An assessment of restoration microleakage *in vitro* following three-body wear

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Abstract

This study assessed the microleakage of different intracoronal restorations (100 teeth). The teeth were restored using either a porcelain inlay or an amalgam restoration. The porcelain inlays were placed with one of two composite resins (Scotchbond Multi-Purpose Plus, 3M, resin A: Nexus Universal Luting System, Kerr, resin B). The amalgam restorations were placed either with one of the two composite resins or, without any resin. All restorations were subject to one of two wear cycles. These were a tooth-restoration-tooth wear cycle or a restoration-tooth wear cycle. Measurements of microleakage were made every 5,000 cycles of wear for 25,000 cycles using a microleakage model developed by Pashley (Derkson et al., 1986).

The results were analysed using two-sample t-tests, one-way analysis of variance (ANOVA) to determine the presence of any differences between groups and Tukey tests to determine the nature of such differences where appropriate.

1. The results indicated that microleakage increased with increasing exposure to wear cycles.
2. Amalgam restorations with no resin leaked more than amalgam restorations placed with resin.
3. Surprisingly porcelain resin restorations exhibited greater levels of microleakage than amalgam restorations, with or without resin.
4. There were no statistically significant differences between the resin bonding systems used in the study.

In conclusion this model has demonstrated increased microleakage with increased wear for a number of different restoration types. However, improved specimen grouping prior to exposure to different wear cycles would have made differences between restorations more meaningful. Further work should address this problem.

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Declaration

This thesis is the original work of the author

George McR. Smith

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Chapter 1.

Introduction

This study was a laboratory-based investigation of microleakage of direct amalgam and indirect porcelain class I inlays following three body wear.

Assessment of marginal leakage at the restoration - tooth interface has been researched for over a century. The results of many studies indicate that the margins of restorations are not fixed, inert and impenetrable borders. Margins of restorations have been described as 'dynamic microcrevices which contain a busy traffic of ions and molecules' (Myers, 1966).

Clinicians have sought to combat the effects of microleakage with the aim of developing an ideal restorative material. This material would provide a perfect seal between the tooth structure and the restorative material thus reducing the opportunity for microleakage to develop. The ultimate aim of dental researchers is a leak-free restoration. The aim is slowly becoming a reality with improved clinical techniques that are the result of extensive research using studies conducted both *in vivo* and *in vitro*. *In vitro* studies have used many techniques for example, dye penetration, radioactive isotopes and air pressure to assess the sealing properties of restorations. In the majority of cases they only provided data on microleakage at the conclusion of the experiment.

Factors that influence the successful reduction of microleakage of direct and indirect restorations are cavity size, the bonding system used and placement techniques. After

placement of the restoration, microleakage may still occur during function because of chemical, thermal and mechanical stress.

This project assessed the microleakage of different intracoronal restorations *in vitro* subject to occlusal stress when a simulated biting force impacts and slides across the tooth/ restoration interface producing wear. The project also measured variations in microleakage of different restorations with time.

1.0. Literature Review

1.1. Definition

Microleakage has been described as the 'clinically undetectable passage of bacteria, fluids, molecules or ions between a cavity wall and the restorative material applied to it' (Kidd, 1976[a]).

1.2. Sequelae of microleakage

Microleakage may lead to recurrent caries at the tooth/restoration interface, hypersensitivity of restored teeth, staining at the margins of restorations, a hastening of the breakdown of marginal areas of the restorations and the development of pulpal injury (Going, 1972). The ingress of bacteria at the tooth/restoration interface is believed to be responsible for pulpal irritation (Brannstrom, 1986). Chemical toxic factors such as acid and components of the restorative material *per se* were shown to be less significant in causing pulpal injury than bacteria around the restoration margins (Cox et al., 1987). Marginal leakage has been implicated as an aetiological factor in the inflammation of the dental pulp following insertion of restorations (Cox et al., 1988). Gaps around the restoration provide pathways for the ingress of oral micro-organisms and / or their metabolic products. A large number of studies have shown that bacteria can successfully colonise the walls of cavities (Brannstrom,1982). Clinically this can result in secondary caries which may lead to pulpal damage.

A bacterium may be approximately 2μm long/wide thus it should be able to enter a very small space, but for the formation of plaque a larger marginal defect "20μm" may be required. Jorgesen and Wakumoto, (1968) found no evidence of secondary caries where the gap size between the tooth and amalgam filling was less than "50μm", however these investigators did not attempt to determine the extent of the bacterial penetration into the underlying crevice.

1.3. Factors affecting microleakage

It is considered that microleakage at the tooth/restoration interface is a major factor affecting the long term success of dental restorations. Microleakage is a dynamic process that can increase or decrease with time. Following long term exposure to pellicle, saliva and bacterial plaque, changes may occur that will serve to obturate the space between the tooth and restoration.

1.3.1. Tooth/restoration adhesion

A major cause of microleakage is the poor union of restorative materials to tooth structure, which may in part be because of operator error, or the ability of the material to adhere to the tooth structure. It has been shown that leakage of fluid will occur between the restoration and the prepared cavity (Barber et al., 1964). Without microchannels or microgaps between the cavity wall and the restoration there would be no microleakage of oral fluid in either direction.

1.3.2. Intrinsic post-placement changes in restorative materials

Another major cause is the shrinkage of the material, following placement, due to chemical or physical changes. The initial contraction of amalgams and polymerisation contraction of resins are forms of chemical shrinkage whereas thermal changes may introduce gaps as a consequence of the physical alterations in the material (Van Noort, 1994).

1.3.3. Extrinsic post-placement changes in restorative materials

The space between the tooth structure and restorative material could be increased because of masticatory forces, which creates elastic deformation of the tooth structure (Granath and Moller, 1975). Granath and Moller found that in mesial-occlusal-distal (MOD), distal-occlusal (DO) and mesial-occlusal (MO) cavity preparations that the cavity wall could be bent outwards because of the mechanical loading of the restored tooth. Qvist, (1983) reported that he found the development of marginal leakage to be significantly greater in teeth that were in functional occlusion than those without antagonists.

1.4. Studies of microleakage *in vivo*

Microleakage *in vivo* poses the problem for clinicians as it may be clinically undetectable in its early stages. Leakage of fluid may occur between the restoration and the prepared cavity structure. The detrimental effects of marginal leakage of restorations include hypersensitivity, staining and discoloration, secondary caries and eventually pulpal irritation (Mjor, 1978).

Ideally for a clinically relevant assessment of microleakage it would be best to conduct the examination *in vivo*. However carrying out these experiments in a strictly-controlled study requires large numbers of specimens, is expensive and time consuming (Alani and Toh, 1997). As a consequence of these limitations there have only been a small number of studies of microleakage carried out, with most of the studies producing conflicting results when compared to tests *in vitro* (Kidd, 1976).

Going et al., (1968) using neutron activation analysis found more leakage *in vivo* than *in vitro*. Loiselle et al., (1969), and Stuever et al., (1971) used a fluorescein dye method and found microleakage *in vivo* to be less than that *in vitro*. There has also been some studies that have combined *in vivo* and *in vitro* methods of studying microleakage (Going et al., 1968; Lenarda et al., 2000). The combined study carried out by Lenarda et al. (2000) aged restorations for 30 days *in vivo* prior to extraction and measured the microleakage *in vitro* (using scanning electron microscopy and a dye penetration technique).

The main problem with clinical studies is that several years must elapse before data can be analysed and reported. The time delay in reporting is significant as the constant development of new dental materials often results in the test material being obsolete before any results are available. As a result of the problems with methods *in vivo*, the assessment and investigation of microleakage has been mainly carried out *in vitro*.

1.5. Studies of microleakage *in vitro*

1.5.1. *In vitro* Models

In producing models for studies *in vitro*, researchers have encountered various difficulties in relation to the simulation of conditions found in the oral cavity for example, the hydrodynamic pressure differential between pulp and oral cavity. In addition in the oral cavity, both tooth and restoration are subjected to temperature variations and, also are in contact with food, saliva, micro-organisms and mechanical loading. Thus the problems researchers face have been to produce *in vitro* a test model that encompasses all these factors. Trowbridge, (1987) indicated that the greatest problem facing researchers is the susceptibility of the interface between tooth structure and restoration to dimensional change as a consequence of experiment manipulation of specimens.

Many different techniques have been used to determine/measure the effective sealing ability of direct and indirect restorations using models which attempt to reproduce the oral situation. These techniques include the use of dyes, air pressure, radioactive isotopes, bacteria, artificial caries and other methods. In most experiments some form of thermal stressing has often been included in the regime.

1.5.2. Dye penetration

The use of coloured agents as tracers to demonstrate microleakage continues to be the most popular method used. It is one of the oldest methods for detecting microleakage.

Early studies were carried out by King, (1874) using blue ink and Tomes, (1875) who used drapers ink.

In general terms the technique involves coating the unfilled areas of the tooth with a waterproof varnish prior to immersing the extracted, restored tooth in a dye solution for a specific period. At the conclusion of the time period the tooth is washed and sectioned for examination (usually under magnification) to assess the amount of penetration of the dye at the tooth/restoration interface. The ingress of the dye at the tooth/restoration interface provides a positive record of leakage in a contrasting colour to both tooth and restoration.

Many different dyes have been used in dye penetration studies to assess microleakage. No one dye appears to more suitable than any other although variations have been shown between dental researchers in the levels of concentration and penetration times used when similar dyes have been used (Alani and Toh, 1997). At present there does not appear to be an ideal regime consisting of dye, penetration time or concentration, which would permit a standard comparison of leakage tests.

The problems with dye penetration techniques include:

(a) Leakage is dependent on the size of the dye molecule or particle, it must be small enough to penetrate dentinal tubules (1 - 4μm).

(b) The dye molecule must not bind to tooth or restoration.

(c) Dentine permeability and the dimensions of dentinal tubules can effect the degree of dentine staining.

(d) Assessment is usually carried out using a numerical scoring system of increasing degrees of leakage. This system can be subjective even if more than one assessor is used.

(e) Dye penetration studies demand the destruction of the specimen and thus make it impossible to use fully quantitative techniques for evaluation.

(f) Often only single sections are taken through a tooth, thus the technique will only pick up one area where leakage has occurred or alternatively an area where leakage does not exist.

(Taylor and Lynch, 1992; Alani and Toh, 1997)

1.5.3. Chemical Tracers

Non-radioactive chemical tracers are distinct from dyes in that these tracers rely upon the reaction of a second chemical to cause a visible effect. The normal method requires the use of two colourless chemical compounds to produce an opaque precipitate. The standard has been a silver salt detected using photographic techniques. The most commonly used solution is a 50% aqueous silver nitrate solution for immersion of the specimen, which later is reacted with a photographic developing solution such as benzene 1, 4-diol (hydroquinone) which precipitates silver as the marker. Many variations of the silver nitrate method have been employed by a number of researchers to measure microleakage.

An early use of a chemical tracer was described by Kornfield, (1953). The method described used an acrylic resin with lead glass incorporated in it to assess the leakage of an acrylic restoration. When the restoration was immersed in a solution of barium

sulphate marginal leakage could be demonstrated by the black precipitate of the lead sulphate.

The main problems using chemical tracer techniques relate to the interpretation of the results as single sections of the tooth provide, at best, a two dimensional representation of the three dimensional restoration. Position and angle of the section can affect both the length of the restoration margin exposed and hence the proportion of leakage significantly. A single section may only show one site where the marginal seal has failed, or conversely the only area where it has not. These are the same problems that are encountered with dye penetration studies.

Swift & Hansen, (1989) used similar techniques. They attempted to overcome the problem of single sections, using three, 150μm thick sections and calculated the mean leakage. However, difficulties in their measuring protocol yielded results that could not give an accurate representation of the leakage.

Chemical tracer studies share many similar problems to those encountered in Dye-leakage studies, especially problems of interpretation.

1.5.4. Radioactive Isotopes

The development of radioactive isotopes for medical investigations has resulted in their increased use in dental research. The use of isotopes permits the detection of minute amounts of leakage. The smallest isotope tracer measures only 4.32 angstrom units compared to the molecular proportion of the dye particle (120 angstrom units) (Going,

1964). Many different radioisotopes have been used for assessment of marginal leakage. They include ^{45}Ca, ^{131}I, ^{35}S, ^{22}Na, ^{32}P, ^{86}Rb and ^{14}C. There has been no particular rational for the use of any specific isotope. Long-term monitoring of microleakage can be obtained using radioactive sucrose containing ^{14}C.

Radioactive ^{14}C in sugar molecules was used in a study by Powis et al., (1988) as sugar is metabolised by dental plaque to form acids which may result in dental caries. However penetration of sugar molecules *per se* does not cause caries. In addition, microleakage of this particular molecule is no more valid than any other radioactive molecule of a similar size.

The method used for many radioactive isotopes to detect microleakage *in vitro* involves coating all surfaces of extracted teeth with a varnish (except the surfaces immediately adjacent to the experimental restoration) before immersing the sealed teeth in the isotope for several hours. Varnishing prevents leakage through cracks in the enamel, exposed dentine or the root canal, which could influence any measurements of microleakage. Following removal from the isotope the teeth are rinsed for a prolonged period before longitudinal sections are made through each tooth and restoration. The cut surfaces are then applied to a photographic film. The resulting autoradiographs indicate the location of any isotope that has penetrated between the restoration and the cavity wall. Going et al., (1960) suggested that the small size of radioisotopes provided a more accurate measurement of leakage than other methods. However it was later reported that the accuracy was so great and that leak free restorations were virtually

impossible to achieve when microleakage was measured with this method (Going, 1979).

There are several factors to be considered in relation to radioisotopes to measure microleakage:

(a) The procedure is relatively complex and expensive because of safety requirements at all stages of the procedure.

(b) Most investigators assessed the leakage on a scoring system that increased with severity but, as in other leakage systems, the results are again evaluated by subjective scoring and not measured quantitatively. However scoring can be carried out using computer technology to assess the depth of penetration.

(c) The choice of isotope. A high energy isotope produces more scatter on films artificially increasing the apparent leakage, conversely isotopes with low energies result in less scatter.

(d) Length of exposure. The longer a film is exposed, the greater the chance, that the area of reacted emulsion will increase which may affect the resolution of the autoradiograph because of the random behaviour of beta particle emission.

(e) Source and emulsion distance. Increasing the distance magnifies the image but reduces the resolution.

(f) The fact that ions may react with the filling material or tooth structure may and result in incorrect leakage scores.

(Taylor and Lynch, 1992; Alani and Toh, 1997)

Autoradiography therefore is still a qualitative technique-sensitive means of determining microleakage.

A closely-allied technique is called Reverse Radioactive Absorption, which allows some quantification of the leakage (Herrin and Shen, 1985). A radioactive tracer is placed as a lining beneath the restoration and the tooth immersed in a non-radioactive solution. Subsequent monitoring of the surrounding solution in relation to level of radioactivity and time gives a measure of the amount of leakage. Herrin and Shen, (1985) found that leakage of a radioactive tracer placed in this manner could be shown to increase with time, but it was not clear where the leakage had occurred i.e. the material itself could be responsible; or diffusion through the tooth structure; or a gap at the restoration margin.

1.5.5. Air Pressure

Air pressure was introduced by Harper, (1912) as a method of detecting microleakage in class II amalgam restorations. He placed an amalgam restoration in a pre-cut steel die, stored it under water and delivered compressed air to the floor of the cavity. The resultant air bubbles indicated where leakage had occurred. This method proved to be a valuable technique for comparing the sealing ability of different amalgams and cements (Moller et al., 1983). Several investigators have also used air pressure to evaluate restorative materials (Fiasconaro & Sherman, 1952; Pickard & Gayford, 1965; Granath & Svensson, 1970). They delivered compressed air through the root canals of the teeth in a closed system and measured the loss of pressure as the degree of leakage. Microscopic examination of the escaping air bubbles from the margin of the submerged

restoration provided a subjective view of the marginal seal. The method had the advantages that it was non-destructive and could measure leakage over a set period. No attempt was made to relate the tests clinically or to simulate conditions *in vivo*. Furthermore no account was taken of the drying effect of compressed air on the tooth and restoration. Glass ionomer cements for instance are prone to crack on drying (Mount, 1994) and would result in aberrant results as the air could escape through the filling rather than around its margin.

Air pressure tests otherwise treat the restoration as leaking equally along the entire margin when this is unlikely to be the case. It is also possible some leakage may occur through clinically sound tooth tissue (Taylor and Lynch, 1992). Air pressure systems have the distinct advantage of permitting longitudinal and repeated observations of microleakage

1.5.6. Liquid Pressure

Derkson et al., (1986) developed a liquid pressure method as an alternative to the normal air pressure measuring techniques. They indicated that dentine permeability is directly related to flow rates across dentine via dentinal tubules. The method provided a technique for quantitative assessment of microleakage between dentine cavity walls and the restorative material. They measured the movement of an air bubble through a micropipette using a coloured dye pressurised by Nitrogen gas (N_2). Similar to other air pressure systems, it delivered the pressurised liquid into the pulp chamber of a restored tooth in a closed system (the pulp chambers and tubes were filled with the solution at all times). The dye indicator permitted a photographic record to be made of the

longitudinal development of leakage. The leakage was quantified by the movement of the air bubble (mm/min) in the micropipette and expressed in μl/min.

The liquid pressure system allowed quantitative, sequential measurement of dentine permeability and microleakage.

1.5.7. Electrical Current

The use of electrochemistry in the detection of marginal leakage in coronal restorations was first reported by Jacobsen and von Fraunhofer, (1975). The technique has been used in endodontic research as a quantitative method of assessing microleakage by utilising the flow of electricity (Delivanis and Chapman, 1982). The reported technique required the insertion of an electrode into the root canal of an extracted restored tooth so that it made contact with the base of the restoration. Prior to immersion in the electrolyte bath, the tooth was sealed to prevent electrical leakage through the surrounding tooth structure. Following production of a voltage between tooth and bath, the current flowing was a measure of the leakage present. Using this technique, comparisons were made with dye penetration and autoradiography systems (Delivanis and Chapman, 1982). They concluded that neither technique correlated well with the mid-range values of the current flow while at the two extremes of current flow there was a close relationship.

Although this method can be used to assess leakage over time *in vitro* it does not show where leakage occurs and similar to air pressure studies there is an assumption that

leakage occurs evenly around the restoration margin. As in other methods of assessing leakage *in vitro*, it is destructive of tooth substance and cannot be used in *in vivo*.

1.5.8. Bacteria

Fraser, (1929) carried out the earliest reported leakage study using bacteria. The technique involved the packing of amalgam into glass tubing. Fraser's study was purely qualitative. It observed bacterial penetration through or around fillings by assessing clouding of the culture medium placed below the restoration. Further studies by Kraus and Kraus, (1951), Seltzer, (1955) and also, Rose et al, (1955) involved the placing of restored teeth in bacterial broth mixtures. The filling materials were subsequently removed and dentine shavings from below the restoration cultured.

Marginal gaps required for bacterial penetration are expected to be in the region of 0.5 -1.0μm, therefore smaller gaps, which would permit bacterial toxins or acids to penetrate the restoration margin, go unrecorded (Taylor and Lynch, 1992). Bacterial penetration studies to assess leakage are still used today and could be viewed as more clinically-related because of their association with recurrent decay (Fayyad and Ball, 1987). Fayyad and Ball, (1987) in their new approach to bacterial penetration using a bacteriologic technique found a statistical difference between three silver amalgams which they assessed.

Most bacterial studies appear to be difficult, time consuming and are considered to be unreliable due to the many variables in the studies (Bauer and Henson, 1984). Like

other microleakage studies they only provide purely qualitative results, depending mainly upon the presence or absence of bacteria in the specimens of dentine examined.

1.5.9. Artificial Caries

Ellis and Brown, (1967) used a bacterial technique to produce artificial secondary caries at the tooth interface of an amalgam restoration, linking the development of carious lesions to microleakage. A later report by Hals and Nernaes, (1971) associated microleakage with spread of secondary (recurrent) caries. Using *in vitro* systems artificial secondary caries like lesions have been produced using either bacterial cultures or a chemical system in an acidified gel (Grieve, 1973). It has been suggested that this method is clinically relevant as it links microleakage with one of its consequences i.e. cavity wall demineralisation. Demineralisation of the cavity wall is evidence of microleakage. Using polarising light microscopy the extent of demineralisation of cavity walls adjacent to composite resin restorations following the application of an acidified gelatin to the tooth surface to simulate caries was recorded (Jensen and Chan, 1985). The use of this technique is clinically relevant in the evaluation of microleakage as it possible to link it to the development and spread of secondary caries.

Quantification of the results is also possible using microdensitrometry (Kidd, 1976[b]), usually depth of lesion penetration is the measured parameter.

In a study of marginal leakage associated with composite restorations it was noted that acid etching alone was enough to create mild demineralisation along the cavity wall

(Grieve and Glyn Jones, 1980). However, this is distinct from an artificial caries system, which should induce sub-surface mineral loss.

The acidified gel technique has been reported as being a suitable method for the creation of artificial caries and appears similar to natural lesions when viewed under polarised light and microradiography (Silverstone et al., 1981; Kidd, 1983). However it remains to be established how closely artificial caries systems resemble caries activity *in vivo*. Problems exist with both systems as they are devoid of bacteria, bacterial by-products and other aqueous contaminants, which are relevant to the microleakage process.

1.5.10. Scanning Electron Microscopy (SEM)

The adaptation of restorative materials to cavity margins can be viewed directly using Scanning Electron Microscopy (SEM) because of its high magnification (Boyde and Knight, 1969). However, the technique is limited in that it can only be used outside the oral environment and often requires surfaces to be coated with gold prior to examination. Some researchers have used microscopic analysis of cavity margins to assist in the correlation of results from other leakage detection methods. Replicas of marginal defects recorded at various time intervals viewed using SEM were reported to provide a longitudinal assessment of marginal defects (Barnes,1977). Measurement of gap formation occurring between restoration, walls and floor of the preparation was reported by Davila et al., (1986).

It can be concluded that the availability of the SEM in dental research is a useful adjunct to other methods used to investigate microleakage. The relationship between SEM observations and those made using other methods has yet to be established.

1.5.11. Neutron Activation Analysis

Neutron activation analysis has been used to study microleakage both *in vivo* and *in vitro* (Going et al., 1968). The technique uses a chemical marker (manganese) which leaks around the margin of a restoration *in vivo* prior to the extraction of the tooth. The extracted tooth is placed in the core of a nuclear reactor and bombarded with neutrons, which energise the tracer (Mn^{56}). The radiation subsequently emitted from the tooth can then quantify the volume of tracer present. Douglas et al., (1980) used this method to demonstrate the ability of a hydrophobic composite material to reduce marginal leakage when compared to a conventional composite. These studies were unable to identify the points where the restoration leaked nor do they take account of the manganese absorption at sites other than the restoration margin. Going, (1972) reported neutron activation analysis had the advantage that results could be quantified.

The use of the technique has to be weighed against its limitations. These are the complexity of the method, high costs and the hazards associated with radiation.

1.5.12. Summary

Although some of the techniques used to measure microleakage simulate some of the conditions found in the oral cavity, the development of an "ideal" test model has yet to

be completed. In general, models used *in vitro* fail to simulate all conditions found in the oral cavity. Thus, the results obtained have to be interpreted in this context and may not reflect the situation *in vivo*.

1.6. The Role of Thermal Cycling in Studies of Microleakage

1.6.1. Introduction

The oral cavity is subjected to many changes in temperature each day. Teeth undergo thermal stress each time the temperature changes. For example eating or drinking of hot and cold foods. Thermal stress results when any part of the structure is restricted from expanding or contracting during changes in temperature. During the eating or ingestion of cold food or liquid results in enamel contraction whereas dentine tends to retain its original dimensions as it has a lower thermal diffusivity than enamel. Enamel has a low tensile strength and may crack as the result of tensile stress induced (Brown et al., 1972). Conversely, as the temperature of the tooth rises the reverse action develops. The daily temperature changes during eating and drinking would indicate that that any laboratory study should, where possible, simulate oral conditions by stressing the test specimen through a range of temperatures.

Laboratory simulations of the clinical environment are regularly used because of the time and cost of clinical trials. Thermal cycling is often used to evaluate marginal leakage of restorations *in vitro*. It is used to simulate the extremes of temperatures found in the oral cavity by mechanically transferring specimens in and out of hot and

cold solutions to apply stress to the tooth /restoration interface. An early study by Nelsen et al., (1952) showed the different coefficients of thermal expansion between tooth and restoration caused "percolation" resulting in the development of microleakage of the materials used. For this reason most researchers include thermal cycling as a standard protocol in microleakage experiments. However, the clinical significance of thermal cycling is questionable when specimens are subjected to temperature regimes that differ from those found in the oral cavity. Studies have shown the use of thermal cycling increases the degree of leakage observed (Crim and Mattingly, 1981).

There has been some research that has questioned the use of thermal cycling as a method of stressing the tooth/restoration interface (Crim and Garcia-Godoy, 1987). The use of experiments *in vitro* to correctly compare the materials within the scope of the experiment may at times create conditions that are more severe than those occurring in the oral cavity. These severe conditions are used despite the fact that the conclusions from such studies may guide clinicians towards untested clinical procedures.

1.6.2. Temperature Ranges

There is varied range of reported temperatures used by researchers, (Gale and Darvell, review 1999). Researchers have generally chosen ranges of 5^0C - 55^0 C to mimic conditions in the oral cavity, however in many reports the regimes chosen are used without reference to observations made *in vivo*.

The surface temperature of teeth is dependant on the temperature of fluid that

humans can ingest comfortably, the size of the oral cavity and the particular surface used to record data. Longman and Pearson, (1987) suggested that a realistic thermal cycling regime to simulate the clinical situation should employ a temperature range of between 15^0 and 45^0 C. Other experiments, that have attempted, to measure the temperature changes during eating and drinking. Longman and Pearson, (1984) and Spierings et al., (1987) reported the temperature variations recorded *in vivo* from eating and drinking at different locations in the mouth and in different subjects.

Breathing was shown to alter the resting mouth temperature including air temperature, humidity and air velocity (Palmer et al., 1992). The pilot study by Michailesco et al., (1995) recorded the variations, in temperature of teeth during meals and compared the results with laboratory thermal cycling regimes. They reported thermal variations of 29.5^0C (18.9^0C to 48.4^0C) at the base of a silver amalgam occlusal restoration and lower variations within the root canal. They found that the temperatures recorded at the surface and those at the base of the restoration indicated the ease with which changes in temperature are transmitted through metallic restorations. However the range of temperature reported differed slightly from the results of Nelsen et al., (1952) but were similar to Petersen et al., (1966). Following their study, Michailesco et al., (1995) suggested that an " ideal" thermal cycling regime could be designed to include several phases of different time periods, with various ranges and rates of temperature changes corresponding to temperatures recorded during the ingestion of food. Their suggested regime was a range of 30^0C from 17^0C to 47^0C with an intermediate phase of 37^0C (Michailesco et al., 1995). The literature review by Gale and Darvell, (1999) reported that most studies using thermal cycling regimes involved temperature ranges of 4^0C - 60^0C with a mid-range of 37^0C. In some extreme conditions a range of 0^0C -

100^{0}C was used. The most common regime chosen had a range of 5^{0}C - 55^{0}C. Based on a review of the available literature, Gale and Darvell, (1999) concluded that no definitive statement of a relevant regime could be made that would fully mimic conditions found in the oral cavity.

The range of temperatures used by different researchers varies considerably but they have generally been selected to mirror the upper and lower ranges of temperature found in the oral cavity (4.8^{0}C minimum to 45^{0}C - 60^0 C maximum).

