Chapter 2 LITERATURE REVIEW

This chapter will discuss current knowledge of the pulp-dentine complex; dental caries and its removal; adhesion to enamel/dentine with dental adhesive; resin composite and polymerization shrinkage; glass-ionomer cement; dentine permeability and its effect on restorative dentistry; and postoperative tooth sensitivity associated with resin composite restoration.

2.1 PULPO-DENTINE COMPLEX

2.1.1 Normal dentine

*Basic structure of normal dentine*

Dentine is a living, vital portion of a tooth, which is covered with enamel on the anatomical crown and cementum on the anatomical root. Dentine encloses the pulp chamber which contains odontoblast cells, blood vessels and nerve fibres in a loose extracellular matrix. Basically, dentine and dental pulp are considered as a single unit called the “pulpo-dentine complex” (1). Dentine is composed of approximately 50% inorganic apatite crystals, 30% organic collagen fibre matrix and 20% water by volume (2).

Microscopically, the collagen fibres are cross-linked into a framework in which the apatite crystals are embedded and form intertubular dentine, a collagen-rich and less mineralized part of the dentine (1, 3). Dentine is a porous substrate by virtue of the existence of dentinal tubules that are lined with collagen-poor and mineral-rich
intraglobular/peritubular dentine (1, 3). A dentinal tubule is conical in shape with the larger diameter on the pulpal side and the smaller diameter at the dentino-enamel junction (DEJ) (4, 5). Lateral tubular branches, which differ in size and number depending on their location in the dentine, communicate between dentinal tubules (6). A dentinal tubule contains an odontoblastic process to a varying extent (7-11), and is filled with dentinal fluid which contains approximately one-fifth as much protein as plasma (12). Moreover, it contains albumin and immunoglobulin G (IgG) in smaller concentrations than the interstitial fluid of the pulp (13).

The density of dentinal tubules varies from area to area within a tooth (1, 3, 6) and depends on depth of dentine (1, 3, 5, 6). Superficial coronal dentine has approximately 15,000-20,000 dentinal tubules per mm$^2$, and the diameter is around 0.5-0.9 μm. By comparison, deep coronal dentine contains about 45,000-65,000 dentinal tubules per mm$^2$, which are approximately 2-3 μm in diameter. Thus, the intertubular dentine constitutes a smaller percentage of deep dentine than of superficial dentine (1, 4). Root dentine contains fewer and smaller dentinal tubules than the coronal dentine (6).

**Dentine response to age change and irritation**

Dentine formation continues throughout the life of the pulp as either a part of normal function (secondary dentine) or a defence mechanism (tertiary dentine). Predentine subjacent to the odontoblast cell layer is newly formed, unmineralized dentine. Primary dentine is mineralized dentine that forms the initial shape of a tooth. Afterwards, dentine formation continues slowly as secondary dentine in response to mild stimuli from regular tooth function (3), which leads to a gradual decrease in the size of the pulp as a tooth ages. Tertiary (reparative or reactionary) dentine is formed
beneath the affected areas in response to mild to moderate-level irritation, such as dental caries and cavity preparation (14). Usually formed as atubular dentine, reparative dentine is less permeable or impermeable in order to protect the pulp from any irritants. However, reactionary dentine can be formed in a tubular form if the irritation is mild and slowly progressive (14).

2.1.2 Dental pulp

Basic structure of dental pulp

Enclosed by dentine, dental pulp is composed of cellular components and a connective-tissue framework (3). Since the pulp has an intimate relationship with dentine, they are usually considered as a single unit, namely the “pulpo-dentine complex” (1). The odontoblastic layer is a single stratum of odontoblasts lined subjacent to predentine in the peripheral layer of the pulp (3). Odontoblasts generate unmineralized predentine which is then gradually mineralized and develops into dentine (3). An odontoblast has a cytoplasmic process, namely the odontoblastic process, which extends into a dentinal tubule for some distance (8, 9). A cell-free zone, which is the area deep to the odontoblastic layer, is relatively free of cells and contains processes of fibroblasts, small capillaries and unmyelinated nerve fibres (15). The cell-rich zone is the deeper zone that has similar components to the pulp centre, but the densities of fibroblasts and undifferentiated mesenchymal cells are relatively greater (15). Hence, the cell-rich layer is clearly discernible. The pulpal centre contains fibroblasts, undifferentiated mesenchymal cells, defence cells (i.e. lymphocytes) as well as blood vessels and nerve fibres (15).
Pulpal response to age change and irritation

Significant changes as a result of aging are observed in dental pulp. The number and density of cells (i.e. odontoblasts and fibroblasts) decrease while the amount of collagen fibres markedly increases (16, 17). Secondary dentine is gradually formed so that the thickness of dentine increases throughout the life of the pulp (16, 18). These age changes are greater in the root than the coronal part of a tooth (16). The healing capacity of the pulp in an elderly tooth significantly decreases (16).

The dental pulp can be altered by exposure to irritants, e.g. dental caries, attrition, erosion or trauma, such as tooth preparation for a restoration (18). Pulpal responses primarily depend on the severity and/or progression of the irritation (19, 20). In response to a mild or moderate stimulation, odontoblasts are reduced and altered (19, 20), but retain the capacity to deposit reactionary dentine. With a more severe insult, odontoblasts die and must be replaced. Pulpal inflammation to a varying extent can be observed; the amounts of blood vessels and inflammatory cells markedly increase (21). Reserve pulpal cells proliferate, migrate into the sub-odontoblastic region, and then differentiate into new odontoblasts (20). Reparative dentine is then formed with an atubular structure in an attempt to protect the pulp (19, 20).
2.2 DENTAL CARIES

Dental caries is a multi-factorial, infectious disease that affects enamel, dentine and dental pulp as well as cementum if the root surface is exposed. Bacterial biofilm plays an important role in the formation of dental caries since the biofilm is formed on the tooth surface (22). Fermentable sugar is used by bacteria to produce acid which decreases the pH, and the tooth structure is demineralized if the pH is lower than the critical point at 5.5. Conversely, the pH returns to neutral and tooth structure can be remineralized by the buffering as well calcium, phosphate ions contained of saliva (23, 24). In fact, dental caries is a result of the imbalance between demineralization, namely mineral loss, and remineralization, namely mineral uptake (14, 25).

2.2.1 Contributing factors

Development of dental caries depends on several factors, which are generally categorized into three main factors: a) directly contributing factors, b) oral environment factors, and c) personal factors (25). Firstly, oral biofilm, which is composed of bacteria, salivary components and dietary substrates, is formed on tooth surfaces to become a directly contributing factor. Pathogenic bacteria in the biofilm produce acid that primarily dissolves subsurface enamel by increasing demineralization and inhibiting remineralization (26). Secondly, among the oral environment factors, saliva and fluoride exposure are primary factors. Composition, flow rate and buffer-capacity of saliva strongly influence the development of dental caries; high quality and quantity of saliva are desired to promote remineralization (27). Within enamel, fluoride ions can replace a hydroxyl group in hydroxyapatite so
that fluoroapatite, which is more resistant to acid dissolution (28), is formed. Thirdly, the personal factors are external conditions, i.e. socio-economic status, education, attitude and diet, which influence the development of dental caries, indirectly (25).

