Resin Composites

Sandwich restorations and Curing techniques

Anders Lindberg

Department of Dental Hygienist Education, Faculty of Medicine,
Umeå University, Sweden
2005
“life is a struggle”
Voltaire

To my family
Abstract

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Sandwich restorations and Curing techniques

Anders Lindberg, Department of Dental Hygienist Education, Faculty of Medicine, Umeå University, 901 87 Umeå, Sweden.

Since the mid-1990s resin composite has been used for Class II restorations in stress-bearing areas as an alternative to amalgam. Reasons for this were the patients’ fear of mercury in dental amalgam and a growing demand for aesthetic restorations. During the last decades, the use of new resin composites with more optimized filler loading have resulted in reduced clinical wear. Improved and simplified amphiphilic bonding systems have been introduced. However, one of the main problems with resin composites, its polymerization shrinkage, has not been solved yet. During the polymerization of the resin composites, they shrink as a result of the conversion of the monomers into rigid polymers by a radical addition reaction. The resulting shrinkage stresses in the bonded resin composite restorations may cause adhesive failures at the resin composite/tooth structure interface and/or cohesive failures within the tooth or the resin composite. The interfacial failures may result in post-operative sensitivity, recurrent caries or pulpal injury. This thesis evaluates different restorative and light-curing techniques that are proposed to reduce the polymerization shrinkage and also the effect of new light-curing units, light-emitting diodes (LED) and high-power quartz tungsten halogen (QTH) light on curing depth and degree of conversion of resin composites. Two restorative techniques using a polyacid-modified resin composite or a flowable resin composite in combination with conventional resin composite in sandwich restorations were evaluated in an intraindividual comparison with a conventional resin composite restoration. The durability of the polyacid-modified resin composite sandwich technique was investigated in a three year clinical follow-up study. A scanning electron microscope replica method was used for evaluation of the interfacial adaptation in vivo of both sandwich combinations. The depth of cure of the flowable resin composite was evaluated with the use of Wallace hardness testing. Degree of conversion for resin composite cured with the new LED units was evaluated with Fourier Transform Raman spectroscopy.

Major results and conclusions from the studies are:

- Neither the sandwich restoration with polyacid-modified resin composite nor the flowable resin composite improved the interfacial adaptation of the restorations.
- No difference in durability was found between the sandwich restorations with polyacid-modified resin composite or the resin composite restorations. A low failure rate was observed for both types of restorations after a clinical observation time of three years.
- The depth of cure of the flowable resin composite was higher than the depth of cure of the resin composite. It was found that the curing time of the resin composite studied could be reduced or the increment layer thickness increased compared to earlier recommendations.
- LED curing units of the latest generation were able to cure resin composites to a higher degree of conversion than the control QTH unit.
- The use of soft-start curing did not improve the interfacial adaptation of neither of resin composite restorations tested.

Key words: adaptation, clinical, degree of conversion, depth of cure, flowable, resin composite, restorations, SEM
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Preface

This thesis is based on the following papers. The papers are referred to in the text by their Roman numerals:


IV. **Lindberg A**, Emami-Alagha N, van Dijken JWV. A Fourier Transform Raman spectroscopy analysis of the degree of conversion of a universal hybrid resin composite cured with light-emitting diode curing units. Submitted for publication.


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Introduction

History

At the beginning there was amalgam and nothing but amalgam for the restoration of teeth. (Exaggerated and generalized by the author.)

For more than 200 years amalgam has been used in dentistry and it is still in many ways a suitable restorative material. Its advantages are strength, relatively easy clinical handling and low cost. Disadvantages are lack of adhesive properties to tooth substance and its non-aesthetic character. One of the first aesthetic restorative materials was silicate cement, introduced in 1873 by Thomas Fletcher (1). This cement did not become popular until the early 1900s, when an improved version was introduced. Reasons for the popularity of silicate cements were their superior aesthetic properties compared to amalgam and also their release of fluoride, which prevented secondary caries. Unfortunately, the cement was quite soluble in the oral cavity. Poor mechanical properties limited its use to small cavities, Class III and Class V. Survival time has been reported to be up to 4.5 years (12).

Resin-based materials

Resin-based materials were introduced in dentistry at the end of the 1940s. It did not take many years before their shortcomings became clear, polymerization shrinkage up to 20 - 25%, poor color stability, low stiffness and lack of adhesion to tooth structure. In 1951, Knock and Glenn (58) developed a new type of restorative material, which was supposed to solve the polymerization shrinkage problem, by including inorganic filler particles in the resin. The first versions showed high wear and discoloration, due to absence of coupling agent between the filler particles and the resin matrix.

In the early 1950s, Bjorksten and Yeager (10) published an article concerning a silane coupling compound, which enhanced bonding between ceramic surfaces and resin. The knowledge had earlier been classified by US Air Force.
Bowen, who worked at the National Bureau of Standards in Washington, developed in 1956 the monomer bisphenol A-glycidyl methacrylate (BisGMA) by attaching methylmethacrylate groups to epoxy monomer. Resins containing BisGMA became known as “Bowen’s resins” and resin composites based on BisGMA were introduced in 1962. In 1965 he patented the combination BisGMA resin and silane-treated quartz particles, which is the origin of most resin composites on the market today (12). Together with Buonocore’s (15) publication in 1955 reporting about bonding of resins to etched enamel, a new era started in dentistry. Still it was not until the 1970s that resin composites and enamel etching were generally accepted among dentists and then only as replacement of silicate cements in Class III – V restorations. However, there were still problems with poor marginal adaptation, discoloration and high wear of the materials.