1.6.3. Temperature cycles

A second variable that occurs in thermal cycling regimes is the number of temperature cycles used. A review of the literature reported by Gale and Darvell, (1999) details cycles ranging from 1 to 1,000, 000. Studies by a number of researchers have attempted to relate *in vivo* to *in vitro.* Kim et al., (1992) gave no evidence for his regime of thermal cycling *in vitro* specimens for three short periods each day with each period involving ten cycles however one can speculate that the regime was to simulate three meals per day. Brown et al., (1972) recommended that 10 cycles per day should be used. This was based on a study of human and bovine teeth, however it is not clear whether it applied to cows or humans and, similar to Kim et al., (1992), they did not provide evidence to validate the number of cycles. A study by Chan and Glyn Jones, (1994) assessed the significance of thermal cycling in relation to microleakage of root restorations. They used a regime of 150 cycles for one group and no cycling regime for the other group. Their results showed that there was no statistically significant

difference between the thermal-cycled and non-thermal-cycled group in relation to the severity of microleakage.

From the reports and studies of literature there appears, at present, to be no substantive relationship between the use *in vitro* of thermal cycles and reported clinical conditions.

1.6.4. Dwell Times

The literature shows considerable variations in the use of dwell times in the baths during thermal cycling (Gale and Darvell, 1999) a number of studies list times ranging from less than 4 seconds to some in excess of 120 seconds. Clinical studies to assess normal intra-oral temperature variations suggests that teeth are only in contact with temperature extremes for a very short time (Harper et al., 1980; Longman and Pearson, 1984; Longman and Pearson, 1987; Spierings, 1987). The clinical relevance of the use of shorter dwell times would appear to be justified by this research. In the normal clinical situation patients only appear able to tolerate a small range in temperature as attested by the use of hot and cold sensitivity testing of teeth. It would be unrealistic to expect patients to be able to tolerate extreme temperatures 5^0C - 55^0C. applied to their teeth for long periods.

1.7. Bonding systems

1.7.1. Introduction

Definition

Bonding is the physical or chemical attachment of one substance to another. A bonding agent may be defined as an intermediate substance that, when applied to two or more surfaces enables them to be joined together and resist separation (Kinloch, 1987).

Development

The first reported study on adhesion to teeth was carried out by Kramer (1952). This experiment reported observations of altered staining of dentine surfaces following exposure to glycerophosphoric acid dimethacrylate (GPMD). Later reports by Buonocore et al., (1955, 1956) on an enamel acid-etching technique and a method of bonding to dentine were the catalyst for research, development and the clinical application of adhesive dentistry. These two studies were unique in introducing the dental profession to a new concept. This was the retention of restorations using micromechanical retention rather than conventional grooves or undercuts. A much later review by Pagliarini et al., (1996) suggested enamel and dentine adhesives were developed for two purposes:

(a) to improve the retention of the restoration

(b) to reduce the marginal leakage at the tooth-restoration interface.

Basic concepts of bonding

Bonding to tooth structure is complicated by the different histological structures of enamel and dentine and the different mechanisms by which bonding occurs to each tissue. Current bonding mechanisms require the initial preparation of enamel and dentine to enhance the surface mechanical properties for adhesion. This involves etching. Where possible the prepared surface may be further enhanced using a primer to induce chemical bond formation. This is less applicable for enamel bonding but is an essential step in dentine bonding. Finally, a wetting agent is applied to ensure good physical contact between the prepared enamel and dentine surface and the composite-resin restorative material. This wetting agent is usually an unfilled composite resin.

Bonding mechanisms

Bonding to tooth structure can be achieved in four ways (Setcos, 1988). The first three mechanisms listed are used for enamel bonding whilst all four have been explored for dentine bonding.

1. acid-etch and formation of resin tags;
2. formation of strongly- bonded surface precipitates, to which a resin can be chemically bonded;
3. chemical bonding to the inorganic components of the tooth structure;
4. chemical bonding to the organic components of tooth structure.

1.7.2. Enamel Bonding

The nature of the etched surface

Three distinct types of patterns of etching in enamel have been described (Gwinnett, 1971; Silverstone et al., 1975). The most prevalent etching pattern involves preferential removal of enamel prism cores while prism peripheries remain relatively intact. The second most prevalent etching pattern is the reverse of the first type i.e. the peripheries are removed leaving the cores intact. The third least prevalent etching pattern includes areas resembling the first and second, as well as regions in which the etching pattern appears unrelated to prism morphology. It is generally less distinct than the first two patterns.

Etching agents used for enamel bonding

The majority of studies have used orthophosphoric acid to etch enamel prior to bonding composite resin. However other acids such as nitric, citric and maleic have also been used with varying success. Presently, orthophosphoric and nitric acid are the most commonly used etching agents for enamel (Brown and Barkmeier, 1996).

Concentration of acid used for enamel bonding

Buonocore's initial technique to achieve adhesion to enamel involved etching the enamel with 85% phosphoric acid for 30 seconds, followed by rinsing with water and drying with air (Buonocore et al., 1955). The current commercially marketed etchants use a lower concentration of orthophosphoric acid from 30% up to 40% with the most commonly used being 37.5% (Silverstone, 1974). There have been additional studies

(Gottlieb et al., 1982; Gwinnett and Kanca, 1992) that have demonstrated no reduction in bond strength with lower concentrations of orthophosphoric acid etchant. When nitric acid is used as an enamel etchant a concentration of 2% is generally used. This technique is often described as part of the total-etch technique where enamel and dentine are etched simultaneously.

The etching time for enamel bonding

A further variation of bonding to enamel is the etch time. For a number of years a 60s application was recommended using 37% phosphoric acid. However, current systems have reduced surface contact time to 15s. *In vitro* shear bond and marginal leakage tests of 15s compared with 60s etching periods have produced similar results (Barkmeier et al., 1986; Gilpatrick et al., 1991). Additionally, SEM studies have indicated that etching periods of 15s have achieved the same level of surface roughness as those obtained from the longer 60s etching protocol (Barkmeier et al., 1986).

1.7.3. Dentine bonding

Basic differences between enamel and dentine bonding

The use of enamel bonding as a reliable technique with acceptable bond strengths is accepted generally by the dental profession. However, dentine bonding has provided a greater challenge even though similar techniques to those used in enamel bonding have been employed to achieve a micromechanical union between resins and dentine (Nakabayashi et al., 1982; Erickson, 1992). Several factors account for the difference.

Dental enamel is not a vital tissue. Once formed and fully mineralised it has no capacity for repair other than potential remineralisation of sub-surface mineral loss providing correct mineral saturation conditions exist (Silverstone et al., 1975). Dentine is a vital tissue with the capacity for cellular-induced repair. Additionally, the tubular structure presents a difference in surface morphology compared with enamel and tubular fluid results in a wet cut-surface compared to a dry enamel cut-surface. The significantly higher organic component of dentine further complicates the bonding process. Finally, the process involved in cutting dentine generates a layer of organic and non-organic debris over the cut-surface. This is known as the smear layer.

The predominant microstructural factors that affect resin bonding to dentine are:

(a) the smear layer,

(b) the dentine tubule density, diameter and length,

(c) the degree of dentine tubule sclerosis.

(Brannstrom and Johnson, 1974)

(a) *The smear layer*

A smear layer is created on any material by cutting processes. The dentine smear layer, when observed under a scanning electron microscope, has a rough, smeared appearance, with obliterated tubule orifices. In addition, the dentine smear layer contains varying amounts of blood, saliva, bacteria, enamel and dentine particles (Eick et al., 1970). It is created on dentine and enamel by rotary instruments during cavity preparation (Gwinnett, 1984). The morphology and character of the smear layer are determined mainly by the instrument used to cut the tooth (Ruse and Smith, 1991). A

bur in a slow speed handpiece produces a smoother surface than the coarser surface produced from a similar type of bur in a high-speed handpiece. The dentine smear layer created from the use of rotary instruments contains hydroxyapatite crystals and partially denatured collagen that have come mostly from the underlying dentine (Pashley, 1984).

Pashley, (1984) reported that the thickness of the smear layer also varies as a function of whether the dentine is wet or dry during rotary instrumentation, indicating that it was generally one to five microns thick. Generally speaking, cutting without water spray generates a thicker smear layer than cutting with a copious spray of air and water. Hydraulic conductance studies of the partly porous smear layer have shown that it reduces the fluid flow from underlying dental tubules (Pashley et al., 1978), thus the smear layer acts a biological "bandage", reducing postoperative sensitivity. This process is consistent with the hydrodynamic theory from Brannstrom, (1984[b]) which states that "dentinal pain and hypersensitivity are caused by pulpal fluid movement along tubules".

The composition of the smear layer is influenced by the depth of cut dentine relative to the pulp because of differing organic to inorganic component ratios and percentage area of dentinal tubules (Causton, 1984; Suzuki and Finger, 1988). There are different opinions on the role of the smear layer. Bowen, (1978) argued that the smear layer should be removed as it interferes with adhesion of restorative materials. Douglas, (1989) advocated that the smear layer is a clinical asset as it acts as an effective, natural cavity liner that seals the dentinal tubules and reduces permeability. Pashley et al., (1989) also found the smear layer to be effective in restricting dentine permeability.

(b) *The dentine tubule density, diameter and length*

Dentine permeability is defined as the volume of fluid flow through a defined volume of tubular dentine per minute of time (Pashley, 1984). Dentine permeability is related to a number of physical factors which include, the number of tubules per unit area, the functional diameter of the tubules, the overall thickness of dentine (tubular length) and the concentration gradient between dentine tubular fluid and other fluids at the oral dentine surface (Pashley, 1984). The permeability of dentine also determines its wetness which directly affects dentine bonding agents which are predominantly hydrophobic resins.

Tubule density ranges from 20,000 to 50,000 tubules per square millimetre (Garberoglio and Brannstrom, 1976) with a typical density being 30,000 per square millimeter. Tubules have a diameter of 1.1μm at a distance of 2mm from the pulp. The relative density of tubules is greatest nearest the pulp and least at the enamel-dentine-junction. Tubules nearest the pulp are the least narrowed by peritubular mineralization. Tubular density in dentine varies not only from the pulp to the dentinal enamel junction (DEJ) but also between the occlusal and radicular (root) dentine locations of a tooth. The greatest tubular density is in the inner third of the dentine under the cusps (Fogel et al., 1988) The lowest tubular density is in the outer third of cervical dentine.

(c) *The degree of dentine tubule sclerosis*

In response to trauma, caries or other stimuli, odontoblasts attempt to seal dentine by laying down a bridge of peritubular hydroxyapatite crystals. These microstructural

changes are referred to as dentine sclerosis. It is important that clinicians recognise dentine composition when planning restorations that depend on dentine bonding because bonded restorations are more likely to fail when they are bonded to sclerotic dentine (Duke and Lindemuth, 1990). A visual classification of dentine sclerosis exists (Duke and Lindemuth, 1991). It would appear that as dentine ages and becomes more sclerotic dentine adhesives that are designed to establish mechanical retention in tubular orifices may be less successful (Duke and Lindemuth, 1991). Prati et al., (1999) investigating the thickness and morphology of resin-infiltrated dentin layer in young, old, and sclerotic dentin reported that sclerotic and old dentin showed thinner resin infiltrated dentine layer, with short resin tags, and fewer lateral branches than normal dentine. It would therefore appear that sclerotic and old dentine are relatively acid-resistant substrates that resist infiltration which may reduce bond strengths. This agrees with a recent evaluation that concluded that a decrease in bond strength occurs using a self-etching primer on natural sclerotic cervical lesions because acid-resistant sclerotic casts that obliterate the tubular lumina, prevent effective resin tag formation. (Tay et al., 2000).

1.7.4. Development of dentine bonding

The development of materials that adhere to tooth structure has theoretically permitted a more conservative approach to cavity preparation (Joynt et al., 1991). With the use of a dentine-bonding system the clinician has been able, during operative procedures, to minimise the amount of tooth structure removed for retentive purposes. The bonding technique is aiding the researchers' aim of reducing microleakage by sealing the dentinal tubules, reducing the ingress of bacteria to the pulp and reducing the development of

secondary caries. Dentine bonding agents have been developed over many years from the initial "first" generation to the current "sixth" generation (Kugel and Ferrari, 2000).

First generation dentine bonding agents

The first report of dentine bonding described a method which used dimethacrylate monomer with reactive phosphate groups as the adhesive resin (Buonocore et al., 1956). The bond induced between composite and dentine was believed to be because of the interaction of the bifunctional resin molecule where the phosphate groups reacted with inorganic (calcium) ions in dentine and organic (methacrylate) components in the composite resin. Although a bond to dentine was achieved, the strength of the bond was only 2-3MPa, which was much lower than the 15-20MPa achieved by the enamel acid-etching technique reported earlier.

The principle of resin adhesion to dentine is depicted in figure 1.1. The adhesive molecule is bifunctional and has a methacrylate group (M) at one end. Separated from M by a spacer R, the other end of the molecule has a functional group (X) that is designed to react with, and bond to, dentine. Following this reaction, a composite resin is applied which will co-polymerize with the methacrylate (M). In this manner the composite resin is bonded chemically to the dentine via the adhesive molecule.

Theoretically, there are two reactions of group X to dentine. Although Buonocore et al., (1956) described bonding of group X to inorganic (Ca^{2+}) ions in dentine, it is possible that a reactive group X could bond to the organic part of dentine. Such bonds could exist between X and NH_2^- or HO^- groups. This is depicted in figure1.2.

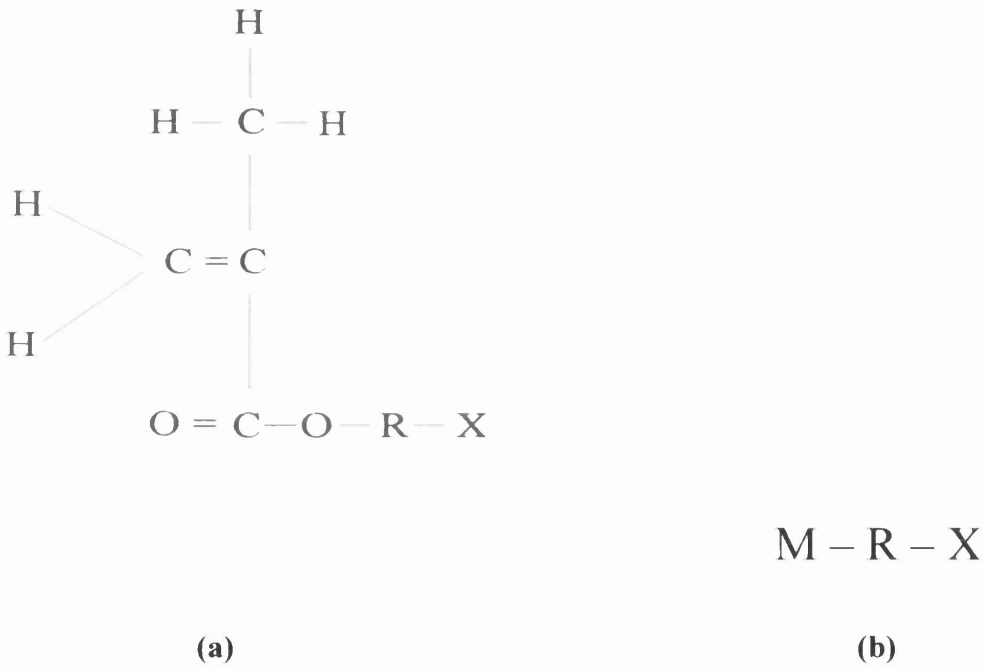


Figure 1.1. Detailed (a) and (b) schematic diagram of the Methacrylate based dentine adhesive molecule described by Buonocore et al., (1956).

M = schematic representation of the methacrylate molecule detailed in (a)
R = spacer
X = group capable of bonding to the dentine surface

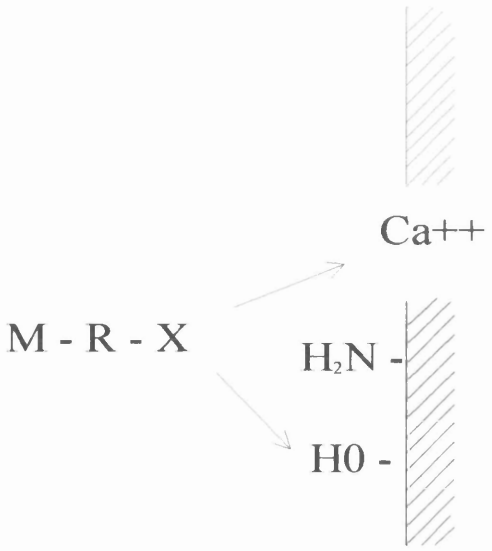


Figure 1.2. A schematic diagram depicting a dentine adhesive M-R-X with a potential for reaction with either Ca^{2+}-ions of the inorganic part of dentine, or with NH_2^- or OH^-groups of the organic part of the dentine.

In a later study Bowen, (1965) used N-phenylglycine and glycidyl methacrylate (NPG-GMA) in his study as a bifunctional molecule or coupling agent. In this instance, one end of the molecule bonds to dentine while the other bonds to the composite resin. The clinical results were poor, and similar to Buonocore et.al, (1956), the bond strengths were only 1-3 MPa.

The first generation of dentine bonding systems based on the concept of adhesion involving chemical reactions resulted in dentine bond strengths that were too small to be of clinical significance (Asmussen and Munksgaard, 1988).

Second generation dentine bonding agents

Towards the end of the 1970's, second generation bonding systems were being developed which had improved adhesion to dentine. Most of the new systems incorporated halophosphorous esters of unfilled resins such as bisphenol-A glycidyl methacrylate (bis-GMA) or hydroxyethyl methacrylate (HEMA) (American Dental Association Council, 1987). The mechanism for bonding involved a surface-wetting phenomenon as well as an ionic interaction between the phosphate groups of the bonding agent and dentinal calcium (Causton, 1984). Dentine was not etched during the clinical application of the second generation bonding materials thus much of the adhesion was as a result of bonding to the smear layer. A major concern was that the phosphate bond to calcium in the dentine was not strong enough to resist the hydrolysis resulting from water immersion (Eliades and Vougiouklakis, 1989), therefore composite resin tended to separate from dentine, forming gaps at the restoration margins which allowed microleakage at restoration margins in dentine or cementum (Barkmeier and Cooley, 1989).

The second generation systems also resulted in bond strengths to dentine that were weak and unreliable.

Third generation dentine bonding agents

In second generation dentine bonding agents the poor bond strengths were because of the relatively weak adhesion of the smear layer to the underlying dentine (Tao et.al, 1988). The development of third generation adhesives were able to modify the smear layer to allow resin penetration into the underlying dentine (Joynt et.al, 1991). The first

dentine bonds of clinical relevance were obtained with Bowen's investigations in the early 1980's, when bonds to dentine of 14MPa were measured (Bowen et al., 1982).

With third generation systems it is the action of acid etching the dentine that partially removes or modifies the smear layer. The action of the acid partially opens the dentinal tubules and increases their permeability.

The bonding technique requires acid etching of the cavity, followed by rinsing with water before a primer is applied. Primers contain hydrophilic resin monomers, which include biphenyl dimethacrylate (BPDM) and hydroxyethyl trimellitate anhydride (4-META). The primers infiltrate the remaining smear layer, promoting adhesion to dentine. In addition the hydrophilic group of the primer creates adhesion to the resin. Following application of the primer an unfilled resin is placed on the dentine and enamel.

Again, similar to the earlier bonding systems, third generation bonding to the smear layer was not very successful with the same problem that the resins did not penetrate through the smear layer and the bond of smear layer to the underlying dentine was still considered weak (Tao et.al, 1988).

Fourth generation

The report by Nakabayashi et.al, (1982) described the formation of a hybrid layer. This layer was described as, "the structure formed in dental hard tissue by demineralization of the surface and sub-surface, followed by infiltration of monomers and subsequent

polymerization". The main characteristic of fourth generation bonding system was the total-etch technique.

The total-etch technique permitted simultaneous etching of enamel and dentine using phosphoric acid with a contact time of 15-20s. This was sufficient to etch the enamel and remove the smear layer from dentine. Additionally it resulted in surface mineral dissolution from dentine, widening the dentinal tubules and exposing collagen fibrils. Tubular fluid from patent dentine tubules makes the resulting dentine bonding surface wet. Therefore, fourth generation dentine bonding agents also introduced the clinician to the concept of "wet bonding".

The concept of "wet bonding" was introduced by Kanca (1992[a]) who demonstrated that some materials produced higher bond strengths to moist compared with dry dentine. To achieve "wet bonding", following acid etching, the cavity was rinsed with water and briefly dried with air to leave it in a moist state. Moist dentine is difficult to define clinically and may compromise the bond if too wet (Tay et al., 1996) or too dry (Nakabayashi et al., 1982).

Dentine primer molecules were still not truly hydrophillic. They had a hydrophillic group added to a mainly hydrophobic molecule. The use of an acetone primer was an additional break through with fourth generation dentine bonding agents. Acetone appears to chase the resin primer monomers into spaces that were occupied by water (Kanca, 1992[b]). This report demonstrated that acetone enabled the primer to diffuse into the water-rich surface. The priming process wets the exposed collagen fibrils. It

displaces any residual surface moisture, transforms a hydrophilic into a hydrophobic surface condition and carries monomers into the interfibrillar channels of the demineralised dentine.

A number of studies have reported that acetone is at present the best solvent for carrying the resin primer into moist dentine (Jacobsen and Söderholm, 1995; Kanca, 1992 [b]; Gwinnett, 1992). However, a recent study has shown that bonding systems which use water-based primers appear to bond with equal efficiency to dry or wet dentine (Van Meerbeek et al., 1998).

Although manufactures have produced various dentine adhesive systems using different types of conditioners, primers and adhesive resins, all have broadly similar bonding mechanisms. Acid etching removes the smear layer, opens the dentinal tubules, increases dentinal permeability, and decalcifies the intertubular and peritubular dentine. Following conditioning, maintenance of a moist dentinal surface to prevent collapse of unsupported collagen is required to promote subsequent wetting and infiltration of resin (Kanca, 1992[b]). The formation of resin tags and adhesive lateral branches complete the bonding between the adhesive material and etched dentine substrate.

Fifth generation

Fifth generation dentine bonding systems were introduced to reduce the number of clinical stages used during adhesive bonding procedures and to offer clinicians a better way of preventing collagen collapse of demineralized dentine. The most common

method of simplification is the combining of the primer and bonding-agent steps to make the so-called "one bottle systems".

Watanabe and Nakabayashi, (1993) developed a self-etching primer for bonding, simultaneously, to enamel and dentine. The primer was an aqueous solution of 20% phenyl-P in 30% HEMA. The combination of etching and priming stages, eliminates the washing out of the acidic gel and the risk of collagen collapse and reduces the working time

The use of one bottle systems is applied following simultaneous etching of the enamel and dentine (total etch technique) These bonding systems create a mechanical interlocking with etched dentine by means of resin tags, adhesive lateral branches and hybrid layer formation (Tay et al., 1994).

Sixth generation

Although fifth generation materials provide the operator with a simplified system, research reports on bond strengths have been variable. Some investigators have reported lower values, whilst others have reported similar bond strengths when compared to conventional three step systems (Swift and Bayne, 1997; Kanca, 1997; Tjan et al., 1996). The sixth generation bonding systems reduce the number of procedural steps required for bonding. The materials use non-rinsing, acidic, polymerizable monomers on dentine and enamel and are able to achieve a bond to enamel and dentine using only one solution. They probably should be referred to as one step bonding systems. On dentine they impregnate the smear plug, fixing it at the

entrance to the tubule unlike the previous systems where the self-etching dentine primer removed the smear layer. The bonding mechanism simultaneously conditions and primes enamel and dentine substrates without rinsing the self-etching primer to form a continuum in the substrate incorporating the smear plug in the resin.

1.7.5. Summary

Buonocore's initial experimental success has lead to changes in the management and treatment of caries enabling the use of adhesive dentistry techniques. Dentists currently have the opportunity to be less invasive and more conservative in their cavity preparation techniques compared to the traditional designs proposed by Black, (1917).

Some of the advantages of adhesive/ bonded restorations compared to traditional non-adhesive fillings are;

(a) A reduction in the amount of sound tooth structure that is required to be removed compared to the amounts removed to prepare a non-adhesive restoration.

(b) Today's patient appears to be more aware of their "dental appearance" and increased versatility of adhesive restorations have expanded the range of possibilities for aesthetic dentistry (Ibsen et al., 1991).

(c) Adhesive systems allow debonded restorations to be rebonded usually without further modification to the preparation.

(d) Adhesive restorations also reduce microleakage at the tooth/restoration interface preventing the ingress of bacteria which could lead to recurrent caries (Phillips, 1982).

(e) Adhesive systems permit deteriorated restorations to be repaired with, in most cases, minimal or no extra loss of tooth structure.

Although the mechanism of adhesion to dentine is understood, there are still some problems for example technique sensitivity. The new adhesives with simplified procedures (one-bottle systems) are a possible solution to reducing problems of technique sensitivity and multi-step processes. One would expect that with refinements to formulation and clinical techniques in the continuing development of bonding systems that an "ideal" system will eventually appear on the market that will achieve a long lasting bond to enamel and dentine. A recent report on concepts in dentine bonding concluded that bonding to dentine is still one of the greatest challenges in adhesive dentistry (Perdigão and Lopes, 1999).

1.8. Dental wear

1.8.1. Definitions

Moon and Draughn, (1982) defined wear as the time-dependant removal of material from surfaces that are in motion relative to each other.

Zum-Gahr (1987) defined wear as a natural process that occurs whenever two or more surfaces move in contact with each other.

Tooth wear has been described as the surface loss of hard tissue other than by caries or trauma and is commonly classified as abrasion, attrition and erosion (Kidd and Smith, 1990).

Abrasion

The term abrasion has the most diverse use when used to describe wear in dentistry. It is used to describe the wear of restorations at the non-contacting sites of restorations. Abrasion has been described as the wearing away of tooth surfaces by the friction of foreign or solid substances forced over tooth surfaces rather than by the opposing dentition. For example, abrasion by food or toothbrushes (Kaidonis et al., 1998). The degree of abrasion is affected by diet, consistency of food and amount of chewing. Smith and Knight (1984[a]) found that the occurrence of abrasion wear was very infrequent compared to other types of tooth wear.

Attrition

The term attrition is used to describe tooth wear caused by tooth-to-tooth contact without the presence of food. Smith (1989) defined attrition as the physical wear of one tooth surface against another. Every (1972) defined it as "wear caused by endogenous material such as microfine particles of enamel prisms caught between two opposing surfaces".

Attrition of the teeth manifests in the flattening of the cusp tips or the incisal edges with associated wear facets on the occlusal or palatal surfaces. If the area of contact between two teeth during mastication involves a restoration margin then the attrition facet will involve both the tooth and the restoration (Mair et al., 1990). Attrition may be accelerated by erosion or may be caused entirely by bruxism or other parafunctional activities.

Erosion

Erosion is defined as the loss of dental hard tissue as a result of a chemical process not involving bacteria (Kidd and Smith, 1990). Erosion occurs clinically when tooth surface loss results from acid attack. Although the degraded surface is further reduced by the movement of soft tissues or food slurry, the surface loss is predominantly chemical in nature (Smith, 1989). The chemical involved is usually an acid. The causes of erosion have been subdivided into dietary, regurgitation and industrial erosion depending on the source of the acid (Smith & Knight, 1984[b]). Erosion can also be classified as intrinsic or extrinsic. Intrinsic erosion occurs when the source of acid is from within the body and extrinsic erosion if the source is either dietary or environmental.

1.8.2. Factors affecting dental wear

The clinical evaluation of wear has been limited. This is because it is expensive, time consuming and difficult to conduct controlled studies. The variation of dental wear between patients makes interpretation of the results difficult. Wear of dental tissues and restorations may result from physiological or pathological conditions. Wear and loss of enamel are irreversible and can result in the need for complex restorative procedures. Wear of teeth is considered a natural process and can be expected to occur to some degree in all dentitions (DeLong et al., 1989). As the teeth move in contact with each other wear is inevitable. A number of clinical studies have provided information on the nature of tooth wear in humans (Smith & Knight, 1984; Lambrechts et al., 1989; Smith & Robb, 1996). These studies provided some understanding of the nature of wear but were limited by the difficulties of accurate quantification of intra-oral wear and by the diversity of the oral environment.