2.2.2 Categories of dental caries

Dental caries can be divided into various categories: *cavitation*- cavitated or non-cavitated caries; *rate of progression*- rapidly (active) or slowly (inactive) progressing caries; and *tooth structure involved*- enamel, dentinal or root caries (14, 25, 29). Classified by cavitation, initial caries is usually a non-cavitated lesion of enamel that can be remineralized if preventive treatment is provided. A cavitated lesion needs restorative treatment, in which the infected tooth structure is removed and then restored to normal function and aesthetics (14). Due to the rate of progression, rapidly progressing caries is a lesion that progresses quickly and can develop a cavity within months after an initial (non-cavitated) lesion has begun (14). In a slowly progressing lesion, it might take years to form a cavity after initial caries is firstly detected (14). Generally, an active lesion is soft, light yellow and wet, whereas an inactive lesion is relatively harder, dark brown and dry (14, 30).

Frequently, dental caries primarily occurs on coronal tooth structure within the fissure system. An enamel lesion is the initial stage of the coronal caries, which further extends to dentine and then initiates dentinal caries if untreated. Occasionally, dental caries occurs on an exposed root surface, namely root caries (31). Furthermore, dental caries can be divided into a) primary caries, a lesion beginning in previously sound enamel/dentine; b) secondary caries, a recurrent lesion at the cavosurface margins of a restoration; and c) remaining caries, residual caries left under a restoration (14, 32).
2.2.3 Pulpo-dentine complex reaction to dental caries

Carious dentine is significantly altered from sound dentine: loss of mineral as well as degradation of collagen fibres is observed (33). Peritubular and intratubular dentine are lost while reduced mineralization and smaller apatite crystals are detected within intertubular dentine (34). The calcium-phosphate ratio of carious dentine markedly decreases, especially at the superficial layer (35). Moreover, the amount of water in carious dentine is higher than in sound dentine (36). The mechanical properties of the carious dentine [i.e. micro-hardness (35), tensile strength (36) and stiffness (37)], which are directly correlated to the mineral content (37), are inferior to those of unaffected, normal dentine.

Dentine affected by dental caries is distinctly classified into two layers: outer, heavily infected, softer dentine, namely caries-infected dentine; and inner, harder dentine, namely caries-affected dentine (30, 38-40). These two layers are distinguished by staining with a caries detecting dye, such as an acid red in propylene glycol (41). Theoretically, caries detecting dye stains only the outer, infected layer while the inner, caries-affected dentine is unstained (39). Outer, caries-infected dentine is greatly demineralized, and the degradation of collagen fibres is also noticed (38). In contrast, inner, caries-affected dentine is partly demineralized, and collagen fibres are minimally changed (38). Hence, caries-affected dentine can be remineralized and should be preserved during caries removal (42). Usually, dentinal sclerosis and hypermineralization are naturally formed beneath the affected dentine (18, 34, 40). In dentinal sclerosis due to caries, intertubular dentine is highly mineralized, and dentinal tubules are partially or totally occluded by the deposition of intratubular dentine as well as the precipitation of mineral crystals (34, 38, 40, 43).
Dentine permeability of this hypermineralized dentine is severely reduced (43, 44) as a natural defence mechanism to protect the pulp.

When a non-cavitated enamel lesion is initiated, dentine subjacent to the lesion is affected and hypermineralized even though the lesion has not reached the DEJ (45-47). The reaction in dentine beneath slowly progressing caries is likely to develop more slowly than that subjacent to a rapidly progressing lesion (45-47). Once dental caries reaches the DEJ, the superficial layer of hypermineralized dentine is dissolved and demineralized while the subjacent dentine becomes hypermineralized and sclerotic (14, 33). Usually, the dentinal sclerosis below a rapidly progressing lesion is formed to a lesser extent than that subjacent to a slowly progressing lesion (14, 30).

Initial pulpal responses to dental caries are microscopic changes in the odontoblastic layer and the cell-free zone limited to the area below the lesion (14, 19, 20). Reduction in odontoblast cell numbers as well as alterations in cellular components and shape are observed (14, 19, 20). When a carious lesion progresses and invades deeper into middle/deep dentine, odontoblast numbers are markedly reduced, and there is a proliferation of undifferentiated mesenchymal cells in the area below (14, 19, 20). The pulpal responses are greater in the pulp affected by a rapidly progressing lesion while the responses influenced by a slowly progressing lesion are usually observed to a lesser degree (14, 19, 20).

Tertiary dentine, namely reparative or reactionary dentine, is formed in the area related to a dentinal caries lesion (18). The quantity and quality of tertiary dentine are directly influenced by the progression of the caries lesion (19, 20, 48). In response to a mild to moderate insult, reactionary dentine is formed by the surviving odontoblasts, with a tubular structure continuing as in secondary dentine (19, 20, 48).
If the insult is severe and odontoblasts are destroyed, new odontoblasts regenerate from the undifferentiated reserve cells, and reparative dentine is initially formed with an atubular structure (14, 20). Reactionary dentine formed under slowly progressing caries is usually tubular (19, 20, 48), and a continuance of dentinal tubules between physiological, secondary dentine and the tertiary dentine is observed (19, 20, 48). In contrast, reparative dentine induced by rapidly progressing caries is often atubular at the beginning and subsequently formed as completely or partially tubular dentine (14, 20).
2.3 Caries Removal

Conventionally, a caries lesion is removed using slow-speed burs and spoon excavators until the dentine surface is relatively hard (14). Controversially, a clinical study showed that incomplete removal of dental caries does not negatively affect the longevity of bonded resin composite restorations (49). However, it is still generally accepted that dental caries must be removed until soft, infected dentine is totally removed (14). Other methods for removing dental caries have been introduced, i.e. chemo-mechanical methods, air abrasion and laser devices (50-52), which are advocated for their specificity in selective removal of caries-infected dentine and also patients’ preferences.

In the chemo-mechanical method, a gel consisting of 0.5% sodium hypochlorite and amino acids (Carisolv™, MediTeam, Göteborg, Sweden) is applied to the lesion, and N-monochloroamino acids are formed which selectively degrade demineralized collagen in carious dentine (50). Specially-designed hand instruments are used to remove the chemically-treated lesion (50). Preferably, a rotary cutting bur is still needed to open up the cavity initially through the enamel. The procedure is repeated until the gel removed from the cavity is clear (50). The slower chemo-mechanical method has been shown to adequately remove the soft, infected outer carious dentine (53). Recently, a new version of the gel has been introduced, and faster treatment is achieved (54).

The ability to remove carious dentine by the air abrasion technique depends upon the abrasive particle used (51). However, aluminium oxide abrasive particles can remove not only carious dentine, but also normal dentine/enamel (52, 55). In fact, the
effectiveness of air abrasion on carious dentine is less than on normal dentine due to
the lower hardness of the former (55). Thus, the specificity in removal of carious
dentine when using air abrasion has been questioned (51).

Recently, using erbium and other lasers to remove dental caries have become
an alternative choice to conventional methods (56). The capacity for caries removal
depends on type, wavelength and intensity of the laser (57). In particular, the erbium
laser irradiation is absorbed by water in the caries lesion (and tooth substrate, also) so
that water is rapidly vaporized, and then the caries lesion is ‘exploded’ away, a
process known as ablation (57, 58). Since dentine contains a higher water content than
enamel, the ablation rate of dentine is faster than that of enamel (57). However, using
the laser to remove dental caries is not specifically selective; sound tooth substrate can
also be ablated (51, 57).

2.3.1 Caries detector dye

Caries detector dye, traditionally composed of 0.5% basic fuchsin in propylene
glycol, was introduced in the 1970s in an attempt to distinguish between the two
layers of carious dentine (38, 39, 41). The composition has been changed to 1% acid
red in propylene glycol since the carcinogenic potential of the traditional formula is a
concern (42). Caries detector dye specifically stains the demineralized collagen fibres
in the outer carious dentine, which are significantly degraded and cannot be
remineralized (38, 39, 59). Caries removal is undertaken following the stain
application and repeated until the dentine is no longer stained or slightly stained pale
pink (42). However, caries detector dye can stain less-mineralized dentine at the DEJ
and over the pulp (59). Hence, the dye must be used with caution. Furthermore, a
common removal method following dye staining is the conventional technique using
slow-speed burs and hand excavators, which non-selectively removes the lesion (53). Therefore, carious dentine is potentially over-removed by the conventional technique even when caries detector dye is used (39).

