CHAPTER 2: LITERATURE REVIEW

2.1. Restoration of access cavities through crowns in endodontically treated teeth:

Ideally, if root canal treatment is indicated, it should be completed prior to placement of the restoration. Nonetheless, more than 50 % of teeth with PFM crowns or bridges required non-surgical root canal treatment (Goldman et al., 1992). This can be due to the extensive effect of the restorative procedure, the possible leakage of bacteria and their by-products at imperfect crown margins or recurrent marginal caries that cannot always be detected clinically (Larson and Jensen, 1980; Trautmann et al., 2001a). Occasionally, pulps undergo irreversible pulpitis or necrosis after placement of a crown, requiring root canal treatment. Access through the restoration, with subsequent permanent repair of the opening is often preferred (Messer and Wilson, 2002).

2.1.1. Coronal microleakage of restored endodontically treated access cavities:

In recent years, the concept of coronal leakage has taken on a life of its own in various attempts to explain endodontic treatment failures. Coronal leakage at the margin of an artificial crown for endodontically treated teeth may result in recurrent caries and failure of both the restoration and the root canal treatment (Saunders and Saunders, 1994). Leakage from the crown to the apex is probably of greater clinical relevance than leakage from apex to crown (Wu and Wesselink, 1993).

The quality of coronal restoration is of prime importance to create a bacteria impervious seal after root canal treatment. Several investigators have assessed the sealing ability of restorative materials to prevent coronal microleakage (Noguera and McDonald, 1990; Saunders and Saunders, 1994; Trautmann et al., 2001b) with different results. Ray and Trope (1995) came to the conclusion, disquieting for the endodontic profession, that the technical quality of the coronal restoration was more important for the result than the technical quality of the endodontic treatment. However, subsequent studies have not

supported this (Chailertvanitkul et al., 1996; Oliver and Abbott, 1998; Alves et al., 1998; Uranga et al., 1999; Haikel et al., 1999; Timpawat et al., 2001; Heling et al., 2002).

At times, coronal leakage may be suspected but the source cannot be confirmed. One option would be to remove all restorations completely. This approach will be the most reliable way to prevent leakage and eliminate the probability of inter-appointment flare-up. However, complete removal of existing restorations is not always practical or desirable and the routine use of this approach is not recommended when clinically sound restorative dentistry is in place (Gutmann and Lovdahl, 1997).

2.1.2. Endodontic access openings through existing crowns:

Many dentists are confronted with the need to gain access to a root canal through an existing porcelain or metal crown. Endodontic access preparation therefore has the potential to affect crown retention as access preparation creates vibratory forces that may disrupt the seal and modify the retention. Regardless of the cause of the reduction in retention, certain measures should always be taken to minimize retention reduction. Such measures include use of sharp burs in high-speed rotary cutting instruments under light pressure. Cutting access through gold crowns which are not as hard as the cast metal used in metal-ceramic crowns might not cause as much loss of retention because not as much cutting force is needed to cut through a gold crown (McMullen et al., 1989). In such a case, one can remove the crown or cut an endodontic access preparation through the crown; either of which may lead to permanent deformation of the crown (McMullen et al., 1990). It has been noted that crowns may become displaced during endodontic access preparation in a clinical situation (Bergenholtz and Nyman, 1984).

Ideally, it should be decided if the tooth restored with metal-ceramic crown is restorable before endodontic treatment is carried out and this is a primary element of the basic treatment plan. When a tooth has been crowned it is very important to assess the position of the pulp space in relation to the artificial crown, or else the access cavity may be misdirected (Pitt Ford et al., 2002).

2.1.3. Burs for preparing endodontic access cavities through existing crowns:

Ensuring that the crown does not fracture is always a concern for the practitioner while making access openings for endodontic therapy (McLean, 1983). This was never a problem with gold occlusal or lingual surfaces, but with the advent of porcelain fused to metal and the all-porcelain crown the incidence of shattering became a factor (Grossman, 1985). Diamond burs have proven to be effective for the preparation of endodontic access cavities through aluminous porcelain crowns, whereas tungsten carbide burs dull rapidly and are ineffective (Teplitsky and Sutherland, 1985). The preparation of cavities through metal-ceramic crowns involves the penetration of an outer layer of porcelain and an inner shell of metal. Diamond burs which easily penetrate porcelain are generally much less efficient with metal. Some tungsten carbide burs have been designed to cut silver amalgam and gold alloys quickly and smoothly (Howell, 1984), but there remains a real difficulty in cutting endodontic access cavities in non-precious metal-ceramic crowns and in severing the non-precious metal framework of some bridges (McLean, 1984). This has led to suggestions for ready-made endodontic access cavities in some types of crowns (Burrell and Goldberg, 1974; Chandler and Stockdale, 1987). A few studies have evaluated the effect of endodontic access on the structure of PFM crowns. Teplitsky and Sutherland (1985) reported that none of the Cerestore crowns fractured as a result of the stress caused by access opening

preparation using high-speed diamond instrumentation with water spray, whereas carbide instrumentation is not effective.

Comparative studies pertaining to the relative effectiveness of each bur have been few and are limited in their application (Teplistsky and Sutherland, 1985; Sutherland et al., 1989). Consequently, for guidance in bur selection, clinicians have depended on anecdotal reporting in the literature and advertising from companies that manufacture burs (Haselton et al., 2000). Bur selection also varied from study to study. Information on the exact specifications for diamond burs used, including diameters and grit size, was not provided (Stokes and Tidmarsh, 1988; Haselton et al., 2000). It was not always stated which burs were used to access which crowns (Sutherland et al., 1989; Cohen and Wallace, 1991). An uneven distribution of bur usage, without explanation, was noted in one study (Teplistsky and Sutherland, 1985).

At present, other factors such as the resistance to fracture of PFM crowns following endodontic access, the effects of different burs on endodontic access in PFM crowns, and the effects of different burs on roughness of the inner walls of the access openings had not been addressed.

2.1.4. Coronal Repair Restorations:

For the restoration to remain functional, three conditions must be met: (1) the interface between the restoration and the repair material must provide a good coronal seal; (2) retention of the restoration must not be compromised; and (3) the final core structure must support the restoration against functional or minor traumatic stresses (Messer and Wilson, 2002). The repair material should have high compressive and shear strength. In most situations, amalgam is preferred. It improves retention, maintains and even

improves its seal with time, and is easily condensed into the entire chamber and access cavity as a single unit. Composite resins, glass ionomer cements and glass cermets do not have the requisite shear strength. Amalgam also functions well in anterior teeth with porcelain-fused-to-metal restorations. If aesthetics is a problem, a new restoration is the first choice. A layer of composite can be placed over the amalgam core but serves only as a short-term repair. Inlays or gold foil to restore access openings through gold casting offer no advantage and do not merit the effort and cost (Messer and Wilson, 2002).

2.1.4.1. Repair of Access Cavities through Coronal Restorations:

Trautmann et al. (2000) presented the results of a survey given to endodontists, prosthodontists and general practitioners as to material of choice for a direct repair. The preferred and most frequently used material to restore a metal crown was a bonded silver amalgam restoration, whereas composite resin was the material of choice for metal-ceramic crowns.

Root canal treatment through an existing crown presents two challenges. First, access orientation is difficult because the crown masks the coronal tooth structure; so clinicians must use their best judgment to determine pulp chamber location. Second, the restorative dentist must determine how to manage the access opening; either by placing a direct restorative material or remaking the entire restoration. For the tooth with minimal or no dental caries, application of a restorative material to prevent marginal and intermaterial leakage should be considered. With this approach, the long-term success of the root canal treatment through an existing artificial crown is highly dependent on the seal of the restored access opening. Unfortunately, there is no evidence-based research suggesting the best material for these access repairs (Wood et al., 2006).

2.1.4.2. The advantages of restoring the endodontic access cavities through an existing crown:

The remake process is both costly and time consuming and therefore remains a clinical problem. It is therefore more practical for function and economic considerations (Marroquin et al., 1995) to retain a good crown for continued serviceability. Besides the stated economic and technical reasons, the repair options provide the possibility of repairing the access cavities in the patient's mouth thereby preventing replacement of the complete restoration. Aesthetic and functional repair, in most instances, has many advantages over time-consuming and expensive remakes of crowns or bridges. Given these problems and concerns, it is desirable to repair the access cavities through fixed functional crowns in the mouth in a less time consuming and more conservative approach.

2.1.4.3. The disadvantages of restoring the endodontic access cavities through an existing crown:

1. It should be noted that working through a crown is always more difficult and that further damage can be done (Whitworth et al., 2002).

2. Just piercing the glaze of a porcelain crown dramatically reduces its strength (McLean, 1979), whilst cutting through a metal ceramic crown can weaken the porcelain bond and predispose the porcelain to fracture (Whitworth et al., 2002).

3. Of equal importance is the damage that can be done to patient confidence and trust if a recently crowned tooth becomes troublesome and has to be accessed or the restoration removed for endodontic treatment. As the complexity of the crown and bridgework increases, so the consequences become more serious. Replacing a single crown damaged during access is one matter; replacing a large

bridge which has suffered irreparable damage to one of its abutments is quite another (Whitworth et al., 2002).

2.1.4.4. Coronal Restorative Materials:

Restoration of an access cavity in a full coverage crown will allow the life of the crown to be extended by restoring its retentive properties but other factors need to be considered, such as the integrity of the crown margins which cannot be accurately assessed clinically. Marginal microleakage may have been the original cause of the pulpal disease (Goldman et al., 1992) and, if this problem is not addressed, the tooth may be predisposed to further problems due to bacterial ingress. These problems include caries in the region of the leaking margin (which may result in further destruction of tooth substance) and bacterial penetration into the dentine and subsequent re-infection of the root canal treatment system.

The choice of appropriate restorations should be guided by both physical properties and aesthetics. A restoration has several purposes: to repair the cavity, to strengthen the tooth and to provide an effective seal between the root canal system and the oral environment (Belli et al., 2005).

Marroquin et al. (1995) concluded that amalgam could be considered the best restorative material for cavities prepared in cast crowns in molars and premolars. The use of lathe-cut or irregularly shaped particle amalgam should be considered instead of spherical amalgam when restoring cavities prepared in gold cast restorations. They suggested that, concerning microleakage, composites do not represent the material of choice for restoration of endodontic-access cavities in cast crowns. Additionally, glass

ionomer cement can wash out with time and is therefore generally not recommended as definitive filling materials.