The demands of patients and dentists, who are seeking alternatives to amalgam for more aesthetic restorations, has led to a greater use of composite and porcelain restorations. Mair et al., (1990) reporting on a 36-month clinical study of amalgam and composite concluded that composites should not be used as a replacement for amalgam, especially in patients exhibiting high masticatory stress as the composite is likely to wear away. The wear of human enamel opposing restorations is often a critical concern for dentists when choosing which type of restoration to use. The rate of wear may be altered by the introduction of restorations with wear properties that differ from tooth structure (Jagger and Harrison, 1995). The wear rate of an ideal restoration should be similar to that of enamel (Seghi et al., 1991) A clinical investigation (Lambrechts et al., 1989)

attempted to quantify vertical wear of enamel. Their study quantified human enamel wear rates during a four-year period. They reported that occlusal contacts had an average steady rate of wear of approximately 29μm per year for molars and 15 μm per year for premolars when opposed by enamel in the premolar and molar regions, respectively.

A number of variables influence the extent and rate at which dental enamel wears. They are structure and hardness of enamel; distance of movement; the biting force during mastication; contact area; frequency of contact; quality and quantity of lubricant; environmental factors; diet; pH; surface roughness; age (Kaidonis et al., 1998; Moon and Draughn, 1982).

The structure and hardness of enamel as a factor in dental enamel wear

Enamel is highly mineralised tissue predominately composed of hydroxyapatite, which accounts for 97% of enamel by weight. Water and organic substances make up the remaining 3% with 1% organic substances consisting of soluble and insoluble protein (Combe et al., 1999). It is generally accepted that it is the hardest tissue in the human body, is relatively inelastic and rather brittle. The physical structure of enamel consists of interlinked rods. When enamel fractures it usually does so along the grain of these rods. The enamel rods in the region of cusp tips are often arranged more irregularly. It is believed that the twisting formation increases the strength. Its hardness when measured by indentation testing achieves a Knoop Hardness Number of 200 to 500 KHN, the wide variability being due to variations in the plane in which testing is carried

out. Other factors affect the hardness such as prism orientation, degree of calcification and distribution of metallic ions.

The sliding movement as a factor in the rate of dental enamel wear

The natural process of wear occurs when tooth surfaces move against one another during contact. A sliding movement occurs during mastication or bruxing. The sliding motion is primarily responsible for wear in natural teeth. The distance of sliding movement during mastication varies from 1.00mm to almost zero in a canine guided occlusion with the normal range of sliding movement being 0.3mm – 0.6mm (Combe et al., 1999). It has been shown that an increase in sliding contact distance between teeth results in an increase in wear (Moon and Draughn, 1982).

The biting force as a factor in the rate of dental enamel wear

The forces developed between opposing teeth are those produced during the normal chewing of food or those that occur when a biting load is applied without the presence of food. Thus the greater the force developed during chewing the greater will be the resulting wear (Moon and Draughn, 1982).

The measurement of biting forces found in the oral cavity has been recorded using a variety of methods and equipment (Bates et al., 1975). A common method used is to place a transducer between the maxillary and mandibular teeth. However, the interference from the intra-oral measuring equipment can result in variable results. There is substantial disagreement in the literature as to the force developed during mastication. De long and Douglas (1983) in a literature review of a variety of methods

found that the magnitude of forces ranged from 9 to 180 N. However, the parafunction of bruxism generates forces that have been measured at 40 N on a sustained basis compared with 15 N during mastication (Coombe et al., 1999).

Contact area and frequency of contact as a factor in the rate of dental enamel wear

When the force of mastication is acting over a small area, the stress will be greater than when the same force is exerted over a larger area. A decrease in the overall contact area between opposing teeth results tooth wear. A sharp cusp tip with a small contact area would therefore promote a greater degree of wear than a tooth cusp with a larger contact area. Graf and Zander, (1963) in a study of tooth contact patterns, reported that teeth contact in the intercuspal position during mastication and swallowing of food. Teeth are only in contact for short periods during each chewing cycle. The time the teeth are in contact is approximately 0.25 seconds during a chewing cycle of approximately 1Hz (one per second) (Coombe et al., 1999). Harrison and Lewis (1975) and later Bates et al., (1975) reported that a chewing rate of 60 to 80 cycles per minute was a reasonable estimate.

Patients exhibiting bruxism have increased wear because they are capable of exerting greater forces with their developed musculature and have more frequent contacts. Wear is increased with the accumulated number of occlusal contacts, as shown by the increased wear with age (Moon and Draughn, 1982).

The surface roughness of teeth as a factor in the rate of enamel wear

Rough surfaces increase wear because only the high spots are in contact, producing high localised stresses. This is most evident when a restoration following trimming/adjustment is left with roughened surface. For example, when unglazed porcelain opposes a natural tooth it will increase the wear. The wear can be reduced in the case of a porcelain restoration if it is polished or reglazed (Monasky and Taylor 1971; Patterson et al., 1991).

The age of the patient as a factor in the rate of dental enamel wear

The age of the patient is an important factor in relation to wear. Tooth wear is generally associated with age and the cumulative effect of wear can be observed in elderly patients. It is normal to find that dentitions of older patients will show some degree of tooth wear (Smith, 1989). However, the aetiology of the wear may be varied.

Environmental factors related to dental enamel wear

The chemical environment in the mouth can also affect the wear process with factors for example of a coarse diet, excessive tooth brushing, saliva with a low pH, exposure to abrasives atmospheres and lack of salivary flow (Moon and Draughn, 1982). Industrial erosion results from occupational exposure to acids. For example workers in factories that manufacture batteries (Petersen and Gormsen, 1991). Their study reported 31% of workers in a German battery factory were exposed to airborne acid mists (Sulphuric acid). However, they also reported that 92% of workers were also affected by attrition. Erosion only appeared on the anterior teeth while attrition was evident on posterior teeth. They concluded that the prevalence of erosion was environmental because it first

affected the labial surfaces of the anterior teeth and no erosion of the posterior teeth was observed. This pattern of labial erosion of upper anterior teeth is in contrast to intrinsic erosion where erosive wear mainly affects the palatal surfaces.

Summary

Although a number of clinical studies have been conducted into the rate and nature of wear. They have been limited because they have proved difficult to give accurate quantification of intra-oral wear, are expensive and time consuming. This has resulted in many researchers choosing to assess wear in a controlled environment *in vitro*.

1.8.3. Development of dental wear studies *in vitro*

The majority of tooth-wear studies *in vitro* have focussed on the characteristics of dental materials. The wear rate is of great importance in the development of restorative materials. Many machines have been used for the assessment of the wear properties of dental restorations. A prerequisite of any artificial assessment of wear is that it should mimic clinical conditions. These conditions should encompass forces and motions associated with chewing and a third-body medium with components resembling those, which are present in natural food (De Gee and Pallav, 1994). However, because of the different types of clinical wear which act simultaneously and/or sequentially and often influence each other in a complex way a machine that simulates all of the clinical characteristics of wear will perhaps never be achieved. A number of researchers have developed *in vitro* wear simulation studies and these are discussed, principally in relation to abrasive wear, in the next section.

1.8.4. *In vitro* simulation of abrasive dental wear

Researchers have used a varied range of machines to assess dental wear and wear of restorative materials *in vitro*. The models described in the literature are as follows:

(a) The artificial mouth abrasive-wear model

(b) Electro mechanical tooth-wear model

(c) Pin-on-disc abrasive-wear model

(d) Sliding abrasive-wear model

(e) Wheel to wheel model

(f) Dual-axis chewing simulator model

Each method will be discussed in greater detail in the following sections.

(a) *Artificial mouth abrasive wear model*

Simulation of the movement of mastication was one of the aims in the machine constructed by Delong and Douglas (1983). They designed a machine to reproduce both the movement and force of mastication against anatomical samples, using servo-hydraulics. In their construction criteria they attempted to reproduce mastication forces, chewing rates and the three phases of the chewing cycle.

The chewing cycle phases were:

(a) the preparatory phase, during which the mandible is positioned

(b) the crushing phase, which occurs from contact with the food bolus until contact with the tooth

(c) the grinding phase (gliding phase)

During the first two phases the motion of the mandible is variable, and is influenced by the type of food being chewed. During the third phase (gliding phase), the motion of chewing occurs with eccentric contact of the mandibular buccal cusps to the inner inclines of the maxillary buccal cusps followed by a working movement to centric occlusion. The movement continues through centric occlusion to a balancing movement before the initiation of the preparatory phase (Gibbs et al., 1981; Suit et al., 1975). The machine used two servo-hydraulic units to produce many of the features of the masticatory cycle. The three-dimensional motion was approximated by the use of vertical and horizontal hydraulic actuators using a judicious rotation of the horizontal and frontal planes. The machine was capable of producing constant occlusal forces from 1 to 100lb (4.45-445 N) and could follow any shape of the occlusal anatomy. During its operation deionised water was continually circulated over the surface of the test specimens.

The machine has been used in a number of studies using extracted natural teeth against artificial teeth and different restorative materials (Delong et al., 1985; Delong et al., 1986; Delong et al., 1989; Delong et al., 1992). The 'artificial mouth' concept allows natural teeth to be loaded in a manner that simulates physiological movement and is a useful method of wear assessment.

(b) *Electro mechanical tooth-wear model*

Researchers have used electro-mechanical tooth wear machines designed to assess the variables that influence enamel wear (Al-Hiyasat et al., 1997; Al-Hiyasat et al., 1998[b]; Kaidonis et al., 1998; Al-Hiyasat et al., 1999). Although these machines in some

instances have actions similar to sliding wear machines they differ because of the range of variables that can be included in the test regimes. The machines are driven by electric motors and constructed in a manner that permits opposing tooth specimens to wear against each other or restorative materials. The wear occurs under controlled variables such as load, direction of movement, number of cycles, speed of cycles, a range of lubricants for example carbonated beverages with a low pH, natural saliva (pH = 7) and various food preparations. The use of food permits three-body wear assessment to be employed as part of the testing regime. With these systems tooth specimens can be measured at various stages during the wear process. Al-Hiyasat et al., (1997, 1998[a]) used regimes of 80 cycles per minute under a load of 40 N with either distilled water, carbonated beverages or a food slurry of flour and corngrits mixed in distilled water They assessed the wear of enamel against a range of restorative materials. Wear was quantified by measuring the reduction in the cusp length in the tooth specimen and in the restorative material by the use of surface profilometery.

Kaidonis et al., (1998) used a range of lubricants pH =1.2 - 7 with loads 1.7 kg - 16.2 kg. Their study examined tooth wear under experimental conditions simulating the behaviour of tooth grinding or bruxism although wear can occur both in enamel and dentine they concentrated their study on enamel. They quantified wear by calculating the weight of tooth structure removed during grinding. They found that enamel wear under dry conditions increased with increasing loads. At light loads with water as the lubricant the rate of enamel wear was reduced. They did have some results that were unexpected. Using an acid of pH = 3 as the lubricant with a load of 9.95g the wear rate fell well below that of dry conditions. However, when the load was increased to 16.5g

with the same acid the wear was similar to that of dry conditions. These results are contrary to the expectation that the combination of the mechanical action, increased load and acid would result in an increase of wear.

The methods used in these studies to assess tooth wear permits quantitative assessment of wear.

(c) *The pin-on-disc abrasive-wear model*

The pin-on-disc device is the simplest machine used to assess abrasive-wear (Mair et al., 1996). It has been used in engineering for many years and is basically a two-body wear test. It consists of a pin of tooth specimen, contacting under load, a disc of restorative material and uses saliva or deionised water as the lubricating medium. Test specimens can be either the pin or the disc. The wear is produced by rotating either the pin or the disc resulting in a circular wear track on the surface of the restorative material disc. The specimens slide over each other through a full circle (360°). Three-body wear can be simulated by replacing the abrasive disc with a softer surface to support an abrasive slurry. Hengchang et al., (1990) modified the pin-on-disc machine to include both compressive and impulsive forces and employed three body-wear using a slurry mixed in water of fluorite (fluorspar) powder and carboxymethyl cellulose.

The pin-on-disc system has been used extensively by researchers (Young and Suzuki, 1999; Hacker et al., 1996; Suzuki and Leinfielder, 1993; Palmer et al., 1991; Hengchang et al., 1990). The system has been mainly used to assess composite

materials. However, the pin-on-disc machine design only permits ranking of restorative materials in accordance to their resistance to wear.

(d) *Sliding abrasive-wear from intermittent and reciprocating machines*

Most of the machines that use sliding technology to assess wear have the same characteristic as pin-on-disc machines but they normally only simulate two-body wear whereas wear in the mouth usually involves food (three-body wear). The sliding machines can operate with either a reciprocating sliding mechanism or an intermittent sliding action. Powell et al., (1975) developed a two-body wear testing machine to assess the wear of composite resin, amalgam and enamel. Their electrically driven machine was designed to initially produce a reciprocal sliding contact between a restorative material and an enamel specimen on one side of the machine whilst simultaneously on the opposite side of the machine another enamel specimen was impacting on another restorative material.

However, their impact test was unsuccessful, as it did not produce any meaningful results. Their test regime only produced results from the reciprocating sliding test. The test regime consisted of 25,000 cycles at rates per minute of 80, 150 and 235 cycles using a 1 Kg/mm^2 load. The point of contact was constantly covered by distilled water at 37^0 C.

Many researchers have used reciprocal sliding technology but with differences in the test regime from that used by Powell (Smalley and Nicholls, 1986; Jacobi et al., 1991). The main differences in their regimes were cycle rates, loads and fluid.

Jacobi et al., (1991) used tap water and a rate of 58 cycles per minute with a load of 4 Kg whereas Smalley and Nicholls, (1986) used distilled water with a rate of 45 cycles per minute and a load of 0.3 Kg/mm^2. Other researchers used sliding systems to investigate vertical height loss of enamel when opposing restorative materials (Krejci et al., 1993[a]; Ramp et al., 1997; Ramp et al., 1999; Young and Suzuki, 1999). Their conclusions agreed with other studies on the rates of enamel wear occurring when teeth were opposed with ceramic materials (Monasky & Taylor, 1971; Wiley, 1989; Ratledge et al., 1994). However, Young and Suzuki, (1999) measuring wear of enamel opposing indirect quartz composite resin materials indicated that the quartz filled composite provoked greater wear of the enamel antagonistic cusp. Krejci et al., (1993[b]) concluded from their study that wear resistance of all ceramic materials was not critical because it was in the range of enamel and that measurements confined to restoration wear are not enough to predict clinical performance. However, in their evaluation of luting composites also assessed in their study they reported that the wear resistance needs to be improved because they abrade more than the other contact areas of ceramic inlays and enamel.

Intermittent sliding machines have been used to assess the wear of porcelain, enamel and gold. They were developed in an attempt to simulate the intermittent sliding action of teeth. An early report of a sliding machine used in the study of wear of porcelain, enamel and gold was a machine that provided an intermittent contact between the specimens (Monasky and Taylor 1971). In their system the specimens were immersed in a solution of artificial saliva and white flour with a load of 1lb (4. 45 N).

Harrison and Lewis (1975) used specimens in the form of a pin/stud and plate. Their machine consisted of an electric motor, a digital display to monitor the number of contacts between the stud and plate specimens, a water pump and heater. The wear cycles were produced from the movement of a series of cams on the machine. The machine had ten stations housing loading rods weights were added to the upper end of the rods to produce the desired contact force. The contact frequency of 70 cycles per minute under a load of 50-1000g (0.49-9.8 N) was used.

Ratledge et al., (1994) also devised a machine using similar principles to that of Harrison and Lewis (1975) assessed the wear effects of different restorative materials on enamel. Their version of an intermittent sliding machine operated with a load of 40 N at a rate 70 strokes per minute. The experiments were carried out for 25,000 cycles in either tap water or citric acid (pH 4).

Jagger and Harrison (1997) also used the apparatus developed by Harrison and Lewis (1975). In their experiments they added weights of 395g to each loading rod to produce a force of 0.4MPa perpindicular to the wear face. The contact time for each stud/plate was 0.20 seconds. The wear was carried under water at 37^0 C for a total of 62 hours. Wear of the stud specimens was measured with a bench micrometer and the plate assessed with surface profilometery.

The aim, when restoring teeth is to provide occluding surfaces that not only resist wear but also do not wear opposing surfaces (Wiley, 1989) thus the range of machines to

assess sliding wear are invaluable in the assessment of wear inflicted on opposing tooth surfaces or restorative materials.

(e) *Wheel to wheel model for abrasive-wear*

The wear rate is a property of great importance in the characterisation of a restorative material especially when used in stress bearing areas. It probably will occur as a result of the combined action of chemical and mechanical erosive processes. De Gee et al., (1986) developed the ACTA wear machine intending to design a machine for testing wear *in vitro* that could be directly compared with results of clinical trials. An important consideration for them was that their machine would have the ability to simulate a wear pattern and relative wear rate for a broad class of materials. It was designed to operate with food slurries with various activities, as determined by pressure, shear stress and food film thickness.

The machine was equipped with two electric motors operating in different directions. The motors drove two stainless steel cylindrical wheels of different diameters rotating against each other and operated inside a bowl containing an abrasive slurry (third body medium). The wheel with the larger diameter (10mm) was constructed with rectangular grooves to accommodate the test samples. The smaller wheel (2.5mm in width) functioned as the antagonist and had a scaled surface to provide grip of the three-body slurry. A force of 15 N was applied through the small wheel against the larger test sample wheel. The test set up caused the resultant wear from the antagonist to occur in the middle of the samples leaving the unworn outer areas as references in profilometry. The slurry was agitated with a stirrer mounted under the sample wheel. The rotational

speed of the two wheels could be independently adjusted. The shear stress was related to the film thickness of the third body medium between the small wheel and the test sample wheel. The film thickness could be varied from relatively thick with a low shear stress to a very thin with a high shear stress. The thickest film dragged between the wheels represented 0% slip when the velocities of both wheels were equal. The film thickness is reduced and the slip increased by reducing the speed of the smaller wheel whilst maintaining the sample carrying wheel at a constant speed (1 revolution per second). The greater the slip the higher the shear stress. Up to approximately 45% slip the wheels remain separated by a food film and the wear occurring will be of an erosive nature. Beyond 45% the wheels are not able to drag the slurry through the area of junction and will touch each other. The wear from this point forward will be from direct contact between the small antagonist wheel and the large sample wheel instead of through the three-body slurry.

The machine has been used by researchers to assess rates of wear in amalgam, composites and dual-cured resin luting agents using a variety of different food slurries (De Gee et al., 1986; Pallav et al., 1988; De Gee and Pallav 1994; Sarrett and Ray 1994; Frazier and Sarrett 1995). In a later study De Gee and Pallav, (1994) reported that the 15 N load used in all their previous studies was below the level required to induce contact stress for surface fatigue phenomena. However, they indicated that once a realistic contact load has been defined then their machine should be suitable for occlusal impact situations.

(f) The dual-axis chewing simulator model of abrasive-wear

The wear resistance of restorative materials to attrition is an important property because it limits the life of dental restorations (Kern et al., 1999). A dual-axis chewing simulator was developed in 1999 by Kern et al., in co-operation with the Willytec Company Munich, Germany. The machine consisted of eight identical sample chambers, two-stepper motors and water baths. The three dimensional masticatory loading curve from the two-stepper motors was computer-controlled. The computers controlled the vertical and horizontal movements between two antagonistic specimen in each chamber. Thermal cycling of the sample chamber during the wearing cycles was carried with computer controlled water flow being sprayed alternatively with warm and cold water. Variable chewing forces were possible from adjustable weights mounted on top of guide rails on the upper crossbeam. The enamel abraders were 6 mm steatite ceramic balls and the loading force was 49 N.

Kern et al., (1999) used the machine to study wear of composite against enamel and because of the machine had eight sample chambers they were able to carry out over a short period of time a study that represented five years of chewing. Their results were not surprising as they reported that enamel demonstrated less wear than all of the tested veneering composites. However, the ultrafine Targis® showed wear not statistically different from enamel.

The instrument differs from other chewing machines in that allows simultaneous testing of eight samples which has the benefit of testing statistically sufficient numbers of

samples over a short period of time. It also has improvements in regard to movement and force control being able to mimic the three dimensional masticatory loading curve.

Summary

The machines that have been used to assess enamel wear and restorative materials *in vitro* have many differences. Currently an "ideal" wear simulator has not been produced to fully mimic the clinical situation. The systems in use, at best, only produce guidance on some of the multiplicity of factors that influence different types of clinical wear.

1.9. Amalgam

Definition of a dental amalgam

An amalgam is an alloy of one or more metals with mercury. Dental amalgam has been described as "the product of an amalgamation reaction between particles of an alloy, containing varying amounts of silver, copper and tin with mercury" (Bryant, 1998)

1.9.1. Classification dental amalgam

Classification by chemical composition

The alloy amalgamated with mercury in dental amalgam is essentially a combination of silver and tin. Minor amounts of copper, zinc and gold may be included. Additionally manufacturers of dental amalgam include traces (<1%) of indium, palladium and platinum in most alloys. The addition of metals other than silver and tin alters the corrosion and certain mechanical properties of the finished amalgam mass. The amount of copper in dental amalgam alloy is often used as a method of classification as this influences the setting reaction and hence the physical properties of set amalgam.
When dental amalgam sets, several metal-metal compounds form.
These are:-

The gamma (γ) phase

This is a silver-tin compound that forms a substantial part of the amalgam alloy and is also present in the resulting amalgam structure after reaction with mercury has occurred.

The gamma 1 (γ_1) *phase*

This is a silver-mercury compound.

The gamma 2 (γ_2) *phase*

This is a tin-mercury compound.

(O'Brien, 1997).

The relative proportions of the gamma phases in dental amalgam dictate the physical properties of the set alloy. The proportion of copper in dental amalgam alloy is a major factor determining the relative proportions of the gamma phases. Modern high-copper, dental amalgam alloys have been in clinical use since the 1960's. The high-copper alloys have superior physical properties and improved clinical performance compared with their low copper counterparts. This is because high-copper dental amalgam alloys have a virtual absence of the gamma 2, phase (Mahler and Adey 1979; Mahler et al., 1982). High-copper amalgam alloys contain 41%-61% silver, 28%-31% tin, 12%-27% copper plus some minor elements. (Innes and Youdelis, 1963).

Classification of method of manufacture

Dental amalgam alloy particles may have different physical forms prior to their amalgamation with mercury. Lathe-cut dental amalgam refers to the irregularly shaped filings produced by cutting an ingot of alloy on a lathe. Spherical dental amalgam alloy particles are produced by atomising molten alloy into a stream of inert gas. This produces an amalgam that requires less condensation pressure but one which is difficult in which to generate any condensation pressure. The combination of spherical and lathe

–cut dental amalgam alloy particles is an ideal combination which demonstrates improved clinical handling.

1.9.2. Current problems with dental amalgam as a restorative material

As a restorative material, dental amalgam has been used for over a century with distinct advantages such as ease of manipulation and placement, low technique sensitivity, relatively low cost, acceptable life expectancy, good wear resistance and self-sealing ability (Leinfelder, 1993). However some of the drawbacks to its use are that its colour does not match tooth structure, it is subject to corrosion and galvanic action and although it fills the cavity it does not restore the strength of the tooth (Craig, 1989).

The first reported uses of a room-temperature mixed amalgam as a restorative material are attributed to the Englishman Bell, 1819 and the Frenchman Taveau,1826 (Mackert, 1991).

In 1896, Black identified the amount of silver and tin in an amalgam alloy that would work best as a restorative material, describing it as a " balanced" composition alloy. Later a small amount of copper was added to the amalgam alloy which served to increase the strength and decrease the flow (Skinner, 1946).

Dental amalgam is still the most widely used restorative material for posterior teeth. It has been used extensively by dental practitioners for over 100 years. Large numbers of amalgam fillings are placed every year as the low cost per unit is unmatched by any other dental restorative material. A recent report in 1998 indicated that 80% of all

posterior restorations are amalgam (Sepetcioglu and Altman, 1998). Although it is a popular material for posterior restorations there are some major problems related to its use and areas of concern related to its "safety". These are discussed in the following sub-sections.

Dimensional changes on setting.

In the first 20 minutes after packing amalgam undergoes dimensional changes. First it contracts and then expands as the result of gamma phase creation (Skinner and Phillips, 1967). Phase creation occurs when triturated amalgam alloy is intimately mixed with mercury, during the process mercury diffuses into the alloy particles and forms the gamma (γ) phase (Craig, 1989). The expansion continues for a few hours until complete crystallisation of the γ_1 and γ_2 occurs. In theory, these changes could affect the width of the gap at the tooth-restoration interface. Greasley and Baker, (1978) reported expansion differences depending on the type of alloy used. They found that spherical amalgam contracted slightly whereas lathe-cut amalgam expanded during the first 24 hours following placement. Mahler and Nelson, (1983) in a study on the mechanism of marginal leakage and dimensional change of amalgams during setting, found that both dimensional change and surface texture of amalgam at the restoration-margin interface were contributing factors in marginal leakage. They found that expanding amalgams with smooth textures exhibited low leakage but expanding amalgams with coarse texture exhibited high leakage. Viewed under a microscope the coarse texture may have microchannels on the surface of the amalgam at the interface with the tooth structure through which microleakage could more easily occur (Mahler and Nikutowski, 1989).

High coefficient of thermal expansion compared with tooth structure.

The coefficient of thermal expansion of amalgam is about two to three times that of the surrounding tooth structure (Craig, 1985). Changes in the oral cavity temperature affect the sealing capacity of the restoration. For example cooling results in greater contraction of the amalgam compared to the tooth structure. Similarly differences in expansion occur when hot food or beverages are ingested. The amalgam expands more than the tooth thereby reducing the width of the tooth-restoration interface gap.

Inconsistency of condensation.

The amalgam condensation procedure has a major role in reducing microleakage. Condensation of the amalgam mass adapts it to the cavity walls and margins (Craig et al., 1975). Failure to achieve adequate condensation could result in gaps within the bulk of the amalgam as well as between the amalgam restoration and the cavity wall, or any lining material. The gaps may permit the ingress, of bacteria, which could lead to the development of secondary caries.

The gap between the amalgam and the tooth structure is gradually reduced by corrosion products, which improve the chances for self-sealing of the restoration. However, the corrosion process can be variable, depending on the nobility of the type of amalgam used and the initial gap size (Mahler, 1996). Corrosion products eventually fill the gap but the process takes a few months, especially with high-copper alloys (Ben-Amar, 1989).

To reduce the possibility of gaps and voids, it is recommended that amalgam is condensed in small increments with each increment condensed against the cavity walls, vertically and laterally (Symons et al., 1987). Chapman and Crim, (1992) assessed methods of amalgam condensation and concluded that pneumatic condensation was better than hand condensation.

Persistent fears over safety.

The concern about mercury in amalgam has continually been raised during its 150- year history. The continued use of dental amalgam is being challenged because of "safety" fears. During the last century there have been many reports raising concerns relating to potential for allergy to, or toxicity from, mercury and the possible dangers to the patient and dental personnel (Gay et al., 1979; Mackert et al., 1991; Eley, 1998).

Some countries have banned amalgam because of mercury pollution from crematoria rather than as a result of danger to the patient. In the recent report from The British Dental Association, (1999) it was concluded that most fears appeared to be unjustified as, "to date, extensive research has failed to establish any links between amalgam use and general ill health. Those countries that are limiting the use of amalgam are doing so to lower environmental mercury levels," (BDA fact file, 1999).

Non-adhesion to tooth structure.

Because of the lack of adhesion of amalgam to tooth structure there is always a gap at the tooth-restoration interface. The clinical retention of an amalgam restoration is achieved by the retention-form and resistance-form of the cavity. The width of the

tooth-restoration gap ranges from 1-20μm and is filled with the outward flow of dentinal fluid and to some extent by oral fluids (Saltzberg et al., 1976). The fluid filled gap becomes an area for the growth of oral bacteria, which may lead to postoperative sensitivity, pulpal irritation and secondary caries (Al-Jazairy and Louka, 1999).

