Evaluation of Marginal and internal adaptation of adhesive class II restorations, in vitro fatigue tests
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Chapter 1:

Historical Perspectives & Current Status of Adhesive Techniques and Composite Resins
The evolution of composite materials

It started with the invention of epoxy resins, by Castan in 1937, a Swiss chemist. The use of this molecule proved extremely successful in Dentistry, as well as in many other industrial applications. In 1958, Schmidt and Purmann in Germany were producing the first low-shrinkage resin; the material was based on a novel low-viscosity epimine resin and was marketed under the name of P-Cadurit (McLean, 1961). Dr. Bowen's first composite formulation (1961) did follow the publication of Dr. Buonocore's technique for adhesion to enamel (using phosphoric acid as etchant) (1954), and provided the necessary complement for developing tooth-bonded restorations. The first composite resin from 3M, combining these two major technological advances was rapidly produced and available for clinical testing since 1961; it then was introduced in 1965 after a thorough evaluation period, under the name of Adent 35. The works of Drs. Buonocore and Bowen together really constitute the starting point of Adhesive Dentistry. Adent 12 (3M) appeared just two years after Adent 35 and was the first composite ever to be developed for an application on posterior teeth. This material, such as all those from the first generation, was macrofilled composites, using only one type of filler (Lutz, 1983; Willems et al, 1993). These products proved clinically rather unsuccessful in posterior teeth, mainly due to material's insufficient physical properties and the absence of adhesion with dentin. Common problems were post-operative sensitivity and marginal leakage, as biological behaviour is concerned, while rapid wear, marginal degradation and poor color stability were their main physical drawbacks (Fig 1.1A and 1.1B).

The next breakthrough in composite technology was the introduction of visible light-curing systems (Dart and Nemcock, 1971).

Vivadent introduced Microfilled composites in 1974, with a rather successful behaviour in anterior teeth. Although aesthetically largely superior to macrofilled materials, microfilled composites however did not proved an adequate formulation for posterior restorations (Leinfelder, 1980; Dietschi and Holz, 1990; Hickel and Manhart, 2001).

The development of hybrid composite resins was the next innovation in composite technology and made the use of composite resins also possible and successful in stress bearing areas. Since 1985, a number of so called 'posterior composites' were introduced on the market and for which we have today long term, satisfactory clinical data (Hickel and Manhart, 2001) (Fig 1.2A and 1.2B). The main features of this later composite generation:

- a bi-modal (hybrid) filler composition (macro and micro particles)
- an increased filler content
- a reduction in the average particle size
- a better and complete filler silanization
- light polymerisation activation

These changes in composite formulation have improved all their physical properties, including a reduction (but not suppression) of polymerisation shrinkage. These materials can be regarded as extremely advanced considering aesthetic integration, fracture or wear resistance. The remaining polymerisation shrinkage certainly is the "Achilles tendon" of modern composite resins, which still make their direct application problematic in large cavities.

The evolution of adhesive materials

The history of dental adhesives started as early as 1949, when Dr. Hagger, a Swiss chemist, applied the patent for the first dental adhesive, later known as "Sevriton Cavity Seal" and to be used in combination with the chemically curing resin "Sevriton". This invention surprisingly remains almost unrecognised in the dental literature, despite the fact it was the first time that bonding to tooth structure became commercially available through the formation of an interface very similar to what is called today the hybrid layer (Kramer and Mc Lean, 1952). In 1954, Buonocore conducted successfully his first experiments on adhesion to enamel trough acid etching, while the same concept applied to dentin (1958) remained problematic, due to the use of strictly hydrophobic resins. As well, the high polymerisation shrinkage of acrylic filling materials gave Buonocore's invention only little impact on Restorative Dentistry at this time. The advent of composite materials with reduced polymerisation shrinkage gave the necessary input to finally enter the era of "Adhesive Dentistry.

While adhesion became immediately successful on enamel, through micro-mechanical retentions created by acid etching and the application of a low viscosity resin, dentin adhesion went over a long development phase, which led to many concepts and several generations of adhesive systems.

Apart from the technology derived from the glass ionomer chemistry, which was only recently applied to dental adhesives (Van Meerbeek, 2001), attempts to develop a chemical bond to hard tissues proved clinically rather unsuccessful, due to the high structural variability and inherent moisture of the dentin substrate.

The effectiveness of current adhesive systems depends on two critical steps, which are the dentin demineralisation (etching) and application of hydrophilic monomers (priming) which allow an inter-diffusion zone (hybrid layer) to be created (Nakabayashi et al, 1982). Actually, adhesion relies on the existence of this resin-collagen interface (the collagen fibbers being partially or completely demineralised) having a few microns thickness and which is located at the dentin surface, on the walls of the tubules at their entrance, and possibly in the lateral
tubules branches (Van Meerbeek, 1992, 1993). Still, 3 kinds of adhesives are currently proposed:

- total etch adhesives (separate etching step involved)
- self-etch adhesives (no etching step)
- glass ionomer adhesives

Each concept includes several sub-classes of adhesive systems.