### 2.3.2 Effect of caries removal/cavity preparation on the pulpo-dentine complex

A smear layer and plugs, which consist of loosely bound cutting debris, bacterial remnants and water, are formed on the prepared surface and in dentinal tubules (60). The smear layer and plugs act as natural semi-permeable barriers, so dentine permeability and outward flow of dentinal fluid is reduced (61, 62). The smear layer is usually removed or modified before a dentine adhesive is applied, but sometimes it is incorporated into the adhesive layer (63).

If caries removal and cavity preparation are performed under copious water coolant, minimal effects on dentine and the pulp are observed (64). Nevertheless, if the procedures are performed without caution and heat is generated, structural and physiological changes in the pulp are detected (64, 65). Aspiration of odontoblastic processes into dentinal tubules as well as protrusion of tubular contents into the cavity have been detected (66-68), which might lead to degeneration of the odontoblasts. Alteration of both the odontoblast layer and the sub-odontoblast region below the cavity have been observed (69). Pulpal blood and lymphatic vessels are increased, so pulpal blood flow is escalated (70). Furthermore, neural responses which depend on the severity of pulpal injury are observed (71). If the cavity is biologically sealed, the pulp will gradually heal to varying extents, depending on the regenerative capacity of the pulp (young or elderly pulp) (72).
2.4 ADHESION TO TOOTH SUBSTRATE

2.4.1 Adhesion concept

Adhesive techniques in dentistry have been established and continuously developed since the mid-1950s. An increase in the adhesion of acrylic resin to enamel by acid etching with 85% phosphoric acid (73) as well as an attempt to bond resin materials to dentine (74) were reported in 1955 and 1956. Currently, resin composite restorative materials can effectively bond to tooth substrate when used with a dental adhesive.

After conventional caries removal and cavity preparation, a smear layer covers the cavity surface, and smear plugs are observed in dentinal tubules (75). The smear layer and smear plugs form a semi-permeable barrier which can limit outward flow of dentinal fluid and is loosely bound to the underlying tooth structure (76). The application of a dental adhesive ought to deal firstly with the smear layer and plugs before subsequently interacting with tooth substrates below.

The principle of adhesion to enamel and dentine is that polymerizable resin monomers infiltrate into the conditioned tooth substrates to replace completely or partially removed hydroxyapatite crystals (77). Adhesion between resin composite and the tooth substrate is predominantly based on a micromechanical bond between adhesive monomers and modified tooth substrate (77). With enamel, macro- and micro-resin tags are micromechanically interlocked with the acid-etched enamel surface (78). With dentine, the micromechanical bond depends on a “hybrid layer” or “resin-dentine interdiffusion zone”, which is a layer/zone of polymerized adhesive
resin infiltration into hydroxyapatite-removed collagen fibre scaffold (79, 80). Moreover, the bond is also achieved from polymerized resin tags inside dentinal tubules. Chemical adhesion, in the form of an ionic bond between calcium ions of hydroxyapatites and functional carboxylate-based or phosphate-based monomers, is an additional adhesion mechanism in some of the more recent dental adhesives (81) and depends specifically on the monomer used.

2.4.2 Dental adhesives

Basic composition

Dental adhesives are primarily categorized into two major types: resin-based and glass-ionomer-based (GIC-based) (77). Resin-based adhesives are composed of resin monomers, a solvent, initiator, inhibitor, filler and other specific ingredients (82). A GIC-based adhesive is available commercially; it has a composition similar to resin-modified GIC cements (83), but will not be considered in this review.

In a resin-based adhesive, the main components are resin monomers that contain polymerizable group(s), a spacer and a functional group in its structure (82). Basically, two types of resin monomers are classified as cross-linking and functional monomers (82). Cross-linking monomers, e.g. Bis-phenol A glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA), contain two polymerizable groups that can be polymerized as well as cross-linked (82). Functional monomers, e.g. 10-methacryloyloxydecyl dihydrogen phosphate (MDP-10), 4-methacryloyloxyethyl trimellitate anhydride (4-META) and 11-methacryloyloxy-1,1'-undecanedicarboxylic acid (MAC-10), commonly have one
polymerizable group with a particular functional group, such as a phosphate or carboxyl group (82).

The bonding ability of a resin-based adhesive is greatly influenced by the chemical composition of the resin components (84), which usually vary between products and manufacturers. Traditionally, the adhesive did not contain fillers. In the mid-1990s, fillers were incorporated into dental adhesives in an attempt to improve the bond quality and strength, but failed to do so (85, 86). Initiator, which usually is camphorquinone, is responsible for initiating the polymerization reaction of the resin components (82) when exposed to a visible light source. Inhibitor is added to prevent the initiator from prematurely reacting as well as to promote the shelf-life (82). Specific ingredients are occasionally added in some dental adhesives. For example, methacryloyloxydodecylpyridinium bromide (MDPB), which is an antibacterial functional monomer with a bromide group attached to the modified original functional monomer MDP-10, is used in a two-step, self-etching adhesive (Clearfil Protect Bond, Kuraray Medical, Japan) (87, 88).

The solvent in a dental adhesive is capable of dissolving the other components and also helps promote penetration of the monomers into demineralized tooth substrate (82). Acetone, ethanol and water are the most commonly used solvents in dental adhesives (82). Water is necessary to maintain ionization of acidic monomers in a self-etching adhesive (88, 89). Water removing capacities and evaporation of the organic solvents are dissimilar, which can affect the bonding performance and clinical use of the adhesive (90-92). Usually, an acetone-based adhesive bonds most effectively to wet dentine, while its bond strength is likely to decrease when bonded to dry dentine (90, 92). Bond strength to dentine of a water/ethanol-based adhesive is
less negatively affected by ‘dry’ bonding than an acetone-based adhesive, but optimal adhesion is achieved when the adhesive is applied to moist dentine (90-92). However, the lowest bond strength was obtained when a water-based adhesive was used on wet dentine (92).

**Classification**

Many researchers have classified dental adhesives by “generation” (93), which is not practical and may not be correct. Recently, the classification has been changed according to “system” and “step” of the adhesive, which is categorized into two major types- total-etching (etch & rinse) and self-etching adhesive systems (63, 77, 94).

The total-etching (TE) adhesive system can be further subdivided into three-step and two-step systems (63, 77, 94). Traditionally, a three-step TE system consists of separate acid etching, primer and bonding agent (63, 77, 94). In a two-step TE system, the primer is combined with the bonding agent into a single liquid (63, 77, 94).

In a conventional, three-step TE adhesive, enamel and dentine are simultaneously etched, usually with phosphoric acid, and then rinsed (63, 77). The smear layer/plugs are removed, and the tooth substrates are demineralized (63, 77). Etched dentine must be moist (not desiccated) to prevent collagen fibre collapse before application of the primer/bonding agent so that penetration of the monomers into etched collagen fibre network is maximized and a strong, stable bond is achieved. This technique is so-called “wet-bonding” (95, 96). The primer, which is a hydrophilic adhesion-promoting agent, is applied on dentine (and enamel) to remove residual water and promote the penetration of the adhesive into the demineralized
dentine (82). Next, the bonding agent, which is relatively hydrophobic (82), is applied and polymerized. In a two-step TE adhesive, a single component of primer/bonding agent is applied on enamel and dentine after acid etching.