Microleakage

Most amalgams show a small degree of contraction after placement (Van Noort, 1994). In the initial weeks following placement amalgam may exhibit a lack of marginal adaptation which permits microleakage of fluids and bacteria between the restoration and the cavity walls and may result in marginal deterioration, accumulation of plaque, recurrent caries and post-restoration sensitivity or pulpal reaction. However after 48 hours the process termed "self sealing" occurs in a "well packed" amalgam restoration (Leinfelder, 1993). The tooth will begin to exhibit a reduction in microleakage that can be attributed to the formation of corrosion products at the amalgam- cavity interface. Corrosion of the amalgam alloy over time has been shown to reduce microleakage (Craig, 1993). The amalgam corrosion products coming out of the restoration have a positive effect if they precipitate in the gap between the amalgam and the tooth structure and inhibit marginal leakage. The corrosion products at the cavosurface margin are phosphates, whereas the corrosion products seen within the mass of the restoration are oxides and hydroxychlorides. Both traditional and high-copper amalgams display this effect (O'Brien, 1997). There are various views on the success of sealing from corrosion products as conventional amalgam restorations require several months to exhibit self-sealing properties and high copper amalgams about twice as long (Liberman et al., 1989). Ben-Amar, (1989) reported that minimising the gap at the

amalgam / tooth interface improves the chances for self-sealing by corrosive products. Symons et al., (1987), confirmed this as they concluded from their study that restorations with small interface spaces may seal earlier as less corrosion is required to obturate the space.

1.9.3. Methods to reduce amalgam microleakage

A number of techniques have been used to minimise or prevent the initial marginal leakage or to seal the dentine tubules beneath the amalgam. The techniques have included for example the use of varnishes, zinc-oxide/eugenol, glass ionomer and resin-modified glass ionomer.

Varnish

Varnishes on the cavity walls under amalgam restorations have been widely used in an attempt to reduce marginal leakage (Sepetcioglu and Altman, 1998). Their use has been advocated for many years (Barber et al., 1964; Yates et al., 1980; Murray et al., 1983). Although the varnish creates a mechanical barrier it does not bond to either the amalgam or the tooth structure (Ben-Amar et al., 1990). It has also been demonstrated (Ben-Amar et al., 1990; Saiku et al., 1993) that varnishes cannot produce a long lasting seal. Gottlieb et al., (1985) reported using a varnish as a cavity liner under a high copper amalgam restoration, produced increased microleakage when compared to varnish under a conventional amalgam. Furthermore, the use of cavity varnish demonstrated no significant advantage.

Other studies have demonstrated that copal varnish does not significantly reduce microleakage although other resin liners have been more successful (Edgren and Denehy, 1992; Berry and Tjan, 1994).

The suggested method to control leakage until the amalgam corrosion products seal the gap requires copal varnish to be applied to the cavity walls and margins prior to the placement of amalgam. Two applications of varnish are reported to be more effective than one (Ben-Amar, et al., 1986). However, Liberman et al., (1989) in their *in vitro* study disagreed over the effectiveness of cavity sealing using varnish. This study reported that after 14 months, copal varnish did not improve the sealing of conventional or high-copper amalgams. This could be as a result of the varnish dissolving before the corrosion products are fully formed. Andrews and Hembree, (1980) reported that a thin coating of a copal resin varnish applied to the cavity walls and margins before packing the amalgam alloy helped to seal the marginal discrepancies. They postulated that as the varnish gradually dissolved out, the gap was filled with corrosion products from the amalgam. The dissolution of the varnish ceased with the action of the corrosion activity, which helped to seal the marginal discrepancy. However Fitchie et al., (1990) who studied leakage in relation to cavity varnish, reported after 6 months the dissolution of the varnish was too great for the corrosion products from high-copper amalgams to seal the marginal gap.

Therefore, it appears from the literature that researchers have many different views as to the effectiveness of copal varnish to provide a marginal seal for amalgam restorations.

Adhesive resins

Developments in adhesive dentistry suggest that using an etch-retained unfilled resin bonded to dentine may be an effective alternative to varnishes in amalgam restorations (Ben-Amar et al., 1990, Gwinnett et al., 1994; Al-Jazairy and Louka, 1999).

The method to reduce marginal leakage is to coat the cavity walls with the etch-retained, unfilled resin prior to packing the amalgam. Although the resin will gradually wear away and allow the corrosion products to fill the marginal gaps, it delays the onset of microleakage. A six-year study comparing traditional amalgam and composite restorations, and amalgam restorations placed in cavities previously coated with unfilled resin reported that amalgam restorations with resins had the best survival rate and the least number of marginal deficiencies compared to the other types of restorations (Mertz-Fairhurst et al., 1992). An interim report (Smales and Wetherel, 1994) using a high copper alloy with three resin bonding systems and a resin cavity varnish as adhesive linings clinically reported promising results with no failures during a 5 - 39 month period.

Some studies have reported the use of adhesive resins as liners to significantly reduce microleakage (Edgren and Denehy, 1992; Berry and Tjan, 1994; Setcos et al., 2000) and provide increased retention of amalgam (Staninec and Holt, 1989; Charlton et al., 1992). The use of chemically-activated or light-activated bonding or luting agents, to achieve " bonded amalgams" will also seal the cavity walls against microleakage (Zardiackas and Stoner, 1983). The goal of the unfilled resin intermediary is to seal the dentinal tubules against the entry of bacteria. The mechanism for adhesion between

enamel, dentine and resin, with the formation of the so called hybrid layer is generally accepted as the main mechanism for micromechanical retention. However, between resin and amalgam, both chemical coupling mechanisms and mechanical intermingling of polymer and amalgam have been suggested as the bonding principles (Boston, 1997)

Glass- ionomers

Reductions in microleakage have been reported when cavities were lined with glass-ionomer cements (Manders et al., 1990; Arcoria et al., 1991; Tjan 1997). The use of glass-ionomer as a liner has some advantages over other materials. The advantages are high compressive strength; adhesion to enamel, dentine and cementum (Lacefield et al., 1985); the ability to release fluoride (Swartz et al., 1984) and compatibility with the oral tissue and other restorative materials. When an amalgam restoration leaks there is the possibility of recurrent caries which may be reduced because of the release of fluoride ions from the lining material. The fluoride ions inhibit bacterial activity and increase tooth resistance against demineralisation. Additionally the use of a glass-ionomer cement liner has been advocated to reduce microleakage and possibly improve the life expectancy of the restoration (Manders et al., 1990, Aboush and Elderton 1991, Arcoria et al., 1991). Aboush and Elderton (1991) suggested that amalgam/ glass-ionomer bonds are probably as the result of mechanical interlocking of the amalgam triturate and the glass-ionomer cement. However ionic exchange at the interface cannot be excluded. Their study reported mean tensile strengths of 5MPa, which are similar to that which can be expected between dentine and glass-ionomer (Aboush and Jenkins, 1986). They concluded from their study that the tensile bond strengths achieved were clinically relevant.

Resin modified glass-ionomers

Resin-modified glass-ionomers under amalgams are used because they bond to dentine and release fluoride (Barakat et al., 1988).

A comparative study of bond strengths of glass-ionomers, composite resin adhesives and amalgam compared with resin-modified glass-ionomer cements reported a substantially greater retention of amalgam restorations with the resin-modified glass ionomer (Vitrebond) being an effective amalgam adhesive resin (Al- Moayad et al., 1993).

Although the benefits of improvement in tensile and bond strength are advantages it is the reduction in microleakage that is of clinical significance. Tjan et al., (1997) reported reduced microleakage using Amalcoden and Fuji Duet as a complete interface liner between tooth and amalgam.

Other lining materials for reducing the marginal leakage of amalgam

Other materials under amalgam have been used such as zinc-oxide/eugenol or calcium hydroxide base material. Research has suggested that microleakage is reduced when these materials are placed under amalgam restorations (Bartlett, 1992). They partially inhibit bacterial penetration into the dentinal tubules and bacterial growth at the tooth-restoration interface (fluid-filled gap). In time the fluid movement in the gap may partially or totally dissolve the lining material resulting in a larger gap with a higher risk for caries (Brannstrom, 1984). However, according to some researchers, these lining materials, do not reduce microleakage around amalgam restorations (Ben-Amar, 1989).

Zinc phosphate is also used as a liner under amalgams and is usually prepared from a high powder / liquid ratio. The amalgam alloy may be packed on top before it is entirely set. Zinc phosphate has a low pH and has been used for many decades as an insulating base material (to provide thermal protection for the pulp) beneath metallic restorations. Despite its acidic nature it is well tolerated by the pulp if placed on intact dentine, presumably as a result of the buffering of the unreacted acid by hydroxyapatite. While it is not proven that $ZnPO_4$ reduces microleakage, it may be a contributory factor until dissolution of the $ZnPO_4$ can be replaced by amalgam corrosion products.

1.9.4. Amalgam Bonding

In 1983 the concept of bonding amalgam restorations to tooth structure was introduced (Zardiackas and Stoner, 1983). The development of bonded amalgams aimed to determine if the advantages gained from bonding composites could be employed with traditional amalgam restorations. The aim was to create a strong bond between tooth structure and amalgam without the need for conventional retentive cavity design.

Various *in vitro* studies found an improvement in retention of amalgams bonded using composite resin to cavities without undercut preparations compared to traditionally-retained amalgam restorations (Eakle et al., 1994; Charlton et al., 1992; Staninec and Holt 1989). Current bonded amalgam techniques utilise dentine-bonding agents to achieve attachment to tooth structure (Staninec and Holt 1988).

After cavity preparation, the technique requires the application of an acid to etch the enamel and decalcify the dentine surface, followed by the application of hydrophilic

primers to penetrate the remaining collagen network. With subsequent adhesive application a "hybrid layer" results, and a micromechanical bond is formed to the dentin surface (Nakabayashi et al., 1982). The bond to the amalgam is achieved through the use of an autopolymerising adhesive. The mixed adhesive is applied to the prepared cavity and the amalgam is immediately packed/condensed onto the unset polymer. Some of the adhesive is forced into the amalgam forming a mechanical-interlock between the resin and amalgam. The technique began to be used by many practitioners in the 1990's.

The benefit of the technique is that the tooth would still be protected should debonding of the amalgam occur, provided of course that the adhesive remained totally bonded to all areas of the cavity preparation. SEM examination of bond failures between bonded amalgam and tooth structure show that the weak link is at the amalgam-adhesive interface (Santos and Meiers, 1994)

There have been some clinical reports (Staninec et al., 1993; Wetherell and Smales, 1993) published that confirm the laboratory assessment of amalgam bonding techniques (Scherer, 1992). Clinical studies of 4-META based adhesive resins reported a decrease in post-operative sensitivity with reduced instances of cusp fracture (Ueno, 1989; Trushkowsky, 1991). Other clinical reports have provided evidence of improved retention (Setcos et al., 1998; Ruzickova et al., 1997; Bearn et al., 1994).

Some of the advantages achieved using bonding techniques for amalgam are:

(a) Retention of complex restorations may be enhanced.

(b) Conservation of tooth structure due to the fact that there is less need for the preparation of specific retention elements.

(c) Cusp strengthening - resistance to cusp fracture.

(d) Improved marginal sealing.

(e) Reduction in post-operative sensitivity and subsequent secondary caries. (Staninec and Holt 1988)

Factors that may be considered as a disadvantage to amalgam bonding are:

(a) Clinical technique is more challenging, as there can be difficulty with the application of viscous bonding agents

(b) Excess resin bond and amalgam tend to blend at the margins of the cavity, which may make carving of the amalgam difficult.

(c) Lightly filled resin bonding agents with a high thermal coefficient of expansion can pool at the gingival margin resulting in a greater potential for microleakage. (Bryant, 1998)

(d) Moisture contamination inhibits the adhesion of the bonding agent to dentine.

Accepting the constraints of the procedures, it would appear from limited reports that using amalgam bonding techniques significantly reduces microleakage (Al-Jazairy and Louka, 1999) and increases the strength and stiffness of the restored teeth (Ario et al., 1995; Eakle et al., 1992; Varga et al., 1986).

1.9.5. Summary

Traditionally, amalgam restorations have been retained mechanically. However, this is changing with techniques using adhesive resins that bond to amalgam, enamel and dentine (Setcos et al., 2000). The benefits are a reduction in microleakage, enhanced retention and the conserving of sound tooth structure (Staninec and Holt, 1989). However, the lack of adhesion to tooth structure, marginal leakage, susceptibility to tarnish and corrosion, and loss of marginal integrity have either restricted the use or limited the success of amalgam restorations (Reese and Valega, 1985). Even with all its problems, currently, more than a century after its introduction, there is still no adequate, economic alternative for dental amalgam as a restorative material.

1.10. Porcelain inlays

1.10.1. Definitions

Dental ceramics are defined as non-metallic and inorganic materials formed after baking at high temperatures (Rosenblum & Schulman, 1997)

Porcelain is a group of materials classified as ceramics (Giordano, 1996). The word ceramic is derived from the Greek 'Keramos' meaning " a potter or pottery" (Giordano, 1996). Another interpretation of the Greek for ceramic is 'Keramikos' meaning "earthen" thus ceramic can be described as an earthy material, usually silicate or of a silicate nature (McLean, 1979).

Porcelain inlays are intracoronal restorations that replace small to medium amounts of tooth structure. A porcelain inlay is a restoration made outside the mouth, usually in a dental laboratory (Gladwin and Bagby, 2000).

1.10.2. Classification of porcelain

Traditional ceramics typically contain ingredients of feldspar, silica and kaolin as the main components with oxides such as alumina (Al_2O_3), potash (K_2O), and soda (Na_2O). Stone ware (tiles), porcelain (tableware, china), earthenware (pottery), bricks and sanitary ware are all characterised as traditional ceramics (Giordano, 1996).

Conventional dental porcelain is a vitreous ceramic based on silica (SiO_2), potash and feldspar ($K_2O.Al_2O_3.6SiO_2$), soda feldspar ($Na_2O.\ Al_2O_3.6SiO_2$) or both (Anusavice, 1996). In its mineral state, feldspar, the main constituent of dental porcelain is crystalline and opaque. Chemically it is designated as potassium aluminium silicate ($K_2O.Al_2O_3.6SiO_2$).

In dentistry different types of porcelain are used depending on their application

a) Porcelain is used in the commercial manufacture of artificial teeth for dentures. It comprises of a mixture of feldspar, clay and quartz powders. It is referred to as high-fusing porcelain (1300^0 C)
b) Porcelains used in the fabrication of metal-ceramic restorations are normally medium fusing (1100 -1300^0 C) or low fusing (850 –1100^0 C). They contain a mixture of potassium feldspar and silica (SiO_2).
c) Porcelain jacket crown, veneer and inlay porcelains are medium fusing (1100 - 1300^0 C). They contain feldspar, quartz, kaolin and metallic pigments.
   Low fusing (850 – 1100^0 C) and ultra-low fusing (<850^0 C) porcelains are also used, in some instances for the fabrication of crowns inlays and veneers.

All of the above types of dental porcelain contain pigments and opacifying agents to create various shades and translucencies. The pigments fused within the glassy material are usually oxides of chromium, cobalt, nickel and titanium. However glazes and stains may be used to achieve a specific aesthetic effect as requested by the dentist. For example crack lines and cervical staining.

A typical medium-fusing porcelain used for vacuum firing will contain (by weight) SiO_2 - 65%, Al_2O_2 -19% and a number of fluxes, B_2O, K_2O, NaO_2, MgO, Li_2O, P_2O_5 - 16% (Combe et al., 1999).

The porcelains used in the fabrication of restorations are also classified according to their application:

Core porcelain – This is normally aluminous porcelain and is the basis of a porcelain jacket crown.

Dentine porcelain - The major shape of the restoration is usually built with dentine porcelain. It is more translucent than the core porcelain and normally dictates the colour of the restoration.

Enamel porcelain - This is used in areas requiring maximum translucency, for example at the incisal edge.

1.10.3. History of dental porcelain and inlays

Ceramics are thought to be the first materials ever made by human beings. The use of ceramic materials in dentistry goes back over two hundred years (Kelly et al., 1996) and can be traced to 1728, when Fauchard suggested the use of ceramics to restore teeth. Later the French chemist and pharmacist Duchâteau, who was unhappy with the taste and odour of his ivory dentures, observed that the glazed porcelain utensils in daily use for mixing and grinding his various chemical compounds appeared to resist staining and

abrasion. With the help of porcelain manufactures he succeeded in making himself a set of porcelain dentures that were unaffected by taste or abrasion (Guerini, 1909). Later, Duchâteau working with a dentist named Nicholas Dubois de Chemont, was successful in producing dentures from porcelain that used using lower firing temperatures compared to the earlier attempts that had used high fusing porcelain pastes.

In Italy, (1808) the first individual porcelain teeth were manufactured with small hooks embedded in the porcelain teeth for attaching them to the denture bases (Guerini, 1909). Individual inlays and crowns were not developed until the 1800's.

Land, (1886) fabricated the first fused feldspathic porcelain crown, using platinum foil as a substructure with the high, controlled heat of a gas furnace (Jones, 1985). However, despite the popularity of the crowns there were problems relating to strength which were only solved with the introduction of alumina as a reinforcing phase in dental porcelain (McLean & Hughes, 1965).

Porcelain inlays have been used in dentistry for over 100 years (Qualtrough et al., 1990). Murphy of London in 1839 introduced a platinum-foil technique which made the present day development of porcelain-inlay construction possible (Huff, 1928). Another technique was developed by Herbst of Germany in 1882 who produced inlays of "pulverised" glass. The technique involved recording an impression of a cavity in wax, casting two models using a mixture of asbestos and plaster. The firing was carried out in two stages. The first mould was filled with the pulverised glass frit (prepared by glass manufacturers by blending and melting raw materials together) and fired using a Bunsen

burner and blow-pipe. Following firing it was transferred to the second mould and more glass added to compensate for the firing shrinkage that occurred in the first mould, Similar to the first firing, it was again fused with the use of a Bunsen. The firing was carried out in two stages.

The initial porcelains were weak and were cemented with zinc phosphate cement. The main application for the early fabricated ceramic inlays was the Class V restoration. Developing better porcelain inlay systems has challenged researchers to improve both technique and materials to overcome the initial problems of porcelain weakness, poor fit, cement failure and microleakage (Kelly et al., 1996, Banks, 1990, Qualtrough et al., 1990). In addition, the fabrication technique of the early porcelain inlays was very difficult and often inaccurate (Krejci et al., 1993[a]).

1.10.4. Firing of dental porcelain

Before 1960 firing of porcelain was normally carried out within an air-fired gas or electric furnace. After 1960 porcelain restorations have normally been fired within an electrically heated vacuum furnace in order to reduce porosity in the porcelain. Porosities and cracks have been shown to be sites of fracture initiation. Sintering under vacuum helps reduce the amount of porosity (Van Dijken. 1999). Sintering changes the powder to a solid whilst maintaining the shape of the mass. Firing porcelain causes the powders to become "sintered".

During sintering the density of porcelain greatly increases and is associated with a substantial volumetric shrinkage ranging from 30-40% (Combe et al., 1999). The

volume of shrinkage relates to the amount of condensing of the porcelain that is achieved during the "building-up" stage. During fabrication the porcelain particles are bound together with modelling fluid (distilled water and surfactants) to form a plastic mass (which shrinks on firing), the greater the condensing (compacting) of the mass the less is the contraction. After firing, all three types of porcelain contain similar components: small crystals (leucite and/or other alumino-silicate crystals) embedded in a silicate glass (a non-crystalline, amorphous matrix). The relative amounts of crystal and glass depend on the specific type of porcelain in question. Leucite is an important component in dental porcelain because it affects the thermal expansion, strength, hardness and optical properties (Rosenblum and Schulman, 1997).

To reduce porosity, the initial and intermediate (correction) firing of porcelain restorations is performed under a vacuum. The less porous (more dense) the porcelain is, the greater will be the strength of the restoration. After trimming, the final firing (glaze firing) in the furnace is carried out without vacuum (air firing). The glaze cycle seals the surface of the trimmed porcelain giving it a surface gloss necessary to simulate the natural tooth surface (Craig et al., 1987). Alternatively a glaze powder, containing low fusing fluxes and silica, can be applied to the surface and the restoration fired (without vacuum).

1.10.5. Alternative materials used for posterior inlay fabrication

The popularity of tooth-coloured posterior restorations has increased because of a demand for an aesthetic restorative material. Amalgam still remains the most widely used material for posterior restorations, but new approaches toward cavity design,

changing patterns in disease and concerns about possible side effects and environmental effects has resulted in the development of alternatives to amalgam. Posterior composite resins have been used increasingly during recent years. Despite promising results, problems with polymerisation shrinkage, surface wear and questions about biocompatibility have been highlighted as disadvantages to their use (Wilson et al., 1988).

The modern highly-filled, small-particle hybrid composites, with an average particle size of aproximately1μm, have been shown to have improved clinical wear characteristics over three years (Willems et al., 1990). The problem of polymerisation shrinkage especially at margins is influenced by the properties of the material. For example the resin composition, filler content, stiffness, application techniques and direction of light application (Lutz et al., 1986 & 1991). The larger the volume of composite to be cured the larger will be the polymerisation shrinkage and if it is bonded to enamel margins, polymerisation shrinkage will generate internal stress in the material. The problems of marginal behaviour shrinkage and wear encountered with the use of posterior composite resins has led to a revival of interest in all-ceramic restorations (Tyas, 1994).

Ceramics exhibit excellent aesthetics and are considered one of the most biocompatable of all dental materials. The advantages of ceramic restorations over direct composite resin restorations are the control of polymerisation shrinkage, improved marginal adaptation and anatomical form (Van Dijken, 1999)

1.10.6. Methods of producing porcelain inlays

A number of methods are available for the fabrication of porcelain inlays. These are:

conventional porcelains

castable ceramics

machinable ceramics

pressable ceramics

infiltrated ceramics

They are discussed in detail in the following section.

Conventional porcelains

Porcelain jacket crowns were the first all ceramic restoration used in dentistry. The entire crown is made of porcelain, it has good aesthetics and is biocompatible (Gladwin and Bagby, 2000). Porcelain inlays are constructed from porcelains similar to those used to fabricate crowns using regular feldspathic porcelain. Inlays are fabricated by applying a powder-water slurry in layers on either a thin platinum matrix or a refractory die. The platinium matrix is adapted to the die and supports the porcelain during the building, firing and finishing stages. The alternative method uses a phosphate bonded investment as the refractory material on which the porcelain slurry is built and fired. The investment is compatible with the porcelain coefficient of expansion. Before delivery to the patient the foil is removed from the fitting surface of the inlay or, alternatively, the investment is removed by sand blasting using 50μm aluminium oxide. The fitting surface of the inlay is laboratory etched with 9.5% hydrofluoric acid to produce a rough surface for the attachment of the luting resin.

Despite their lifelike aesthetics, problems of relatively low tensile strength, brittleness and the potential to cause abrasive wear of the opposing tooth structure has limited the use of porcelain inlays made from medium fusing porcelain (Rosenblum & Schulman, 1997). There were reports, of failure rates of 2% - 12% (6 years) for feldspathic porcelain inlays (Mirage™) when the inlays were luted with dual-cured resin composite cement (Van Dijken et al., 1998). Results after 40 months for inlays cemented with light-cured resin composite cement were very disappointing with failure rates as high as 80% being reported (Isidor and Brondum, 1995). The main reasons for failure reported in the studies were fracture or loss of inlays.

Castable ceramics

The search for stronger all ceramic restorations resulted in the development of castable glass materials. These products are supplied as solid glass ingots, which are used for fabrications of cores or full-contour-restorations. The glass (DICOR ®) is produced in only one white shade. It was developed by Corning (Corning Glass Works, Corning, NY, USA) and marketed by Dentsply International (Gladwin and Bagby, 2000). It is a polycrystalline material, initially formed as a glass and subsequently heat- treated under controlled crystallisation conditions to produce a ceramic-material. The glass is cast, using a lost wax technique and then given a strengthening heat treatment to induce partial crystallisation (ceramming) (Rosenblum, & Schulman, 1997). The desired shade to match the patients tooth shade is achieved by veneering the cast glass with a thin layer of medium fusing feldspathic porcelain.

Castable ceramic inlays are an improvement over conventional porcelain restorations. However, high failure rates have been reported for resin composite luted DICOR ® inlays 6% -13% after four years (Roulet, 1995, Noack and Roulet, 1994). With glass ionomer luted inlays, the failure rate was 23% after five years (Stenberg and Matsson, 1993)

Machinable ceramics

Computer-aided design / computer aided manufacturer (CAD-CAM) restorations are produced from ceramic ingots. The system requires an optical scan to be made rather than a physical impression of the prepared tooth. A computer controlled miniature milling machine with four axes mills to shape a ceramic block using a water-cooled, diamond coated disc. The final adjustment and polishing is performed by the dentist (Qualtrough et al., 1990). The main advantage of CAD / CAM restorations are a chairside ceramic inlay in one visit (Smith and Cardwell, 1989).

Disadvantages relating to this developing technique are:

1. A lack of variation of shade. The inlays are machined out of single-shade blocks. However they can be stained and glazed to obtain the desired characterisation.
2. The potential for occlusal wear as the surface roughness of the restoration may result in abrasive wear of opposing teeth. Newer systems have a finer grain size and evaluation *in vitro* shows that this produces less abrasive wear (Krejci, 1991).
3. The initial and running costs of the equipment are very expensive (O'Brien, 1997).
4. The clinical technique required for surface imaging. This is a very technique sensitive procedure (Goldstein et al., 1998).

There have been conflicting reports of clinical success. Evaluations carried out over a two to four year period of CEREC® inlays have reported failure rates of 6% (Sjögren et al., 1992, Zuellig-Singer and Bryant, 1998). However, 100% success was reported for three and four year evaluations undertaken (Gladys et al., 1995; Heymann et al., 1996). Differences in failure rates were apparent and thought to depend on the resin used for bonding. Failure rates of 6% for inlays luted with a chemically-cured resin and 15% for inlays luted with a dual-cured resin composite cement (Sjögren et al., 1998).

Pressable ceramics

Pressable ceramics are also supplied ingot form. They are melted at high temperatures and pressed into a phosphate investment mould that has been created using the lost wax technique. Pressable ceramic restorations can be made to the full contour of the tooth and finished either by staining or glazing techniques. This method can also be used as core material and built up using conventional porcelain.

The advantages of a pressable ceramic restoration include excellent marginal adaptation, moderate flexural strength and good aesthetics. The translucency of the material is chiefly responsible for its aesthetic qualities. The disadvantages are the need for special laboratory equipment its potential to fracture in areas of high occlusal loading (Anuasavice, 1996).

There have been a number of clinical studies where results show varying degrees of failure. Two-year results of a pressable ceramic system (Empress®) reported failure rates of 2% -5% when luted with a dual-cured resin composite (Tidehag & Gunne,

1995; Studer et al., 1996). One, five-year follow up study reported failure rates of 20% (Molin and Karlson, 1998). However, this conflicts with a reported 7% failure rate at six years (Studer et al., 1998). The main reason for failure, reported from these studies, appears to be fracture of the heat pressed inlays. However, some instances of secondary caries were reported, which could be interpreted as evidence for microleakage.

Infiltrated ceramics

Infiltrated ceramic inlays and crowns are based on the slip-casting science of preparing stable suspensions and fabricating structures by building a solid layer on the surface of a porous mould that absorbs the liquid phase by means of capillary forces (McLean, 2001). The technique of slip casting has been used in pottery firing for over two hundred years. Sadoun (1989) refined the technique to produce a high strength alumina coping (In-Ceram, Vita Zahanfabrik, Säckingen Germany) (McLean, 1991). The system has two components: a powder (Al_2O_3 or spinel) and a low firing glass. The powder is made into a porous structure, which is infiltrated at high temperatures by the low fusing glass. The diffusion of glass through the porous alumina fills the spaces between the alumina particles resulting in a dense material that has a very high strength. This system is often used for crown copings, which are veneered with more aesthetic porcelain. Infiltrated ceramics made using Al_2O_3 as the powder have concentrations of pure alumina in excess of 70% making it one of the strongest ceramic restorations with a flexural strength of up 630MPa (McLean, 1995).