The most common monomers in modern resin composites are BisGMA and urethane dimethacrylate (UDMA). These are large, high-molecular weight molecules with high viscosity. To reduce their viscosity, low viscosity monomers are added, such as methyl methacrylate (MMA), ethylene glycol dimethacrylate (EDMA) and triethylene glycol dimethacrylate (TEGDMA), of which TEGDMA is the most commonly used. A small amount, usually 0.1% or less, of inhibitor is also added to the resin to prevent it from self polymerization. Activator/initiator system are added either for chemically or photo activated curing.

Classification of resin composites

During the 1970s and 1980s the development of new resin composites focused mainly on the size and amount of filler particles. Resin composites were classified in three main groups concerning filler content: macrofilled, microfilled, and hybrid composites (Table 1).

Conventional or macrofilled resin composites had filler particles with a size of 10 – 40 µm and their disadvantages were poor finish and relatively high wear. The most common used fillers in composites were quartz and strontium or barium glass. Quartz filler had good aesthetics and durability but suffered from
absence of radiopacity and high wear of antagonist teeth. Barium and strontium glass particles are radiopaque, but are unfortunately less stable than quartz.

**Microfilled** resin composites were introduced in the late 1970s. They contain colloidal silica filler with a particle size of 0.01 – 0.05 µm. The small size made it possible to polish the resin composite to a smooth surface finish. A problem was to obtain a high filler load. Compared to macrofilled resin composites, the microfilled did not have as good physical properties.

**Hybrid** resin composites were introduced to solve this and the shrinkage problem of resin composites. The first introduced hybrid resin composites contained large filler particles of a size of 15 – 20 µm as well as colloidal silica of a particle size of 0.01 – 0.05 µm.

**Modern hybrid** composites, contain reduced submicron fillers. These composites are supposed to combine the advantages of macrofilled and microfilled composites, but they do not have the final finish or translucency of microfilled resin composites.

**Nanocomposites** are a recent development on the market. They contain filler particles with sizes less than 10 nm (0.01 µm) and are claimed to provide increased aesthetics, strength and durability.

Table 1. Filler sizes and materials in dental composite materials

<table>
<thead>
<tr>
<th>Composite type</th>
<th>Filler size (µm)</th>
<th>Filler material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrofilled</td>
<td>10 – 40</td>
<td>Quartz or glass</td>
</tr>
<tr>
<td>Microfilled</td>
<td>0.01 – 0.1</td>
<td>Colloidal silica</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15 – 20 and 0.01 – 0.05</td>
<td>Glass and colloidal silica</td>
</tr>
<tr>
<td>Modern hybrid</td>
<td>0.5 – 1 and 0.01 – 0.05</td>
<td>Glass, Zirkonia and colloidal silica</td>
</tr>
<tr>
<td>Nanofiller</td>
<td>&lt; 0.01 (10 nm)</td>
<td>Silica or Zirkonia</td>
</tr>
</tbody>
</table>
Other tooth-colored materials for direct use

Another tooth-colored restorative material was introduced in the early 1970s by Wilson and Kent (111). They observed first the acid-base reaction between glass powder and phosphoric acid, which formed a salt and ended up by combining polyacrylic acid with a silicate powder. This was the origin of today’s glass ionomer cements, which showed relatively poor aesthetics because of their opacity, poor physical properties and high solubility in the oral environment. Their advantages were chemical adhesion to enamel and dentin and cariostatic properties due to their rechargeable fluoride property.

In an effort to combine the advantages of glass ionomer cement and resin composite, a new type of material was developed in the late 1980s, modifying the original glass ionomer cement: the resin-modified glass ionomer cement. These materials have two setting mechanisms: a glass ionomer acid-base reaction and a resin light-activated polymerization reaction. The resin-modified glass ionomer cement show better aesthetic properties and is less technique sensible and soluble compared to the conventional glass ionomer cement because of the resin content.

Another material group, the polyacid-modified resin composites, was introduced in 1993. These materials are essentially resin composites, but their glass filler is quite similar to the fluoride-containing glasses used in glass ionomer cement and they are supposed to be able to leach fluoride over time.