Composite apparently offers adequate strength clinically; its ultimate strength being somewhat lower than that of amalgam. Its resistance to leakage is almost totally dependent on the luting agent and the ability of dentine bonding agents to prevent leakage over the long term is unproven (McLean, 1998). The coefficient of thermal expansion for most modern self-polymerizing composite build-up materials is significantly higher than that of tooth substance (Roberson et al., 2002). However, composites show significant setting shrinkage. This shrinkage results in stresses on the bonding systems that may contribute to long-term bond failure (McLean, 1998). The clinical success of the ceramic repair system is almost entirely dependent on the integrity of the bond between the ceramic and the composite resin. This integrity is achieved either by chemical or mechanical bonds (Chung and Hwang, 1997). The restorative material which can ensure this bond should have a minimal coefficient of thermal expansion and minimal polymerization shrinkage. The type of composite resin also affects its bond strength to ceramic; such as larger particle size composite resins or hybrid type resins at the ceramic interface can achieve higher bond strength than those of microfilled composite resins (Gregory and Moss, 1990). For repair purposes, use of the hybrid composite resins was advised as the most suitable ones (Lutz and Phillips, 1983). A hybrid composite resin is also recommended to be used where fatigue loading is of consideration (Llobell et al., 1992).

Microhybrid and flowable resin materials in the self-curing or light-activated formulation are characterized by different strength, stiffness and elasticity and these properties could affect the longevity of the restoration (Asmussen et al., 1999; Ferrari et

al., 2000). Such resin composites can be used together in the so called "sandwich technique", in order to join the mechanical properties of both materials (Croll, 2004). Up to date, there is still no agreement regarding the best composite for direct coronal build up of endodontically treated teeth (Ferrari et al., 2000, Monticelli et al., 2004).

Many new materials, such as packable composite resins (Tung et al., 2000; Yap, 2000; Görgül et al., 2002, Papadogiannis et al., 2007), and techniques, such as incremental and bulk-pack techniques (Neiva et al., 1998; Cobb et al., 2000; Lopes et al., 2004, Blalock et al., 2006), have been proposed recently to minimize the problem of microleakage in resin restorations with variable results (Leevailoj et al., 2001; Meiers et al., 2001; Tredwin et al., 2005; Pongprueksa et al., 2007). However, there are very few studies evaluating the sealability of packable composite materials/techniques in endodontic access cavities.

2.2. Dental Porcelain

2.2.1. Definitions:

Dental ceramic is defined as an inorganic compound with nonmetallic properties typically consisting of oxygen and one or more metallic or semimetallic elements (e.g., aluminum, calcium, lithium, magnesium, potassium, silicon, sodium, tin, titanium, and zirconium) that are formulated to produce the whole or part of a ceramic-based dental prosthesis (Anusavice, 2003). Feldspathic porcelain is defined as a ceramic composed of a glass matrix phase and one or more crystalline phases (such as leucite, $K_2O \cdot Al_2O_3 \cdot 4SiO_2$) (Anusavice, 2003).

2.2.2. Historical Perspective of Porcelain:

Ceramic objects have been constructed for thousands of years (Rosenstiel et al., 2001). The first porcelain tooth material was patented in 1789 by a French dentist (de Chemant) in collaboration with a French pharmacist (Duchateau). The product, an improved version of "mineral paste teeth" that was produced in 1774 by Duchateau, was introduced in England soon thereafter by de Chemant. However, this baked compound was not used to produce individual teeth because there was no effective way at that time to attach the teeth to a denture base material. In the past 210 years there has been an incredible improvement in the standards and quality of dental porcelain restorations with their translucency and colour depth in which artificial crowns are undetectable from their human counterparts (Jones, 1985). According to Jones (1985), Wain in 1923, described the technique of fabricating porcelain restorations by casting the molten porcelain into a refractory mould. In 1932, Fenn described a method of casting porcelain onto metal.

In 1956, a significant development occurred with the fusion of porcelain to certain gold alloys to form crowns and bridges. The fusing of porcelain to gold alloys allowed the

combination of aesthetics of porcelain and the ductility, strength and toughness of the gold alloy. The palladium silver alloys were introduced in 1974 for use as porcelain fused to metal systems. In the 1980s, well over 40% of such restorations would be porcelain fused to base metal (nickel-chromium) alloys (Jones, 1985). The first commercial porcelain was developed by Vita Zahnfabrik in about 1963. Although the first Vita porcelain products were known for their aesthetic properties, the subsequent introduction of the more versatile Ceramco porcelain led to thermal expansion behavior that allowed this porcelain to be used safely with a wider variety of alloys (Anusavice, 2003). The porcelain fused to metal crowns are very widely used due to their strength, low cost and ease of production (Phillips, 1982).

Today, porcelain plays a vital role in restorative dentistry. Common uses include crowns, inlays, onlays, porcelain bridges veneering agents, castable ceramic and porcelain fused to metal (PFM) restoration (Leinfelder, 2000), and the technique of the metal-ceramic restoration is considered a routine procedure with high predictability (Rosenstiel et al., 2001). PFM restorations were selected for most clinical situation for several reasons: (1) PFM crowns are stronger than other ceramic restorations; (2) They possess more durability; (3) They are aesthetic in the presence of thick gingival tissue; (4) Fabrication is a familiar procedure to dental laboratories; (5) PFM crowns are selected for anterior and posterior teeth; (6) They are suitable for fixed partial dentures (FPDs); (7) They are indicated for implant prosthesis; and (8) PFM crowns are acceptable for extremely dark teeth (Bello and Jarvis, 1997) . PFM restorations are currently the most common type of ceramic dental restoration and have sufficient strength to be used in long-span bridges (fixed partial dentures) or in restorations for posterior teeth (Craig et al., 2004). These bonded porcelain restorations are three times stronger than all porcelain restorations (Campbell, 1989).

2.2.3. Alloys for Porcelain Fused to Metal

Alloys should have a coefficient of thermal expansion closely matching that of porcelain veneer. High melting point is necessary to withstand fusing temperature of the applied porcelain and chemical compatibility with the porcelain is essential as the alloy must not contain any element likely to discolour the porcelain during firing. In addition, the alloy should possess high modulus of elasticity, high yield strength, fine grain structure, sag resistance during porcelain firing and function, proper castability and bond potential to porcelain veneer (Vincent et al., 1977).

Meyer et al. (1979) and ADA CDMIE (1981) classified the PFM alloys into:

1- Precious alloys: Gold content is higher than 80% by weight.

2- Semiprecious alloys: do not contain more than 50% gold and 30% palladium, with the balance made up of silver and non-precious metals. platinum is no longer present.

3- Non-precious alloys: do not contain gold, platinum, palladium and silver. The main constituents are nickel and chromium usually with molybdenum. Addition of aluminum, manganese, ferrous, silicon, or beryllium can be found besides the three main components.

Recent classification of PFM Alloys by Wang and Fung (1997) was based on the major constituents. They divided PFM alloys into four groups:

1- Gold-Platinum-Palladium alloys.

2- Gold-Palladium alloys.

3- High Palladium content alloys (silver and non-silver alloys).

4- Base metal alloys.

2.2.3.1. Base Metal Alloys:

The noble metal content of these alloys is below 25% with no gold. Some authors attributed the increased use of these alloys in addition to cost, to their low density and high mechanical properties, ease of manipulation, proper castability, corrosion resistance and, the most important, biologic compatibility (Asger and Arfaei, 1985). The two most commonly used base metal alloys in dentistry are the nickel-chromium (Ni/Cr) alloys which are commonly used for crown and bridge casting, including PFM restorations, and the cobalt-chromium (Co/Cr) alloys which are commonly used for partial denture framework castings (McCabe and Walls, 1998).

Ni-Cr alloys have become widely used as substitutes for the higher cost precious metal alloys and possible alternatives to gold alloys (Meyer et al., 1979). They can be divided into those containing or not containing beryllium (Naylor, 1992). Beryllium containing alloys have higher porcelain bond strength than the non Beryllium containing alloys (Moffa et al., 1984). Beryllium, added to alloys to control oxide formation, is a carcinogen. It can pose a hazard to laboratory personnel who may inhale it as dust in improperly ventilated work areas (Moffa et al., 1973). A recent investigation found that Ni-Cr alloys not containing beryllium were more resistant than beryllium-containing alloys to in vitro corrosion (Rosenstiel et al., 2001).

2.3. Resin-Based Composites (RBCs)

2.3.1. Introduction

The introduction of resin composite technology to restorative dentistry was one of the most significant contributions to dentistry in the last century. Today, improvements in formulations, optimization of properties and the development of new techniques for placement have made the restoration of direct composite more reliable and predictable (Fortine and Vargas, 2000). One of the major improvements in resin-based composite has resulted from increased filler loading along with varying its distribution, size, shape and composition. Later development of bonding agents for bonding composites to tooth structure has also improved the quality of composite restorations (Craig and Powers, 2002; Gallo et al., 2005; Araujo et al., 2006; Blalock et al., 2006; Beun et al., 2007).

2.3.2. Definition of Dental Composites

A composite is a physical mixture of materials. The parts of the mixture generally are chosen with the purpose of averaging the properties of the parts to achieve intermediate properties (Roberson et al., 2002). Composites of polymers and ceramics are now widely used in restorative dentistry and are currently termed resin-based composites (RBCs) (Combe and Burke, 2000).

2.3.3. Composition of Dental Composite:

By definition, a composite is therefore a material that consists of two or more components. Typically, a dental resin composite contains an organic binder and an inorganic filler incorporated into a system that would induce polymerization. Usually, the filler particles are coated with a coupling agent to bond to the resin matrix (Phillips, 1982). Composite resin material consists mainly of:

2.3.3.1. Organic Phase:

The two most common oligomers that have been used in dental composites are dimethacrylates (Bis-GMA) 2, 2-bis [4(2-hydroxy-3 methacryloxy-propyloxy)-phenyl] propane and urethane dimethacrylate (UDMA) (Craig and Powers, 2002). Both Bis-GMA and UDMA oligomers are highly viscous and sticky and require dilution by low molecular weight monomers like Triethylene Glycol Dimethacrylate (TEGDMA), which are added to control the consistency of the composite. Both oligomers and the lower molecular weight monomers have carbon double bonds that react to convert them to a polymer.The matrix of most resin-based composites is a mixture of di-functional monomers containing Bis-GMA, TEGDMA, or UDMA in some combination (Craig et al., 2004; Papadoginannis et al., 2007).

2.3.3.2. Inorganic Fillers:

Inorganic fillers play an important role in properties of the resin composite material (Combe and Burke, 2000), as shown in the Table 2.1.