It is also quite useful to organize existing adhesive systems, according to the number of clinical steps involved:

- Conventional 3-steps adhesives (1. etching – 2. priming – 3. bonding)
- One bottle adhesive to be used after etching (1. etching – 2. priming/bonding)
- One bottle adhesive with self etching primer (1. etching/priming – 2. bonding)
- All-in-one adhesive (1. etching/priming/bonding)

The later generation of adhesive systems is showing a clear trend; manufacturers are trying to reduce the application time and make their use as easy as possible. Actually, while conventional 3 step adhesives remain the most effective ones (as demonstrated in numerous in vitro as well as clinical studies) (Van Meerbeek et al, 2001), their successful application depends a good control of the substrate moisture and a proper evaporation of the solvent contained in the primer solution. In case the operator had not optimally controlled these two parameters, the over-wet phenomenon (Tay et al, 1996 a and b) or a collapse of the collagen fibber network can occur (Pashley et al, 1993). In both situations, a significant reduction in adhesion efficiency and durability is to be expected. Therefore, the type of solvent contained in the primer solution (acetone, ethanol and water) makes the substrate humidity more or less controllable; the trend is now to incorporate water in the primer and to use ethanol more than acetone. For the same reasons, self etching systems (included in one or two steps adhesive systems) are getting more popular as their application technique is less operator or substrate dependant. Actually, the advantage is that the resin components can penetrate the tissue together with the etchant. Although the thickness of the hybrid layer is reduced in many of these systems, bond strength reaches values similar to many 3-components systems.
Efficacy of adhesives in a clinical configuration

When using modern adhesives, shear and tensile bond strengths to dentin in vitro were reported to be comparable if not superior to the values obtained on enamel (Sano et al, 1994; Gwinnett and Yu, 1995; Hasegawa et al, 1995, Tanumiharja et al, 2000). However, because of the specific conditions related to laboratory testing methodologies, these performances may be considered superior to those attained in vivo (Carvalho et al, 1996). The conventional methodology for evaluating dentin bond strength is even contested by some authors (Versluis et al, 1997). In clinical conditions, the development of adhesion is influenced by numerous parameters, which mostly are obstacles. Actually, variations in dentine quality related to location, depth, previous pathologies and contamination by dental products may alter dentin bond strength (Cagidiaco and Ferrari, 1995; Nakijima et al, 1995; Pashley et al, 1995; Eick et al, 1997). The operator is also known to have a significant influence on the bond strength to dentin (Ciucchi et al, 1996). Furthermore, one has to consider the influence of the cavity configuration (factor C) (Bowen et al, 1983; Davidson et al, 1984; Feilzer et al, 1987), the direct relation between stresses within the adhesive interfaces and restoration and the composite volume cured in situ (Feilzer, 1997) and the effects of the restorative material and method (Lutz et al, 1986). Furthermore, when using a direct restorative method, the polymerization stresses are generated immediately after bonding procedures, well before maximal bond strength is achieved (Burrow et al, 1994; Carvalho, 1996).

All these facts turn adhesion to dentine into a multi-factorial problem, which can not be dissociated from the restorative technique.

The evolution of adhesive concepts

Former generations of adhesives, making use of hydrophobic monomers which were directly applied on the smear layer, appeared poorly effective and were not able to prevent adhesive failures, despite the inclusion of components providing a potential chemical bond to either the organic or inorganic tooth components (Eliades et al, 1990). In the absence of a hybrid layer, the main problem encountered with all types of tooth-colored restorations was marginal leakage or post-operative sensitivity. This later phenomenon has many known causes such as dentin dehydration, bacterial contamination, thermal injury of the pulp due to preparation, chemical irritation of the pulp (i.e.: in presence of uncured monomers), lack of internal or marginal adaptation and tooth deformation (due to polymerisation shrinkage). While most of potential causes could be eliminated by cautious working conditions and applying the rubber dam, gap formation underneath the restoration, in particular in the occlusal area, proved to be the chief origin of this clinical problem such as suggested by Gysi (1900) and further, by Bränström (1966), who proposed the so called "hydrodynamic theory". This theory, today largely
accepted, considers that liquid micro-movements between the gap and open tubules, due to occlusal forces or temperature changes, result in pain by direct or indirect nerve stimulation. Likewise, post-operative sensitivity is more likely to occur in case of an internal gap (Fig 1.3). Clinicians and researchers then developed different adhesive concepts, which were adapted to the efficacy of the adhesive system.