The self-etching (SE) adhesive system is sub-classified into two-step and one-step (all-in-one) systems (63, 77, 94). Neither a separate etching nor rinsing step is required for this adhesive system, so that the technique sensitivity associated with the acid-etching step is eliminated (97, 98). In a two-step SE system, an acidic primer, consisting of acidic monomers modified with phosphate or carboxylic groups, initially dissolves or modifies the smear layer and smear plugs. Next, the acidic monomers simultaneously penetrate and demineralize the enamel/dentine (63, 77), and then the hydrophobic bonding agent is applied. In a one-step SE system, acidic primer is combined with the bonding agent into a single solution, consisting of pre-mixed (one bottle) or immediately mixed (two bottle) ingredients, which can etch, prime and bond simultaneously (63, 77).

**Bond to enamel/dentine**

The bonding mechanism of a three-step or two-step TE adhesive system is described as follows. Bonding to enamel, which is mostly composed of inorganic hydroxyapatite crystals, is not as complicated as bonding to dentine, which contains a high organic content, dentinal tubules and dentinal fluid (99). Enamel is firstly etched with an acid (usually with 30-40 % phosphoric acid) to remove any overlying smear layer and selectively dissolve hydroxyapatite crystals. Etched enamel is irregular and porous and is effectively infiltrated with bonding agent to create macro and micro resin tags; excellent and reliable micromechanical bonding is achieved (100, 101). Intimate adaptation at bonded interfaces and high bond strengths to enamel can be
obtained (101). Using a conventional TE adhesive is still the most effective technique to bond to enamel (101).

In contrast, adhesion to dentine is more complicated and a predictable bond is difficult to achieve due to the complexity in the structure of dentine (99). Unlike enamel, dentine contains a high organic content that is mostly collagen fibres which are the framework for the hydroxyapatite crystals (99). Moreover, dentine is a wet, permeable substrate as it contains dentinal tubules filled with dentinal fluid (1). Phosphoric acid is applied to dentine to remove the smear layer and to dissolve inorganic hydroxyapatite crystals between the collagen framework (63, 77). Microspaces exist between the collagen fibres after acid etching (63, 77). Importantly, moist dentine must be preserved after acid etching to prevent collagen fibres collapsing, resulting in incomplete penetration of resin monomers so that optimal bonding is impaired (95, 96). Desiccation of dentine after acid etching should be avoided especially when an acetone-based adhesive is used (90). Dentine bond strengths of acetone-based adhesives severely decrease with a dry-bonding technique, while those of ethanol/water-based adhesives are only slightly affected (90). Moreover, the stability of the dentine bond is negatively affected by dry-bonding, regardless of whether acetone-based or ethanol/water-based adhesive is used (90).

Next, the applied primer/bonding agent penetrates into the interfibrillar spaces in the dentine, and this structure is polymerized. An adhesion layer, which is composed of collagen fibres and polymerized primer/bonding agent, is formed and known as the hybrid layer (79, 80). The hybrid layer is relatively thin (about 5 μm for TE adhesives), yet the hybrid layer is able to provide a micromechanical bond between restoration and dentine (80). In addition, the bond is also achieved from
“resin tags” which are the polymerized resin components penetrating into etched dentinal tubules (79). Smear plugs in the tubules as well as intratubular dentine are removed by acid etching (79). Primer/bonding agent penetrates into the patent tubules and their lateral branches and is then polymerized to form macro- and micro-resin tags (79).

When a SE adhesive system is used, the bonding process and mechanism are changed. Apart from being categorized as one-step or two-step SE adhesive following the number of steps involved, SE adhesives are alternatively classified into three classifications according to the pH of the acidic primer: (1) mild SE, the pH is about 2; (2) intermediate (moderate) SE, the pH is between 1 and 2; and (3) aggressive (or strong) SE, the pH is lower than 1 (77, 102, 103). With enamel, etching effectiveness of mild and intermediate SE adhesives is weaker than phosphoric acid, due to their relatively high pH (low acidity) (102, 104, 105). The conventional pattern after acid etching with phosphoric acid is not clearly seen in enamel treated with these SE adhesives (102, 105, 106). In contrast, aggressive SE adhesive provides an etching effect comparable to phosphoric acid etching (102, 106). Bond strengths of SE adhesives to un-ground enamel are usually lower than those of TE adhesives (102, 105). Pre-treatment of the enamel surface with phosphoric acid etching or grinding with a bur prior using an SE adhesive is recommended to improve the adhesion and the bond strength (100, 104, 105). Bond strengths of SE adhesives to these modified enamel surfaces are comparable to or slightly lower than those of TE adhesives (104, 105, 107).

With dentine, the acidic primer of a two-step SE adhesive is applied to dissolve/modify the smear layer and deplete inorganic hydroxyapatite crystals
between the collagen fibres to a varying extent depending on the pH of the self-
etching primer (77, 103). The acidic primer functions as an etching and priming agent simultaneously (108), and then the bonding agent is applied and polymerized. In a one-step SE adhesive (all-in-one system), a combined acidic primer and bonding agent is responsible for the whole bonding process (63). The hybrid layer achieved from SE adhesive is thinner (1-2 μm) than TE system, yet bond strengths to dentine and the durability of two-step SE adhesives are comparable to those achieved with TE adhesives (109, 110). The quality of the hybrid layer, which depends on the complete infiltration of the monomers into the spaces between demineralized collagen fibres, is more important than the quantity (thickness) (111, 112).

Due to the weakly acidic properties of mild SE adhesives, the smear layer and plugs are not completely removed and are often incorporated into the polymerized hybrid layer (77, 103). The quality and stability of a smear-layer incorporated hybrid layer are a concern. Mild SE adhesives incompletely remove hydroxyapatite crystals which partially remain between collagen fibres after priming (77, 81). Functional monomers in the SE adhesive can form a chemical bond with the residual hydroxyapatites, in addition to the micromechanical bond (77, 81), but this is very much dependent on the functional monomers used. Nevertheless, there is still no strong evidence to support that an adhesive can bond chemically to dentine. On the other hand, smear layer and plugs are completely removed by aggressive SE adhesives (103). Moreover, aggressive SE adhesives almost entirely remove hydroxyapatite crystals from the dentine surface, so that only minimal mineral remains to interactchemically with the functional monomers (77, 81). Thus, a chemical bond is unlikely to occur when an aggressive SE adhesive is used (77, 81).
Interaction with dentine of intermediate SE adhesives is between the mild and aggressive SE adhesives (77, 81, 103). Intermediate SE adhesives can totally remove a thin smear layer, created by a fine grit diamond bur, but the adhesive is not able to eliminate a thick smear layer which is created when a coarse grit diamond bur is used (103). Hydroxyapatite crystals are completely removed from the superficial area of demineralized dentine by intermediate SE adhesives, but the mineral at the base is only partially depleted and still partly remains to interact chemically with the functional monomers (77, 81).
2.5 Resin Composite

Resin composite, a tooth-coloured restorative material, has been extensively developed since its introduction in the 1960s (113). While the use of dental amalgam as a direct restorative material gradually decreases (and is even restricted or prohibited in some countries), use of resin composite is increasing due to minimal intervention techniques, advances in adhesive dentistry and patients’ desire for natural-looking restorations (63, 114-116).