Table 2.1. Function of fillers*.

- Improve mechanical properties such as compressive strength, modulus of elasticity and hardness.
- Reduce the coefficient of thermal expansion.
- Reduce the setting contraction.
- Reduce the heat evolved during polymerization.
- Contribute to the aesthetics of the restoration.
- Produce radio-opaque materials if barium or strontium glasses are used.

*. Adapted from (Combe and Burke, 2000).

2.3.3.3. Coupling Agents:

The most common coupling agents are organic silicon compounds called silanes. This coupling reaction binds the filler and the oligomer, so when a stress is applied to a composite, the stress can be transferred from one strong filler particle to another through the rather low-strength polymer (Craig and Powers, 2002). To achieve and maintain the optimum properties of the composite, it is important that the filler particles be bonded to

the resin matrix. The silica glasses are covered with silane coupling agents, difunctional molecules, which bond with the silica's hydroxyl groups at one end and with the double bond of the monomer matrix at the other end (Fortin and Vargas, 2000).

2.3.4. Classification of Resin Composites:

Composite-based resins have historically been classified according to their particle size (Bayne et al., 1994) as shown in Table 2.2.

Table 2.2. Classification of resin composites by filler particles size.

Category	Particle Size
Megafill	0.5 – 2 mm
Macrofill	10 – 100 µm
Midfill	1 – 10 µm
Minifill	0.1 – 1 µm
Microfill	0.01 – 0.1 µm
Nanofill	0.005 – 0.01 µm

A classification system by Bayne and others, based on particle size, was introduced in 1994 as shown in Table 2.2. The various groups included megafill – 0.5 to 2 millimeters; macrofill – 10 to 100 micron; midifill – 1 to 10 micron; minifill – 0.1 to 1.0 micron; microfill – 0.01 to 0.1 micron and nanofill – 0.005 to 0.01 micron (Bayne et al., 1994). Nanofilled resin composites utilize nanometer-sized particles throughout the resin matrix. Nanohybrids combine nanometer-sized particles with more conventional filler technology (Swift, 2005). A newer functional classification system of resin composites is one based on filler particle size and size distribution, as shown in Table 2.3. Subgroups and overlapping may exist, particularly for the hybrid category. A hybrid composite combines filler from either the small or the tradiational category, with microfillers (submicron, colloidal filler particles) (Anusavice, 2003). Any resin with fillers from two or more size ranges can, in principle, be considered a hybrid. Future composites that contain fiber and/or nanoparticle fillers can be classified in a similar way (Anusavice, 2003; Craig et al., 2004; Beun et al., 2007).

A single classification of hybrid composite is not very meaningful because most modern dental composites that use fillers in the micrometer (μm) size range also contain small amounts (< 5 wt%) of microfillers to adjust the paste to the desired viscosity. The most commonly used hybrid composites in the early 2000s usually refer to resins that contain fillers having an average particle size of ~ 0.5 to 1.0 μm in combination with 10 to 15 wt% microfiller. Two special categories of hybrids that vary somewhat from this definition are also described: flowable and packable composites (Craig and Powers, 2002; Anusavice, 2003). The characteristic properties of various types of composites are shown in Table 2.4.

Table 2.3. Classification of resin-based composites and indications for use*.

Class of compsite	Particle size	Clinical use
Traditional (large particle)	1-50 μm glass	High-stress areas.
Hybrid (large particle)	(1) 1-20 μm glass (2) 0.04 μm silica	High-stress areas requiring improved polishability (Classes I, II, III, and IV).
Hybrid (midifiller)	(1) 0.1-10 μm glass (2) 0.04 μm silica	High-stress areas requiring improved polishability (Classes III and IV).
Hybrid (minifiller/Small-particle filled)	(1) 0.1-2 μm glass (2) 0.04 μm silica	Moderate-stress areas requiring optimal polishability (Classes III and IV).
Packable hybrid	Midifiller/minifiller hybrid, but with lower filler fraction	Situations in which improved condensability is needed (Classes I and II).
Flowable hybrid	Midifiller hybrid, but with finer particle size distribution	Situations in which improved flow is needed and/or where access is difficult (Class II).
Homogeneous microfill	0.04 μm silica	Low-stress and subgingival areas that require a high luster and polish.
Heterogenous microfill	(1) 0.04 μm silica (2) Prepolymerized resin particle containing 0.04 μm silica	Low-stress and subgingival areas where reduced shrinkage is essential.

*. Adapted from (Anusavice, 2003).

Table 2.4. Characteristics of various types of composites[*].

Type of composite	Handling Characteristics and Properties	
	Advantage	Disadvantage
All-purpose	High strength, high modulus	
Microfilled	Best polish, best esthetic	Higher shrinkage
Packable	Packable, less shrinkage, Lower wear.	
Flowable	Syringeable, lower modulus	Higher wear
Laboratory	Best anatomy and contacts, Lower wear	Lab cost, special equipment, requires resin cement.

[*]. Adapted from (Craig and Powers, 2002).

New research is under way on fillers called "nanofillers" that are even smaller than microfillers. Nano fillers are extremely small and almost invisible which allow them to fit into spaces between other particles, thus increasing filler levels, reduce polymerization shrinkage and improving radiopacity, physical and mechanical properties (Bayne et al, 1994; Combe and Burke, 2000; Beun et al., 2007). The nanofilled composites have values similar to the microhybrid composites (Craig et al., 2004). The properties of composite restorative materials are listed in Table 2.5.

Table 2.5. Properties of composite restorative materials*.

Characteristic/property	Hybrid(all-purpose)	Microfilled	Flowable	Packable
Size (μm)	0.4-1.0	0.04-0.4	0.6-1.0	Fibrous
Inorganic filler (vol%)	60-65	20-59	30-55	48-67
Inorganic filler (wt%)	75-80	35-67	40-60	65-81
Compressive strength (MPa)	300-350	250-350	210-300	390
Tensile strength (MPa)	40-50	30-50	75-115	40-45
Elastic modulus (GPa)	11-15	3-6	4-8	3-13
Hardness (VHS)	60-80	25-53	40-60	75
Flexural strength (MPa)	90-140	-	-	72-154
Wear resistance (Davidson/ de Gee, μm/100,000 cycles)				4
LCTE[†] (ppm/ ºC)	30-40	50-60	35-50	28-35
Thermal conductivity (10^{-4} cal/sec/cm^2[ºC/cm])	25-30	2-15	-	-
Water absorption (mg/cm^2)	0.5-0.7	1.4-1.7	-	-
Curing shrinkage (vol%)	2-3	2-3	3-6	2-3

*. Adapted from (Anusavice, 2003; Craig et al., 2004, Dhuru, 2004).
[†]. LCTE = Linear Coefficient of thermal expansion.

2.3.5. Problems associated with resin-based composites:

Marginal microleakage is one of the major disadvantages of resin composite restorations. It results from failure of the material to adapt to walls of access cavities of PFM. When a layer of resin composite is inserted into the access cavity and cured, a competition between shrinkage of the composite and adhesion to the substrate begins. Stresses produced by polymerization shrinkage are critical to adhesion between the resin composite and the walls of the access cavity. This shrinkage stress depends on various factors, such as cavity size and shape, substrate type and location of the margins, restorative material and technique of placement and polymerization. If shrinkage stresses are stronger than the bond strength between the resin and adhesive system, the PFM-restoration interface can break, forming a gap that will allow marginal microleakage (Davidson et al., 1984; Araujo et al., 2006; Maghaireh et al., 2007).

2.3.5.1. Polymerization Shrinkage:

The polymerization shrinkage of a composite is dependent upon the type of resin employed and the amount of resin present in its unpolymerised form. In general, a higher proportion of glass filler results in a lower final shrinkage. The filler loading and particle size can affect the leakage. Fine particle composite shrink less during polymerization than micro filled types, since the shrinkage is a direct function of the amount of organic matrix (Craig et al., 1996).

An increased C-ratio leads to a decreased flow capacity which causes a higher rate of shrinkage stress development (Feilzer et al., 1987). The less the restoration is bonded to opposing walls, the less shrinkage interference there will be (Davidson, 1986). When there is a small ratio of contact area to free surface, flow occurs readily over the free area in order to minimize the stress at the interface. On the contrary, larger stress occurs when there is little free surface area (McCabe and Walls, 1998; Braga et al., 2006).

Several clinical techniques have been proposed to minimize the problem of polymerization shrinkage. One way to reduce the effect of contraction stress is the incremental layering of resin-based composites during placement to minimize bridging between cavity walls and to reduce shrinkage stresses through the sequential use of small volumes of material. But, the benefit of the incremental technique for reducing polymerization contraction stress is somewhat controversial (Verslius et al., 1996; Jedrychowski et al., 1998; Hilton, 2002a; Giachetti et al., 2006; Maghaireh et al., 2007). Etching prior to placement of dentine bonding was significantly more effective for pulling resin-based composite toward the walls of the preparation, reduction of microleakage and better adhesion as well marginal integrity in vitro (Haller, 2000; Leinfelder, 2001; Pucket et al., 2001; Gallo et al., 2005).

2.3.5.2. The Coefficient of Thermal Expansion (CTE):

The CTE is the rate of dimensional change of a material per unit change in temperature (Roberson et al., 2002). The higher the amount of organic matrix, the higher the linear coefficients of thermal expansion since the polymer has a higher value than the filler. As a result the microfilled composites have higher linear coefficient of thermal expansion than fine particle composite and hybrid composite (Craig and Ward, 1997). To minimize the possibility of stresses being developed due to differential expansion and contraction, the coefficient of thermal expansion of composite needs to be as close as possible to that of tooth tissue. The glass fillers have a low coefficient of expansion, whereas the resin has a high coefficient of expansion, so the higher the inorganic filler content, the lower the coefficient of expansion will be (Van Noort, 2002).

2.3.5.3. Water Sorption and Solibility:

The water sorption of composite materials is a diffusion-controlled process, and water uptake largely occurs in the resin matrix (Øysæd and Ruyter, 1986). The organic matrix

is mainly responsible for the absorption of water. Water with other small molecules potentially plasticize the composite, as well as, chemically degrade the matrix into monomer or other derivatives (Malacarne et al., 2006; Fabre et al., 2007). Materials with higher filler contents exhibit lower water absorption values (Phillips, 1991; Roberson et al., 2002). The water sorption values for microfine composites are 1.2-2.2 mg/cm² which are greater than for fine composites which are 0.3-0.6 mg/cm², as well as, for hybrid composites because of the higher volume of polymer (Craig and Ward, 1997; Örtengren et al., 2000).