The materials mentioned above can be classified on a continuum line according to setting mode with conventionally cured glass ionomer cement to the left and resin composites (RC) to the right (Fig 1). The glass ionomer cement is a result of an acid-base reaction, the resin-modified glass ionomer cement from both an acid-base reaction and the light activation of the resin. In polyacid-modified resin composite the acid base reaction is very slow and low and the cure is mainly a result of the light activation of the resinous part. In resin composites, the setting of the material is based upon a free radical polymerization of monomers.
Glass ionomer cements | Resin-modified glass ionomer cements | Polyacid-modified resin composites | Resin composites

**Figure 1.** Classification of tooth-colored restoratives according to setting mode.

**Bonding of resin composites to enamel and dentin**

Enamel consists of 96% minerals, hydroxyapatite, Ca$_{10}$(PO$_4$)$_6$(OH)$_2$, packed in prisms, 1% organic material and 3% water (72). Buonocore (15) showed that it was possible to bond resin to enamel after etching with phosphoric acid. During etching, about 10 µm of enamel is removed from the surface and a very rough surface with porosities of 25 to 75 µm deep is created. Etching increases the surface area more than 2000 times and improves the surface energy and wettability of the enamel. This allows the resin to penetrate the micro-irregularities and results in the formation of an intimate micromechanical bond between enamel and resin. Buonocore (15) started using 85% phosphoric acid, but subsequent studies have shown that etching with 20 to 50% phosphoric acid creates the best bond strength to enamel (115).

Dentin consists of approximately 70% inorganic material (hydroxyapatite), 20% organic material (mainly collagen) and 10% water (72). It is not homogenous but contains also dentin tubules which traverse its entire thickness. These tubules contain a fluid, which flows from the pulp to the surface and makes dentin hydrophilic. As a consequence bonding of a hydrophobic resin to vital dentin is difficult. In 1982, Nakabayashi et al (70) described the formation of the hybrid layer: penetration of hydrophilic monomers in acid-etched dentin. In 1987, Fusayama (41) introduced the total etch technique, a simultaneous conditioning of the whole cavity. A three-step enamel-dentin bonding system consists of three components.
• A conditioner in the form of an acid (e.g. phosphoric acid, maleic acid, EDTA).
• A primer in the form of bifunctional/amphiphilic monomers in suitable solvent(s). One of the monomers most often used is hydroxyethyl methacrylate (HEMA). The solvents used are acetone, ethanol, water or a mixture of these.
• A sealer or bonding agent, which may consist of a mixture of Bis-GMA and HEMA.

The first step, the conditioner, is used to modify and/or remove the smear-layer and demineralize the surface of the enamel and dentin hydroxyapatite. In the dentin surface the collagenous network is uncovered. The smear layer consists mostly of coagulated proteins and is generally highly contaminated with bacteria and can have different thickness depending on preparation procedure.

The second step, the primer, will penetrate the demineralised enamel and dentin. In the dentin the primer interpenetrates the collagenous network and the outer part of the demineralised dentin tubule walls. Its amphiphilic character makes it possible to bond to both the hydrophilic dentin surface and the hydrophobic sealer or resin composite.

The third step, the sealer or bonding agent, will bond to the hydrophobic part of the primer, together creating the hybrid layer. Dentin tubules will be sealed thereby preventing leakage of bacteria or toxins, and the resin composite is bonded to the tooth tissues.

Modern enamel-dentin bonding systems can be divided into different categories.

• Three-step or two-step etch & rinse systems. In the two-step systems the primer and sealer are combined.
• Two- or one step self-etching systems. In these systems the acidic primers are not rinsed off.

From current research it seems that self-etching systems are not as reliable as the three- and two-step etch & rinse systems (16).
Although bonding to dentin was improving, it was not until mid 1990s that dentin bonding was generally accepted among dentists. Most dental schools in the US claimed that total-etching was harmful to the pulp but this was dismissed by Kanca (55). Gwinnett and Kanca (45) showed that bonding to dentin could be improved if the dentin surface was kept moist during the bonding procedure. Today, total-etch and dentine bonding is a generally accepted concept and the basis of modern operative dentistry. It allows larger resin composite restorations, bonding of ceramic crowns, inlays and veneers as well as minimally invasive dentistry.

**Activation of resin composite**

For the early resin composites, polymerization was initiated by mixing of two pastes. One paste contained an activator, such as a tertiary amine, which was used to split the initiator, usually benzoyl peroxide, which was found in the second paste. In the early 1970s, ultraviolet (UV) light-activated resin composites became available. The UV light, with a wavelength of approximately 365 nm, splits benzoin methyl ether into free radicals, without the presence of tertiary amines, thus starting the polymerization. In this way, only one paste of composite was necessary and polymerization would not start until it was activated by the UV light. Unfortunately, there were some serious drawbacks attached to the UV light-curing systems. Because of the spectral distribution of UV light it may cause damage to the eye and soft tissue burns. The depth of cure achieved with UV light-curing units was limited due to high light absorption in the resin composite. However the benefits of having one paste resin composites, which sets on demand by the curing light, gave rise to the development of visible light activated resin composites. In 1978, Dart et al (21), at ICI (Imperial Chemical Industries) in London, received a patent for the visible light curing of resins. In modern light-cured resin composites, the most common photo initiator is camphoroquinone. It is sensitive to light with a wavelength in the blue range, approximately 420 to 490 nm with a peak at 468 nm. After irradiation, it works as a source of free radicals for the curing process.
Light-curing units

Light-curing units can be divided into different groups according to the light source and/or curing mode used. As mentioned above, the first light source used for resin composite polymerization was **UV light**, which was produced from a mercury discharge lamp. These units were replaced in the early 1980s by the **Quartz**.