Selective bonding versus total bonding

The application of base-liners was quite early considered as the best solution to seal dentin underneath tooth-coloured restorations (Wilson & Mc lean, 1985; Lutz et al, 1986). Glass ionomers have been quite successful in this indication; this was the first application of the selective concept (Krejci et Stavridakis, 2000). On the contrary, the total bonding concept (Krejci et Stavridakis, 2000) relies on nature’s example, which did not make available any weak internal interface or free surface. Ideally, a restoration should be perfectly cohesive with the dental tissues, in order to guaranty a biological seal around and underneath the restoration, and as well to provide a uniform distribution of functional stresses in the restoration-tooth system. In their 6 and 10 Year reports, Gaengler and co-workers (1993 and 2001) reported significant proportions of bulk fractures or partial loss of composite material, using a glass-ionomer / composite sandwich technique, which might be attributed to an insufficient restoration support or cohesion with the tooth substrate, likewise some types of bonded ceramic restorations. Therefore, the relevance of every improvement made in the direct application of composite resins following the total bonding concept will be extremely high.

The evolution of restorative techniques

Direct techniques – Incremental techniques

The first attempt to reduce polymerisation shrinkage stress in class II restorations was to apply the composite in several horizontal layers (Lutz and Kull, 1980). As mentioned already, this concept was further developed and implemented by incorporating a glass ionomer base, to reduce the amount of composite to be cured in situ, and as well by applying a more sophisticated layering method, namely "the 3-sited light curing technique" (Lutz & others, 1986a and b). Several alternative incremental methods were still described, such as oblique layering techniques (Weaver & others, 1988; Tjan & others, 1992) or the combination of chemical (as a base) and light curing materials (Bertolotti, 1991). These different methods proved rather helpful to better control polymerisation shrinkage vectors and related stresses. Actually, this reduction in overall stress development is mainly achieved by maximising the free surface (optimal configuration factor), which allows deformation to occur during setting without stress (flow) (Davidson and de Gee, 1984; Lutz & others, 1986a and b; Feilzer & others; 1987). However,
currently, none of these incremental methods allow for a direct composite restoration to be placed without residual stresses in the material, tooth substance and adhesive interface.

In addition to the tensions existing in the tooth-restoration system, further stresses induced by the composite spontaneous post-polymerization (developing over a period of 7 to 10 days following the restoration placement) (Leung et al, 1983; Kidler an Ruyther, 1994) and the masticatory function, have the potential to produce adhesive or even cohesive failures (Dietschi & Krejci, 2001). In consideration also of the diverse composite physical characteristics (i.e.: Elasticity module) we need to better define which combination of material and restorative technique is best indicated for each clinical situation.

The use of direct techniques is anyhow questionable in large cavities with usually a "poor" dentine substrate and, or when the configuration factor is unfavourable (i.e.: adhesive cavity design and class I).

Semi-direct or Indirect techniques

In such unfavourable conditions and in consideration of the stresses, which will further arise due to function and spontaneous post-curing, the relative equilibrium initially achieved through the use of an appropriate and sophisticated layering technique might be disrupted causing adhesive or cohesive failures. Here, the semi-direct or indirect approach appears as feasible alternatives (Blankenau et al, 1984; Mörmann et al, 1982; Dietschi and Holz, 1990; Dietschi et al, 1994). Actually, with inlays and onlays, made either of ceramic or composite, polymerization stresses are restricted to the luting gap. This approach appeared valuable in vitro and in vivo as well (Fülleman, 1986 and 1988; Herder, 1988; Salchow, 1989). In addition, the use of a semi-direct or indirect technique can help to control function and anatomy.

Today, the successful use of tooth coloured restorations certainly relies on proper selection of the restorative material and technique. This implies a thorough understanding of composite properties, in particular their curing mechanism. Moreover, it becomes increasingly important to screen the overwhelming number of publications and to chiefly consider those which are relevant to clinical dentistry and which are in agreement with known and confirmed scientific facts (evidence based dentistry). This paper will present a modern method for evaluating, in-vitro, but in a clinically relevant environment, the potential of different adhesives, restorative materials and application techniques to be used in class II restorations. Updated and innovative clinical guidelines will tentatively be drawn from these different experiments.
Figure 1.1A:

SEM microphotograph showing large macrofiller particles extruding the surface of the composite restoration.

Figure 1.1B:

Intra-oral pictures show the corresponding clinical finding. In addition to insufficient wear resistance, former composite restorations did show marginal discoloration and leakage due to partially defective adhesive systems.
Figure 1.2A:
Direct composite after 17 years of clinical service. There is no sign of marginal discoloration or significant wear.

Figure 1.2B:
Composite inlay after 10 years of clinical service. The lateral view shows that wear of modern composite reins is almost identical to natural enamel.

Fig 1.3: Such gaps, when located on the cavity floor, are frequently responsible for post-operative sensitivity, due to fluid micro-movements between the gap and open tubules.
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