2.5.1 Basic composition and classification

Resin composite consists of three main components: (1) resin matrix, including initiator and inhibitor (stabilizer); (2) inorganic fillers; and (3) coupling agent (113), which define the properties of resin composite. The resin matrix most commonly used in current resin composites is Bis-GMA and/or its derivatives such as UDMA (113). Bis-GMA, a high molecular weight monomer, is highly viscous (117), so the amount of added filler is limited. Low molecular weight monomers, such as TEGDMA, are incorporated as diluents to reduce the viscosity and improve the quantity of filler loading (117). The initiator of light-cured resin composite is usually camphorquinone, which is activated by visible light at wave lengths between 450-475 nm (118, 119). Inhibitors are added to enhance the stability as well as extend the shelf-life of the materials (113). Inorganic fillers, e.g. silicon dioxide, zirconium dioxide or barium glass, are incorporated into resin composite as a reinforcing phase to improve material strength and wear resistance (119). A coupling agent is usually an organo-silane that creates a chemical bond between the resin matrix and the fillers (113, 120).
Resin composite is traditionally categorized according to the size of inorganic fillers: macro-filled, micro-filled and hybrid resin composites (119). Due to the limitations of the manufacturing process in the past, traditional fillers in macro-filled resin composite usually ranged from 0.1-100 \( \mu \text{m} \) in size (119). Because of unacceptable physical and mechanical properties, macro-filled resin composites are no longer used (119). Micro-filled resin composites contain small silica filler particles which are 0.04 \( \mu \text{m} \) in size (119), so that the material is highly polishable. However, the amount of filler loading is limited due to the high ratio of surface area to volume, which causes the uncured material to become highly viscous (119). Adding pre-polymerized filler into the resin increases the amount of filler loading and improves the properties of micro-filled resin composite (119, 121). Nevertheless, the properties are still inferior for use in stress-bearing areas (119, 121, 122).

Hybrid resin composite is modified by using a combination of sub-micrometer (0.04 \( \mu \text{m} \)) and micrometer (1-4 \( \mu \text{m} \)) filler particles (119, 123). This modification allows an increase in the amount of filler incorporated into the resin matrix as well as an enhancement of the material’s physical properties (119, 123). Hybrid resin composite can be used in posterior restorations and is still polishable. Micro-hybrid resin composite is a continuing development by reducing the average sizes of the fillers to 0.1-1 \( \mu \text{m} \) (119). While the physical/mechanical properties are maintained, the polishing ability of this material is improved, though still slightly inferior to the micro-filled type (124).

Recently, nano-filled resin composites have been introduced. This material contains nano-sized (0.005-0.01 \( \mu \text{m} \)) filler particles in combination with micrometer-sized filler particles (119, 125). Recent technology in manufacturing allows coating of
nano-particles with silane coupling agent, so that enhanced integration between the resin matrix and the nano-fillers is achieved (125). Mechanical and physical properties of this material are comparable to the micro-hybrid resin composite (126, 127) while the polishing ability is superior (128).

2.5.2 Polymerization shrinkage

Basic knowledge

Polymerization shrinkage, which is a major disadvantage of resin composite, is influenced by filler content, types of monomer, modulus of elasticity and polymerization rate (129). When polymerization begins, free-radical activated monomers interact with the other molecules to develop a polymer chain that subsequently links with other chains to establish a cross-linked polymer network (113). This polymerization process causes significant reduction in the total volume, namely polymerization volumetric shrinkage (129). Once the reaction begins, stiffness (rigidity) of the material increases until reaching the stage where molecular motion is limited; this stage is the so-called “gel-point” or “gel-range” (130). After this period, stress relief in the material is constrained due to the restricted molecular movement and the increase in the stiffness (130). Either the volumetric shrinkage or the stiffness increase during the polymerization reaction, generating polymerization shrinkage stresses (130). The volumetric shrinkage of current resin composite restorative materials ranges from 1-4% (131). Polymerization shrinkage stresses of 1-7 MPa, which depend on the material and testing method, have been reported (132).

Cavity configuration (C-factor), which is a ratio of bonded surface area to unbonded (free) surface area, is an important factor determining polymerization
shrinkage stress and may disrupt the adhesion to cavity floor and walls (133, 134). For example, an occlusal cavity has five bonded surfaces and one unbonded surface, so the C-factor is 5 (if each surface area is equal), which is the greatest value among cavity types. Polymerization shrinkage stress has a direct relationship with the C-factor; the higher C-factor, the greater shrinkage stress that will occur at the bonded walls (133, 134). Bond strengths of dentine adhesives tested when an occlusal cavity is used for specimen production usually decrease, compared with resin bonded to a flat dentine surface (C-factor is 1) (135, 136).

**Effects of polymerization shrinkage stress on restorations**

Polymerization shrinkage stress does not only exist as an internal stress within resin composite, but is also distributed to the bonded interface between the restoration and cavity walls (137). If the shrinkage stress is higher than the adhesive strength, the bond can be disrupted (134), and micro-gaps are formed. In a high-caries risk patient, secondary caries is likely to form at defective margins. If the adhesion can withstand the shrinkage stress, cuspal deformation might be anticipated in an occluso-proximal restoration (138-140). Moreover, enamel at the margins may be cracked by the shrinkage force (141). If a lining material is applied, e.g. GIC liner or flowable resin composite, the lining material may be deformed under the shrinkage stress (142). Occasionally, the bond between the lining material and cavity floor is ruptured, and micro-gaps are sometimes detected beneath the lining (143, 144). Micro-gaps as well as other defects caused by the shrinkage-stress may be responsible for postoperative tooth sensitivity in a tooth restored with resin composite.

It was believed that polymerization shrinkage occurred in the direction towards the light-curing source. However, from finite element analysis, it was found
that resin composite shrinks towards the bonded surfaces (rather than a light source) and away from free, unbonded surfaces (145). Moreover, the direction of polymerization shrinkage also depends on the bond quality, light-curing angle and depth of resin composite (145-147). Thus, a strong bond must be achieved to prevent micro-gap formation caused by the polymerization shrinkage (148).

**Minimizing the negative effects of polymerization shrinkage**

To reduce polymerization shrinkage, resin composite has been improved, and some alternative clinical techniques have been introduced. High filler loading results in a lesser amount of resin matrix and consequently the volumetric shrinkage (149). For instance, a flowable resin composite has higher shrinkage than a hybrid resin composite because of the lower filler content (150). Using a low-shrink or expanding monomers is another attempt to reduce the shrinkage (151). Recently introduced, a silorane-based (opening ring monomer) resin composite has a volumetric shrinkage less than 1% (131). The polymerization reaction of silorane resin starts with the opening of the ring monomer which initially gains spaces to compensate the subsequent volume loss caused by liner connections to form a chemical bond between each molecule.

Practically, resin composite should be incrementally placed, not only to ensure adequate light-curing, but also to enhance the stress relief (152). However, total shrinkage stresses when using incremental techniques are not significantly lower than that when the material is placed in bulk (153).

A slower curing rate of resin composite might decrease the polymerization shrinkage stresses by extending the gel-range and consequently the stress relief period
In the “soft-start” polymerization technique (ramped or step cure), light intensity is initially low for a specific period and then gradually increases up to the maximum intensity which is maintained until light curing is complete (154) so that the gel-range may be prolonged. Thus, the shrinkage stresses are possibly relieved to a greater extent without a detrimental effect to the degree of conversion (154, 155).

Polymerization shrinkage may be reduced if a liner is placed beneath resin composite (156, 157). Flowable resin composite is applied as an intermediate liner, between the adhesive layer and resin composite restorative material, to act as a stress absorber (158), and an improvement in dentine bond strength and adaptation was reported (159). Nevertheless, in a recent study, an intermediate layer of a low-viscosity resin had no effect on micro-tensile bond strength to dentine and provided less fatigue resistance than the group without a resin liner (160).