**Tungsten Halogen light units (QTH).** In these curing units the bulb is filled with halogen, iodine or bromine gas, and contains a tungsten filament. When connected to an electric current the tungsten filament glows and produces a very powerful white light, which is filtered to the range of blue light (400-500 nm) (69). This matches the sensitivity of the photo-initiator used in the resin composite. Heat generation is a major disadvantage of QTH units and increases with increasing radiation time (99,103). Other drawbacks are limited lifetime of the bulb and degradation of the reflector and filter over time. It has been recommended that a QTH curing unit should deliver a power density of 300-400 mW/cm² to adequately cure a 2 mm increment of resin composite during a 40 s light cure (89).

The visible light units are both cheaper and also less damaging for the eye and tissues compared to UV-light units and for almost 15 years it has been the only light-curing device used in dentistry. In most cases the output of these curing units was less than 500 mW/cm².

In the mid 1990s a new type of high intensity light-curing unit was introduced. In the **plasma arc (PAC)** light unit, the light is generated by high voltage between two tungsten electrodes, separated by a small gap. The resulting spark ionizes the gaseous environment (Xenon) and creates a conductive gas known as plasma. This light curing unit was able to generate power densities more than 2000 mW/cm² and was marketed with recommended curing times of 3 s per increment of resin composite. However later studies showed that the 3 s cure was far too short to obtain a good conversion (77).

The **Argon Laser** has also been proposed as a curing device providing a very high irradiance optimised for initiation of polymerization. Five seconds argon laser exposure resulted in a resin composite cure at 2-mm depth
which was equivalent to that obtained by a 40 s cure with a standard QTH unit (92). A serious drawback with the argon laser was its cost, and argon lasers were not commonly used.

In the late 1990s a new light source was introduced, the light emitting diodes unit (LED). In LED devices, junctions of doped gallium nitride semiconductors (p-n junctions) are subjected to an electric current and blue light is generated. Compared to QTH curing units, LED curing units have a narrower wavelength spectrum and require no filters (54). For most units the spectrum is in the range of 440-490 nm, close to the efficient wavelength for activation of camphoroquinone. The LED curing units have several obvious advantages compared with the QTH units. The diodes have a life-time of more than 10,000 hours compared to the 40–100 hours effective life-time of QTH bulbs, and there is no degrading of bulb, reflector or filter over time which results in reduction of curing effectiveness (91). They produce less heat than the QTH curing units and therefore most of the LED units do not need a fan. The first LED units showed far lower power densities than QTH curing units. The semiconductors were aligned in arrays or small groups of LED’s limited by the surface area of the light guide. In newer generations of LEDs, the conventional diodes have been replaced by large-surfaced emitting LED chips, and power densities up to 900 mW/cm² are now possible (18). A great advantage with LED compared to other light sources is its energy efficiency, i.e. the relation between power input and light output. For QTH the energy efficiency is 0.7%, for PAC 0.2%, for Laser 0.02% and for LED 13% (35). Because of this high energy efficiency of the LED and the absence of a fan, the LED units are not as energy consuming as QTH units. Therefore, they are often battery-operated.

**Light curing techniques**

One of the major problems with resin composite restorations is the effect of polymerization shrinkage and the resulting stress at the interface between restoration and tooth tissue. To reduce the shrinkage and the following
stress, different kinds of curing modes have been proposed. Traditionally the curing mode used has been a **continuous cure** at constant irradiance. In 1995, Feilzer et al (39) showed that the use of high intensity curing light negatively affected the integrity of the restoration-cavity interface. They explained this by the high reaction rate. With low intensity curing light the visco-elastic stage, the period before the gel-point of the composite, is extended. A low intensity will also slow down the rate of conversion and has been reported to result in lower post-gel shrinkage values (110). As a result, so-called **soft-start** curing has been recommended. With this mode the light intensity is low at the beginning of the curing cycle. Then it will either exponentially rise to full during the first half of the curing cycle or stay low for the first half and then be shifted to high for the rest of each curing cycle. **Pulse-curing** or pulse delay curing was proposed by Kanca and Suh (56). With this technique, which is mainly proposed for class I cavities, the last, most occlusal increment of the resin composite is activated with a short pulse of light at rather low irradiance, 100 – 300 mW/cm² for 3 s. This is followed by a pause for 3 – 5 min and then a second pulse cure of greater intensity, 500 – 600 mW/cm², is applied for 30 s. Kanca and Suh (56) showed a reduction in enamel fractures and a general improvement of marginal adaptation for Class I cavities by using this technique in comparison with a continuous cure.

**Factors effecting the degree of cure**

The irradiance of the curing unit, the exposure time, the resin shade, the filler size, the filler load and the distance between the light-tip and the resin composite, all affect the depth of cure (88). As light passes through the bulk of the restoration, its intensity decreases greatly, thus decreasing the curing efficacy and limiting the depth of cure (93). Inadequate cure hampers physical and biological properties of
the resin composite restoration (17,24,108). In certain clinical situations there is unavoidable a distance between the light-tip and the surface of the composite. Price et al (82) have shown that the mean distance of the light-tip to the gingival floor of a Class II molar cavity is 6.3 mm.