2.3.5.4. Modulus of Elasticity:

Elastic modulus (Young's Modulus) describes the relative stiffness or rigidity of a resin composite, which is measured by the slope of the elastic region of the stress-strain graph (Feilzer et al., 1990; Anusavice, 2003). A composite with a high modulus of elasticity would be the appropriate choice for such restorations (Prasad and Sarkar, 2004).

Low-modulus composite resins are able to relieve some of the polymerization contraction stresses by flow relaxation, stiffer, high-modulus materials do not flow as well and therefore compensate less for polymerization contraction stresses. In addition, highly filled composite resins cannot flex adequately when subjected to flexural forces and may transfer stress to the bonding interface (Swift et al., 1995; Helvatjoglu-Antoniades et al., 2006; da Silva et al., 2007). Reduced flow is a particular problem with light curing composite resins because polymerization is initiated at the restoration surface, effectively eliminating that surface as a source of flow for stress relief. One method for reducing overall restoration stiffness is the application of a low-viscosity, low-modulus intermediate resin between the bonding agent and restorative resin to act as an "elastic buffer" or "stress breaker" that can relieve contraction stresses and improve marginal integrity (Kemp-Scholte and Davidson, 1990; Swift et al., 1995; Giachetti et al., 2006; Helvatjoglu-Antoniades et al., 2006; Pongpureksa et al., 2007).

2.3.6. Packable Composites:

Another consequence of advances in the control of filler particle size, particle size distribution, particle morphology, and monomer technology has been the introduction of composites with specific handling characteristics. These include flowable composites and packable composites (Roberson et al., 2002). Depending on where the composites are placed in the mouth, they can be sub-classified as anterior, posterior or universal anterior/posterior composites (Prasad and Sarkar, 2004). Currently there are no long-term clinical studies to equate packable composites' promoted benefits with improved clinical results when compared to hybrid composites. Their development is an attempt to accomplish two goals: (1) easier restoration of a proximal contact, and (2) similarity to the handling properties of amalgam (Roberson et al., 2002).

Some manufacturers are marketing these packable composites as condensable. (The dictionary defines condensable as being able to be compacted or made denser by reducing the volume.) Unlike amalgam, composite resins cannot be compacted (or condensed). However, it is not necessary for composite resins to demonstrate this property to be used expediently and successfully for posterior restorations. The new resins can be described as packable (The dictionary defines packable as the ability to organize the composition of, in order to achieve a favourable or hoped-for result.) and stay where placed, regardless of the time required for sculpting before light-curing. In addition, these materials are easily manipulated because they are virtually nonsticky when clean, scratch-free instruments are used (Jackson and Morgan, 2000; Papadogiannis et al., 2007).

New composites, called packable or condensable composites are being promoted as amalgam alternatives. The term packable is preferable to condensable for describing this new class of materials. Packable composites are therefore a new class of highly filled

composite resins with a filler distribution that gives them a different consistency compared with hybrid composites. They are mainly characterized by less stickiness or stiffer viscosity than conventional composites, and are therefore claimed for use in stress-bearing posterior restorations; as an alternative to amalgam based on an application technique that somewhat resembles amalgam placement. Packable composites may allow more convenient placement in posterior sites and may offer some technique advantages over conventional composites (Leinfelder et al., 1999; Tredwin et al., 2005; Helvatjoglu-Antoniades et al., 2006; Blalock et al., 2006; Papadogiannis et al., 2007).

Packable composite using amalgam techniques for replacement can produce acceptable interproximal contacts (Leinfelder and Prasad, 1998). Because of high depth of cure and low polymerization shrinkage of packable composites, a bulk-fill technique may be possible (Affleck et al., 1999; Aw and Nicholls, 1999; Kerby et al., 1999; So et al., 1999; Helvatjoglu-Antoniades et al., 2006). However, concerns related to the ability of these stiffer materials to adequately adapt to internal areas and cavosurface margins have been raised, particularly at the cervical (Leevailoj et al., 2001). To offset this problem, using "flowable" composites as liners has been suggested. Flowable composites have low viscosity and may adapt to the cavity better than packable composites (Bayne et al., 1998). Though the efficacy of this technique is unproven, Leevailoj et al. (2001) concluded that flowable composite or compomer liners reduced microleakage in Class II packable and microhybrid resin composite restorations at the gingival margins. Without flowable liners, packable composites showed higher leakage than a microhybrid resin composite.

Owing to its inherent handling characteristics, the packable resin-based composite makes it easy for the clinician to create successful restorations. A thin base of flowable

composite is placed and cured before the bulk of composite is added. This keeps polymerization shrinkage from pulling the materials away from margins and the internal aspect of the preparation, and it provides the opportunity for bulk placement of the restorative composite (Miranda, et al., 1999).

The introduction of condensable or packable composites offers the possibility of replacing amalgam with composites as a major restorative material for posterior restorations. Physical properties of packable composites such as reduced initial polymerization shrinkage, a coefficient of thermal expansion close to that of the tooth structure, and a modulus of elasticity similar to that of amalgam have been reported. There are also improvements in their handling properties that should ease marginal adaptability. These composites are supposedly not sticky because of modification of the filler particles by the manufacturer. They do not slump; their high viscosity allows for carving the composites without slumping. These resins can be handled and placed with techniques similar to those used for amalgam (Tung et al., 2000; Görgül et al., 2002; Tredwin et al., 2005; Helvatjoglu-Antoniades et al., 2006; Blalock et al., 2006). To improve ease of manipulation, the ideal resin-based composite should have a viscosity stiff enough to be adhering to the condensing instrument (Opdam et al., 1996; El-Mowafy et al., 2007).

Currently, available materials include Solitaire (Heraeus Kulzer, Dormagen, Germany), Surefil (Dentsply, Weybridge, Surrey), Alert (Jeneric-Pentron, Wallingford, CT, US), P60 (3M, St.Paul, MN, USA), and Prodigy Condensable (Kerr Mfg. Co. Romulus, MI, US). These materials contain between 60% and 70% filler by volume as shown in Table 3.10. The range of particle sizes in many of these materials is greater than for 'conventional' hybrid RBCs, filler sizes being 0.04 to 20 microns (Combe and Burke, 2000; Craig and Powers, 2002). Important properties include high depth of cure, low polymerization shrinkage, radiopacity, and low wear rate (3.5 μm/year), which is

similar to that of amalgam. Several packable composites are packaged in unit-dose compules. A bulk-fill technique is recommended by manufacturers but has not yet been demonstrated effective in clinical studies (Craig and Powers, 2002).

Table 2.6. Packable composite materials*.

Material	Filler Volume (%)	Manufacturers' Comments
Solitaire	66	Porous filler particles. Filler size 2-20 μm. Fluoride release.
Surefil	60	Filler particles with wide divergence in size 0.03-3.0 μm. Interlocking filler technology claimed.
Alert	70	Fibres in filler 40-60 μm long and 6-10μm diameter.
P60	61	High filler loading. Non-stick resin. Polymerization shrinkage reduced by use of newly developed resin. Filler particle sizes in the range 0.01μm to 3.5μm.
Prodigy Condensable	61.7	Filler particle 0.6 μm diameter.

*. Adapted from (Combe and Burke, 2000; Bala et al., 2003).

Table 2.6 shows that the fillers of packable resin-based composites may be added in the form of fibers (Alert: 84% filled by weight, particle size range 0.01-3.0 μm), porous filler particles (Solitaire: 66% filled by weight, particle size range 2-20 μm), irregular particles (SureFil- 82% filled by weight, particle size range 0.01-3.0 μm), irregular rounded zirconia/ silica particles (Filtek™ P60: 61% filled by volume, particle size range 0.01-3.5 μm), and viscosity modifiers (Prodigy Condensable: 78-80% filled by weight, particle size range 0.01-3.0 μm) (Gallo et al., 2000; Leevailoj et al., 2001; Bala et al., 2003; Tredwin et al., 2005).

Filtek™ P60 is designed for use in posterior direct or indirect restorations. The inorganic filler loading is 61% by volume (without silane treatment). It contains BIS-GMA, UDMA and BIS-EMA resins. It is indicated for use in the following types of restorations: (1) Direct posterior restorations; (2) Sandwich technique with glass ionomer resin material; (3) Cusp buildup; (4) Core buildup; (5) Splinting, and (6) Indirect posterior restorations including inlays and onlays (3M, 1998).

2.3.7. Flowable Composites:

The introduction of flowable composite-based resins is a recent event. Since 1995, a new type of composite described as flowable has become popular. To make a composite of low viscosity, or flowable, two processes must be accomplished: (1) The particle size is increased, and (2) the filler amount is decreased. Compared with microfills and hybrid, flowables are less sticky and are advertised to have exceptional handling properties (Bayne et al., 1998). Most of these flowable composites are significantly less filled than microfills (Wakefield and Kofford, 2001).

The first generation of flowable composites was introduced in late 1996, just before condensable composites. Flowable composites were created by retaining the same small particle sizes of traditional hybrid composites, but reducing the filler content and allowing the increased resin to reduce the viscosity of the mixture (Bayne et al., 1998; Unterbrink and Liebenberg, 1999; Helvatjoglu-Antoniades et al., 2006). Despite the numerous refinements made in traditional composite over the past decade, two desirable clinical handling characteristics for composites have not existed until very recently: (1) Non stickiness, so that materials could be packed or condensed like dental amalgam and (2) Fluid injectability (Bayne et al., 1998; Tredwin et al., 2005; Stavridakis et al., 2005; Helvatjoglu-Antoniades et al., 2006; Blalock et al., 2006; Celik et al., 2007).

Typical properties of flowable composites are listed in Table 2.5. Flowable composites have a low modulus of elasticity, which may make them useful in cervical abfraction areas. Because of their lower filler content, they exhibit higher polymerization shrinkage and lower wear resistance than microhybrid composites. The viscosity of this composite allows it to be dispensed by a syringe for easy handling. These light-cured, low-viscosity composites are recommended for cervical lesions, pediatric restorations,

and other small, low stress-bearing restorations. They are advocated for a wide variety of applications, such as preventive resin restorations, cavity liners, restoration repairs, and cervical restorations. These applications are not well supported with data, but their clinical use is widespread. They contain dimethacrylate resin and inorganic fillers with a particle size of 0.7 to 3.0 µm and filler loading of 42% to 53% by volume (Craig and Powers, 2002). In a study by Bayne et al. (1998), the mechanical properties of several commercial flowable composites were about 60% to 90% of those of conventional composites. Flowable composites shrink more than traditional composites because they have less filler loading (Bayne et al., 1998). This was confirmed in studies where polymerization shrinkage of a series of materials, including a few flowable composites, was measured and high polymerization shrinkage values (3.65% to 6.0%) were reported for flowable composites (Labella et al., 1999; Stavridakis et al., 2005; Tredwin et al., 2005).