Infiltrated ceramics made using spinel as the powder (In-Ceram® spinel) are more than twice as translucent as the alumina coping and are more suited for aesthetically critical areas and inlays (Van Dijken, 1999).

The main advantage of the system is the increased strength compared to conventional porcelain restorations. Disadvantages of the system are the expense, the process is technique sensitive and its use in bridgework is questionable with high failure rates being reported (Dürr et al., 1993).

1.10.7. Summary

Development and the use porcelain inlays has fluctuated during the last century. During recent years there has been a revival of interest in their use with the development of innovative materials coupled with new methods of luting. Aesthetic intracoronal porcelain inlays appear to have performed reasonably well in some clinical situations compared with other materials. Currently there does not appear to be any one ceramic inlay material or technique that is better than the others.

In future the use of ceramic inlays (adhesively-luted) may be used more than amalgams for large cavity restorations because of their conservative nature and aesthetic qualities. However, the revival of interest in ceramic inlay restorations must be tempered with continuing problems relating to the technique sensitivity of both clinical and laboratory stages, as well as the expense of the technique and the clinical failure rate.

Comment

Posterior intracoronal restorations have traditionally been filled with amalgam and luted with various materials to reduce leakage. However, with the introduction of resins they are now being bonded to reduce microleakage. The aesthetics of posterior restorations is a concern for patients thus there is an increasing trend to restore posterior teeth with porcelain or tooth coloured restorations. Although many researchers have published studies of amalgam, porcelain, microleakage and bonding resins *in vitro* and *in vivo* at present there appears to be limited published research that links/correlates the effect of restoration wear and the development of microleakage because of occlusal loading and wear. The aim of this study described in chapter 2 was to assess microleakage in relation to wear *in vitro*.

Chapter 2.

2.0. Materials and Methods

2.1. Introduction and Aims

The wear of human enamel opposing restorative materials is a concern, for clinicians, when selecting materials for clinical treatment. A number of *in vitro* studies have been carried out to assess the amount of wear. The majority of research has mainly been carried out with two-body-wear systems and only a small number simulating the food bolus employing three-body-wear (Al-Hiyasat et al., 1999; Al-Hiyasat et al.1998[a]; Kaidonis et al., 1998; Ramp et al., 1997). The reports have described different rates of wear but none of the reports relate the effect of wear to the possible development of microleakage or the methods used to retain the restoration.

The aims of this *in vitro* study were

- to examine marginal leakage of intracoronal restorations subject to occlusal stress when a simulated biting force impacts and slides over the surface of the tooth.

- to assess the ability of two bonding systems to seal restorations over a predetermined period in relation to wear (three body) of the restoration.

2.2. Experimental Design

One hundred teeth were randomly assigned to groups as shown in figure 2.1. The control group used twenty specimens restored using a conventional amalgam technique. Forty specimens were filled using bonded amalgam and the remaining forty specimens were restored with indirect porcelain inlays.

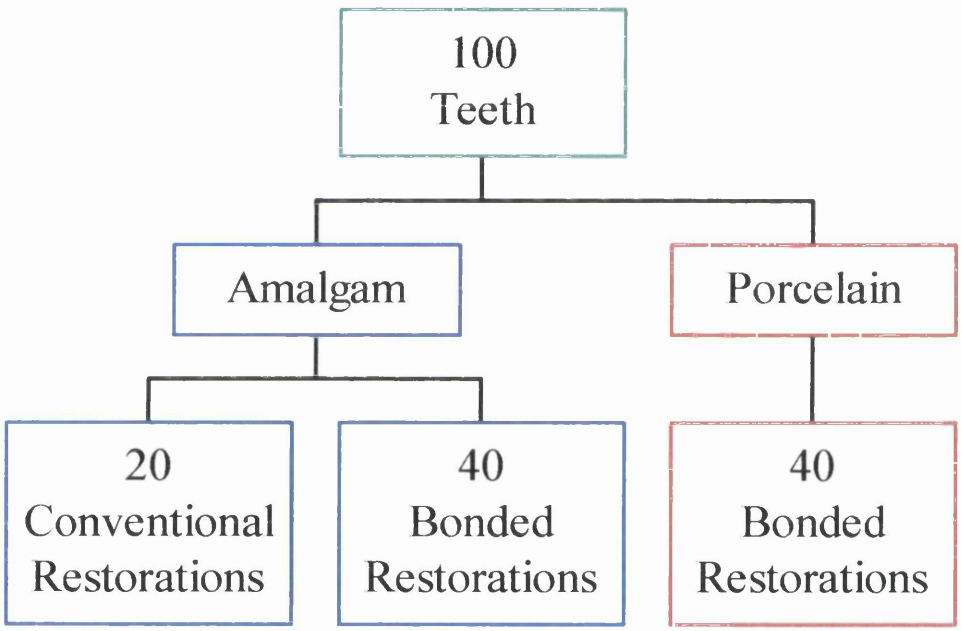


Figure 2.1. Flow chart of restoration groups.
Forty indirect inlays (porcelain).
Twenty direct restorations (amalgam control group)
Forty direct restorations (bonded amalgam)

2.3. Tooth Preparation

2.3.1. Tooth collection

At the start of the study one hundred and ten extracted caries free human molar teeth and fifty-five caries free human pre-molars (antagonists to provide the impact biting force) were collected from Glasgow Dental Hospital and a number of General Dental Practices in Glasgow. They were cleaned, stored in 0.12% thymol solution and kept refrigerated at 4^0C. until required. Ten molars and five pre-molars were assigned for developing operating procedures/techniques.

2.3.2. Mounting and identification of teeth

For ease of handling and identification the one hundred specimens were mounted in individual stone blocks (Kaffir D - Lafarge/Prestia, Meriel, France) and marked with an identifying code. During the preparation and subsequent stages, all of the specimens were stored in de-ionised water.

2.3.3. Cuspal reduction of teeth

The cusps of the molar teeth were reduced to form a flat occlusal surface to correspond with the "travel" pattern of the horizontal arm in the dental wear machine. The height of the cusps were reduced with a 22mm diameter diamond coated disc (0.12mm thick) (Chaperln & Jacobs Ltd, Sutton, UK) mounted in a K9 laboratory handpiece (Kavo Elektrotechnisches Werk, Leutkirch im Allgäu, Germany) running at 25,000rpm.

Final smoothing of the flattened occlusal was achieved by hand abrading the tooth against a range of silicon grit papers (Bramet, Kemet International Ltd., Maidstone, UK), initially with a 400 grade, followed by reducing grades of fineness (800 and 1200) to create a smooth surface.

2.3.4. Cavity preparation

All of the class I cavities were cut, in the flat occlusal surface, to the same shape and size using a template placed over each tooth. The cavity dimensions were:

(a) mesial-distal length of 6mm

(b) buccal-lingual width of 4mm

(c) 1mm deep into dentine.

The cavities were cut using a size 040 straight diamond bur (806 104 198 524 - Komet, Lemgo, West Germany) at high speed with water coolant and finished with a size 009 bur (500 313 287 072 - Komet, Lemgo, West Germany) in a high-speed handpiece.

2.3.5. Preparation of tooth antagonists

An opposing force was provided by sectioned premolars to assess if impact and wear contributed to microleakage of restorations.

Fifty caries-free human mandibular premolars were prepared by reducing the lingual cusp(s) to leave only the buccal cusp. Each tooth was carefully cut through the long axis of the tooth sectioning it in half in a buccal-lingual direction through the tip of the buccal cusp. They teeth were sectioned using a Labcut 1010 machine (Agar Scientific

Ltd., Stansted, UK) with a water cooled edge-coated diamond blade (continuous rim disc 4" diameter and 250 μm thickness) (D.K. Holdings Ltd., Staplehurst, Kent, UK).

The cut edges, of the two antagonists obtained from each tooth, were smoothed using Sof-lex finishing discs (3M Dental Products, St Paul, MN, USA) of increasing degrees of fineness with care being taken to avoid damage to the cusp tip. The tooth was positioned in a predetermined position using an acrylic jig (figure 2.2). A scale, which related to impact points, was used to site the tooth. The jig was constructed to ensure that the tooth was perpendicular to the horizontal plane. The tooth was sealed to the jig in the position that would ensure that the cusp tip would impact on the selected surface of the tooth/restoration when mounted in the wear machine. The root portion was embedded in the upper specimen holder using autopolymerising resin (Formatray).

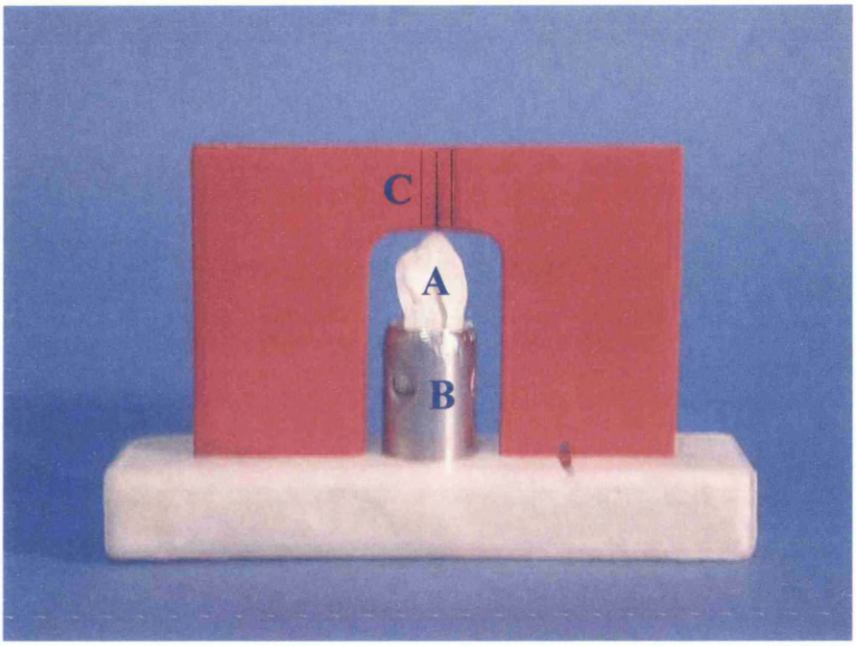


Figure 2.2. Antagonist in alignment jig

A. **Sectioned premolar**
B. **Wear machine specimen holder**
C. **Alignment points**

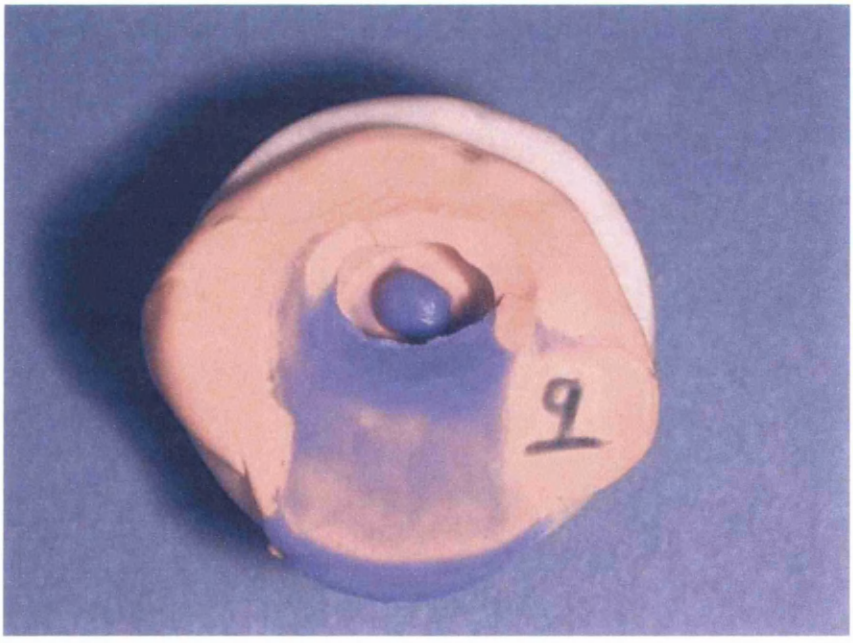


Figure 2.3. Polyvinylsiloxane Impression
in customised impression tray

2.4. Indirect Inlay Fabrication and Bonding

2.4.1. Impression technique

Individual trays were constructed for forty specimens requiring porcelain inlays using an autopolymerising resin (Formatray - Kerr, Romulus MI, USA) and stored for twenty four hours before the impressions were recorded.

Individual impressions of the prepared cavities were recorded with a polyvinylsiloxane impression material (President - Coltene/Whaledent Inc., Mahwah, NJ, USA) using a one stage technique (figure 2.3.). Following setting of the impression material, it was withdrawn from the tooth, labelled and stored at room temperature for four hours before being poured. The four-hour delay was to ensure that any residual chemical reaction (release of hydrogen gas from the platinum salts in the catalyst (McCrosson et al., 1987) had finished. Early pouring of the impressions could result in poor surface detail due to the hydrogen gas imploding into the surface of the setting diestone resulting in an inaccurate cast.

2.4.2. Die construction

The casts were poured in a diestone material (Velmix - Kerr, Romulus MI, USA). The diestone was mixed, in the correct water-powder ratio, under vacuum (Multivac 4 – Degussa AG, Geschäftsbereich Dental, Frankfurt am Main, Germany) according to manufacturers' instructions. The diestone material was carefully vibrated into the impressions using a dental vibrator (KV 36 – Wassermann Dental Maschinen Gmbh,

Rudorffweg, Hamburg, Germany) to achieve a surface without any air entrapments. The filled impressions were left to set for twenty-four hours before removal.
Following removal, from the impressions, the casts were trimmed, inspected under magnification (X 4) (Mantis – Vision Engineering Ltd., Woking, Surrey, UK) and labelled for ease of identification.

2.4.3. Refractory Construction

Forty refractory casts were produced from duplicates of the diestone casts. Although an accurate fitting porcelain inlay was required, it was found during the initial development stages that, when the inlays were constructed without a die spacer they resulted in a fit that was too tight. This created problems during the seating/bonding of the restoration to tooth structure. Thus, to ensure ease of seating of the indirect restorations, the cavity fitting surface of the diestone casts were coated with a 25 μm liquid spacer (Tru-Fit – George Taub Products, Jersey City, NJ, USA) prior to duplication. Following duplication, with a laboratory silicone (C& J Pourable Silicon - Chaperlin & Jacobs Ltd., Sutton UK) the moulds were poured in a refractory investment (Lamina Vest - Shofu Dental Gmbh Am Brüll 17, D-40878 Ratingen, Germany). The coefficients of expansion of the investment matched those of the porcelain powders. The refractory was mixed in a liquid /powder ratio (6ml liquid - 40g investment) under vacuum for thirty seconds. To ensure the elimination of air bubble entrapment, the mixed investment was carefully poured, under vibration into the duplicated moulds. A carbon rod was positioned in the setting investment of each mould (the carbon rod was used as the carrier when transferring the refractory models in and out of the firing furnace). The set investment was left for one hour before it was carefully removed from the mould.

Following removal from the moulds the refractory models were marked with the appropriate identification code.

In preparation for the porcelain "building-up" stages and firing of the porcelain, the refractory models were placed in a wax burnout furnace (Kavo 5636 - Kavo Elektrotechnisches Werk, Leutkirch im Allgäu, Germany), heated from room temperature to 700^0C and held for thirty minutes. Lamina Vest is a phosphate-bonded investment that releases ammoniated gases at the first firing. These gases, inherent in phosphate refractory materials, have to be eliminated in order to avoid contaminating the porcelain.

The final stage of the refractory process was carried out in the porcelain furnace (Vita Vacumat 100 - Vita Zahnfabrik, H. Rauter Gmbh & Co. KG, D-7880 Bad Säckingen, Germany). The refractory models were heated from 700^0 C to 980^0 C in air and heat-soaked at 980^0 C for five minutes. At the completion of the heating cycle the refractory casts were removed from the furnace and allowed to bench cool.

2.4.4. Porcelain build up and firing

Forty porcelain inlays were constructed using feldspathic porcelain (Vintage Lamina Porcelain – Shofu Dental Gmbh, Ratingen, Germany) according to the manufacturers' instructions. All of the inlays were made with the same batch of porcelain and fired using three firing cycles (table 2.1) in a programmed controlled furnace (Vita Vacumat 100 - Vita Zahnfabrik, H. Rauter Gmbh & Co. KG, D-7880 Bad Säckingen, Germany).

At the finish of each firing cycle the refractory casts were cooled slowly to room temperature.

On completion of the second firing cycle the porcelain restorations were finished using green silicon carbide stones (Meisinger 731- Chaperlin & Jacobs Ltd., Sutton UK) and sintered diamonds (Meisinger 850S-031- Chaperlin & Jacobs Ltd., Sutton UK) mounted in a laboratory handpiece. Following trimming, the porcelain inlays were washed, inspected under magnification (X4) and glazed (cycle 3).

Firing cycles:

Firing Cycle	Programme	Start temperature	Pre-Drying Time	Heating upTime	Vacuum Firing Time	End Temperature Firing Time	End Temperature
	No.	^{0}C	Mins.	Mins.	Mins.	Mins.	^{0}C
1	6	600	6	6	6	1	940
2	6	600	6	6	6	1	935
3	3	600	0	3	0	1	930

Cycles: 1 - build up stage; 2 – addition and correction firing; 3 – glaze.

Table 2.1. Porcelain firing cycle regime.

2.4.5. Laboratory finishing stages

The final stages of the laboratory fabrication required the removal of the refractory investment, checking the fit of the inlay in the master die and chemically etching the fitting surface of the inlays.

Investment removal

A polishing bead particle abrasive was used to carefully remove the refractory material from the porcelain inlays, as it does not damage porcelain. The investment was air abraded (pressure - 6 bar) with 50μm aluminium oxide polishing bead (Rolloblast – Renfert Gmbh & Co., Hilzingen, Germany) using a pencil microblaster (Keramo 3 - Renfert Gmbh & Co., Singen, Germany).

Trial fit

The fit of the porcelain inlay in the master diestone cast was inspected under magnification and in some instances minor adjustments of the fitting surface (using a sintered diamond bur mounted in a laboratory handpiece) were required to achieve a satisfactory fit.

Chemical etching

To prevent etching of the inlay's glazed surface, it was sealed with model cement (Sticky wax, Kemdent, Associated Dental Products Ltd., Swindon Wiltshire, UK). The fitting surfaces of the inlays were etched, using 9.5 % hydrofluoric acid (Ceram-etch-Cresco Products Inc., Stafford England), for eight minutes. Following etching the inlays were rinsed under running water and ultrasonically cleaned (L & R Ultrasonics Ltd. Wealdstone, Harrow, England) in water for five minutes to ensure complete removal of all traces of the acid. The etched inlays were placed in labelled containers and stored in preparation for the insertion/bonding stages.

2.4.6. Bonding systems

The tooth specimens and corresponding inlays were randomly divided into two groups. The inlays were bonded using either Scotchbond Multi-Purpose Plus with 3M Opal luting cement (3M Dental Products, St Paul, MN, USA) **"A"** or Nexus Universal Luting System (Kerr UK Ltd., Bretton, Peterborough UK) **"B"** as shown in figure 2.4. All restorations were bonded according to manufacturers' instructions.

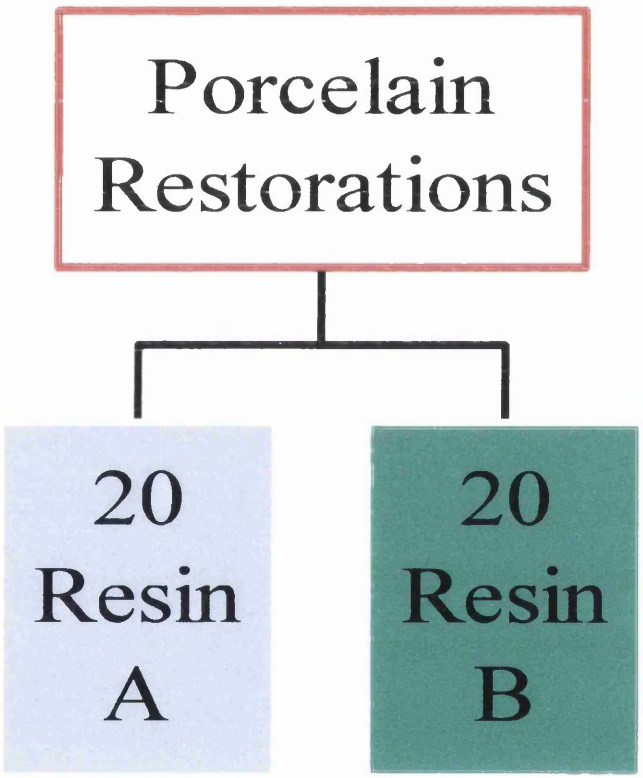


Figure 2.4. Flow chart of bonding systems.
A: Scotchbond Multi-Purpose Plus with 3M Opal luting cement system.
B: Nexus Universal Luting System

2.4.7. Bonding regime - Resin A (Scotchbond Multipurpose Plus)

Trial fitting

The restoration was picked up with a Pic-N-Stic (Pulpdent Corp. Watertown, MA, USA) and the fit checked within in the cavity. Following satisfactory trial seating of the restoration, the tooth/cavity was washed and dried with a 3-in-1 syringe.

Cavity surface preparation

(a) Etching: Gel etchant (37.5% phosphoric acid) was applied for fifteen seconds to the dentine and enamel, rinsed for fifteen seconds and dried for two seconds leaving the surface moist.

(b) Activation: The activator was applied to the etched enamel and dentine and gently dried, with medically pure air, for five seconds.

(c) Priming: The primer was applied to the activated enamel and dentine and dried for five seconds.

(d) Catalyst: The catalyst was applied to the primed surfaces of the tooth.

Ceramic inlay surface preparation

(a) Silane treatment: The etched surfaces of the porcelain restoration were coated with silane (ceramic primer) and gently dried with medically pure air for five seconds.

(b) Catalyst: The catalyst was applied to the treated surface of the indirect restoration.

Fitting of inlay

Dual-Cure resin was applied to the fitting surface of the restoration and the restoration seated in the cavity. Excess paste was carefully removed from the margins of the restoration. Initial polymerisation of the dual cure luting resin was achieved using a dental curing light (XL3000, 3M Dental Products, St Paul, MN, USA). The light was tested with a radiometer (Centronics silicon photodiode – RS Components, Corby Northants UK) to verify intensity prior to the polymerisation of each group. The resin was light cured for three, forty-second periods with light being applied to the buccal, lingual/palatal and occlusal surfaces of the restored tooth.

2.4.8. Bonding - Resin B (Nexus)

Trial fitting

The fit of the restoration was confirmed in the prepared tooth and tooth/cavity washed and rinsed.

Cavity surface preparation

(a) Etching: Gel etchant (37.5% phosphoric acid) was applied for fifteen seconds to the dentine and enamel, rinsed for fifteen seconds and lightly dried for five seconds without desiccating the surface.

(b) Activation: The activator was applied to the etched enamel and dentine and gently dried with medically pure air for five seconds.

(c) Priming: The primer was applied to the activated enamel and dentine and dried for five seconds.

(d) Catalyst: The catalyst was applied to the primed surfaces of the tooth.

Ceramic inlay surface preparation

Silane treatment: The etched surfaces of the porcelain restoration were coated with silane (ceramic primer) and gently dried with medically pure air for five seconds.

Fitting of inlay

The luting resin was applied thinly to the prepared fitting surface of the restoration and the restoration seated in the cavity. Excess resin was carefully removed from the margins of the restoration and the tooth. The resin was light cured for three, forty second periods with the light being applied to each of the buccal, lingual/palatal and occlusal surfaces of the restored tooth.

2.4.9. Finishing and polishing of bonded inlays

Following light curing, the restorations were finished using Sof-lex finishing discs (3M Dental Products, St Paul, MN, USA) of increasing degrees of fineness. The specimens were inspected under magnification (X4) to check that the restorations finished flush with the tooth surface. The restored specimens were stored for twenty-four hours in de-ionised water, in a humidor at 37^0 C. prior to thermal cycling.

2.5. Amalgam restorations

2.5.1. Control group (conventional amalgam restorations).

Twenty specimens with class l cavities were used as the control group.

Inserting the amalgam.

The cavities were filled with amalgam (Sybraloy regular set, Lot 9-1025 - Kerr, Romulus MI, USA). No cavity varnish or lining material was used in this study. The amalgam was triturated for eight seconds (Silamat - Vivadent, Schaan , Liechtenstein) and transferred in an amalgam carrier to the cavities. It was condensed with a pneumatic amalgam packer (Dentatus - Sweden) starting from the centre of the cavity base moving outwards towards the cavity walls. The cavities were filled using a number of increments until an excess was built up over the ultimate level of the finished restorations.

Carving the amalgam.

When the setting amalgam was sufficiently firm, the surface was carved flush with the flat occlusal of the tooth using a Wards wax carver (Ash instruments - Dentsply Ltd., UK). To ensure complete set of the amalgam, before finishing, the specimens were stored in de-ionised water in a humidor at 37^0 C. for twenty-four hours.

Finishing/polishing

The initial smoothing of the amalgam was carried out in stages using brown and green rubber wheels (Shofu Inc.- Kyoto, Japan) mounted in a laboratory handpiece, running at

10,000rpm. Followed by polishing with a pumice slurry and a felt wheel mounted in a laboratory handpiece until the surface presented a uniform "satin" finish and the final polish was completed using a slurry of water and whitening applied with a wool mop.

The specimens were checked under magnification (X4) to assess that the restoration margins were intact. The completed restorations were stored for twenty-four hours in de-ionised water, in a humidor at 37^0 C. prior to thermal cycling.

2.5.2. Bonded Amalgam Restorations

Forty specimens were restored using the same batch of amalgam as used in the control group and the same batch of resins used for bonding the porcelain restorations.

Twenty restorations were bonded with resin "**A**" and twenty with resin "**B**" as shown in figure 2.5.

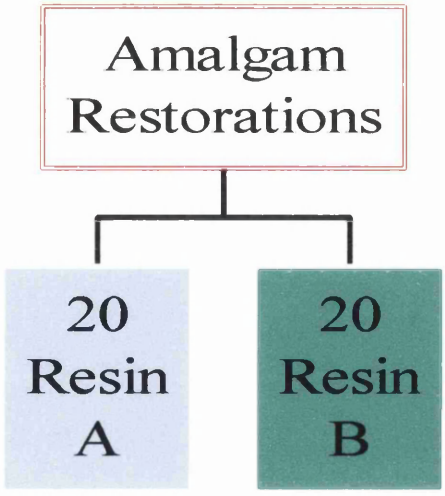


Figure 2.5. Flow chart of bonded amalgam restorations.
A: Scotchbond Multi-Purpose Plus with
3M Opal luting cement system.
B: Nexus Universal Luting System

Cavity surface preparation

The techniques, previously described, for bonding the porcelain inlays with resins **"A"** and **"B"** were used to bond the amalgam.

The cavities were prepared with similar stages of etching, activation, priming and catalyst applications.

Amalgam placement

Luting resin was applied in a thin layer using a brush to the cavities and the amalgam packed immediately over the resin, expressing excess material at the margins. Once again amalgam was condensed with a pneumatic amalgam packer in increments until excess was built up over the occlusal surface of the tooth.

Amalgam Carving

The setting amalgam and excess resin was carved flush with the flat occlusal of the tooth. The specimens were stored in de-ionised water, in a humidor at 37^0 C. for twenty-four hours before final finishing and polishing.

Finishing/polishing

The bonded amalgam restorations were trimmed and polished using the regime described for finishing the control group.