Restorative techniques

Another approach which has been proposed to overcome the polymerization shrinkage stress is the use of different restorative techniques. The traditional way to fill the cavity is the horizontal incremental technique (Fig 2). The thickness of each increment of resin composite is not more than 2 mm. Each increment shall be fully polymerized before the next one is inserted into the cavity. Another incremental technique is the oblique incremental technique (Fig 2) introduced to direct the shrinkage stress in the direction of the bonding surface (49). The oblique technique will also reduce the configuration factor (C-factor). The concept of the C-factor was first presented by Feilzer et al (38). The C-factor is the relation between the number of bonded surfaces divided by the number of free, unbonded, surfaces. As the configuration factor increases, the effects of polymerization stress and strain become more significant in the maintaining of the marginal seal. One of the first techniques to reduce shrinkage stress was the “three-sited light-curing technique” proposed by Lutz and Krejci in 1986 (65,66). According to this technique, the polymerization was intended to be guided towards the cervical cavity margins via light-conducting wedges and with a direct curing through the cusps, thought to result in better marginal adaptation.

Resin composites vary with respect to modulus of elasticity and ability to flow during the initial phase of the polymerization process. To combine resin composite with a material with a higher flow may lessen the stress at the interfacial margins. Different kinds of resin composite sandwich restorations have therefore been proposed. In a sandwich restoration the resin composite is replaced in the dentin part of the cavity by another material with lower elastic modulus. A sandwich restoration can either be closed or open. In both the closed and opened
sandwich, the first horizontal layer can be conventional glass ionomer cement, resin-modified glass ionomer cement, polyacid-modified resin composite or flowable resin composite. In the closed sandwich restoration the first layer is completely covered by the resin composite, while in the open sandwich restoration (Fig 2) the first layer reaches the outer cervical margins.

Figure 2. To the left a Class II open sandwich restoration with polyacid-modified resin composite (PMRC) or flowable resin composite (FRC) as first layer covered with resin composite (RC). A horizontal incremental technique is used. To the right, a Class II restoration where an oblique layering technique is used.

Sandwich restorations with conventional glass ionomer cement were introduced in the early 1990s (22,59). The aim was to minimize the effects of the resin composite shrinkage. The technique was especially recommended in high-caries-risk patients because of the continuous fluoride release from the glass ionomer cement. However the technique showed high early clinical failure rates, between 13% and 35% after 2 years and 75% after 6 years (28,107). The main reasons for failure were partial or total dissolution of the conventional glass ionomer cement and fracture of the resin composite part. Modified open sandwich techniques, using a resin-modified glass ionomer cement, polyacid-modified resin composite, or flowable resin composite have been suggested. These materials were also supposed to act as a stress-absorbing barrier in the sandwich technique.
because of their low modulus of elasticity and able to reduce the fracture rate of the restoration, but with less dissolution (3,7,8,57).

Aims

General aim
- To improve the quality of dental resin composite restorations.

Specific aims
- To evaluate the interfacial adaptation of Class II polyacid-modified resin composite/resin composite open sandwich restorations placed in vivo with a quantitative scanning electron microscopic marginal analysis technique (Paper I).
- To evaluate the durability of the polyacid-modified resin composite/resin composite open sandwich restoration and to compare them intra-individually with a direct resin composite restoration for 3 years (Paper II).
- To evaluate the influence of the filler load of a hybrid resin composite on curing depth by comparing the highly loaded restorative version with its less loaded flowable version. To evaluate the effectiveness of six QTH and LED curing units used for different curing times (Paper III).
- To evaluate the degree of conversion of specimens of a universal hybrid resin composite cured with LED curing units of low and high power densities and a 510 mW/cm² quartz tungsten halogen unit, with FT-Raman spectroscopy, at different depths and light tip-resin composite distances (Paper IV).
- To evaluate the interfacial adaptation of Class II flowable resin composite/resin composite open sandwich restorations, cured with three different curing modes (standard, soft-start and high-energy) with a quantitative scanning electron microscopic marginal analysis technique (Paper V).
Materials and methods

Below follows a brief description of the various materials and techniques used in the studies. They are in detail described in respective paper.

Interfacial adaptation of a Class II polyacid-modified resin composite/resin composite laminate restoration in vivo (paper I)

Ten premolars scheduled for extraction for orthodontic reasons were used in the study, which was approved by the Ethics Committee of the University of Umeå. In each tooth a mesial and a distal box-shaped Class II cavity was prepared with a cylindrical diamond bur in a high-speed handpiece with copious water-cooling. No bevels were prepared and all cervical margins were located in enamel. The prepared cavities of each tooth were arbitrarily assigned to one of the two experimental groups, polyacid-modified resin composite/resin composite (Dyract/Tetric Ceram) open sandwich or resin composite (Tetric Ceram) control restoration. The restorations were finished with fine diamond finishing burs followed by the Enhance finishing system. All restorations were made by one operator. After a function time in the mouth of one month, the experimental teeth were extracted, sectioned and prepared for scanning electron microscopic analysis.