Use of flowable composites in conjunction with the very high viscosity, high-modulus packable composites is a common clinical technique. However, the effects of the higher-than-expected polymerization shrinkage of the flowable material (because of lower filler loading) and the effects of possible flexure of the restoration when it is supported by the lower-modulus flowable "liner" are unknown (Bayne et al., 1998; Nattar et al., 2003; Stavridakis et al., 2005; Helvatjoglu-Antoniades et al., 2006; Blalock et al., 2006). Indeed, the so-called "flowable" resin-based composites are now being promoted for initial placement along the external cavity margins, followed by heavily filled "condensable" materials for the bulk of the restoration (Bala et al., 2003; Pongprueksa et al., 2007).

Although some in vitro studies have shown that use of flowable composites reduced restoration microleakage and the occurrence of voids, (Payne, 1999; Malmstrom et al., 2002) other research has shown no apparent advantage over universal hybrid composites (Nattar et al., 2003). Acoording to Behle (1998), flowable composites have another advantage over resin cements, as they prevent the incorporation of air. Peris et al. (2003) concluded that the combination of a low-viscosity resin composite with a compactable resin composite significantly decreased the microleakage, though it did not completely eliminate it. A thick adhesive layer or a composite-based-resin showing greater toughness similar to the flowable may be sufficiently energy-absorbing (Ferdianakis, 1998), may compensate for the polymerization stress due to elastic properties and may reduce gap formation. Composite resin polymerization stresses may surpass the adhesive bonding strength, resulting in gap formation. The creation of elastic cavity walls may improve the marginal composite adaptation (Kemp-Scholte and Davidson, 1990; Helvatjoglu-Antoniades et al., 2006; Blalock et al., 2006).

Unterbrink and Liebenberg (1999) concluded that the use of highly radiopaque flowable composite as a first thin layer helps to establish the dentin bond, can create a truly elastic cavity wall, and appears to be one of the keys to achieving clinically acceptable results with single-component dentine adhesives. The application of a low-viscosity, low modulus intermediate resin between the bonding agent and restorative resin acting as an "elastic buffer" or "stress breaker" can relieve contraction stresses and improve marginal integrity (Kem-Scholte and Davidson, 1990; Belli et al., 2001; Tredwin et al., 2005; Giachetti et al., 2006; Helvatjoglu-Antoniades et al., 2006; Pongprueksa et al., 2007).

2.4. Resin Modified Glass Ionomer Cements (RMGICs)

Glass ionomer cements have evolved with composite resin technology to produce a variety of new materials which are now commonly used in restorative dentistry. These materials aim to combine the advantages of glass ionomers and composites in one material. Antonucci et al. (1988) and Mathis and Ferracane (1989) developed the first resin modified glass ionomer cements. They were used in restorative dentistry as base material and Class V restorative materials, but their aesthetic and physical properties never reached the standards of composites. Recently, there have been rapid developments in the field of hybrid resin-ionomer restorative materials. It has opened up new dimensions in restorative dentistry (Nicholson and Croll, 1997; Dhuru, 2004).

RMGIC is defined as a material that undergoes both polymerization reaction and acid-base reaction (Davidson, 1999). RMGIC, unlike a light-cured resin composite or a glass ionomer cement, has a dual setting reaction that consists of an acid–base reaction and a photochemical polymerization process. The final set materials are described as having a complex structure in which glass particles are sheathed in a matrix consisting of two networks, one derived from the glass ionomer, the other from the resin (Wilson, 1990; Mitra, 1991; Pitt Ford et al., 2002). Despite the aesthetic disadvantages, resin-modified glass-ionomer restoratives provide a viable alternative for Class V restorations (De Munck et al., 2005).

In modern adhesive dentistry, using a cavity liner appropriately can minimize some of the most troublesome problems with direct posterior composites. Although there are several materials that can be used as liners, only two types of materials had been recommended i.e. low viscosity (flowable) composites and light-cured resin-modified glass ionomers (Chuang et al., 2003; Ruiz and Mitra, 2006).

2.5. Bonding Agents (Adhesive Systems)

2.5.1. Definitions:

A bonding agent or adhesive system may be defined as an intermediate substance that when applied to the surface of other substances can join them together and make them resist the separation (Fusayama et al., 1979). A bonding agent is a material used to promote adhesion between dissimilar substances, or between a material and tooth structure (Dhuru, 2004). The magnitude of this bond must be sufficient to withstand the stress caused by the polymerization contraction of resin-based materials (Burke et al., 2000). In the current dental literature, bonding and adhesion refer to adhesion between: (a) resin polymers and tooth structure; (b) amalgam and tooth structure; (c) resin polymers and ceramic materials, and (d) resin polymers and cast metal structure (Dhuru, 2004).

2.5.2. General Aspects of Bonding System:

Adhesive dentistry began in 1955 when Buonocore observed that it was possible to obtain a micromechanical bond with resin restorative material on acid-treated enamel surfaces (Buonocore, 1955). Adhesion dentistry promotes the use of preparations that preserve tooth substance, durable adhesion between cavity walls and restorative material to produce well-sealed and long lasting restorations (Alavi and Kianimannesh, 2002). Dentine adhesives have also been used to promote bonding of restorations to cavity walls, thereby minimizing microleakage, post-operative sensitivity and cuspal flexion (Al-Turki and Akpata, 2002).

Recent development in adhesion technology have led to new indications for bonding to the tooth structure, such as indirect composite and ceramic restorations (crowns, inlays, onlays and veneers); the use of a universal adhesive system in conjunction with a resin

cement provide durable bonding of indirect restorations to tooth structure (Burke and Watts, 1994). Several of these new adhesive systems are considered to be universal dental adhesives because they bond not only to dentin and enamel, but also to metal alloys, porcelain and composite resin (Barkmeier et al., 1992; Swift et al., 1995; Roberson et al., 2002). The availability of dentin adhesives has profoundly improved the quality of conservative work performed in pediatric and geriatric dentistry, prosthodontics, and lately, in endodontic (Tay et al., 2005).

For many years, there was a popular classification system that suggested that bonding systems evolved in generations (Kugel and Ferrari, 2000; Dhuru, 2004; Bayne, 2005), but finally that concept has fallen out of vogue. A better approach for classifying bonding systems is in terms of the number of components, their actions, and/or the type of acid being used (Bayne, 2005). The concept of 'total etch' technique which was introduced in Japan by Fusayama and his research team has developed into an acceptable practice (Dhuru, 2004). From current research it seems that self-etching systems are not as reliable as the three- and two-step etch and rinse systems (Ernst et al., 2002; Cao et al., 2003; Ateyah and Elhejazi, 2004; Frankenberger et al., 2005; De Munck et al., 2005; Tay et al., 2005; Fabre et al., 2007).

2.5.3. Composition of Bonding System:

Modern bonding agents contain three major ingredients (etchant, primer, adhesive) that may be packaged separately or combined. Most bonding agents are light cured (3 components) and contain an activator such as camphoroquinone and an organic amine. Dual-cured bonding agents include a catalyst to promote self-curing (Craig and Powers, 2002; Fabre et al., 2007).

2.5.3.1. Etchants:

Etchants are relatively strong acid solutions that are mainly based on phosphoric acid. A wide range of organic (maleic, tartaric, citric, EDTA, acidic monomers), polymeric (polymeric acid), and mineral (hydrochloric, nitric, hydrofluoric) acids has been investigated as etchants, but phosphoric acid solutions and gels (37%, 35%, 10%) have been shown to produce the most reliable etching patterns (Craig and Powers, 2002).

2.5.3.2. Primers:

Primers contain hydrophilic monomers to produce good wetting usually carried in a solvent. The solvents used in primers are acetone, ethanol-water, or primarily water. A few fourth generation bonding agents are solvent-free (Craig and Powers, 2002; Yiu et al., 2004; Malacarne et al., 2006).

For bonding to porcelain, a silane coupling agent acts as a primer because it modifies the surface characteristics of etched porcelain. Because etched porcelain is an inorganic substrate, the coupling agent makes this surface more receptive to organic materials; the adhesive system and composite resin cement. The use of silanes may actually increase the bond between composite and porcelain in the range of 25 % (Roberson et al., 2002; Blatz et al., 2003; Kurtzman and Schneider, 2006).

2.5.3.3. Adhesives:

Adhesives are generally hydrophobic, dimethacrylate oligomers that are compatible with monomers used in the primer and composite. These oligomers are usually diluted with lower-molecular weight monomers. Although most bonding agents are unfilled, some products contain inorganic fillers ranging from 0.5% to 40% by weight. Filled bonding agents tend to produce higher *in-vitro* bond strengths (Craig and Powers, 2002; Fabre et al., 2007).

2.6. Microleakage

Leakage of water and other products can occur along the interface through voids created during insertion or function. Based upon the size of these voids, two types of leakage can be distinguished: (1) If large voids are present, water, large molecules, and even bacteria can migrate along the restoration, in a process called "microleakage"; or (2) if the voids are so small that only water and some small molecules can pass, the leakage is called "nanoleakage". The difference between both types is somewhat arbitrary, since both may occur simultaneously (De Munck et al., 2005).

Microleakage has been defined as the clinically undetectable passage of fluids and bacteria between a restorative material and the prepared tooth (Kidd, 1976a). Leakage is an inherent shortcoming of all restorative materials when used according to the traditional recommended procedure. A great deal of dental research has been replete with studies related to the subject of marginal penetration around dental restorations (Craig and Ward, 1997). Many techniques have been used to assess microleakage and the results vary considerably (Hilton, 2002b; De Munck et al. 2005; Verissimo and do Vale, 2006; Fabianelli et al., 2007).

Nanoleakage was originally used to describe microporous zones beneath or within hybrid layers that permitted tracer penetration to occur in the absence of interfacial gaps (Sano et al., 1995). One can also assess nanoleakage quantitively by measuring the dye penetration depth using confocal laser scanning microscopy (Dörfer et al., 2000) or SEM (Li et al., 2002a, 2002b). The same artificial aging factors as used for other tests can also be applied to nanoleakage assessments. However, nanoleakage seems little affected by thermo-cycling (Li et al., 2002b) or by mechanical load-cycling (Li et al., 2002a). Water storage of the specimens, in contrast, resulted in increased nanoleakage, (Okuda et al., 2001; De Munck et al., 2005).