The specimens were checked under magnification (X4) to ensure that the finished margins were satisfactory and the polished surface blemish free. The finished restorations were stored for twenty-four hours in de-ionised water, in a humidor at

37^0 C. prior to thermal cycling.

2.6. Thermal Cycling

The specimens were thermal cycled to mimic temperature changes in the oral cavity.

The thermal cycle used in this study consisted of a dwell time in each bath of five seconds at temperatures of 5^0 C, 37^0 C and 55^0 C. Each specimen was thermal cycled for 720 cycles. On completion of thermal cycling the restored teeth were stored in de-ionised water in a humidor at 37^0 C.

The teeth restored with the porcelain restorations were stored for one week before being prepared and attached to the testing apparatus for assessment of microleakage.

The amalgam restorations were stored for a longer period (six weeks), before testing, to allow for the development of corrosion products at the tooth restoration interface.

2.7. Setting up of Wear Machine

2.7.1. Wear Machine

The wear machine as described by Al-Hiyasat et al., (1997, 1998[b]) used in the present study is shown in figure 2.6. It consists of an electrically driven rotating disc connected to a horizontal arm, which holds the upper tooth specimen (antagonist). The horizontal arm is suspended centrally by a rocking arm through which desired loads can be applied.

The test specimens (teeth with class l restorations) were mounted in the lower holder. Both upper and lower holders were seated in the water bath which contained a mixture of 20g cornmeal grit (East End Foods plc, Birmingham, UK) 5g wholemeal brown flour (Dove Farm Foods Ltd., Berkshire, UK) and 25ml de-ionised water. This quantity was enough to fill the water bath covering both the antagonist and the test specimen. The level of the medium was kept constant during the wear cycle. The food slurry was renewed every 5,000 cycles when the specimen was removed for leakage testing.

The food slurry, contained within the water bath, is agitated by an electrical stirrer (inset figure 2.6.1.) running at a constant speed. The wear machine was connected to the electrical supply through a control box from which the rate and number of cycles were monitored with a digital counter.

The operating cycle moves the rotating disc that brings the horizontal arm, holding the upper specimen, down onto the restored tooth (inset figure 2.6.2.). The upper specimen then slides over the surface of the tooth/restoration and back to the starting position.

During the study the operating rate was 80 rpm for a total of 25,000 cycles.
Each cycle consisted of an impact action, using a load (40N), followed by the sliding movement across the tooth/restoration (the machine permits different loads and rates of wear to be set).

Figure 2.6. **Dental Wear Machine**

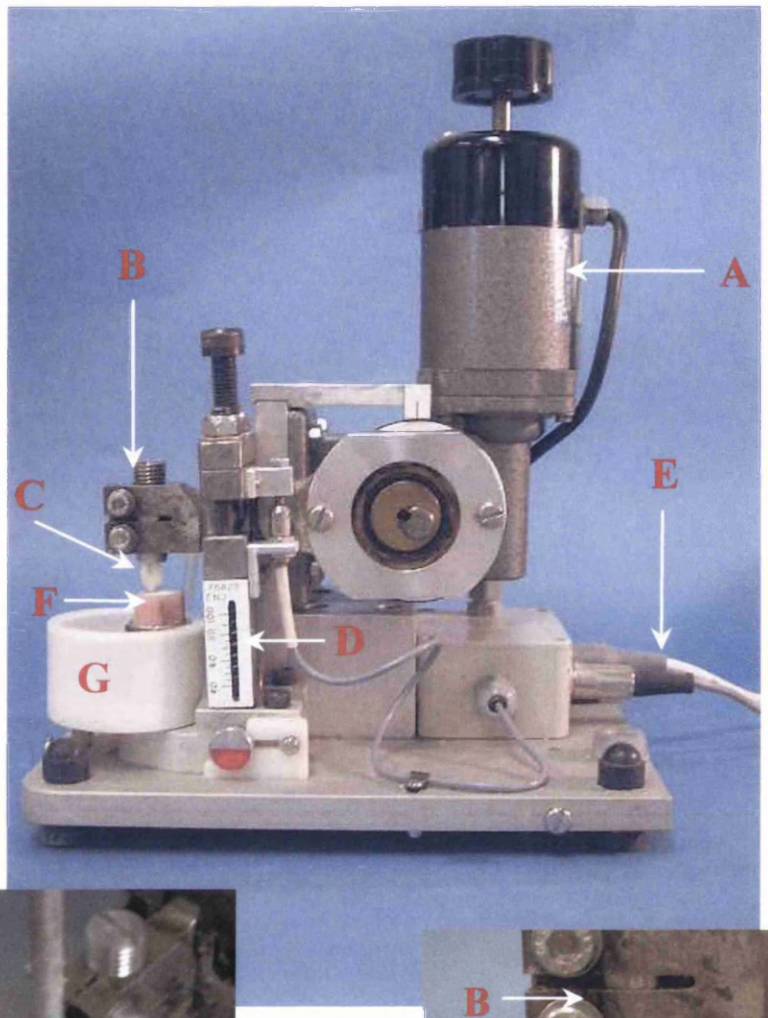


Figure 2.6.1.

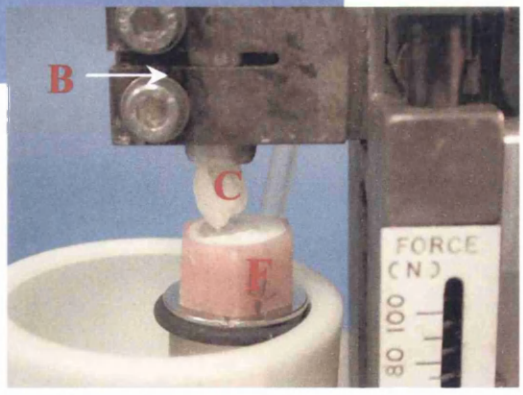


Figure 2.6.2.

A. **Electric Motor**

B. **Horizontal Arm**

C. **Upper Tooth specimem**

D. **Pre loaded spring cell**

E. **Connections to control box**

F. **Restoration in transfer Jig**

G. **Water bath**

H. **Stirrer in water bath**

2.7.2. Sample preparation for testing regime

The test assembly for each specimen was constructed using coronal tooth sections, Bioglas (acrylic sheet), stainless steel tubing and customised acrylic bolts:

Following restoration of the teeth, thermal cycling and storage the tooth roots were removed. The teeth were sectioned at the cementoenamel junction with a 22mm diameter diamond disc (0.12mm thick) running at 10,000 rpm in a laboratory handpiece to provide crown segments. To ensure a perfect seal to the clear 2mm thick Bioglas acrylic sheet (Dreve, Bioglas XD, Panadent, London,UK), the cut surfaces, of the crown segments, were finished by hand abrading using 800grit silicon paper. The coronal pulps were removed using fine forceps.

3.5 cm lengths, size 18 gauge stainless steel tubes (K.C.Smith & Co., Monmouth UK.) were positioned in pre-drilled holes, cut in the centre, of one hundred clear Bioglas sheets. The metal tubes were positioned 1mm through the inner surface of the Bioglas and sealed in position using cyanoacrylate glue (T.L.I.P. Adhesives Ltd. Swingbridge, UK).

The crown segments were sealed to the Bioglas with cyanoacrylate glue. To ensure that the pulp chamber was centred on the metal tube, during the gluing stage, a stainless steel guide wire was inserted through the tubing into the pulp chamber. The wire was withdrawn when the glue had set. An example of a specimen is shown figure2.7.

Customised threaded acrylic bolts were manufactured using autopolymersing resin (I.P. Rapid - Meadway Dental Supplies Ltd., Old Woking, Surrey, UK) The internal of the bolthead was drilled out to create space for the tooth specimen. A hole was drilled through the threaded portion to accommodate the stainless steel tube as shown in figure 2.8.

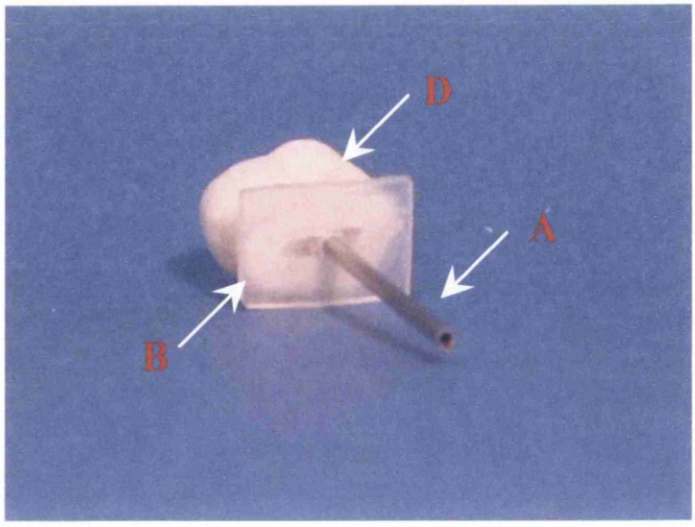


Figure 2.7. Tube inserted into pulp chamber

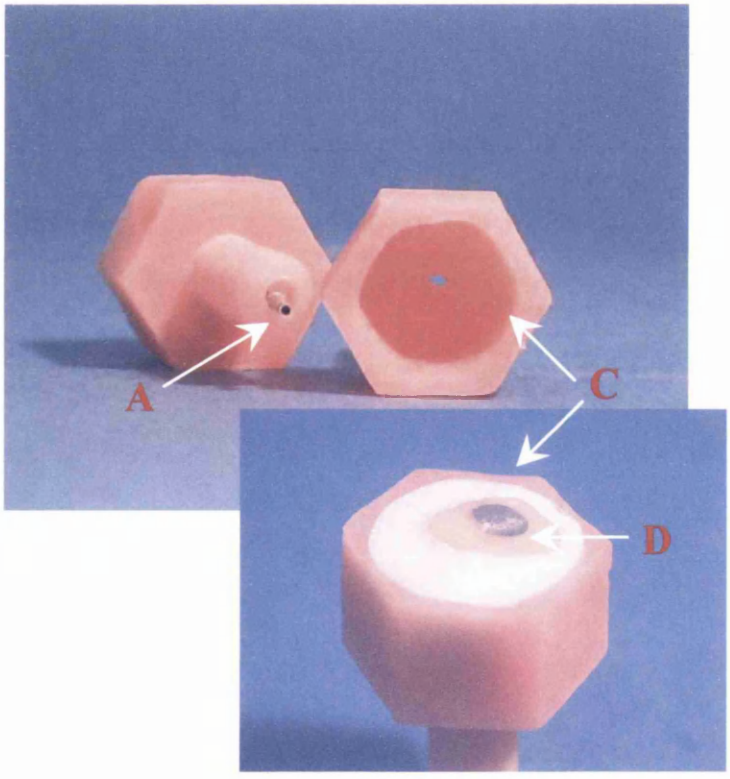


Figure 2.8. Specimen holders - Acrylic bolts

A. 19 gauge stainless steel tube
B. Bioglas
C. Sample carrier
D. Tooth / restoration

2.7.3. Wear cycle patterns

Two wear cycle patterns, with different impact positions, were used. All cycles commenced on the occlusal surface (mesial) of the tooth or the restoration and finished on the occlusal surface (distal) of each tooth.

Pattern 1. Tooth - restoration - tooth.

The cycle commenced when the upper antagonist struck the surface of the specimen (clear of the margins of the restoration), sliding across, in a straight line, over the flattened surface. The antagonist travelled from the initial contact on the occlusal surface of the tooth crossing over the mesial margin of the restoration, the restoration, the distal margin of the restoration, finishing on the occlusal surface of the distal aspect of the tooth (figure 2.9.).

Pattern 2. Restoration - tooth.

The cycle commenced when the upper antagonist struck the surface of the restoration, sliding in a straight line over its flattened surface, passing over one restoration margin, finishing on tooth structure (figure 2.9.). Figure 2.10. shows the cycles used.

Pattern 1 Pattern 2

Figure 2.9. Schematic diagram of wear patterns
A. Initial impact point
B. Direction of slide
C. Finish point (return to A)
D. Restoration
E. Natural tooth

The start /impact position of the antagonist was either on the tooth or the restoration.

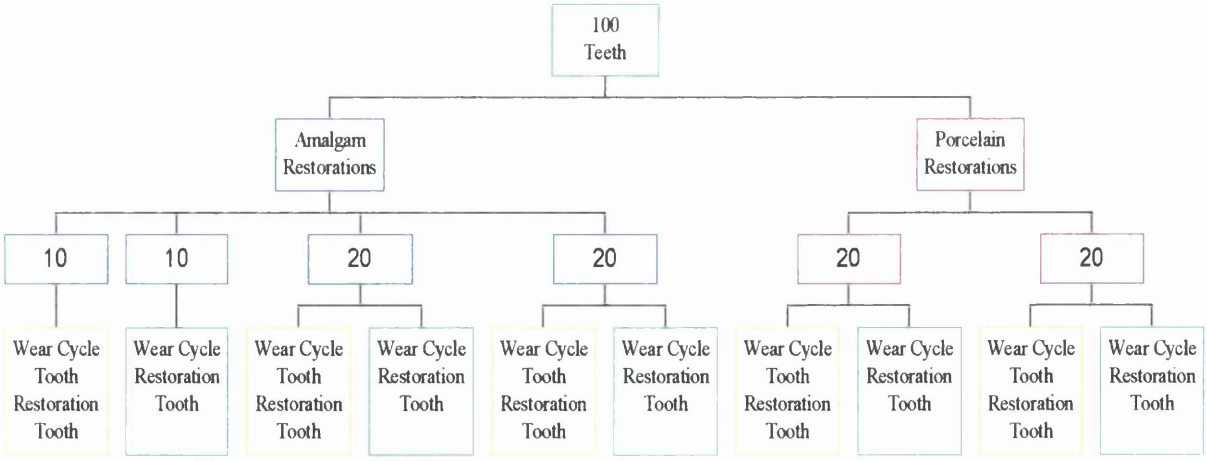


Figure 2.10. Flow chart of wear cycles
Pattern 1. Pattern 2.

2.7.4. Wear test procedure

The specimens were installed in the dental wear machine by:

(a) Inserting the threaded acrylic bolt into the wear machine.

(b) Positioning the specimen (with its metal tube extending into and out through the screw thread) in the acrylic bolt head cavity.

(c) Moving the rotating disc to align it with the fixed red mark for positioning of the initial impact point by the antagonist (in the upper arm) on the lower specimen Following positioning of the antagonist in relation to the impact point it was locked in position with the retaining screws.

(d) The test specimen was secured in a level position within the acrylic bolt head using autopolymerising acrylic (Formatray). Following polymerisation two alignment marks were recorded on the outside of the acrylic bolt to correspond with similar marks on the wear machine. The marks guaranteed that when the acrylic bolt/specimen was removed from the wear machine for pressure testing that it would be returned to the machine in the same position.

In this study each sample was subjected to 25,000 wear cycles. The cycles were interrupted at various times to permit pressure testing by removing the specimen from the dental wear machine and attaching it to the pressure testing apparatus.

2.8. Microleakage test system (microleakage evaluation)

2.8.1. System for evaluation of microleakage

The pressure testing system (figure 2.11.) described by Pashley & Depew, (1986) and Derkson et al., (1986) was used in this study. The system consisted of Nitrogen gas (oxygen free), at a pressure of 0.069MPa, from a pressure tank (Nitrogen – BOC Ltd., Guildford, UK) being applied through a pressurised reservoir containing a beaker of phosphate buffered saline (I C N Biomedicals Inc., Aurora, Ohio, USA) and connected to the specimen with 1.14mm internal diameter polythene tubing (Smiths Industries, Portex Ltd., Kent, UK). The polythene tubing was sealed to the steel tube/specimen with cyanoacrylate glue. A 25mL micropipette (Drummond Scientific Co. Broomall, Pa) was sealed into the polythene tubing using cyanoacrylate glue. A 2.0mL microsyringe (GS-1200- Gilmont Instruments Barnet Co. Barrington, USA) was attached to one end of the " T " junction tubing connector with cyanoacrylate glue. The microsyringe allowed the introduction of a small air bubble into the micropipette, which permitted the fluid movement to be quantified. Measurements of the bubble/fluid movement were made through the clear micropipette positioned over a coloured millimetre scale.

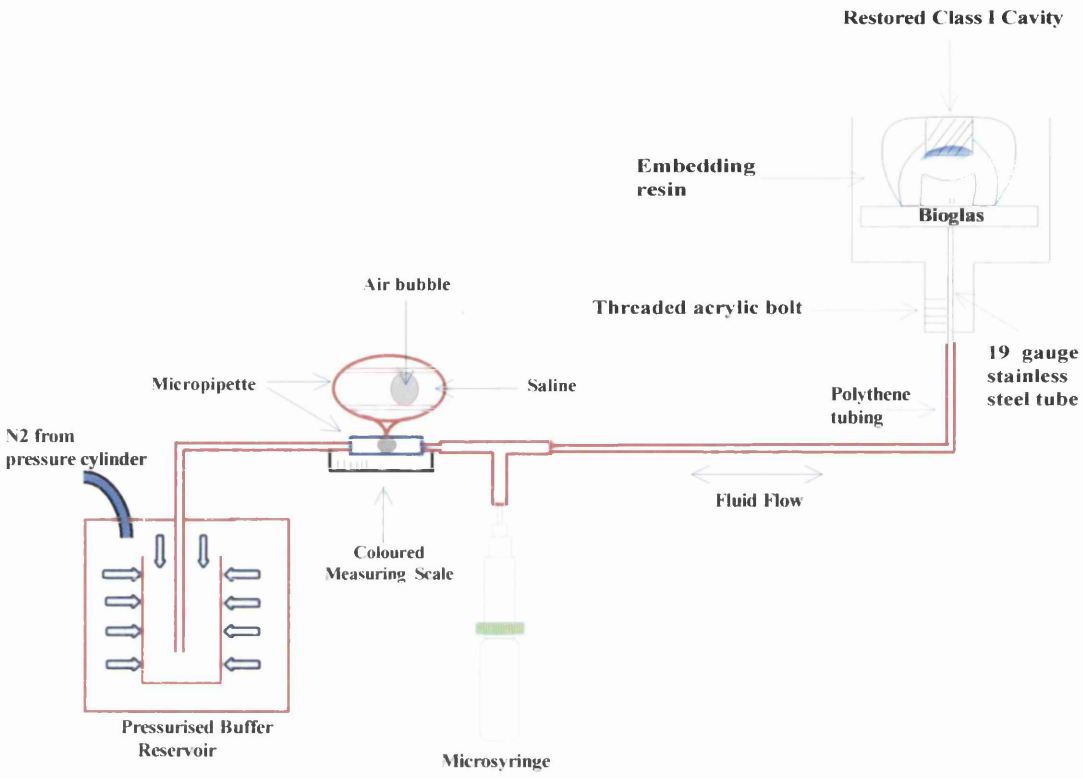


Figure 2.11. Outline of system used to assess dentine permeability and microleakage.

Nitrogen gas at a pressure of 0.069MPa is applied to the pressurised reservoir containing a beaker of saline.
The small air bubble in the micropipette permits the fluid movement to be quantified.

2.8.2. Microleakage measurement

As dentine permeability is directly related to the fluid flow rates across the dentine via the dentinal tubules (Ciucchi et al., 1995; Pashley, 1984), microleakage was measured by observing the movement of the bubble and quantified. The movement of the air bubble (mm/min) in the micropipette was expressed as μl/min.

All microleakage measurements used the same regime:

(a) Following sealing of the stainless steel tube/specimen to the pressure testing apparatus with cyanoacrylate glue, the system was pressurised to 0.069MPa.

(b) To ensure that the pressure was constant, before measuring of the fluid movement, measuring was delayed for 5 minutes.

(c) An air bubble was moved into the micropipette from the microsyringe and the movement observed over the coloured millimetre scale.

(d) Following recording of the time/movement of the bubble inside the micropipette the pressure was released.

(e) The system was re-pressurised (stage 2 repeated)

(f) Each specimen was measured 4 times when attached to the pressure system.

(g) The specimen was returned to the machine and subjected to further wear cycles.

The first measurement of permeability was made of the restored tooth before it was placed in the wear machine and this was used as the baseline to see if leakage occurred during the wear cycles. Pressure testing to assess microleakage was carried out following 5,000, 10,000, 15,000, 20,000 and 25,000 cycles in the wear machine.

The complete wear and testing cycle using the different bonding systems and restorations is shown figure 2.12.

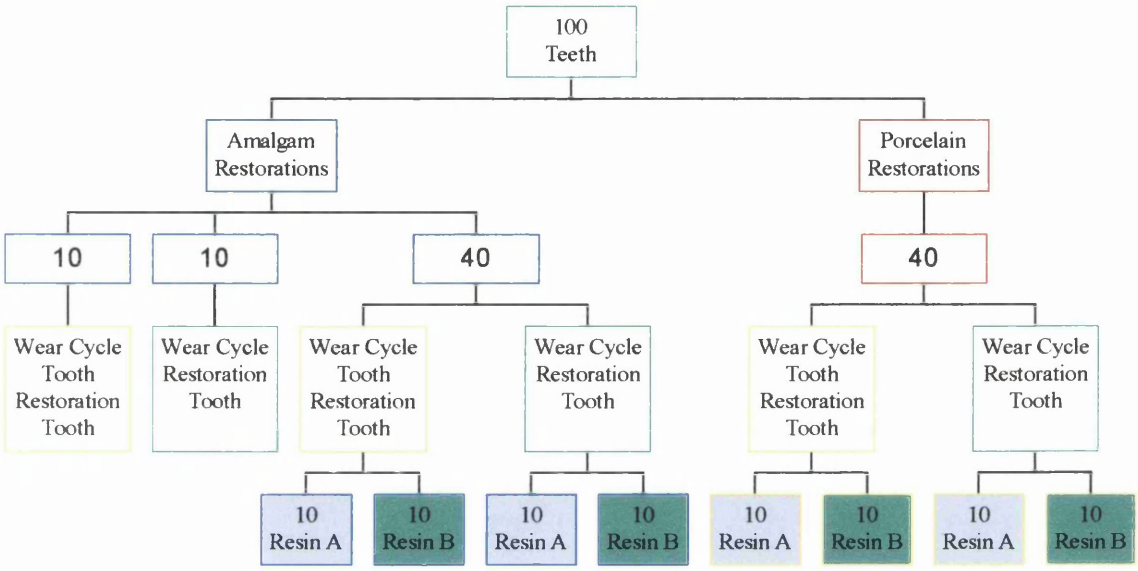


Figure 2.12. Flow chart of wear cycles and bonding systems
Resin A: 3M Scotchbond - Multi-Purpose Plus
Resin B: Nexus Universal Luting System

2.9. Statistical Methodology

The microleakage values for the groups of materials were compared using repeated measures ANOVA, and post hoc Tukey, to establish if there were differences in mean leakage among the groups.

Chapter 3.

3.0. Results

3.1. Introduction

This study involved 100 teeth. The teeth were restored using either a porcelain inlay or an amalgam restoration. The porcelain inlays were placed with one of two composite resins (resin A: Scotchbond Multi-Purpose Plus, 3M, resin B: Nexus Universal Luting System, Kerr). The amalgam restorations were placed either with one of the two composite resins or, without any resin (section 2.5.2). All restorations were subject to one of two wear cycles. These were a tooth-restoration-tooth wear cycle or a restoration-tooth wear cycle. Measurements of microleakage were made every 5,000 cycles of wear for 25,000 cycles. These measurements are described in section 2.8.1. Measurements were made for all teeth at all time points.

The results were analysed in several ways. First, general observations were made from the results. Further analysis assessed the effect of the different restoration types on microleakage, the effect of increasing wear on restoration microleakage and the effect of the type of wear on restoration microleakage.

Analysis involved two-sample t-tests, one-way analysis of variance (ANOVA) to determine the presence of any differences between groups and Tukey tests to determine the nature of such differences where appropriate.

3.2. General observations

The mean and standard deviation data for the whole data set are shown in table 3.1. From this table it can be seen that different restorations exhibited different degrees of microleakage. Such differences were apparent at baseline (0 cycles) and continued throughout the study. Additionally, differences at baseline were evident between groups of the same restoration type but allocated to different wear cycles (figure 3.1.).

In general the least amount of microleakage was observed from the amalgam restorations placed with either of the two resins. Amalgam with no resin tended to exhibit more microleakage than amalgam with resin. The greatest amount of microleakage was observed from the porcelain inlays bonded in place with either of the resins.

Analysis of variance to compare all baseline data demonstrated the existence of significant differences between groups. Tukey tests as a pairwise analysis were performed to determine the nature of the differences. These data are shown in table 3.2. The results of this analysis demonstrated significant differences between baseline microleakage values for the, 'porcelain-resin-B restorations', the 'amalgam-only restorations' and also the 'amalgam-resin-B restorations'.

Evaluation of the differences between resin A and resin B was not possible using the above ANOVA. Instead, the baseline microleakage data were used for all the porcelain restorations placed using resin A regardless of proposed wear regime. These data were compared with similar baseline data for porcelain restorations placed using resin B.

Comparisons were made using a two sample *t*-test. A similar comparison was made for amalgam restorations placed with resins A and B. The results of these comparisons are shown in table 3.3.

A significant difference between resins A and B was observed for porcelain restorations ($p = 0.01$) but not for amalgam restorations ($p = 0.7$). Comparing the mean values, resin A demonstrated significantly more microleakage for the porcelain inlays that resin B. Mean microleakage values were 56.5 and 76.6 Sec/cm, respectively.

3.3. The effect of increasing exposure to wear on restoration microleakage

Observations of microleakage from the 10 specimens within each group were made every 5000 wear cycles for each type of wear cycle. Each specimen was exposed to a total wear challenge of 25,000 cycles. Therefore, observations of microleakage were made for each specimen on five occasions throughout the study. A general trend of increasing microleakage with increasing wear could be made for most of the groups. A one-way ANOVA was used to determine if microleakage changed significantly for each group of specimens as wear progressed. These results are shown in table 3.4. No significant changes were observed in the microleakage of the specimens over the 25,000 cycles, regardless of the type of restoration or the wear cycle used.

3.4. The effect of the type of wear on restoration microleakage

General observations revealed no obvious differences between microleakage values obtained for particular wear patterns. Given the fact that significant differences existed

between the groups at baseline and the lack of any significant change in microleakage with increasing wear, no formal analysis was undertaken.

TABLE 3.1.

Mean and (sd) data for microleakage values (Sec/cm) recorded every 5000 cycles for two types of wear cycle and five different restoration types.

Restoration type	Type of Wear cycle	Mean and (sd) microleakage values (Sec/cm) for Specimens recorded every 5000 wear cycles					
		0	5,000	10,000	15,000	20,000	25,000
Porcelain, Resin A	Tooth - Restoration - Tooth	48.1 (6.77)	47.48 (7.24)	45.63 (7.21)	44.48 (7.32)	42.40 (7.10)	38.85 (7.65)
Porcelain, Resin A	Restoration - Tooth	64.90 (6.86)	64.18 (6.98)	63.45 (7.65)	62.63 (7.36)	60.80 (7.22)	60.38 (7.04)
Porcelain, Resin B	Tooth - Restoration - Tooth	60.35 (32.84)	68.03 (25.41)	76.20 (9.47)	75.45 (10.23)	72.00 (11.08)	69.60 (11.01)
Porcelain, Resin B	Restoration - Tooth	92.83 (23.44)	92.68 (23.41)	92.13 (23.33)	91.58 (23.63)	90.88 (23.65)	90.23 (23.65)
Amalgam	Tooth - Restoration - Tooth	84.60 (17.93)	84.10 (18.17)	83.05 (18.03)	81.03 (18.12)	79.93 (18.57)	78.60 (19.04)
Amalgam	Restoration - Tooth	111.78 (11.41)	111.65 (11.43)	111.5 (11.61)	110.38 (11.88)	109.75 (11.67)	108.93 (11.84)
Amalgam, Resin A	Tooth - Restoration - Tooth	132.88 (14.66)	132.23 (14.35)	131.35 (14.45)	30.63 (14.56)	129.93 (14.64)	128.98 (14.61)
Amalgam, Resin A	Restoration - Tooth	120.03 (21.49)	119.95 (21.29)	119.45 (21.44)	119.20 (21.46)	118.85 (21.62)	118.40 (21.38)
Amalgam, Resin B	Tooth - Restoration - Tooth	109.50 (21.85)	109.45 (21.70)	108.65 (21.66)	107.95 (21.67)	107.08 (21.68)	106.43 (21.66)
Amalgam, Resin B	Restoration- Tooth	138.23 (13.18)	138.18 (13.22)	137.73 (13.30)	137.23 (13.36)	136.75 (13.32)	136.28 (13.19)

Note.
Larger values represent less microleakage compared with smaller values.