If a GIC liner is applied beneath resin composite, polymerization contraction stress is reduced (157, 161). Moreover, the GIC lining can also act as a stress absorber (162). Fluoride release, which may prevent secondary caries formation, is an additional advantage of the GIC lining. Nevertheless, it has been reported that micro-gaps are more frequently detected at the bonded interface of restorations lined with GIC liner than without a lining (143, 144). This might be explained on the basis that the initial adhesive strength of GIC liners to dentine is not enough to withstand the shrinkage forces from the polymerization reaction of subsequent resin composite filling material (143, 144).
2.6 **GLASS-IONOMER CEMENTS**

First introduced by Wilson and Kent in the early 1970s (163), glass-ionomer cements (GICs) have been continuously developed and widely used for many purposes, such as restorations, liner/bases, luting, endodontic sealer cements or pit and fissure sealants. GICs are able to bond chemically to enamel/dentine, release fluoride which may prevent further dental caries, and have excellent biocompatibility (94). Cement acidity is neutralized by the enamel/dentine as well as the setting reaction of the cement (164, 165). Apart from use for dental purposes, GICs have also been used as a cement for fixation of medical implants (166).

### 2.6.1 Composition and classification

Conventional GICs are water-based cements that set by an acid-base reaction between a fluoroaluminosilicate glass and a poly (alkenoic) acid (94). The materials are provided in two separate components, a glass powder and a liquid (acid).

GICs have been continuously improved since the original cements were developed. Glass particles are modified by partial removal of calcium ions from the surface to speed up the setting reaction and maturation (167). However, the radiopacity of the modified cements has been considerably increased resulting in the aesthetic quality of restorations being sacrificed (167). To enhance the reaction without affecting translucency of the cements, tartaric acid was added to the polyacid components (168, 169). Setting time as well as physical properties of the cements are improved while working time is slightly affected when tartaric acid is incorporated (167, 170).
Increase in the molecular weight and concentration of the polyacid also accelerates the setting reaction. However, this increases the viscosity of the cement and makes it difficult to handle, thus limiting the amount of the polyacid that can be incorporated (167, 171). Highly reactive polyacids, i.e. copolymers of acrylic, itaconic acid and maleic acid, are combined with the polyacid (172). Setting time of the cements is improved, but the viscosity is still high (167, 171). To achieve a desirable and workable viscosity, the polyacid is dried into an anhydrous form before being incorporated with the glass powder, and the mixing liquid is distilled water or tartaric acid (167, 173). Another modification of conventional GICs has been the addition of metal components, such as silver particles, that are sintered into the glass powder in the GICs to form “cermet” cements or simply adding silver particles to achieve an “admixed” GIC (174, 175).

Resin-modified GICs (RM-GICs) were introduced in the early 1990s, which consist of a fluoroaluminosilicate glass, polyacid (as in conventional GICs) and polymerizable resin monomers (176). The resin monomers are simply added into the cements or chemically attached to modified polyacid groups (171). The polymerization reaction of the monomers, whether self-cured or light-cured, improves the physical properties and reduces water sensitivity of the cement at least in the early stages (177).

Conventional GIC was specifically developed as a high powder-liquid ratio GIC (HPL-GIC) (171). By increasing the powder:liquid ratio and polyacid concentration/molecular weight, more favourable physical and mechanical properties of HPL-GIC can be achieved (171). Moreover, adding a small amount of dried polyacid into the glass powder as well as optimizing the glass particle size into
smaller particles also improves the properties of this GIC (171). Compressive strength and surface hardness of HPL-GIC are superior to conventional GICs while its relative wear and water solubility are lower than the conventional cements (171, 178, 179).

Most recently, novel RM-GICs have been released as a paste-paste system. The polyacids are greatly modified with methyl-methacrylate in these novel cements, which contain higher amounts of polymerizable resin monomers than the original RM-GICs. Simplifying the mixing procedure, better control of the mixing ratio and reduction in light-curing time are publicised by the manufacturers (180, 181). The amount of 2-hydroxyethyl methacrylate (HEMA) is increased in these products, which may negatively affect material properties of these paste-paste RM-GICs (182). It seems that the material properties are likely to be less like the conventional GICs and more like resin-based polyacid modified resin composite than RM-GICs. Recent research data have been released, but most has been conducted by manufacturers’ researchers and/or supported by companies. Hence, independent research studies are still required.

Practically, GICs are classified following their clinical use- type I, luting; type 2, restorative and type 3, liner/base (94, 183). Type 2 GICs are further subdivided into subtype 1, aesthetic restorative cements, and subtype 2, reinforced restorative cements (94, 183). Pit and fissure sealant GICs may be categorised as a supplementary classification.

**2.6.2 Setting mechanism and water sensitivity**

Conventional GICs set by an acid-base reaction (94, 167, 170). Immediately after mixing, a polyacid attacks the glass particles. As a result, metal and other ions
are released from the surface-degraded particles. Next, the divalent metal ions react with the carboxyl groups of the polyacid to form an initial polyacid salt, the cement matrix. The glass particle surface is transformed into a silica hydrogel covering the un-reacted core, which finally becomes the cement (94, 167, 170).

For RM-GICs, the polymerization reaction of the resin components, whether light-cured or chemical-cured, occurs immediately. In the meantime, the acid-base reaction starts simultaneously after mixing and then slowly progresses (177). Although the acid-base reaction is slightly slowed by the presence of the resin component (170), a complete reaction is ultimately obtained. Hence, RM-GICs are less sensitive to water imbalance than conventional cements because the immediate polymerization reaction prevents further water uptake and loss of these resin-modified cements (167, 177). However, depth of light curing is limited and is a limitation of the light-cured RM-GICs (170, 177, 184, 185).

After the initial set, the cement is still immature since the polyacid salt is initially formed as a strontium- or calcium-polyacid salt (Sr-PAA, Ca-PAA), which is highly soluble and sensitive to water uptake (168, 170). Subsequently, the carboxyl groups react with the aluminium ions (which are also released early, but react slowly with the polyacid) to form an aluminium-polyacid salt (Al-PAA) that is more stable and less sensitive to water imbalance (168, 170). Gradually, GICs mature over time, but the cements are still sensitive to water loss (evaporation of loosely bound water) for months after the initial set (167). It is noted that conventional GICs are sensitive to water uptake up to 24 h and water loss for 6 months (167). Water sensitivity of RM-GICs and HPL-GICs is significantly lower. These “fast setting” materials are sensitive to water uptake just 5 min after setting and water loss for up to 2 weeks (167). Stable
Al-PAA is formed more rapidly in HPL-GICs (171), so the water imbalance is reduced quickly. Polymer chains in RM-GICs, which act like initial protective shields around the sensitive Ca-PAA at the early stage improve properties of the resin-modified cements including reduction in water sensitivity (167, 177).

Fluoride is available as a free ion formed in the set GICs, which is not a part of the cement matrix (94, 167). Therefore, fluoride release from GICs does not negatively affect mechanical and physical properties of these materials (94, 167). As a result of early cement dissolution, fluoride ion release from the cements is initially high for a short period. After the initial burst, fluoride diffusion declines rapidly and then is gradually released as a constant small amount, thereafter (186-188).