Scanning electron microscopy

To allow evaluation of interfacial adaptation, the restorations were sectioned in mesio-distal direction through the middle of the restorations with a low speed diamond disk in a handpiece with copious water spray. The sections were then planed with medium and fine polishing discs under continuous water spray in order to minimize smear layer formation. To remove the smear layer, the sections were slightly etched with 35% phosphoric acid for 3–5 seconds, rinsed with water for 20 seconds and briefly dried. Replica impressions were then made of the buccal and
lingual sections with a polyvinyl silicone impression material. The negative impressions were replicated in epoxy resin to obtain positive casts. The casts were prepared for SEM by mounting on metal stubs and coating with gold by a standard evaporation technique. All interfaces were evaluated with SEM at x200 and x1000 and completed when necessary with other magnifications. The quality of the interfaces and degree of interfacial breakdown were compared to standard microphotographs of marginal degradations and the final evaluations were made double blind on the microphotographs. The quality of the interfacial marginal adaptation was evaluated according to a five-point rating scale with increasing degree of openings and breakdown. Score 1-3 represents acceptable adaptation and score 4 and 5 unacceptable adaptation with crack or gap formation (Table 2). The scoring on the micrographs was performed by two operators separately. Quantitative data were obtained by measuring the length of each evaluation score expressed as percentage of the total length of the examined interface. Fractures in enamel and dentin were also recorded.

**Table 2.** The interfacial adaptation scores.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Good adaptation, no interfacial opening, no deficiencies</td>
</tr>
<tr>
<td>2.</td>
<td>Slight marginal irregularities</td>
</tr>
<tr>
<td>3.</td>
<td>Severe marginal irregularities, no crack visible</td>
</tr>
<tr>
<td>4.</td>
<td>Hairline crack, wider gap with bottom visible</td>
</tr>
<tr>
<td>5.</td>
<td>Severe gap, bottom hardly or not visible</td>
</tr>
</tbody>
</table>
3-year evaluation of a new open sandwich technique in Class II cavities
(paper II)

Fifty-seven patients, selected from the clinical pool at the Public Dental Health Clinic Seminariegatan (Skellefteå, Sweden), who at the yearly examination needed two or four Class II restorations were invited to join the study. No consideration was taken to caries activity, periodontal condition or parafunctional habits. Each patient provided informed consent to participate in the study which was approved by the ethics committee of the University of Umeå. Reasons for placement were primary or secondary caries and replacements of old amalgam restorations. All teeth were in occlusion. Each patient received at least one pair of restorations, which were randomly chosen, a polyacid-modified resin composite/resin composite (Dyract/Tetric Ceram) open sandwich or resin composite (Tetric Ceram) control restoration. The cavities within the pair were chosen to match each other according to location and size. Seventy-five pairs of restorations were placed by two dentists. The restorations were finished with fine diamond finishing burs followed by the Enhance finishing system.

Evaluation

The restorations were evaluated immediately after placement (baseline), and at 6, 12, 24 and 36 months. Each restoration was evaluated with slightly modified USPHS criteria (73,94)(Table 3). Postoperative sensitivity was registered. The dentists were calibrated before start of the evaluation. At different recalls, part of the restorations was evaluated by two dentists without knowledge of earlier assessments. In case of different scores, the restoration was reevaluated and a joint scoring agreed upon. The characteristics of the restorations were described by descriptive statistics using frequency distributions of the scores.
Table 3. Clinical criteria for evaluation of restoration success. Unacceptable scores in *italics.*
(modified USPHS criteria; van Dijken 1986)

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anatomical Form</strong></td>
<td>0</td>
<td>The restoration is continuous with tooth anatomy</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Slightly under- or over-contoured; contact slightly open</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td><em>Undercontoured, dentin or base exposed, contact is faulty,</em> <em>occlusal height reduced, occlusion affected</em></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><em>Restoration is missing partially or totally, tooth fracture,</em> <em>restoration causes pain</em></td>
</tr>
<tr>
<td><strong>Marginal adaptation</strong></td>
<td>0</td>
<td>Restoration is continuous with existing anatomic form, explorer does not catch</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Explorer catches, no crevice is visible into which explorer will penetrate</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Crevice at margin, enamel exposed</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><em>Obvious crevice at margin, dentin or base exposed</em></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td><em>Restoration mobile, fractured or missing</em></td>
</tr>
<tr>
<td><strong>Color match</strong></td>
<td>0</td>
<td>Very good color match</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Good color match</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Slight mismatch in color, shade or translucency</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><em>Obvious mismatch, outside the normal range</em></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td><em>Gross mismatch</em></td>
</tr>
<tr>
<td><strong>Marginal discoloration</strong></td>
<td>0</td>
<td>No discoloration evident</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Slight staining, can be polished away</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Obvious staining cannot be polished away</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><em>Gross staining</em></td>
</tr>
<tr>
<td><strong>Surface roughness</strong></td>
<td>0</td>
<td>Smooth surface</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Slightly rough or pitted</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Rough, cannot be refinished</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td><em>Surface deeply pitted, irregular grooves</em></td>
</tr>
<tr>
<td><strong>Caries</strong></td>
<td>0</td>
<td>No evidence of caries contiguous with the margin of the restoration</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td><em>Caries is evident contiguous with the margin of the restoration</em></td>
</tr>
</tbody>
</table>
Curing depths of a universal hybrid and a flowable resin composite cured with quartz tungsten halogen and light emitting diode units (paper III)

