cement liner on all exposed dentine before etching. This was supported in a study by Meyer *et al* (1998) who concluded that polyacid-modified resin composites behave more like composite resins than glass ionomer cements. It would often bevery difficult, however, to apply a liner to dentine within a tunnel preparation due to the limited access.

The degree of microleakage and the adaptation results of this *in vitro* investigation suggest that a significant failure rate would be expected in a clinical environment. It is possible that a correlation does not always exist between microleakage and adaptation, which emphasises the importance of choosing a material which exhibits ease of delivery and handling and good bonding characteristics, in addition to cariostatic properties through fluoride release. Once developed, future studies could include nanoparticle-containing composites, and other experimental materials such as cyclic silicon compounds, ortho-spirocarbonates and epoxides (Hickel *et al*, 1988) to establish their sealing ability and cariostatic nature.

Following the results of this study, further investigations should compare the efficiency of different cavity designs on the ease of material placement and the subsequent sealing and adaptation effectiveness. Manufacturers could consider modifying their capsule tip shapes to aid in effective material delivery. Materials that bond chemically to the tooth surface have a more effective seal and are better suited to situations where limited access to the cavosurface margins exists. Therefore, different materials and placement techniques should be investigated to produce the best possible seal and adaptation at these margins.

Chapter 9

CONCLUSION

This *in vitro* investigation compared the effectiveness of different restorative materials in their ability to prevent microleakage and adapt to proximal cavosurface margins in tunnel restorations. This was studied by developing artificial carious lesions and restoring the tunnel preparations in a simulated clinical model, which included accelerated ageing of the restored teeth with load and thermal cycling.

It was found that no restorative material prevented microleakage in all restorations at the proximal cavosurface margins. From the results, however, the ability of glass ionomer cement materials to seal the proximal enamel was found to be more effective than the compomer material Dyract. Fuji IX provided the most effective seal, while comparable results were obtained for those teeth restored with Fuji II, Fuji II LC, Ketac Silver and the control restorations. The similar results of Ketac Silver and control suggest that the preparation techniques of a tunnel restoration did not influence the performance of the material. Rather, it is thought that the viscosity of Fuji IX, its bonding mechanism or the ease of placement of the material due to the capsule design, resulted in the superior performance.

Scanning electron microscope studies found that Dyract displayed the worst adaptation of all restorative materials tested. It was thought that the poor performance of Dyract was due to the lack of bonding at the proximal enamel margins. No significant differences were observed between the adaptation of the other materials before load and thermal cycling. After accelerated ageing, however, a greater deterioration had occurred in the control and Ketac Silver restorations. This suggested that Ketac Silver fatigued during the accelerated ageing, producing further gaps around the perimeter of proximal cavosurface margins.

A comparison of the microleakage and adaptation found no correlation between Fuji II and Fuji IX results, while a correlation existed for the other restorative materials. It was noted that not all restorations with marginal deficiencies displayed microleakage, and the possibility exists that clinical effectiveness may be more greatly influenced by the performance of the restorative material rather than by the preparation techniques. It may be possible, however, to influence the performance of the restorative material by providing better access for easier placement of the material, by altering cavity design or through further development of nozzle design of capsules. Further studies could also evaluate newer materials, particularly the new generation auto-cure glass ionomer cements, and their ability to adapt and seal at the cavosurface margins of tunnel preparations. Studies should also investigate the level of fluoride release from these materials and determine their effectiveness as a cariostatic and antibacterial material.

Chapter 10

SUMMARY

Within the parameters of this investigation, no restorative material was able to prevent microleakage in all tunnel restorations, as evidenced by penetration of fuchsin dye and the presence of cavosurface marginal defects. It was confirmed, however, that glass ionomer cement restorations, particularly Fuji IX, provided a better seal than the compomer material Dyract under the simulated clinical model. Fuji IX was the only restorative material to provide perfect adaptation around the proximal cavosurface margins. A correlation did not always exist between the degree of microleakage and the adaptation of the restorative material.

The level of microleakage and marginal defects found may be attributable to a number of factors, principally the ability to remove caries and adapt the restorative material to the cavosurface margins, the effectiveness of the bonding mechanisms and surface pretreatment of tooth structure, and the influence of age cycling techniques representative of the forces within the oral environment. As the clinical viability of any restorative technique is reliant upon an effective seal of the restorative material, the findings of this investigation suggest that further development of adhesive materials is required to overcome the lack of control over material placement in the tunnel restoration.

Chapter 11

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