2.6.1. Factors contributing to Microleakage

The factors which contribute to microleakage include the following:

2.6.1.1. Interfacial space:

The interfacial space exists between the tooth structure and the restorative material, base, or liner. However, it is the size of this space and the bacterial activity occurring within that contributes to microleakage which can lead to recurrent caries (Bauer and Henson, 1984).

2.6.1.2. Physical Properties of restorative Materials:

The failure of a restorative material to adapt to the cavity wall of a prepared tooth has generally been ascribed to solubility of the material and its coefficient of thermal expansion (Bauer and Henson, 1984). To achieve and maintain the optimum properties of the composite, it is important that the filler particles be bonded to the resin matrix. Therefore; the filler particles are surface treated with silane. This coupling agent not only increases the strength of the composite, but also reduces its solubility and water absorption. This is a very important compound because it allows the transfer of stress from the matrix to the fillers and maintains the integrity of the material (Rees and Jacobsen, 1996).

2.6.1.2.1. Solubility and Water Sorption:

The solubility of the material is affected by adherent foods, inadequate oral hygiene and the amount and the frequency of carbohydrate ingestion. These conditions can promote rapid disintegration of areas of the restorative material especially in the cervical areas which are not readily washed by saliva and in areas where food debris and plaque accumulate (Bauer and Henson, 1984). Laboratory studies showed storage factors such as time, temperature and medium may possibly influence microleakage patterns as they

appear to close the microcrevices at different rates and possibly in different manners (Jodaikin, 1981).

It was reported that polymerization of the commercially available composite resins produced shrinkage and that subsequent water sorption led to the expansion of the restorations (Asmussen et al., 1972). The length of time involved in achieving this compensation was approximately seven days (Hirasawa et al., 1983). It was reported that the water sorption of visible light and chemically activated composite resins ranged from 12.9 to 36.9 µg/mm³ and that it was characterized by a rapid increase within the first seven days which attained equilibrium after one or two months (Øysæd and Ruyter, 1986; Retief, 1994; Momoi and McCabe, 1994; Fabianelli et al., 2007).

In a bonded restoration hygroscopic expansion will contribute to the relaxation of shear stresses induced parallel to the adhesive interface (Feilzer et al., 1990). In contrast to the rapid polymerization contraction stresses, the relief of the stresses by hygroscopic expansion will proceed more slowly. Water sorption increased the creep, and decreased the creep recovery, of posterior composite resins under unaxial static and dynamic compression (Oden et al., 1988), and while water sorption may improve the marginal adaptation of composite resins, it may impair the mechanical properties of the resins (Hansen and Asmussen, 1989). Subsequent water sorption will result in improved marginal adaptation of the restoration but will not re-establish the adhesive bond (Retief, 1994; Fabianelli et al., 2007).

The importance of water uptake in the long-term durability of restorations is still under question, but it may be related to water tree formation as described by Tay and Pashley (2003). The studies on nanoleakage by means of silver nitrate demonstrated the

presence of areas which have a large amount of water and/or hydrophilic monomers in the hybrid layer and in the bonding resin layer. These areas were shown by Transmission Electron Microscopy (TEM) and defined as water trees (Tay and Pashley, 2003). Water trees are real miniature channels that are considered responsible for the passage of fluids from the underlying hydrated dentine, through the bonding layer all the way to the interface with the composite (Tay et al., 2002). The extent of nanoleakage increases with time in relation to water absorption (Tay et al., 2003).

Ideally, dental polymer should remain stable. However, due to their hydrophilic nature, it usually does not occur (Yiu et al., 2004; Witzel et al., 2005; Ito et al., 2005). Most of the dental polymers present ionic functional groups with affinity for water, which in turn optimizes their hydrophilicity. Thus, the polymer network is prone to hydrolysis (Fabre et al., 2007). The presence of water trees show that dentine bonding agent act as permeable membranes which allow water diffusion from dentine to dentine bonding agent, which negatively affect the durability of bonding of restorations (Tay et al., 2002; Tay and Pashley, 2003; Tay et al., 2003; Tay et al., 2005). Theoretically, more water trees can be formed with longer periods of air drying or contact of the adhesive with dentine prior to its polymerization. On other hand, the viscosity of the polymer matrix, cross-linking and the intensity of the interchain hydrogen bonding may determine the specific morphology of the water trees created with the polymerized adhesive (Tay et al., 2005).

Water exerts a plasticizing effect on the polymer which degrades its mechanical properties. As a result, the quality of the bonding interface might be compromised (Fabre et al., 2007). Thus, both water sorption and solubility would lead to a variety of chemical and physical processes that may result in deleterious effects on the structure

and function of dental polymers, including their retentive capacity in adhesive dentistry (Malacarne et al., 2006).

2.6.1.2.2. Coefficient of Thermal Expansion (CTE):

The linear coefficient of thermal expansion has been suggested as an important factor that influences microleakage (Nelsen et al., 1952). If the values for tooth and restorative material were similar, microleakage would be less. The coefficient of thermal expansion contributes to approximately 90% of the exchange of fluid during contraction and expansion with varying temperature. The remaining exchange is caused by differential thermal expansion of oral fluid itself. Setting or curing shrinkage and expansion, porosity, and fracture of the material are additional contributing factors (Bauer and Henson, 1984).

When the coefficient of thermal expansion of a material is significantly different from the dental structure surrounding it, the low temperature generates a negative interfacial pressure, causing the fluids to enter the tooth/restoration interface. In the same way, high temperature decreases pressure, suggesting a direct relationship between the coefficient of thermal expansion and the degree of the marginal leakage (Bullard et al., 1988; Fabianelli et al., 2007).

2.6.1.3. Restorative Technique:

Improper operative technique can result in inadequate adaptation of the restorative material and affecting the physical properties. The restorative material is sensitive to manipulation especially during placement and condensation. A major cause of microleakage is poor adaptation of restorative materials to tooth structure, which may be due to inferior adaptability on the part of the material or inexpert insertion of the material by the operator (Bauer and Henson, 1984; Hilton, 2002a).

2.6.1.4. Effect of Thermocycling:

Two additional variables, the storage time of restored teeth before cycling and the duration of the thermal cycle regimen, may affect the results of microleakage studies (Crim and Garcia-Godoy, 1987). Some investigators begin cycling immediately after the restorations are inserted and finished, while others store the teeth in water for periods of 1 hour to 1 year before testing (Dumsha and Biron, 1984; Chan et al., 1985). A common storage period appears to be 24 to 48 hours (Gross et al., 1984; Tani et al., 1985; Hansen and Asmussen, 1985; Munksgaard et al., 1985). The number of cycles to which restored teeth are subjected has varied greatly, from 1 to over 2500 cycles (Alani and Toh, 1997; Pazinatto et al., 2003).

Crim and Mattingly (1981) indicated that in-vitro testing to evaluate microleakage of restorations should include thermocycling. Research has indicated that using thermocycling will hasten the process of microleakage and causes marginal deterioration of all types of restorative materials as it washes out debris, so it is more potent in demonstrating leakage than the non-cycled method (Crim et al., 1985; Hakimeh et al., 2000).

Composite restorations were shown to exhibit significantly increased leakage after thermocycling even when subjected to relatively few cycles (Cooley and Barkmeier, 1991). Thermocycling is a widely acceptable method used in vitro microleakage studies (Crim and Mattingly, 1981; Crim et al., 1985; Hakimeh et al., 2000). In the thermocycling method, specimens are submitted to thermal cycles that simulate the intraoral temperature. However, the literature shows that there is a wide range in temperature extremes, transfer times between baths and dwell times (Shortall, 1982; Alani and Toh, 1997; Gale and Darvell, 1999).

The value of thermocycling is found in its ability to demonstrate the relative effectiveness of different restorative materials and techniques to prevent microleakage

at the tooth/restoration interface (Crim et al., 1985). Also, it is detrimental to the bond of porcelain and resin because of differences in thermal coefficients of expansion (Newburg and Pameijer, 1978; Eames et al., 1977; Nowlin et al., 1981; Pratt et al., 1989).

In a review of 130 scientific papers utilizing thermal cycling regimens, Gale and Darvell (1999) calculated the following parameters: the median low temperature was 5 ℃ (mean 6.6 ℃; range 0 ℃ to 36 ℃); median high temperature was 55 ℃ (mean 55.5 ℃; rang 40 ℃ to 100 ℃); median dwell time was 30 seconds (mean 53 seconds; range four seconds to 20 minutes); median number of cycles was 500 (mean 10,000; range 1 to 1,000,000). Thus, there is no standard for thermocycling methodology in microleakage studies, and this permits contradictory discussions and results in various laboratory studies. In some studies, the variables chosen are only restricted to the thermocycling method, and are not intended to understand the meaning of these effects (Gale and Darvell, 1999).

2.6.1.5. Effect of Mechanical Load Cycling:

Mechanical loading is one of the factors responsible for marginal leakage (Qvist, 1993; Fabianelli et al., 2007). The independent movement of tooth and restoration has been observed, as have failure of intended bonds between material and tooth. The resultant marginal leakage is one of the most important causes of failure in restorative dentistry. It is possible for bacteria to invade dentine through a marginal gap to cause secondary caries or pulpal damage (Jantarat et al., 2001).

Load cycling effects had not been examined in such great detail but there had been a study by Hakimeh et al. (2000) which concluded that load cycling did not have a significant effect on microleakage; thus confirming the observations of Darbyshire et al. (1988) and Cruz et al. (2002). However, other studies was showed microleakage was

more affected by mechanical load cycling (Abdalla and Davidson, 1990; Krejci et al., 1994; Jang et al., 2001; Kubo et al., 2001; Mitsui et al., 2003; Özcan, 2003) and became even more pronounced with additional thermocycling (Hilton, 2002b; De Munck et al., 2005). The load cycling influence in marginal integrity remains unclear. Thus, further studies about the role of load cycling are considered essential.

2.6.2. Methods of Demonstrating Microleakage:

Many techniques have been devised to test the cavity sealing properties of restorations both *in vivo* and *in vitro*. *In*-vitro, several techniques can be used such as the use of dyes, chemical tracer, radioactive isotopes, air pressure, bacteria, neutron activation analysis, scanning electron microscopy, artificial caries techniques, and electrical conductivity (Alani and Toh, 1997). The two most used methods used to detect marginal leakage are immersion of specimens in solution of dye or radioisotopes (Crim et al., 1985; Hilton, 2002b; Verissimo and do Vale, 2006; Fabianelli et al., 2007).