Brass molds with a diameter of 4 mm and a height of 6 mm were used to make resin composite specimens of Tetric Ceram and Tetric Flow, shade A3. The molds were filled and covered with clear Mylar strips on each side and cured from the top. Six different curing units were used in this study, four quartz tungsten halogen (QTH) and two light emitting diode (LED) units. The irradiance of the curing units was determined before start with a radiometer. The curing times, curing modes, and irradiance of the units are shown in Table 4. A distance of 6 mm between the curing light tip and the top surface of the specimen was used in all groups. Five specimens were made in each group. After curing, the molds were stored in air for 24 hours in a light-proof container at room temperature before the specimens were removed. Then the specimens were stored in air at room temperature in light-proof container for 2 weeks until preparation for hardness testing. Each specimen was ground longitudinally until half through the specimen. Hardness was then measured with a Wallace indentation hardness tester for each half millimeter, starting at 0.5 mm from the top surface. The Wallace hardness (Hw) measures the depth of penetration of a Vickers diamond under a predetermined load of 100 g. The Wallace hardness number is thus a measure of softness: the higher the Hw, the softer the material.

For each specimen, a mean Hw value was calculated from the Hw values determined at the depths of 2.0 mm and less (0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, respectively). The depth of cure for each specimen was then found by determining the greatest depth before a Hw value exceeding the minimal Hw value by 25% occurred.
Table 4. Curing units included in the study.

<table>
<thead>
<tr>
<th>Curing unit</th>
<th>Type/Mode</th>
<th>Irradiance (mW/cm²)</th>
<th>Curing time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 2000</td>
<td>QTH/continuous</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Astralis 7</td>
<td>QTH/continuous</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Luxomax</td>
<td>LED/continuous</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Ultralume</td>
<td>LED/continuous</td>
<td>360</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Bisco VIP</td>
<td>QTH/pulse-cure</td>
<td>200 + 600</td>
<td>3 + 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 + 30</td>
</tr>
<tr>
<td>Elipar Trilight</td>
<td>QTH/soft-start</td>
<td>650</td>
<td>40</td>
</tr>
</tbody>
</table>

A Fourier Transform Raman spectroscopy analysis of the degree of conversion of a universal hybrid resin composite cured with light-emitting diode curing units (paper IV)

Specimens were made of the resin composite, Z100 shade A3. Before curing the specimen, a calibration curve was created to verify that a linear relationship existed between aliphatic:aromatic peak ratios and number of unreacted aliphatic groups. From this we assumed that a linear relationship was valid for the Z100. The specimens were made in aluminium rings with inner diameters of 6 mm and heights of 2 and 4 mm. The rings were filled with resin composite, covered with clear Mylar strips on each side, placed on a white surface and cured from the top at room temperature (21-23°C). Five different curing units were used in this study and curing times, curing modes, and irradiance of the units are shown in Table 5. The specimens were cured at a two light-tip resin composite (LT- RC) distances: 0 and
7 mm. After curing, the Mylar strips on the top and the bottom surfaces were removed and the sample was transferred to the FT-Raman spectrometer.

Collection of FT-Raman spectra started 1 min after termination of each curing procedure. FT-Raman spectra were collected on the bottom surfaces of the 2 and 4 mm specimens. Top surface measurements (recorded as 0) were recorded on 4 mm thick specimens. On each cured specimen, one FT-Raman measurement was performed. The aliphatic:aromatic peak ratios were determined from the spectra. The degree of conversion of the cured specimens could then be determined from the FT-Raman spectra by using the calibration curve. The value for degree of conversion for each experimental condition was based on five measurements, each conducted on a separate composite sample in the centre of the sample surface. Totally, 150 measurements were performed.

**Table 5.** Curing units investigated type/mode, irradiance measured by hand held radiometer and curing times.

<table>
<thead>
<tr>
<th>Curing unit</th>
<th>Type/Mode</th>
<th>Irradiance mW/cm²</th>
<th>Curing times (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 400</td>
<td>QTH/continuous</td>
<td>510</td>
<td>40</td>
</tr>
<tr>
<td>Elipar FreeLight</td>
<td>LED/continuous</td>
<td>250</td>
<td>40</td>
</tr>
<tr>
<td>Elipar FreeLight 2</td>
<td>LED/continuous</td>
<td>900</td>
<td>40</td>
</tr>
<tr>
<td>Ultralume 2</td>
<td>LED/continuous</td>
<td>360</td>
<td>40</td>
</tr>
<tr>
<td>LEDemetron</td>
<td>LED/Continuous</td>
<td>800</td>
<td>40</td>
</tr>
</tbody>
</table>
In vivo interfacial adaptation of Class II resin composite restorations with and without a flowable resin composite liner (paper V)

Forty-eight box-shaped Class II restorations were placed by one dentist in 24 sound and caries-free premolars scheduled for extraction for orthodontic reasons. Each patient provided informed and parental consent to participate in the study which was approved by the Ethics Committee of the University of Umeå. In each tooth a mesial and distal box-shaped Class II cavity were prepared with a cylindrical diamond bur in a high-speed hand-piece using copious water-cooling. No bevels were prepared and all margins were placed in enamel. The prepared cavities of each tooth were randomly assigned to one of the two experimental groups: with flowable resin composite liner (Syntac Single-Component/Tetric Flow/Tetric Ceram) or without (Syntac Single-Component/Tetric Ceram). Three curing units with soft start or continuous curing modes and different irradiances were used (Table 6). After one month functioning time the premolars were extracted, sectioned and prepared for scanning electron microscopy (SEM).