TABLE 3.2.

Results of Tukey tests as a pairwise analysis of baseline data to compare differences between groups following Analysis Of Variance (ANOVA) where $p < 0.05$.

	Porcelain Resin A T-R-T	Porcelain Resin A R-T	Porcelain Resin B T-R-T	Porcelain Resin B R-T	Amalgam T-R-T	Amalgam R-T	Amalgam Resin A T-R-T	Amalgam Resin A R-T	Amalgam Resin B T-R-T
Porcelain Resin A R-T	X								
Porcelain Resin B T-R-T	X	X							
Porcelain Resin B R-T	✓	✓	✓						
Amalgam T-R-T	✓	X	X	X					
Amalgam R-T	✓	✓	✓	X	✓				
Amalgam Resin A T-R-T	✓	✓	✓	✓	✓	X			
Amalgam Resin A R-T	✓	✓	✓	✓	✓	X	X		
Amalgam Resin B T-R-T	✓	✓	✓	X	X	X	X	X	
Amalgam Resin B R-T	✓	✓	✓	✓	✓	X	X	X	✓

Key

✓ = Statistically significant difference between groups ($p < 0.05$)

X = No statistically significant difference between groups ($p > 0.05$)

T-R-T = Tooth-restoration-tooth loading regime

R-T = Restoration-tooth loading regime

TABLE 3.3.

Results of two-sample t-tests to compare baseline restoration microleakage scores for five restoration types exposed to two different wear regimes.

Restoration type	*Results of two-sample t-tests comparing resin A & B*
Porcelain	p = 0.01
Amalgam	p = 0.70

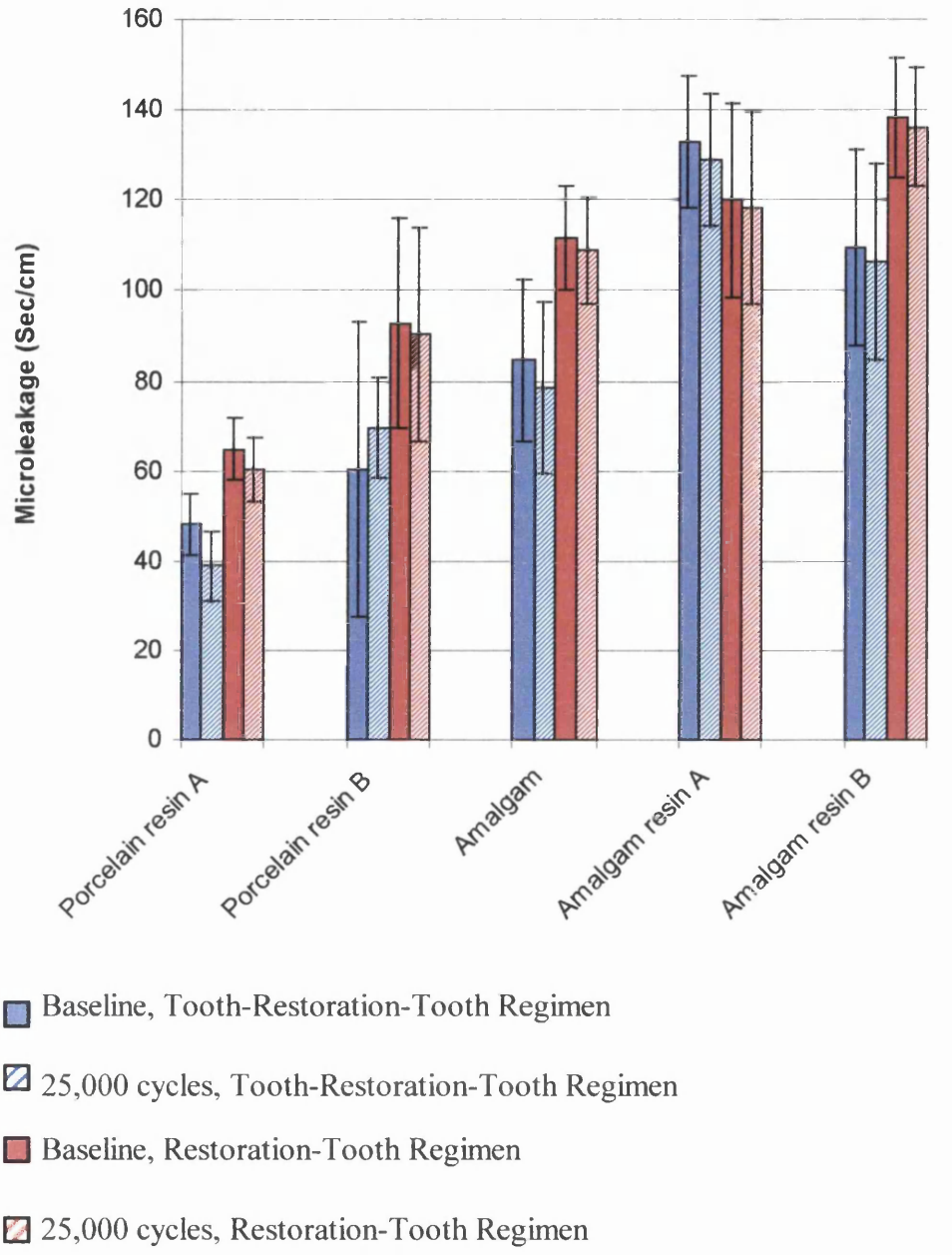
TABLE 3.4.

One-way ANOVA results to compare microleakage scores at 5,000 cycle intervals for five restoration types, subjected to two types of wear cycle over 25,000 cycles.

Restoration Type	Wear Cycle	p-value for one way ANOVA
Porcelain Resin A	Tooth Restoration Tooth	0.06
Porcelain Resin A	Restoration Tooth	0.69
Porcelain Resin B	Tooth Restoration Tooth	0.46
Porcelain Resin B	Restoration Tooth	1.00
Amalgam	Tooth Restoration Tooth	0.97
Amalgam	Restoration Tooth	0.99
Amalgam Resin A	Tooth Restoration Tooth	0.99
Amalgam Resin A	Restoration Tooth	1.00
Amalgam Resin B	Tooth Restoration Tooth	1.00
Amalgam Resin B	Restoration Tooth	1.00

FIGURE 3.1.

Comparison of microleakage values for different restoration groups at baseline (0 cycles) and 25,000 cycles of loading under two different wear regimes.



Chapter 4.

4.0. Discussion

Marginal integrity is perhaps the most important factor in maintaining longevity of any restoration (Roulet, 1994). The absence of a seal at restoration margins may contribute to tooth discoloration, adverse pulp response post-operative sensitivity and recurrent caries because of bacterial ingress (Going, 1972; Crim & Garcia-Godoy, 1987). An additional advantage using adhesive techniques is increased bond strength for greater structural integrity of both tooth and restoration (Boyer and Roth, 1994).

There have been many studies of marginal leakage at the restoration-tooth interface *in vitro*. However, results indicate that the ideal restorative material that completely seals the cavity is still to be developed. Clinically this is confirmed by various studies as some patients, after treatment, still experience sensitivity or pain with some developing secondary caries which occurs as a result of fluid flow through a gap (Staninec and Holt, 1988, Prati, 1994). The system used in this study evaluated the sealing of dentine with adhesive resins by measuring the fluid flow through the dentine after bonding. It provided a technique for quantitative assessment of microleakage between dentine cavity walls, enamel margins and the restorative material. The main advantage of the technique was that it did not require destruction of the samples thus the study could be used longitudinally.

The outward flow of fluid along dentinal tubules has been recognised as physiological (Pashley, 1984). This present study used the fact that dentine permeability is directly related to the fluid flow rates across dentine via the dentinal tubules. The pressure system used provided a technique for quantitative assessment of microleakage between

cavity walls and different restorative materials in relation to permeability *in vitro*. If exposed dentine permits a continuous movement of fluid outwards, in theory the application of a restorative material should stop the flow. However, the results of this study indicate that it did not completely stop the outward flow of fluid movement.

Lining

The use of a lining material can influence the level of microleakage in restored teeth. There are conflicting results between many researchers using lining materials in leakage studies (Derkson et al., 1986, Charlton et al., 1992, Saiku et al., 1993, Tjan et al., 1997, Al-Jazairy and Louka, 1999). Even with great care the varying thickness of liner could have been applied within the cavity therefore which would have affected the leakage results. To remove this anomaly it was decided at the commencement of the study not to line any of the restorations.

Wear

There are many studies reporting wear rates of enamel and restorative materials (Powell et al., 1975, Moon and Draughn, 1982, Delong et al., 1989, Delong et al., 1992, Al-Hiyasat et al., 1997, Ramp et al., 1997, Al-Hiyasat et al., 1998[b], Kaidonis et al., 1998, Al-Hiyasat et al., 1999). Although many of the parameters in this present study were similar to other studies, for example number of wear cycles, occlusal loading and three-body wear. The wear in this study cannot be compared with other results because of the differences in specimen set up. In this study the 10mm wear tract of the antagonist occurred sometimes from contact with the autopolymerising resin (that surrounded the specimen) thus accurate levels of wear of the antagonist were questionable. Also,

because of the increase in the surface contact area of the antagonist (from wear on the autopolymerising resin) on the restoration, the measurements of wear from the surface of the restoration were not included in the results.

A number of studies have been carried using pressure systems similar to that used in this study to assess microleakage (Derkson et al., 1986, Lyons et al., 1997, Al-Jazairy and Louka, 1999, Youngson et al., 1999, Bouillaguet et al., 2000). However, none of the studies included the parameter of mechanical loading. The present study included three-body wear and loading in the test regime. The results of this study indicated that there were some significant differences in leakage among materials for both patterns of occlusal loading.

4.1. Porcelain inlays

The desire for aesthetics and alternatives to amalgam are the two main reasons for placing tooth-coloured restorations. However, results from this study indicate porcelain restorations may be prone to higher levels of microleakage when compared to amalgam restorations. The unexpected results of higher leakage from the porcelain restorations may be as a result of some of the factors that influence the integrity of the marginal seal. For example polymerisation shrinkage, marginal integrity, bond to cavity walls, viscosity of composite, flexibility of the cavity walls, thermal cycling regime, loading regime or operator error.

Polymerisation shrinkage

The porcelain inlays were tested one week after bonding and thermal cycling whereas the amalgam restorations following thermal cycling were not tested until six weeks had elapsed (to utilise additional sealing of the cavity by corrosion products which may have provided a more comprehensive seal). Luting porcelain inlays with composite resins can have problems because of polymerisation shrinkage. The shrinkage is influenced by the properties of the material (filler content, resin composition and stiffness), volume of material, method of polymerisation (light-cured or dual-cured) and direction of light application (Roulet, 1997). Although the porcelain inlays in this study were carefully fabricated to fit the standard cavity preparations and luted with dual-cured resin, some of the inlays could possibly have had undetectable minor discrepancies and did not accurately fit internal areas of the cavity. Therefore, in some areas a greater volume of resin may have been used to seal the inlay into the cavity resulting in increased gaps because of the contraction of the polymer. Also the reduced storage time after bonding prior to the testing regime may not have been sufficient for the resin to have an uptake of water resulting in an expansion of the resin which could increase the tightness of the resin against the cavity wall and reduce any gaps. Although dentine-bonding agents reduce contraction gaps in this study they did not completely eliminate the development of interfacial gaps as confirmed by the dentinal fluid movement. This agrees with two studies that reported that the combination of resin cements and dentine bonding agents were able to reduce contraction gaps but were unable to completely eliminate development of interfacial gaps caused by contraction of the polymer (Sorensen and Munksgaard, 1996[a], Sorensen and Munksgaard, 1996[b]).

Bond to cavity walls

Although the luting procedure was carried out as per the manufacturers' instructions gaps between the prepared dentine and the luting cement may have occurred from the development of interfacial stress because of polymerisation shrinkage. Some studies *in vitro* using bonding agents, have reported that gaps still occur between the prepared dentine and the luting cement because of polymerisation shrinkage (Jacobsen and Rees, 1992, Sorensen and Munksgaard, 1996[a], Sorensen and Munksgaard, 1996[b]). The gap formation from polymerisation shrinkage may have been a contributory factor to the leakage reported in this study.

Loading regime

The use of mechanical loading may also have been a factor in the increased leakage for the porcelain because of cyclic fatigue of the feldspathic porcelain. Although not assessed one can conclude from various studies that crack initiation would have occurred from the cyclic loading (Fairhurst et al., 1993; White et al., 1995; White et al., 1997; Jung et al., 2000). The impact point in the loading cycle (restoration- tooth) was normally near the edge of the restoration. The accumulation of contact damage during the cyclic loading phase from multiple contacts from the antagonist can result in damage inside the contact area with the initiation of radial cracks outside (Jung et al., 2000). Thus it can be postulated that crack propagation could create gaps at the margin and fitting surfaces permitting microleakage to occur. This may be a factor in the increased leakage results from the porcelain specimens.

Marginal integrity

In the two patterns of loading regime the margins were subjected to limited occlusal contact because of the narrowness of the margin. Wear of the margin from occlusal contact and wear across all of the margins from food abrasion cannot be excluded as a factor in the leakage results. This hypothesis of leakage agrees with other studies *in vivo* that have reported significant resin cement wear around ceramic inlays particularly during the first year after placement (Van Meerbeek et al., 1992[b]; Thordrup et al., 1994). When the margin is bevelled and etched with phosphoric acid leakage is usually prevented. However, in this study the margins were finished as butt joints, which may have contributed to the incidence of microleakage. Finally, the bond strengths to dentine with the resins used may now be so strong that polymerisation contraction of the resin composite may result in disruption of the bond at the enamel-resin interface.

4.2. Amalgam restorations – conventional/bonded

A problem common to dental amalgam restorations is microleakage at the amalgam-tooth interface for a time after placement. Using adhesive systems amalgam bonding has become an established clinical procedure to reduce interfacial microleakage. The adhesive bonding agents placed in this study under the amalgam restorations reduced the amount of leakage compared with the conventional amalgams. However, although the resins reduced microleakage they did not completely eliminate it. This agrees with other researchers (Lenarda et al., 2000; Al-Jazairy et al., 1999; Sepetcioglu and Altman, 1998). The reduction observed may be because the amalgam was condensed into the cavity before polymerisation of the bonding resin enabling the resin to be mechanically interlocked into the amalgam thus reducing the possibility of interfacial gaps.

Van Meerbeek et al., (1992[a]) suggested that dentine-bonding systems provide an intermediary elastic layer between restorations and tooth structure. reducing stress during the dimensional change of amalgam. The increased leakage reported for the non-bonded amalgam may be because of the lack of elasticity resulting in dimensional stress during the setting of amalgam producing microscopic gaps between the amalgam and tooth structure.

4.3. Review

A number of factors have become apparent during the progress of this study which had they been included at the outset would have provided more detailed assessment of the leakage observed. In future investigations the following should be included in the test regime which, would provide a comprehensive analysis of dentinal fluid flow in relation to microleakage:

Tooth selection

The bonding and sealing of the dentine can be influenced by the amount of sclerotic dentine. The random selection of teeth should if possible be of teeth of similar age and size.

Sample preparation

In this study it was decided to follow normal clinical procedures and restore the cavities before commencing leakage measurements in vitro.

Baseline measurements were made once the teeth were restored. With hindsight the ideal first point of measurement should have been the intact tooth. Further measurements should have been made once the cavities had been prepared and finally, once the teeth were restored. In this way the effect of any microleakage could be determined. Specimens could then be allocated to tests groups ensuring mean and standard deviation data were comparable between groups. In this manner comparison of the groups would have been easier.

Wear studies

Modification of the wear machine to ensure that all wear tracts only occurred on the samples which would permit assessment of leakage in relation to measurements of abrasive three-body wear.

Conclusions

1. The resins used in the study are claimed by the manufactures to be suitable for wet bonding techniques but the results indicate that they did not completely seal the tooth- restoration interface and stop the outward flow of tubule fluid induced by the pressure system.

2. There were no statistically significant differences between the bonding systems used in the study.

3. The major advantages of the system were:
   (a) it did not require destruction of the samples permitting longitudinal observations to be carried out.
   (b) it permitted the specimens to be assessed following occlusal loading and three-body wear.

4. Microleakage increased with exposure to wear cycles.

Future studies

Once baseline microleakage values have been standardised, the following studies would constitute useful further work.

1. To assess microleakage *in vitro* under simulated occlusal loads.

2. To assess the development of microleakage *in vitro* in relation to different wear patterns and occlusal loads.

3. To assess microleakage longitudinally using various resin bonding systems over a two year period.

Appendix

Results: Raw data (chapter 3).

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	45	42	42	43	39	34
	2	46	43	41	43	37	34
	3	44	43	43	42	37	33
	4	46	42	42	43	38	34
		45.25	42.50	42.00	42.75	37.75	33.75
		0.221	**0.235**	**0.238**	**0.234**	**0.265**	**0.296**
		0.754	**0.708**	**0.700**	**0.713**	**0.629**	**0.563**
2	1	42	40	39	38	38	34
	2	43	41	38	38	39	35
	3	42	40	39	39	38	34
	4	41	41	38	38	38	35
		42.00	40.50	38.50	38.25	38.25	34.50
		0.238	**0.247**	**0.260**	**0.261**	**0.261**	**0.290**
		0.700	**0.675**	**0.642**	**0.638**	**0.638**	**0.575**
3	1	44	44	43	42	41	37
	2	45	43	43	43	41	37
	3	45	44	42	43	42	37
	4	44	44	43	43	41	36
		44.50	43.75	42.75	42.75	41.25	36.75
		0.225	**0.229**	**0.234**	**0.234**	**0.242**	**0.272**
		0.742	**0.729**	**0.713**	**0.713**	**0.688**	**0.613**
4	1	46	45	43	43	41	37
	2	46	45	44	43	40	37
	3	45	46	44	43	41	36
	4	46	45	43	43	40	36
		45.75	45.25	43.50	43.00	40.50	36.50
		0.219	**0.221**	**0.230**	**0.233**	**0.247**	**0.274**
		0.763	**0.754**	**0.725**	**0.717**	**0.675**	**0.608**
5	1	43	43	41	39	38	34
	2	44	43	42	40	39	34
	3	44	43	41	39	38	34
	4	43	43	42	39	38	34
		43.50	43.00	41.50	39.25	38.25	34.00
		0.230	**0.233**	**0.241**	**0.255**	**0.261**	**0.294**
		0.725	**0.717**	**0.692**	**0.654**	**0.638**	**0.567**
6	1	48	49	45	43	39	35
	2	49	48	46	43	40	35
	3	49	49	45	44	41	36
	4	49	49	45	43	41	36
		48.75	48.75	45.25	43.25	40.25	35.50
		0.205	**0.205**	**0.221**	**0.231**	**0.248**	**0.282**
		0.813	**0.813**	**0.754**	**0.721**	**0.671**	**0.592**
7	1	51	51	45	41	40	36
	2	50	49	44	42	39	36
	3	50	49	45	41	39	35
	4	51	50	43	42	40	35
		50.50	49.75	44.25	41.50	39.50	35.50
		0.198	**0.201**	**0.226**	**0.241**	**0.253**	**0.282**
		0.842	**0.829**	**0.738**	**0.692**	**0.658**	**0.592**
8	1	42	42	41	39	38	38
	2	42	41	41	38	39	37
	3	42	42	41	38	38	37
	4	41	42	41	39	38	37
		41.75	41.75	41.00	38.50	38.25	37.25
		0.240	**0.240**	**0.244**	**0.260**	**0.261**	**0.268**
		0.696	**0.696**	**0.683**	**0.642**	**0.638**	**0.621**
9	1	62	63	61	60	60	57
	2	63	62	61	60	60	58
	3	63	63	60	60	60	58
	4	63	63	60	60	59	58
		62.75	62.75	60.50	60.00	59.75	57.75
		0.159	**0.159**	**0.165**	**0.167**	**0.167**	**0.173**
		1.046	**1.046**	**1.008**	**1.000**	**0.996**	**0.963**
10	1	56	57	57	56	51	47
	2	55	56	57	56	50	47
	3	57	57	57	55	50	47
	4	57	57	57	55	50	47
		56.25	56.75	57.00	55.50	50.25	47.00
		0.178	**0.176**	**0.175**	**0.180**	**0.199**	**0.213**
		0.938	**0.946**	**0.950**	**0.925**	**0.838**	**0.783**

Test 2 Restoration -Tooth
Porcelain Resin A

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	52	52	49	49	48	47
	2	52	51	49	49	47	47
	3	52	52	50	49	47	47
	4	53	52	50	49	47	47
		52.25	51.75	49.50	49.00	47.25	47.00
		0.191	**0.193**	**0.202**	**0.204**	**0.212**	**0.213**
		0.871	**0.863**	**0.825**	**0.817**	**0.788**	**0.783**
2	1	56	55	54	55	53	53
	2	57	55	53	54	53	53
	3	57	55	54	54	52	53
	4	56	55	53	54	52	53
		56.50	55.00	53.50	54.25	52.50	53.00
		0.177	**0.182**	**0.187**	**0.184**	**0.190**	**0.189**
		0.942	**0.917**	**0.892**	**0.904**	**0.875**	**0.883**
3	1	74	74	74	74	72	71
	2	75	74	74	74	71	72
	3	75	74	74	74	72	71
	4	76	74	74	74	72	72
		75.00	74.00	74.00	74.00	71.75	71.50
		0.133	**0.135**	**0.135**	**0.135**	**0.139**	**0.140**
		1.250	**1.233**	**1.233**	**1.233**	**1.196**	**1.192**
4	1	69	68	68	66	64	64
	2	68	68	67	67	63	63
	3	68	67	68	65	63	64
	4	68	68	69	65	64	63
		68.25	67.75	68.00	65.75	63.50	63.50
		0.147	**0.148**	**0.147**	**0.152**	**0.157**	**0.157**
		1.138	**1.129**	**1.133**	**1.096**	**1.058**	**1.058**
5	1	68	68	67	67	63	63
	2	68	67	68	65	64	63
	3	67	68	68	65	63	62
	4	68	68	67	66	63	63
		67.75	67.75	67.50	65.75	63.25	62.75
		0.148	**0.148**	**0.148**	**0.152**	**0.158**	**0.159**
		1.129	**1.129**	**1.125**	**1.096**	**1.054**	**1.046**
6	1	68	68	67	66	63	63
	2	67	68	67	67	63	62
	3	68	68	68	66	64	63
	4	68	68	68	67	63	63
		67.75	68.00	67.50	66.50	63.25	62.75
		0.148	**0.147**	**0.148**	**0.150**	**0.158**	**0.159**
		1.129	**1.133**	**1.125**	**1.108**	**1.054**	**1.046**
7	1	64	63	63	62	62	62
	2	64	63	63	62	61	62
	3	65	63	62	61	62	61
	4	65	63	62	62	62	62
		64.50	63.00	62.50	61.75	61.75	61.75
		0.155	**0.159**	**0.160**	**0.162**	**0.162**	**0.162**
		1.075	**1.050**	**1.042**	**1.029**	**1.029**	**1.029**
8	1	67	67	66	64	63	62
	2	68	66	66	64	64	62
	3	67	65	65	65	64	62
	4	67	67	67	65	63	61
		67.25	66.25	66.00	64.50	63.50	61.75
		0.149	**0.151**	**0.152**	**0.155**	**0.157**	**0.162**
		1.121	**1.104**	**1.100**	**1.075**	**1.058**	**1.029**
9	1	59	59	57	57	55	55
	2	60	59	57	57	54	54
	3	59	58	58	56	55	54
	4	60	59	58	57	55	54
		59.50	58.75	57.50	56.75	54.75	54.25
		0.168	**0.170**	**0.174**	**0.176**	**0.183**	**0.184**
		0.992	**0.979**	**0.958**	**0.946**	**0.913**	**0.904**
10	1	70	70	68	68	67	66
	2	71	69	68	68	67	65
	3	70	69	69	68	66	65
	4	70	70	69	68	66	66
		70.25	69.50	68.50	68.00	66.50	65.50
		1.167	**1.167**	**1.150**	**1.133**	**1.100**	**1.100**
		1.171	**1.158**	**1.142**	**1.133**	**1.108**	**1.092**

Test 3 Tooth-Restoration-Tooth
Porcelain Resin B

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	0	0	87	86	83	82
	2	0	0	86	86	86	83
	3	0	0	87	86	84	81
	4	0	0	86	87	87	83
		0.00	0.00	86.50	86.25	85.00	82.25
		0.000	**0.000**	**0.116**	**0.116**	**0.118**	**0.122**
		0.000	**0.000**	**1.442**	**1.438**	**1.417**	**1.371**
2	1	0	81	80	80	71	70
	2	0	82	80	79	72	71
	3	0	80	80	81	71	71
	4	0	81	79	80	72	71
		0.00	81.00	79.75	80.00	71.50	70.75
		0.000	**0.123**	**0.125**	**0.125**	**0.140**	**0.141**
		0.000	**1.350**	**1.329**	**1.333**	**1.192**	**1.179**
3	1	77	77	76	75	73	74
	2	78	76	76	76	74	73
	3	77	78	77	75	74	72
	4	77	77	77	76	74	74
		77.25	77.00	76.50	75.50	73.75	73.25
		0.129	**0.130**	**0.131**	**0.132**	**0.136**	**0.137**
		1.288	**1.283**	**1.275**	**1.258**	**1.229**	**1.221**
4	1	88	89	89	89	87	86
	2	90	89	89	88	88	86
	3	90	88	88	88	87	85
	4	87	89	88	88	88	87
		88.75	88.75	88.50	88.25	87.50	86.00
		0.113	**0.113**	**0.113**	**0.113**	**0.114**	**0.116**
		1.479	**1.479**	**1.475**	**1.471**	**1.458**	**1.433**
5	1	86	86	87	86	85	79
	2	85	86	86	86	84	81
	3	86	87	86	86	85	79
	4	87	86	86	86	85	80
		86.00	86.25	86.25	86.00	84.75	79.75
		0.116	**0.116**	**0.116**	**0.116**	**0.118**	**0.125**
		1.433	**1.438**	**1.438**	**1.433**	**1.413**	**1.329**
6	1	60	61	59	55	52	52
	2	61	60	59	56	53	51
	3	60	59	60	57	52	52
	4	60	60	59	56	54	50
		60.25	60.00	59.25	56.00	52.75	51.25
		0.166	**0.167**	**0.169**	**0.179**	**0.190**	**0.195**
		1.004	**1.000**	**0.988**	**0.933**	**0.879**	**0.854**
7	1	72	71	71	71	66	58
	2	73	70	71	70	65	58
	3	73	71	70	70	65	60
	4	73	70	71	70	64	61
		72.75	70.50	70.75	70.25	65.00	59.25
		0.137	**0.142**	**0.141**	**0.142**	**0.154**	**0.169**
		1.213	**1.175**	**1.179**	**1.171**	**1.083**	**0.988**
8	1	71	71	69	69	66	64
	2	70	71	70	68	65	63
	3	72	70	70	69	66	64
	4	71	70	70	70	66	63
		71.00	70.50	69.75	69.00	65.75	63.50
		0.141	**0.142**	**0.143**	**0.145**	**0.152**	**0.157**
		1.183	**1.175**	**1.163**	**1.150**	**1.096**	**1.058**
9	1	78	78	78	76	70	68
	2	79	78	77	78	70	68
	3	79	77	77	77	70	69
	4	78	78	77	76	71	68
		78.50	77.75	77.25	76.75	70.25	68.25
		0.127	**0.129**	**0.129**	**0.130**	**0.142**	**0.147**
		1.308	**1.296**	**1.288**	**1.279**	**1.171**	**1.138**
10	1	69	69	68	67	63	62
	2	70	68	67	66	64	61
	3	68	68	68	67	64	62
	4	69	69	67	66	64	62
		69.00	68.50	67.50	66.50	63.75	61.75
		0.145	**0.146**	**0.148**	**0.150**	**0.157**	**0.162**
		1.150	**1.142**	**1.125**	**1.108**	**1.063**	**1.029**