2.6.3 Bond to tooth structure

GICs are able to bond chemically to natural tooth substrates- enamel and dentine (94, 167, 189). Ionic bonds between calcium ions of hydroxyapatite in enamel/dentine and carboxyl groups of polyacid in GICs are believed to be formed (190-192). When freshly mixed cement contacts tooth substrates, interactions immediately occur by ion exchange between the cement (i.e. calcium, aluminium, fluoride and carboxyl) and the substrate (i.e. calcium and phosphate ions) (94, 167, 190, 191). An intermediate layer has been detected between GICs and dentine (193, 194). This layer may play an important role in chemical adhesion of GICs to the tooth substrates. However, low bond strengths to dentine or enamel of GICs have been reported (195-197). Bond failures usually occur in the bulk of the cements, rather than at the bonded interfaces (195, 196). Therefore, the reported bond strengths tend to be the cohesive strengths of the cements which mostly depend on the cement’s mechanical properties (197).
Apart from the chemical bond, in addition a micromechanical bond exists when RM-GICs are placed on tooth substrates, (177). Acidic freshly-mixed GICs partially demineralise and simultaneously infiltrate into dentine to form a “hybrid-like” layer as found in resin composite restorations bonded with a resin–based adhesive. However, the hybrid layer at the GICs-dentine interface is relatively thin (192, 194).

Mild-acid conditioning, usually using 10-25% polyacrylic acid, should be used before application of GICs in order to remove the smear layer, clean the cavity surface, pre-activate calcium ions and increase surface wetting-ability (167). If the conditioning is omitted, especially when the cement is applied as a liner/base, the GIC must firstly dissolve the smear layer before subsequently interacting with underlying enamel/dentine (192). The dissolved smear layer is finally incorporated into the GIC as a part of the bonded interface. The ion-exchange layer might not be detected if the conditioning step is omitted (167, 192).

2.6.4 Glass ionomer liner/base (type III)

A liner/base can be applied on the dentine before using a dental adhesive and/or restorative material placement in an attempt to protect pulpal tissues from any threat (liner) or as a substitute for loss of dentine (base) (198). GICs are considered the material of choice because of their chemical adhesion to dentine, fluoride release, suitable radiopacity and excellent biocompatibility (167, 198). Moreover, when GICs are applied as a liner under resin composite restorations, a reduction in the overall polymerization shrinkage stress has been observed (142, 157).
The powder:liquid ratio of the GICs determines whether a liner or base is applied (167). Low powder:liquid ratio cements are suitable for use as a liner due to their superior flow characteristics and ease of application. In contrast, as a dentine replacement, a cement base should be strong and thick enough to support undermined enamel and the final restoration. Hence, a high powder:liquid ratio cement, which has better physical and mechanical properties, is desirable (199-201).

Similar to the restorative type, GIC liner/base materials can bond chemically to dentine (192). Nevertheless, the micromechanical bond between a RM-GIC liner and dentine via the hybrid layer is not observed when the surface is not previously conditioned (192). Conditioning dentine prior to liner/base application with mild polyacrylic acid is recommended (167). A direct chemical bond between un-reacted monomers in RM-GICs liner and resin composite is anticipated without further surface treatment (167, 202). In contrast, a micromechanical bond should be created between conventional GIC liner and resin composite by acid etching and dental adhesive application (167, 202).
CHAPTER 2: LITERATURE REVIEW

2.7 DENTINE PERMEABILITY & RESTORATIVE DENTISTRY

2.7.1 Dentine is a permeable substrate

Generally, sound dentine of a young or adult tooth is permeable because of its tubular structure and dentinal fluid content (203). The degree of dentine permeability depends on the region and depth of dentine (204, 205). Permeability of deep coronal dentine is higher than that of superficial coronal dentine because the number per unit area and the size of dentinal tubules are greater towards the pulp (205). Compared with root dentine, coronal dentine is more permeable as the latter possesses fewer and smaller-diameter dentinal tubules (206).

Dentine permeability decreases with age due to physiological changes of the dentine and pulp from the aging process (43). Intratubular dentine is gradually deposited, so that the diameter of the dentinal tubules is reduced (207). Moreover, the formation of secondary dentine towards the pulp increases dentine thickness while the size of the pulp decreases (3). This combination of events restricts the movement of fluid through dentinal tubules and subsequently reduces dentine permeability of the tooth with increasing age (43).

In addition, pathological changes in response to irritation, e.g. attrition, erosion or abrasion, also decrease the dentine permeability of an involved tooth (207). At the affected area, the rate of intratubular dentine deposition markedly increases, and needle-like/rhomboid crystals are precipitated inside the tubules; as a result, dentinal tubules are completely or partially occluded (207). Furthermore, tertiary dentine is formed at the pulpal side of dentine below the area affected by the irritation (207).
Tertiary dentine can form with either an atubular or tubular structure, which depends on the severity of the irritation (19, 20). If tertiary dentine forms as atubular dentine, permeability is reduced, and dentinal fluid movement is disrupted (207).

**Permeability of dentine affected by dental caries**

Dentine permeability is significantly altered by dental caries. In response to slowly progressing caries, dentine below the lesion is usually hypermineralized and sclerotic to inhibit the invasion of bacteria and their products into the pulp (14). Dentinal tubules are partly or fully occluded by deposition of intratubular dentine as well as precipitation of mineral crystals (43, 44). Additionally, tertiary dentine forms as reactionary or reparative dentine on the pulpal side corresponding to the area of dental caries (19, 20). Hence, dentine affected by dental caries is usually less permeable (43, 44). Nevertheless, these responses are frequently deficient when a caries lesion rapidly progresses (14). Dentine affected by such a lesion might still be permeable.

**2.7.2 Effects of dentine permeability on adhesive restorations**

Dentine permeability is a major concern in restorative dentistry and has been studied extensively (203). When an adhesive restoration is placed, it is potentially influenced by dentine permeability, via dentinal fluid movement and dentine wetness. Permeable dentine should be sealed effectively by an adhesive restoration that is insensitive to this wetting of the surface (203).
Effect of permeability on adhesion to dentine

After caries removal (and cavity preparation), the dentine surface is covered with a smear layer and additionally dentinal tubules are filled with smear plugs (62, 208). Smear layer and plugs act as semi-permeable barriers and inhibit fluid movement outward into the cavity, so dentine permeability does not significantly increase after cavity preparation (62, 208).

However, dentine must be pre-treated (conditioned) with acid or acidic monomers in an adhesive procedure prior to restoration placement (209). The smear layer (and also smear plugs) can be removed or dissolved by the conditioning procedure (209). Permeability of normal dentine dramatically increases after the smear layer/plugs are completely removed and dentinal tubules become patent (76, 210). When there is a positive pulpal pressure producing outward fluid flow, the increase in wetness negatively affects dentine bond strengths of total-etching adhesives (211) while the effect on self-etching adhesives remains controversial (211, 212).

In contrast, dentine affected by caries is quite different. Its permeability is very low even after acid etching (43, 44). Therefore, adhesion to such dentine is not strongly affected by wetness, but rather is influenced by the degree of dentinal sclerosis (213). Hypermineralized dentine is resistant to acid etching so that resin tags are rarely observed and the hybrid layer is altered (213-215), which affect negatively the bond strength (214-217). Nevertheless, normal dentine is inevitably exposed during caries removal and cavity preparation (14). Thus, a dental adhesive must interact with either less permeable, caries-affected dentine or permeable, ‘normal’ dentine.
Contemporary dental adhesives do not provide a better seal of dentine than the seal created by smear layer and smear plugs. Adhesive coated dentine has comparable permeability to smear-layer covered dentine (61). However, an adhesive layer is much more resistant to acid dissolution than the smear layer.

### 2.7.3 Dentine permeability and tooth sensitivity

When dentine is exposed and tubules are patent (by acid etching), dentinal fluid movement at a sufficient rate can trigger free nerve endings in the pulp, and, as a consequence, tooth sensitivity occurs according to the hydrodynamic theory (218). If the dentine surface is not etched and the smear layer is still present, tooth sensitivity cannot be elicited (219). There is a direct relationship between dentine permeability and dentine thickness: fluid flow across dentine increases when dentine thickness decreases (205, 220). Dentine on a deep cavity floor is more permeable than one in superficial dentine. In deep dentine, the diameters of dentinal tubules are larger, and the density is higher (221). As a consequence, tooth sensitivity during cavity preparation is more likely to occur in a deep cavity than in a shallow cavity. The minimum fluid flow rate that can trigger nerve impulses and induce tooth sensitivity has been calculated (222).