The most commonly used method for the evaluation of coronal microleakage is the linear measurement of tracer penetration, such as dyes, e.g. different concentrations of aqueous methylene blue solution (Alhberg et al., 1995; Trautmann et al., 2001b; Almeida et al., 2003; de Camargo et al., 2006), India ink (Saunders and Saunders 1994; Youngson et al., 1998; Howdle et al., 2002), Pelikan ink (Swanson and Madison, 1987), Rotring ink (Kopjar et al., 2006), silver nitrate (Youngson et al., 1998; Tay and Pashley, 2003; de Camargo et al., 2006), radioisotopes (Christen and Mitchell, 1966; Crim et al., 1985), bacteria (Torabinejad et al., 1990; Wolanek et al., 2001; Trautmann et al., 2001a; Timpawat et al., 2001; Britto et al., 2003; Karagenc et al., 2006), electrochemical technique (Momoi et al., 1990; Van Fraunhofer et al., 2000; Karagenc et al., 2006; Iwami et al., 2007), fluid flow technique (Pashley, 1990; Miletic et al., 2002; Orucoglu

et al., 2005; Kopjar et al., 2006), capillary flow porometry (De Bruyne et al., 2006) or glucose (Xu et al., 2005; Xu et al., 2007) along the root canal filling.

The clinical significance of in vitro leakage studies is questionable (Wu and Wesselink, 1993) and the amount of leakage that is clinically significant is not known. Nevertheless, the development and maintenance of a sealed root system are considered to be important for successful endodontic treatment. Hence, evaluation of the quality of the seal using leakage tests is still a relevant concept even though a universally accepted model is nonexistent (Leonard et al., 1996; Wolanek et al., 2001).

2.6.2.1. Direct Visualization

Direct visualization of the marginal gap, either with light microscope or by scanning electron microscopy, is an indirect method of studying microleakage, but it has yielded information regarding the dimension of opening through the leakage (Trowbridge, 1987).

2.6.2.2. Dyes:

One of the oldest and most frequently used methods for the study of microleakage around restorations was the use of organic dyes. Eosin, methylene blue, methylviolet, hematoxylin and mercuric chloride, Prontosil soluble red, aniline dye, basic fuchsin, chromotrope 2R, crystal violet dye, and fluorescent dye (fluorescein) are a few of the many dyes that have been used by countless investigators (Going, 1972). In general, the method involved placing a restoration in an extracted tooth and immersing the specimen in the dye solution. After an interval of time the tooth was removed, washed, sectioned and examined to establish the extent of penetration of the dye around the filling material (Kidd, 1976a; Hilton, 2002b; De Munck et al., 2005).

The main disadvantages with this form of assessment are that it is usually associated with the assessing of a numerical scoring system of increasing degrees of leakage and that this assessment, although often carried out by more than one examiner, is somewhat subjective; also, as previously discussed, the assessment of the restoration as a whole is difficult when viewing only individual small sections of tooth (Taylor and Lynch, 1992). However, others have suggested that dye penetration is nondestructive, thus allowing longitudinal study of restoration margins (Tsuchiya et al., 1986).

The methylene blue dye also presents limitations for its use; for example, in contact with reducing agents that exist in restorative materials, it may be reduced to a colourless substance (Wu et al., 1998). The use of this dye in tests containing alkalis is not recommended as methylene blue is hydrolytic, becoming methylene purple and then Tyonal, which is colourless. Thus, previous knowledge of limitations and pilot studies with dye solutions are essential for the success of this research (Wu and Wesselink, 1993; de Camargo et al., 2006). The methylene blue dye is acidic in nature and may demineralise tooth structure leading to false-positive results (Ravanshed and Torabinejad, 1992). In contrast, the pH of India ink is neutral and therefore does not require buffering. Concern has also been expressed about dissolution of methylene blue during the decalcification stage of the clearing process; the carbon particles of India ink are stable in this environment (Ravanshed and Torabinejad, 1992). The Indian ink is a neutral suspension of carbon particles, the majority around 10 µm in size; this would prevent penetration of the dye into any but corresponding large spaces. The water-shellac solution in which the carbon particles are dispersed may also affect the ability of India ink to penetrate into narrow voids (Alhlberg et al., 1995; Verissimo and do Vale, 2006).

Methylene blue in various concentrations has been for several decades, the most commonly used tracer (Spangberg et al., 1989), but during the last few years the number

of studies using India ink has increased. In a study using methylene blue as a dye medium, Scott et al. (1992) noted that the end-point of leakage were not as clear as hoped for and suggested that India ink might be a better alternative for staining quality. Dye leakage studies can be used to assess the integrity of these materials and their interface with tooth structure to provide the basis for their clinical use (Trautmann et al., 2001b).

In their study, de Camargo et al. (2006) found that the results obtained with silver nitrate dye, regardless of the system tested, were higher than the ones obtained with methylene blue, possibly due to the differing characteristics of the dyes which may influence their penetrating abilities. Although silver nitrate has nanometric particles, with molecules of high molecular weight, it is only possible to observe and measure its infiltration with a radiographic revealer. Despite this technical difficulty, its ability to penetrate dentine remains the same, although it is higher when compared to buffered methylene blue dye (de Camargo et al., 2006). In addition, silver phosphate crystal deposition also occurs inside some of the dentinal tubules which may be a limiting factor for the penetration of this tracer (Youngson et al., 1998).

The major problem associated with interpretation of these results is the handicap exhibited by the deficiency in defining a three-dimensional microleakage pattern by inference from a two-dimensional result, such as that provided by a single longitudinal or transverse section (Gwinnett et al., 1995). A possible criticism of a linear measurement system is that it is difficult to determine clinical relevance for a given length of stain ingress. The same may be said of the ordinal measurement scales of four to six zones that are commonly used (Hembree, 1986). There is also no standard for

scoring the degree of leakage for in vitro sectional microleakage studies (Mixson et al., 1991).

Lucena-Martin et al. (2002) showed that the clearing technique was more precise than transverse sectioning for detecting apical leakage, as it allows the leakage to be visualized in tenths of millimeters, while transverse sectioning only determines whether or not leakage has occurred in each section. The clearing technique makes it easier to observe the lateral and accessory canals and clearly reflects the relation between the sealing material and the apical foramen. However, the clearing technique could not be used to measure the volume of tracer ingress (Youngson et al., 1999).

According to Alhberg et al. (1995) and Lucena-Martin et al. (2002), transverse root sectioning results in loss of part of the dentinal tissue and dye due to the technique itself (saw thickness), and only allows one to determine whether or not there is penetration in each section. Therefore, a tooth clearing protocol has been proposed which offers the advantage of nondestructive, continuous and direct assessment of dye penetration (Verissimo and do Vale, 2006).

Multiple-surface scoring methods are regarded as superior to single-surface scoring methods, because the obtained data are more representative of microleakage (Mixson et al., 1991; Hilton, 2002b; Fabianelli et al., 2007). In 1992, Youngson presented a technique for continuous microleakage assessment employing multiple tooth sections and the construction of perspex models from these sections, using data from areas and volumes of a penetrated dye. Gale et al. (1994) employed a computer-aided reconstruction of microleakage patterns after sequential grinding of a tooth specimen. However, with all the methods mentioned so far, a loss of information occurred because of the loss of material due to the sectioning or grinding. Therefore, a tooth clearing

protocol has been proposed which offers the advantage of nondestructive, continuous, and direct assessment of dye penetration (Federlin et al., 2002).

The assessment of linear dye penetration apically or coronally is the most common in vitro method of examining the adaptation of a root filling to the canal walls because of its sensitivity and ease of use (Camps and Pashley, 2003). The method is based on the supposition that the depth of dye penetration represents the gap between the root filling and the canal walls (Bodrumlu and Tunga, 2007).

Recently, a quantitative three-dimensional method for the evaluation of contraction gap formation was reported (Iwami et al., 2005). This three-dimensional method can assess the condition and amount of microleakage of composite restorations more accurately than the conventional two-dimensional method. Using the three-dimensional method, smaller microleakage can be detected from composite restorations used a dentine bonding system than those placed without the bonding system (Iwami et al., 2007).

Barthel et al. (1999) applied the dye leakage test following bacterial test on the same teeth and found no correlation between the tests. Pommel et al. (2001) also compared fluid filtration, electro-chemical and dye leakage tests for evaluating the sealing ability of single-cone and vertical condensation obturation techniques using the same teeth, and found no correlation among the tests. They indicated that the result was not surprising because correlation implied that the leakage phenomena were governed by electrical, filtration and diffusion laws at the same time. However, the outcome of the study depended on the test method.

Youngson et al. (1999) did not find any statistically significant correlation between fluid filtration measurements and dye penetration measured by a scoring system but fluid filtration was found to be more sensitive.

The fluid transport method was shown to be ineffective for eliciting leakage in coronal or apical sections of the root canal. However, the fluid filtration technique gave results similar to those of the active dye-penetration technique because, like the active penetration method, it took into account all of the porosities of the interfaces between the filling material and the root (Camps and Pashley, 2003; Bodrumlu and Tunga, 2007).

Karagenc et al. (2006) found different results when they used various methods (fluid filtration, electrochemical, bacterial, and dye tests) to assess leakage. This could be due to the differences in working principles of various tests methods and the different nature of the obturation materials. Their study results, however, raised serious doubts about the information obtained by previous microleakage studies when comparing the sealing ability of endodontic materials. This also raised the question regarding the clinical relevance of leakage evaluation in vitro. Thus, correlation is lacking between the sealing quality of root fillings determined in vitro and the tissue response observed in vivo. Therefore, the usefulness of most leakage tests was deemed questionable by some authors (Wu and Wesselink, 1993).

A spectrophotometer and volumetric dye-recovery method had also been used to quantify the amount of dye penetration (Douglas and Zakariasen, 1981). However, it required a specific machine and professional qualification (de Camargo et al., 2006).

Recently, glucose has been proposed as a tracer substance for evaluating endodontic leakage because of its small molecular size and hence it is a sensitive tracer. The

amount of leakage was quantified with spectrophotometry (Xu et al., 2005). The glucose leakage test allows a long-term, quantitative determination of the cumulative amount of microleakage, and it has been suggested to be a more sensitive test than the fluid filtration method (Shemesh et al., 2006; Xu et al., 2007). Glucose was deemed a suitable tracer because of its small molecular size (MW = 180 Da) and as a nutrient for bacteria. So, if glucose could enter the canal from the oral cavity, bacteria that survived root canal preparation and obturation could multiply and lead to periapical inflammation (Verissmo and do Vale, 2006). Therefore, it would appear that root canal fillings that are impervious to small molecules are recommended, and the use of tracers of small molecular size would be indicated (Wu and Wesselink, 1993) to elicit microleakage.