Test 4 Restoration - Tooth
Porcelain Resin B

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	81	80	79	78	75	76
	2	80	81	80	79	76	75
	3	81	80	79	78	76	76
	4	81	81	79	79	76	75
		80.75	80.50	79.25	78.50	75.75	75.50
		0.124	**0.124**	**0.126**	**0.127**	**0.132**	**0.132**
		1.346	**1.342**	**1.321**	**1.308**	**1.263**	**1.258**
2	1	93	92	93	92	89	86
	2	92	93	92	91	89	85
	3	93	92	91	92	90	87
	4	93	93	92	91	90	86
		92.75	92.50	92.00	91.00	89.50	86.00
		0.108	**0.108**	**0.109**	**0.110**	**0.112**	**0.116**
		1.546	**1.542**	**1.533**	**1.517**	**1.492**	**1.433**
3	1	94	94	93	93	93	92
	2	95	93	94	92	92	91
	3	94	94	94	92	92	92
	4	94	95	93	93	92	91
		94.25	94.00	93.50	92.50	92.25	91.50
		0.106	**0.106**	**0.107**	**0.108**	**0.108**	**0.109**
		1.571	**1.567**	**1.558**	**1.542**	**1.538**	**1.525**
4	1	79	79	79	78	77	77
	2	78	79	79	78	77	78
	3	79	79	78	77	78	78
	4	79	79	79	78	78	77
		78.75	79.00	78.75	77.75	77.50	77.50
		0.127	**0.127**	**0.127**	**0.129**	**0.129**	**0.129**
		1.313	**1.317**	**1.313**	**1.296**	**1.292**	**1.292**
5	1	72	71	71	70	71	70
	2	71	72	71	70	70	70
	3	72	71	70	71	70	70
	4	71	72	71	71	71	71
		71.50	71.50	70.75	70.50	70.50	70.25
		0.140	**0.140**	**0.141**	**0.142**	**0.142**	**0.142**
		1.192	**1.192**	**1.179**	**1.175**	**1.175**	**1.171**
6	1	73	72	73	72	72	71
	2	73	73	72	71	72	72
	3	72	72	72	72	71	72
	4	73	73	72	72	72	72
		72.75	72.50	72.25	71.75	71.75	71.75
		0.137	**0.138**	**0.138**	**0.139**	**0.139**	**0.139**
		1.213	**1.208**	**1.204**	**1.196**	**1.196**	**1.196**
7	1	98	98	97	97	97	97
	2	97	98	98	96	97	96
	3	98	97	97	96	96	97
	4	99	97	97	97	97	96
		98.00	97.50	97.25	96.50	96.75	96.50
		0.102	**0.103**	**0.103**	**0.104**	**0.103**	**0.104**
		1.633	**1.625**	**1.621**	**1.608**	**1.613**	**1.608**
8	1	125	125	125	126	125	124
	2	126	124	124	125	124	124
	3	126	126	125	125	124	123
	4	125	126	124	124	124	124
		125.50	125.25	124.50	125.00	124.25	123.75
		0.080	**0.080**	**0.080**	**0.080**	**0.080**	**0.081**
		2.092	**2.088**	**2.075**	**2.083**	**2.071**	**2.063**
9	1	140	141	140	139	139	139
	2	139	140	141	140	139	138
	3	141	141	139	139	138	139
	4	142	140	139	141	140	139
		140.50	140.50	139.75	139.75	139.00	138.75
		0.071	**0.071**	**0.072**	**0.072**	**0.072**	**0.072**
		2.342	**2.342**	**2.329**	**2.329**	**2.317**	**2.313**
10	1	74	73	74	73	71	72
	2	73	74	73	72	72	70
	3	74	73	73	73	72	71
	4	73	74	73	72	71	70
		73.50	73.50	73.25	72.50	71.50	70.75
		0.136	**0.136**	**0.137**	**0.138**	**0.140**	**0.141**
		1.225	**1.225**	**1.221**	**1.208**	**1.192**	**1.179**

Test 5 Tooth-Restoration-Tooth
Amalgam conventional

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	73	70	71	69	68	68
	2	72	71	70	70	69	67
	3	73	71	70	68	70	65
	4	71	71	70	70	68	66
		72.25	70.75	70.25	69.25	68.75	66.50
		0.138	**0.141**	**0.142**	**0.144**	**0.145**	**0.150**
		1.204	**1.179**	**1.171**	**1.154**	**1.146**	**1.108**
2	1	85	87	86	80	77	75
	2	86	86	85	81	78	76
	3	88	86	84	81	77	76
	4	86	85	85	80	77	75
		86.25	86.00	85.00	80.50	77.25	75.50
		0.116	**0.116**	**0.118**	**0.124**	**0.129**	**0.132**
		1.438	**1.433**	**1.417**	**1.342**	**1.288**	**1.258**
3	1	65	64	64	61	60	57
	2	64	64	63	62	59	58
	3	64	65	64	61	59	57
	4	65	64	64	61	59	57
		64.50	64.25	63.75	61.25	59.25	57.25
		0.155	**0.156**	**0.157**	**0.163**	**0.169**	**0.175**
		1.075	**1.071**	**1.063**	**1.021**	**0.988**	**0.954**
4	1	73	72	72	72	71	69
	2	73	72	72	70	71	69
	3	73	72	71	71	70	68
	4	72	72	72	70	71	69
		72.75	72.00	71.75	70.75	70.75	68.75
		0.137	**0.139**	**0.139**	**0.141**	**0.141**	**0.145**
		1.213	**1.200**	**1.196**	**1.179**	**1.179**	**1.146**
5	1	70	70	67	64	63	63
	2	73	70	65	65	64	62
	3	71	71	66	64	63	63
	4	71	70	67	64	65	63
		71.25	70.25	66.25	64.25	63.75	62.75
		0.140	**0.142**	**0.151**	**0.156**	**0.157**	**0.159**
		1.188	**1.171**	**1.104**	**1.071**	**1.063**	**1.046**
6	1	107	107	106	104	105	104
	2	108	107	107	104	104	103
	3	107	107	106	105	104	103
	4	107	107	106	103	105	103
		107.25	107.00	106.25	104.00	104.50	103.25
		0.093	**0.093**	**0.094**	**0.096**	**0.096**	**0.097**
		1.788	**1.783**	**1.771**	**1.733**	**1.742**	**1.721**
7	1	119	119	117	115	115	114
	2	118	119	118	114	114	114
	3	118	118	117	116	114	115
	4	119	118	118	115	115	114
		118.50	118.50	117.50	115.00	114.50	114.25
		0.084	**0.084**	**0.085**	**0.087**	**0.087**	**0.088**
		1.975	**1.975**	**1.958**	**1.917**	**1.908**	**1.904**
8	1	68	69	68	67	65	63
	2	69	69	69	67	64	62
	3	71	70	69	68	64	63
	4	70	69	68	67	65	64
		69.50	69.25	68.50	67.25	64.50	63.00
		0.144	**0.144**	**0.146**	**0.149**	**0.155**	**0.159**
		1.158	**1.154**	**1.142**	**1.121**	**1.075**	**1.050**
9	1	96	95	93	93	91	91
	2	95	94	93	93	92	91
	3	95	94	93	94	92	91
	4	95	95	94	94	93	91
		95.25	94.50	93.25	93.50	92.00	91.00
		0.105	**0.106**	**0.107**	**0.107**	**0.109**	**0.110**
		1.588	**1.575**	**1.554**	**1.558**	**1.533**	**1.517**
10	1	89	88	87	85	84	84
	2	88	89	88	85	84	84
	3	87	88	88	84	85	83
	4	89	89	89	84	83	84
		88.25	88.50	88.00	84.50	84.00	83.75
		0.113	**0.113**	**0.114**	**0.118**	**0.119**	**0.119**
		1.471	**1.475**	**1.467**	**1.408**	**1.400**	**1.396**

Test 6 Restoration -Tooth
Amalgam conventional

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	97	97	96	96	95	94
	2	97	98	97	96	96	94
	3	96	97	96	95	96	94
	4	97	96	96	96	96	94
		96.75	97.00	96.25	95.75	95.75	94.00
		0.103	**0.103**	**0.104**	**0.104**	**0.104**	**0.106**
		1.613	**1.617**	**1.604**	**1.596**	**1.596**	**1.567**
2	1	99	99	99	98	97	97
	2	99	99	99	97	97	96
	3	101	100	98	97	96	96
	4	101	99	99	97	96	96
		100.00	99.25	98.75	97.25	96.50	96.25
		0.100	**0.101**	**0.101**	**0.103**	**0.104**	**0.104**
		1.667	**1.654**	**1.646**	**1.621**	**1.608**	**1.604**
3	1	107	107	116	107	105	104
	2	108	107	117	107	106	103
	3	107	107	116	106	105	104
	4	107	107	107	107	106	104
		107.25	107.00	114.00	106.75	105.50	103.75
		0.093	**0.093**	**0.088**	**0.094**	**0.095**	**0.096**
		1.788	**1.783**	**1.900**	**1.779**	**1.758**	**1.729**
4	1	98	99	98	97	97	96
	2	100	98	98	95	95	95
	3	99	97	97	96	96	96
	4	99	98	96	97	96	95
		99.00	98.00	97.25	96.25	96.00	95.50
		0.101	**0.102**	**0.103**	**0.104**	**0.104**	**0.105**
		1.650	**1.633**	**1.621**	**1.604**	**1.600**	**1.592**
5	1	108	107	108	107	106	105
	2	107	108	108	106	107	105
	3	108	108	108	106	105	105
	4	108	108	108	106	106	105
		107.75	107.75	108.00	106.25	106.00	105.00
		0.093	**0.093**	**0.093**	**0.094**	**0.094**	**0.095**
		1.796	**1.796**	**1.800**	**1.771**	**1.767**	**1.750**
6	1	122	121	121	120	119	119
	2	122	122	120	120	120	118
	3	121	122	120	120	118	119
	4	121	121	120	120	119	118
		121.50	121.50	120.25	120.00	119.00	118.50
		0.082	**0.082**	**0.083**	**0.083**	**0.084**	**0.084**
		2.025	**2.025**	**2.004**	**2.000**	**1.983**	**1.975**
7	1	112	111	110	111	110	110
	2	113	112	111	110	110	110
	3	112	112	111	111	110	109
	4	112	112	111	110	110	109
		112.25	111.75	110.75	110.50	110.00	109.50
		0.089	**0.089**	**0.090**	**0.090**	**0.091**	**0.091**
		1.871	**1.863**	**1.846**	**1.842**	**1.833**	**1.825**
8	1	121	121	121	121	119	119
	2	120	120	119	120	119	118
	3	119	121	120	120	119	118
	4	121	120	120	120	120	118
		120.25	120.50	120.00	120.25	119.25	118.25
		0.083	**0.083**	**0.083**	**0.083**	**0.084**	**0.085**
		2.004	**2.008**	**2.000**	**2.004**	**1.988**	**1.971**
9	1	124	125	123	123	123	123
	2	125	125	122	122	123	122
	3	124	124	124	123	122	123
	4	125	125	124	123	123	122
		124.50	124.75	123.25	122.75	122.75	122.50
		0.080	**0.080**	**0.081**	**0.081**	**0.081**	**0.082**
		2.075	**2.079**	**2.054**	**2.046**	**2.046**	**2.042**
10	1	129	128	128	128	127	126
	2	128	128	127	128	127	126
	3	128	128	129	128	127	126
	4	129	129	128	128	126	126
		128.50	128.25	128.00	128.00	126.75	126.00
		0.078	**0.078**	**0.078**	**0.078**	**0.079**	**0.079**
		2.142	**2.138**	**2.133**	**2.133**	**2.113**	**2.100**

Test 7 Tooth-Restoration-Tooth
Amalgam Resin A

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	116	116	116	114	112	111
	2	116	116	114	114	112	112
	3	115	116	115	113	112	111
	4	115	115	114	112	113	112
		115.50	115.75	114.75	113.25	112.25	111.50
		0.087	**0.086**	**0.087**	**0.088**	**0.089**	**0.090**
		1.925	**1.929**	**1.913**	**1.888**	**1.871**	**1.858**
2	1	138	137	136	136	135	134
	2	138	136	136	135	136	133
	3	138	137	136	136	134	134
	4	138	136	136	135	135	133
		138.00	136.50	136.00	135.50	135.00	133.50
		0.072	**0.073**	**0.074**	**0.074**	**0.074**	**0.075**
		2.300	**2.275**	**2.267**	**2.258**	**2.250**	**2.225**
3	1	119	118	117	117	115	114
	2	118	118	116	115	116	114
	3	119	118	116	116	116	114
	4	118	118	115	115	115	114
		118.50	118.00	116.00	115.75	115.50	114.00
		0.084	**0.085**	**0.086**	**0.086**	**0.087**	**0.088**
		1.975	**1.967**	**1.933**	**1.929**	**1.925**	**1.900**
4	1	142	141	142	141	140	138
	2	142	142	141	141	138	138
	3	143	142	141	140	139	139
	4	143	142	141	140	140	138
		142.50	141.75	141.25	140.50	139.25	138.25
		0.070	**0.071**	**0.071**	**0.071**	**0.072**	**0.072**
		2.375	**2.363**	**2.354**	**2.342**	**2.321**	**2.304**
5	1	118	117	117	116	116	115
	2	117	117	116	116	115	115
	3	118	117	116	116	114	114
	4	118	118	117	116	114	114
		117.75	117.25	116.50	116.00	114.75	114.50
		0.085	**0.085**	**0.086**	**0.086**	**0.087**	**0.087**
		1.963	**1.954**	**1.942**	**1.933**	**1.913**	**1.908**
6	1	132	131	131	130	128	128
	2	132	131	131	129	129	127
	3	131	131	130	128	130	128
	4	131	131	131	130	128	127
		131.50	131.00	130.75	129.25	128.75	127.50
		0.076	**0.076**	**0.076**	**0.077**	**0.078**	**0.078**
		2.192	**2.183**	**2.179**	**2.154**	**2.146**	**2.125**
7	1	152	150	151	149	148	148
	2	153	151	150	148	148	148
	3	152	150	147	148	149	148
	4	152	151	148	149	149	149
		152.25	150.50	149.00	148.50	148.50	148.25
		0.066	**0.066**	**0.067**	**0.067**	**0.067**	**0.067**
		2.538	**2.508**	**2.483**	**2.475**	**2.475**	**2.471**
8	1	121	121	121	120	119	118
	2	122	122	120	120	118	118
	3	122	121	120	120	120	118
	4	121	121	121	119	120	118
		121.50	121.25	120.50	119.75	119.25	118.00
		0.082	**0.082**	**0.083**	**0.084**	**0.084**	**0.085**
		2.025	**2.021**	**2.008**	**1.996**	**1.988**	**1.967**
9	1	134	134	133	133	131	131
	2	135	134	133	132	132	131
	3	134	134	133	132	131	132
	4	135	133	133	133	132	131
		134.50	133.75	133.00	132.50	131.50	131.25
		0.074	**0.075**	**0.075**	**0.075**	**0.076**	**0.076**
		2.242	**2.229**	**2.217**	**2.208**	**2.192**	**2.188**
10	1	157	157	155	155	155	154
	2	157	156	157	156	154	153
	3	156	156	155	155	154	152
	4	157	157	156	155	155	153
		156.75	156.50	155.75	155.25	154.50	153.00
		0.064	**0.064**	**0.064**	**0.064**	**0.065**	**0.065**
		2.613	**2.608**	**2.596**	**2.588**	**2.575**	**2.550**

Test 8 Restoration -Tooth
Amalgam Resin A

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	157	156	156	157	157	156
	2	157	158	157	156	158	155
	3	158	157	158	157	157	156
	4	157	157	156	157	157	155
		157.25	157.00	156.75	156.75	157.25	155.50
		0.064	**0.064**	**0.064**	**0.064**	**0.064**	**0.064**
		2.621	**2.617**	**2.613**	**2.613**	**2.621**	**2.592**
2	1	132	134	132	132	132	131
	2	135	133	132	132	131	132
	3	133	135	134	133	133	132
	4	134	134	133	132	132	131
		133.50	134.00	132.75	132.25	132.00	131.50
		0.075	**0.075**	**0.075**	**0.076**	**0.076**	**0.076**
		2.225	**2.233**	**2.213**	**2.204**	**2.200**	**2.192**
3	1	151	150	152	151	151	150
	2	152	153	152	151	150	150
	3	152	151	150	151	151	150
	4	153	151	151	151	150	151
		152.00	151.25	151.25	151.00	150.50	150.25
		0.066	**0.066**	**0.066**	**0.066**	**0.066**	**0.067**
		2.533	**2.521**	**2.521**	**2.517**	**2.508**	**2.504**
4	1	117	117	117	116	116	116
	2	117	117	117	116	115	116
	3	118	117	116	117	115	115
	4	118	117	117	116	116	116
		117.50	117.00	116.75	116.25	115.50	115.75
		0.085	**0.085**	**0.086**	**0.086**	**0.087**	**0.086**
		1.958	**1.950**	**1.946**	**1.938**	**1.925**	**1.929**
5	1	100	101	99	99	98	98
	2	100	99	100	99	99	99
	3	101	100	98	98	100	99
	4	99	100	99	99	99	98
		100.00	100.00	99.00	98.75	99.00	98.50
		0.100	**0.100**	**0.101**	**0.101**	**0.101**	**0.102**
		1.667	**1.667**	**1.650**	**1.646**	**1.650**	**1.642**
6	1	117	116	116	116	115	115
	2	117	117	117	117	116	116
	3	116	116	116	116	115	115
	4	117	117	116	116	116	115
		116.75	116.50	116.25	116.25	115.50	115.25
		0.086	**0.086**	**0.086**	**0.086**	**0.087**	**0.087**
		1.946	**1.942**	**1.938**	**1.938**	**1.925**	**1.921**
7	1	91	93	93	93	92	90
	2	93	93	92	92	91	91
	3	94	93	93	92	92	91
	4	92	93	92	92	91	91
		92.50	93.00	92.50	92.25	91.50	90.75
		0.108	**0.108**	**0.108**	**0.108**	**0.109**	**0.110**
		1.542	**1.550**	**1.542**	**1.538**	**1.525**	**1.513**
8	1	120	119	118	118	117	117
	2	118	118	119	118	119	117
	3	118	118	118	117	117	117
	4	118	119	119	119	117	117
		118.50	118.50	118.50	118.00	117.50	117.00
		0.084	**0.084**	**0.084**	**0.085**	**0.085**	**0.085**
		1.975	**1.975**	**1.975**	**1.967**	**1.958**	**1.950**
9	1	107	106	106	106	105	105
	2	106	108	106	106	105	106
	3	106	105	105	106	106	105
	4	108	107	105	105	105	105
		106.75	106.50	105.50	105.75	105.25	105.25
		0.094	**0.094**	**0.095**	**0.095**	**0.095**	**0.095**
		1.779	**1.775**	**1.758**	**1.763**	**1.754**	**1.754**
10	1	106	106	105	105	105	104
	2	105	106	106	104	104	105
	3	106	105	105	106	105	104
	4	105	106	105	104	104	104
		105.50	105.75	105.25	104.75	104.50	104.25
		0.095	**0.095**	**0.095**	**0.095**	**0.096**	**0.096**
		1.758	**1.763**	**1.754**	**1.746**	**1.742**	**1.738**

Test 9 Tooth-Restoration-Tooth
Amalgam Resin B

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	111	111	111	110	109	108
	2	112	112	110	109	109	108
	3	112	112	110	109	108	108
	4	112	111	110	110	108	108
		111.75	111.50	110.25	109.50	108.50	108.00
		0.089	**0.090**	**0.091**	**0.091**	**0.092**	**0.093**
		1.863	**1.858**	**1.838**	**1.825**	**1.808**	**1.800**
2	1	111	110	111	110	108	107
	2	110	110	111	110	108	107
	3	111	112	110	109	108	106
	4	112	111	110	109	107	106
		111.00	110.75	110.50	109.50	107.75	106.50
		0.090	**0.090**	**0.090**	**0.091**	**0.093**	**0.094**
		1.850	**1.846**	**1.842**	**1.825**	**1.796**	**1.775**
3	1	105	105	103	103	102	101
	2	105	105	105	103	103	101
	3	104	103	104	104	102	101
	4	105	104	104	103	103	101
		104.75	104.25	104.00	103.25	102.50	101.00
		0.095	**0.096**	**0.096**	**0.097**	**0.098**	**0.099**
		1.746	**1.738**	**1.733**	**1.721**	**1.708**	**1.683**
4	1	127	128	127	125	124	124
	2	128	127	125	126	124	123
	3	126	126	126	125	124	123
	4	127	127	126	125	124	124
		127.00	127.00	126.00	125.25	124.00	123.50
		0.079	**0.079**	**0.079**	**0.080**	**0.081**	**0.081**
		2.117	**2.117**	**2.100**	**2.088**	**2.067**	**2.058**
5	1	133	133	132	132	131	130
	2	134	133	131	131	131	130
	3	133	133	132	131	130	130
	4	134	134	132	132	130	130
		133.50	133.25	131.75	131.50	130.50	130.00
		0.075	**0.075**	**0.076**	**0.076**	**0.077**	**0.077**
		2.225	**2.221**	**2.196**	**2.192**	**2.175**	**2.167**
6	1	56	56	56	55	54	54
	2	58	57	56	56	54	53
	3	56	57	55	55	54	53
	4	57	58	56	55	54	54
		56.75	57.00	55.75	55.25	54.00	53.50
		0.176	**0.175**	**0.179**	**0.181**	**0.185**	**0.187**
		0.946	**0.950**	**0.929**	**0.921**	**0.900**	**0.892**
7	1	110	110	110	108	108	107
	2	111	110	109	108	108	108
	3	110	110	109	108	109	107
	4	111	110	110	108	107	108
		110.50	110.00	109.50	108.00	108.00	107.50
		0.090	**0.091**	**0.091**	**0.093**	**0.093**	**0.093**
		1.842	**1.833**	**1.825**	**1.800**	**1.800**	**1.792**
8	1	132	132	131	131	130	129
	2	133	133	131	132	129	130
	3	133	133	131	130	130	128
	4	132	131	132	130	130	129
		132.50	132.25	131.25	130.75	129.75	129.00
		0.075	**0.076**	**0.076**	**0.076**	**0.077**	**0.078**
		2.208	**2.204**	**2.188**	**2.179**	**2.163**	**2.150**
9	1	103	103	103	102	102	102
	2	103	103	103	102	102	101
	3	102	101	103	102	101	101
	4	102	103	101	102	102	102
		102.50	102.50	102.50	102.00	101.75	101.50
		0.098	**0.098**	**0.098**	**0.098**	**0.098**	**0.099**
		1.708	**1.708**	**1.708**	**1.700**	**1.696**	**1.692**
10	1	104	107	105	104	105	103
	2	106	106	104	104	104	104
	3	105	105	106	105	104	104
	4	104	106	105	105	103	104
		104.75	106.00	105.00	104.50	104.00	103.75
		0.095	**0.094**	**0.095**	**0.096**	**0.096**	**0.096**
		1.746	**1.767**	**1.750**	**1.742**	**1.733**	**1.729**

Test 10 Restoration -Tooth
Amalgam Resin B

Sample	Measurement			Cycles			
		0	5,000	10,000	15,000	20,000	25,000
1	1	141	141	140	140	140	139
	2	139	141	140	139	139	138
	3	140	140	140	140	140	139
	4	141	139	141	140	140	138
		140.25	140.25	140.25	139.75	139.75	138.50
		0.071	**0.071**	**0.071**	**0.072**	**0.072**	**0.072**
		2.338	**2.338**	**2.338**	**2.329**	**2.329**	**2.308**
2	1	120	120	119	119	119	118
	2	120	121	120	120	118	118
	3	121	121	120	119	118	118
	4	120	121	120	120	120	118
		120.25	120.75	119.75	119.50	118.75	118.00
		0.083	**0.083**	**0.084**	**0.084**	**0.084**	**0.085**
		2.004	**2.013**	**1.996**	**1.992**	**1.979**	**1.967**
3	1	153	154	153	153	152	150
	2	154	154	153	152	152	151
	3	152	153	153	153	151	151
	4	154	153	153	152	151	151
		153.25	153.50	153.00	152.50	151.50	150.75
		0.065	**0.065**	**0.065**	**0.066**	**0.066**	**0.066**
		2.554	**2.558**	**2.550**	**2.542**	**2.525**	**2.513**
4	1	129	128	128	127	1127	127
	2	128	128	127	126	126	126
	3	129	128	127	126	126	126
	4	128	128	128	128	126	126
		128.50	128.00	127.50	126.75	376.25	126.25
		0.078	**0.078**	**0.078**	**0.079**	**0.027**	**0.079**
		2.142	**2.133**	**2.125**	**2.113**	**6.271**	**2.104**
5	1	154	154	153	153	153	152
	2	154	153	153	153	152	152
	3	154	154	154	153	153	152
	4	154	154	153	153	152	152
		154.00	153.75	153.25	153.00	152.50	152.00
		0.065	**0.065**	**0.065**	**0.065**	**0.066**	**0.066**
		2.567	**2.563**	**2.554**	**2.550**	**2.542**	**2.533**
6	1	150	151	151	150	149	149
	2	151	150	150	149	149	148
	3	150	150	149	149	149	148
	4	149	150	149	149	1148	149
		150.00	150.25	149.75	149.25	398.75	148.50
		0.067	**0.067**	**0.067**	**0.067**	**0.025**	**0.067**
		2.500	**2.504**	**2.496**	**2.488**	**6.646**	**2.475**
7	1	148	147	147	147	147	146
	2	148	148	148	147	147	145
	3	148	147	146	147	146	146
	4	147	148	148	147	146	146
		147.75	147.50	147.25	147.00	146.50	145.75
		0.068	**0.068**	**0.068**	**0.068**	**0.068**	**0.069**
		2.463	**2.458**	**2.454**	**2.450**	**2.442**	**2.429**
8	1	118	118	117	118	116	117
	2	119	118	119	117	117	116
	3	117	118	118	117	116	116
	4	119	118	117	117	117	117
		118.25	118.00	117.75	117.25	116.50	116.50
		0.085	**0.085**	**0.085**	**0.085**	**0.086**	**0.086**
		1.971	**1.967**	**1.963**	**1.954**	**1.942**	**1.942**
9	1	132	132	130	129	131	130
	2	132	131	131	129	131	130
	3	132	132	131	131	130	130
	4	132	131	131	130	130	130
		132.00	131.50	130.75	129.75	130.50	130.00
		0.076	**0.076**	**0.076**	**0.077**	**0.077**	**0.077**
		2.200	**2.192**	**2.179**	**2.163**	**2.175**	**2.167**
10	1	139	139	138	137	137	137
	2	136	138	138	138	137	136
	3	138	138	138	138	136	136
	4	139	138	138	137	136	137
		138.00	138.25	138.00	137.50	136.50	136.50
		0.072	**0.072**	**0.072**	**0.073**	**0.073**	**0.073**
		2.300	**2.304**	**2.300**	**2.292**	**2.275**	**2.275**

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