Nevertheless, the outward dentinal fluid flow is self-reducing over time; the fluid flow rate steadily declines after 6 hours of dentine exposure in dogs (223). This self-reduction capacity can be explained by coagulation of high-molecular proteins in dentinal fluid, such as fibrinogen (223) or albumin (13). A decrease of fluid flow in vitro was detected when the experimental system was filled with albumin, but the decrease was not found in a water-filled system (224). Thus, tooth sensitivity
during/after cavity preparation may be limited by this self-sealing capacity of dentinal tubules.
2.8 POSTOPERATIVE TOOTH SENSITIVITY

Teeth restored with resin composite materials are at some risk of postoperative sensitivity. Polymerization shrinkage stress might cause bond deterioration and micro-gap formation as well as cuspal movement, which are associated with the development of postoperative tooth sensitivity (130).

2.8.1 Mechanism of tooth sensitivity

The most widely accepted mechanism of tooth sensitivity is the hydrodynamic theory (218). According to this theory, rapid dentinal fluid movement in dentine tubules occurs in response to stimuli, which can induce tooth sensitivity (218). Such fluid movement might create sufficient force to trigger an action potential in free nerve endings in the pulpal periphery (218).

Stimuli, such as cold, heat, pressure, air blowing or cutting, on dentine are able to induce dentinal fluid movement (outward or inward) (225, 226) and, as a consequence, tooth sensitivity. Stimuli that cause a rapid change can induce tooth sensitivity at a higher level than those which create a slower change (219). However, effects of stimulation on dentine covered with a smear layer is less than on dentine etched with an acid (219). Thus, tooth sensitivity has a close, direct relationship with dentine permeability (227).

In contrast, tooth sensitivity cannot be clearly explained by the hydrodynamic theory when a sound tooth with intact enamel is stimulated with thermal stimuli (228). It has been reported that occlusal force can induce dentinal fluid movement in an intact tooth (229) as well as a restored tooth (230), which may trigger a nerve impulse
(230). However, an alternative theory has been recently proposed; tooth deformation mechanically induced by thermal stimuli or occlusal stresses may trigger nerve impulses directly (231). In a combination of the two theories, tooth deformation may mechanically stimulate dentinal fluid flow that subsequently triggers nerve activities (231).

2.8.2 Tooth sensitivity after resin composite restoration

The pulp is traumatized and inflamed to some extent following caries removal and cavity preparation, depending upon the intensity of these irritations (64). This trauma is in addition to the pulpal inflammation resulting from caries. If the procedures are performed carefully with copious water coolant, the pulp is only slightly or moderately inflamed and then can be healed, unless there is an additional injury to the pulp (64). During the period while the pulp is temporarily inflamed, the tooth often becomes hypersensitive to stimuli from regular functions, e.g. cold water or occlusal function, until the pulp has healed (232).

Remaining dentine thickness is an important factor determining the degree of pulpal inflammation (233, 234). The thicker the remaining dentine, the less the extent to which the pulp is affected by cavity preparation (233, 234) as well as restorative materials (235). Hence, dentine must be preserved as much as possible during caries removal and cavity preparation (233). Presumably, postoperative tooth sensitivity is more likely to occur in a restored tooth with a deep cavity, rather than in one with a shallow cavity.

When an adhesive restoration cannot completely seal a cavity, micro-gaps are detected frequently at the bond interface (236). Moreover, adhesive and hybrid layers
are permeable and leak at the nano-metre level (111, 212, 237). Dentinal fluid may move freely through dentinal tubules to these fluid-filled gaps, and the fluid flow rate may increase when there is stimulation (232). Consequently, free nerve endings in the pulp may be activated by a sufficient rate of dentinal fluid movement (232). Occasionally, postoperative tooth sensitivity has been reported in teeth restored with resin composite (238-240).

If a restorative material does not seal properly, bacteria or bacterial products can leak through the bond interface into dentine (241, 242). Bacterial leakage is occasionally found in association with resin composite restorations, but leakage is rarely detected or undetected in the teeth restored with GIC or zinc oxide eugenol cement, possibly due to their biological seal (antibacterial properties) and less gap formation (235, 243). Bacteria and their toxic products can penetrate into the pulp so that pulpal healing is impaired by this additional insult (241, 244, 245), and tooth sensitivity may be prolonged after restoration. When compared with a resin composite restoration, a lower incidence of pulpal inflammation is observed in a cavity filled with GIC (235, 243).

In a resin composite restoration of an occluso-proximal cavity, cuspal deflection during polymerization (138, 139) as well as the deflection due to occlusal loading, possibly causes tooth sensitivity. It has been reported that dentinal fluid movement simultaneously occurs with the cuspal deflection (138, 139), which can induce tooth sensitivity. The larger cavity, the higher amount of cuspal deflection is detected (246). Thus, tooth sensitivity is more anticipated in a large resin composite restoration.
2.8.3 How to prevent or reduce postoperative tooth sensitivity?

As previously mentioned, caries removal and cavity preparation must be done with caution to preserve the remaining dentine as well as to avoid pulpal trauma. Nevertheless, postoperative tooth sensitivity is still an unpredictable problem in restorative dentistry (247). From a strictly clinical point of view, some recommendations have been made in an attempt to prevent or reduce postoperative sensitivity in posterior teeth restored with resin composite (247). It is believed that using a self-etching adhesive, instead of a total-etching adhesive, may eliminate postoperative tooth sensitivity (247). When a self-etching primer is applied to dentine, the smear plugs are not completely removed and are incorporated into the adhesive layer so that dentinal fluid movement and tooth sensitivity is thought to be limited.

Application of a GIC liner/base beneath a resin composite restoration is another recommendation (247). It is believed that the chemical adhesion might provide excellent adaptation and seal the dentine. In addition, antibacterial properties of GIC may inhibit bacterial leakage into a cavity (243). However, micro-gap formation is still frequently detected between GIC liners and dentine when GIC is placed beneath resin composite (144). Some clinical studies have investigated the effect of GIC liner on reducing postoperative tooth sensitivity. One study showed that the prevalence of postoperative tooth sensitivity is lower when GIC liner is applied on the entire exposed dentine (248). In contrast, a protective layer (liner) does not decrease postoperative tooth sensitivity, which has been reported in other studies (249, 250). Hence, the ability of a GIC liner to prevent/reduce postoperative tooth sensitivity remains questionable.
Another technique advocated is flowable resin composite application as a first layer after bonding to improve the adhesion between cavity walls and the restoration. It is thought that the flowable resin might absorb some of the polymerization shrinkage force of the subsequent resin composite filling (161). Less postoperative sensitivity is expected when a cavity is initially lined with flowable resin composite (247). However, no significant difference in short-term postoperative tooth sensitivity was found between teeth restored with or without a lining of flowable resin composite (251).

In conclusion, the methods that have been suggested to solve the problem of postoperative tooth sensitivity still need further investigation to clarify their effectiveness.

The purpose of the studies in this thesis is to investigate the ability of (conventional or resin-modified) glass-ionomer lining or using a self-etching adhesive to improve sealing ability and reduce postoperative tooth sensitivity, when compared with a total-etching adhesive (without liner), in posterior resin composite restorations. If the results are in agreement, the laboratory studies may provide some biological explanations for the clinical outcomes.
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