2.6.2.3. Radioactive Isotopes:

The most widely accepted method of testing marginal leakage has been the use of radioactive isotopes, such as Ca^{45} (Christen and Mitchell, 1966). A large proportion of the experiments reviewed used the radioactive isotope penetration method; within this method Ca^{45} penetration was most often used, although other radioactive isotopes have also been used namely; P^{32}, I^{125}, and S^{35}. Autoradiographs are taken of the cut surfaces of the specimens to detect the radioactive isotope. The isotope was much more sensitive than the dye in showing different degrees of marginal penetration, because it penetrated more deeply. As in the dye studies the autoradiograph relied on quantitative judgments both for the depth and path of tracer penetration (Shortall, 1982). When a radioactive isotope is used, the radiation potential of the isotope, the distance between the source and the target, the period of the exposure, and the cleaning process after sectioning are factors that dramatically affect the results. The method is qualitative and very technique sensitive (Crim et al., 1985; Taylor and Lynch, 1992).

2.6.2.4. Bacteria:

Bacterial penetration studies are a more clinically oriented test for leakage and the results are described on a quantitative basis (Pickard and Gayford, 1965). Bacterial penetration test are often unreliable because of many variables, and an experiment of this nature requires the talents of a trained microbiologist (Christen and Mitchell, 1966). A bacterial model was used to evaluate leakage of restored endodontic access openings in permanently fixed crowns which had undergone nonsurgical root canal therapy (Trautmann et al., 2001a).

According to Timpawat et al. (2001), the use of bacteria to assess leakage (mainly coronal) is considered to be of greater clinical and biological relevance than the dye penetration method. Many different strains of bacteria have been used to assess marginal leakage and this has led to contradictory results because the methods depend on the type of bacteria used (Verissmo and do Vale, 2006). Moreover, if the sealer has antimicrobial activity, it is unfeasible to employ the bacterial method (Schafer and Olthoff, 2002; Maltezos et al., 2006). The bacterial leakage systems generally comprise two chambers and enable the apical and coronal extremities of each specimen to be completely separated. The turbidity of the broth in the apical chamber is the first indication of contamination by microorganisms (Carratu et al., 2002; Britto et al., 2003). These bacterial studies had been qualitative rather than quantitative. If only one bacterium passes through the obturated root canal, it may multiply in the enriched broth and cause turbidity (Britto et al., 2003; Verissmo and do Vale, 2006).

2.6.2.5. Scanning Electron Microscopy (SEM):

The use of SEM provides a means of direct visual observation of the adaptation of restoration materials to cavity margins. It has high magnification and depth of focus. An attempt has been made to correlate microleakage of radioactive isotopes with fissure

size between tooth and restoration as seen in the SEM. No direct correlation was found (Kidd, 1976a). The method of SEM can be improved by the use of replicas. This allows change in the size of marginal defects to be followed on a longitudinal basis and can be applied clinically. Replicas may be repeated many times at different intervals, and this does not change the structures being evaluated. The use of a replica technique may avoid specimen shrinkage and some of the other artifacts usually associated with preparation of biological tissue for SEM examination (Alani and Toh, 1997; de Camargo et al., 2006).

2.6.2.6. Air Pressure:

The air pressure method of testing for microleakage is unnatural, for it does not simulate conditions actually present within the tooth or mouth. Besides, it requires rather elaborate machines and gauges and tends to be laborious and unsuitable for clinical studies (Christen and Mitchell, 1966). The advantage of this method was that the results could be quantified. A further advantage was that the examination of the specimen did not necessitate its destruction. They were, therefore, able to study leakage over a period of time for the same restoration. The main limiting factor of this method of study is that it could only detect leakage pathways that were complete from the floor to the margin of the cavity. Clinically, it does not take into account the drying effect of compressed air that is passing through the restoration. It is also possible some leakage may occur through clinically sound tooth tissue (Taylor and Lynch, 1992; Alani and Toh, 1997).

2.6.2.7. Artificial Caries:

Artificial secondary caries-like lesions have been produced *in-vitro* using either bacterial cultures or a chemical system-the acidified gel technique. In the artificial

caries system, the surface enamel is subjected to a constant attack of hydrogen ions (that is, the dissolution of the mineral is rate controlled) while the gel acts as a diffusion barrier for the dissolved mineral (Alani and Toh, 1997). The lesions produced by this technique are studied in polarized light microscopy and two parts are described: an outer lesion and a cavity wall lesion. The outer lesion results from primary attack of the enamel surface adjacent to the restoration, while the cavity wall lesions are formed by microleakage of ions from the acidified gelatin around the restorations (Alani and Toh, 1997). The use of this technique in the evaluation of microleakage has the advantage that microleakage may be linked directly with one of its possible consequences, namely the development and spread of secondary caries. Quantification of results is possible where the depth of lesion penetration (Kidd, 1976b) and the degree of demineralization may also be assessed quantitatively (Kidd, 1976b) or semiquantitatively (Grieve, 1973).

2.6.2.8. Neutron Activation Analysis:

Neutron activation analysis has been used by Going et al. (1968) to study microleakage both *in-vitro* and *in-vivo*. Going (1972) pointed out that this method had the advantage that results could be quantified, but he also highlighted the limitations of the technique. These were the very high cost and complexity of the method. Serial sections were made to define the path and depth of tracer penetration and this sectioning may create a radiation hazard (Kidd, 1976a; Alani and Toh, 1997).

2.6.2.9. Electrochemical Conductivity:

An electrochemical microleakage test was described by Jacobsen and Van Fraunhofer (1976). It proved sensitive and the results could be quantified (Shortall, 1982). The test method does not demand destruction of the specimen and thus allows changes in the dimensions of the interspace to be followed through different time periods. It is

destructive to tooth structure and cannot be used in the in vivo situation (Alani and Toh, 1997). This method can be applied to ceramic inlay restorations, glass-ionomer restorations and composite restorations because these are highly insulated. However, it cannot be applied to metal restorations because the electric current would flow in the metal itself in addition to the electrolyte (Iwami et al., 2007).

Previously, in vitro electrical methods for the evaluation of microleakage were reported and their clinical use for the future was suggested (Jacobsen and Van Fraunhofer, 1976; Momoi et al., 1990; Van Fraunhofer et al., 2000). However, these electrical methods evaluated the margins of restorations after application of an electrolyte that was not wiped off, so measurements of conductance or impedance depended on the area of applied electrolyte. In addition, these methods cannot be applied to restorations on dentine or cementum surfaces because the influence of the applied area or amount of electrolyte can lead to increased measurement errors. To resolve these problems, a new electrical method was reported (Iwami et al., 2000). Moreover, this new method can detect extensions of microleakage in the direction of the pulp chamber of restorations; also the size of the restorative margin did not influence the results (Iwami et al., 2002). However, it was difficult to evaluate the actual three dimensional microleakage of restorations for comparison using the results of the electrical method if dentine bonding systems were not to be used in composite fillings and where the amount of marginal leakage was determined using the depth of the prepared cavities. Even though previous studies had established the principle of this electrical method, but the accuracy of the results cannot be evaluated clearly in cases where resin composite restorations are filled with a dentine bonding system as is done in the clinical setting (Iwami et al., 2007).

2.6.2.10. Fluid Flow Technique:

The fluid filtration technique first mentioned by Greenhill and Pashley (1981), in which the sealing capacity is measured by means of air bubble movement, inside a capillary tube (Pashley, 1990) and modified by Wu et al. in 1994 was used in the root canal. The fluid flow method presents many advantages in comparison with dye penetration method, as the samples are not destroyed, in that it allows both the apical and coronal sealing to be assessed after a long period (Verissimo and do Vale, 2006). Furthermore, the results are recorded automatically, thus providing quantitative measurements and avoiding operator errors; the results are also precise as small volumes can be recorded (Pommel et al., 2001; Cobankara et al., 2002), and so it would be more sensitive than dye penetration in detecting empty spaces along the canal (Wu et al., 1994; Cobankara et al., 2002). However, according to Pommel and Camps (2001) the materials and methods used in this technique are not standardized as the pressure used may range from 10 to 20 psi, and the measuring time from 1 min to 3 h. This would affect the results obtained; lower filtration values had been found associated with longer recording time and higher values were recorded when high pressure was used in contrast with low pressure. The pressure should therefore be included in the results and should be expressed as µl/min cm H_2O instead of µl/min (Pommel and Camps, 2001; Verissimo and do Vale, 2006). Also, various parameters that could change the test results such as diameter or the capillary that contains the bubble, bubble length, measuring time and the pressure applied (Pommel and Camps, 2001) must be mentioned in the materials and methods section (Verissimo and do Vale, 2006). The main disadvantage is that the nominal values are usually very low so that the actual leakage path is sometimes unclear. Leakage may even occur through the dental substrate itself and so falsely increase the interfacial leakage values (De Munck et al., 2005). According to Miletic et al. (1999), it is very important to assess leakage not only after filling, but also after

some time, because this assessment is required to ensure that sealers are clinically effective. The disadvantage is that the exact location of the leakage cannot be determined (Hilton, 2002b).

Orucoglu et al. (2005) developed a new computerized fluid filtration meter based on light refraction at the starting and ending positions of air bubble movement inside micropipette. It has some advantages over the conventional ones with the computer control and digital air pressure arrangement. Additionally, the movement of air bubbles can be observed by laser diodes which are computer-controlled rather through visual findings (Verissimo and do Vale, 2006).

Capillary flow porometry, which is a well-established method in other domains than dentistry, for example in membrane and filter media testing, measures through pores i.e. pore size distribution. This method, besides an indicating leakage, also provides information on the pore sizes and pore distribution (De Bruyne et al., 2006). Leakage testing based on flow porometry can therefore give highly reproducible and accurate data. More extensive and accurate information is obtained than with the fluid transport model. As described by Pommel and Camps (2001), measurement time and pressure influence the outcome of a fluid filtration test. Several measurement times and pressures have been used with the fluid transport model and the authors emphasized the need for standardization to compare the results from various studies. Capillary flow porometry, which is a standardized method, overcomes these problems and provides reproducible data (De Bruyne et al., 2006).