**Scanning electron microscopic evaluation**

The scanning electron microscope evaluation of the interfaces of the restorations was performed as described for paper I.

**Table 6.** Curing units, curing modes and curing times used.

<table>
<thead>
<tr>
<th>Curing unit</th>
<th>Type/Mode</th>
<th>Irradiance (mW/cm²)</th>
<th>Curing time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 2000</td>
<td>QTH/continuous</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Astralis 7</td>
<td>QTH/continuous</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Elipar Trilight</td>
<td>QTH/soft-start</td>
<td>650</td>
<td>40</td>
</tr>
</tbody>
</table>

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Statistical analysis

In paper I, the data were statistically analyzed by Mann-Whitney U-test and exact test (Monte Carlo).

In paper II, the data were tested with Wilcoxon signed ranks test and the two techniques were compared intra-individually and tested with the Friedman’s two-way analysis of variance test.

In paper III, normally distributed data with homogeneous standard deviations were analyzed by Student’s t-test, one-way ANOVA and in case of statistical differences by Newman-Keuls’ multiple range test. Remaining data were analyzed by Kruskal-Wallis H-test and by Wilcoxon’s rank sum test. In the latter case, adjustments were made for the numerous pair-wise comparisons by the Bonferroni method.

In paper IV, the data were analyzed by Mann-Whitney U-test and exact test (Monte Carlo).

In paper V, the data were analyzed by Mann-Whitney U-test and exact test (Monte Carlo). Difference between gap free scores for occlusal enamel, cervical enamel and dentin for both groups were tested with Wilcoxon signed ranks test and exact test (Monte Carlo).

Results

Interfacial adaptation of a Class II polyacid-modified resin composite/resin composite laminate restoration in vivo (paper I)

The scores of the interfacial quality evaluation of the cervical enamel, dentin and occlusal enamel are shown in Table 7. Gap-free adaptation (score 1-3) to the cervical enamel was observed in 97% for the open sandwich and in 73% for the direct resin composite restorations. For dentin, the corresponding scores were 87% and 64% (Fig 3-4) and for occlusal enamel 98.8% and 100%. The differences in
scores between the two restorative groups were not statistically significant. In the
direct resin composite group the adaptation to occlusal enamel was significantly
better than the adaptation to dentin and to cervical enamel (p < 0.01). No
significant differences were found in the open sandwich group between the
adaptation to enamel and dentin. Openings and areas with good adaptation were
found adjacent to each other (Fig 5). The dentin interfacial failures were in almost
all cases found between the hybrid layer and the resin composite. Tag formation in
the dentin tubules was frequently observed (Fig 6). Enamel fractures parallel to
the margins were observed with a mean value of 8.7%. The cervical margins
showed a higher fracture rate than the occlusal margins. No dentin fractures were
observed in the two studied groups.

Table 7. Interfacial adaptation scores for the Class II open sandwich polyacid-modified resin
composite/resin composite and conventional resin composite restorations determined as
percentages of the margins examined (%).

<table>
<thead>
<tr>
<th>Scores</th>
<th>Group</th>
<th>No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Fractures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Cervical enamel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open sandwich</td>
<td></td>
<td>9</td>
<td>96.9</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>2.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Direct composite</td>
<td></td>
<td>10</td>
<td>69.6</td>
<td>3.1</td>
<td>1.7</td>
<td>25.6</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Dentin</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open sandwich</td>
<td></td>
<td>10</td>
<td>82.9</td>
<td>2.8</td>
<td>1.0</td>
<td>7.5</td>
<td>5.9</td>
<td>-</td>
</tr>
<tr>
<td>Direct composite</td>
<td></td>
<td>10</td>
<td>53.6</td>
<td>6.5</td>
<td>3.6</td>
<td>8.7</td>
<td>27.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><strong>Occlusal enamel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open sandwich</td>
<td></td>
<td>10</td>
<td>98.8</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>1.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Direct composite</td>
<td></td>
<td>10</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.1</td>
</tr>
</tbody>
</table>
**Fig 3.** Excellent interfacial adaptation in the dentin.
Original magnification x200.

**Fig 4.** Higher magnification of the interfacial adaptation shown in Fig 3. Original magnification x1000.
**Fig 5.** Gap formation and areas with good adaptation adjacent to each other. Original magnification x1000.

**Fig 6.** Excellent interfacial adaptation in the dentin with long tags in the dentinal tubule. Original magnification x1000.
3-year evaluation of a new open sandwich technique in Class II cavities
(paper II)

Of fifty-seven patients with 75 pairs of restorations participating in the study, fifty-six with 73 pairs of restorations were evaluated during the 3-year follow-up. The cumulative failure frequency for the polyacid modified resin composite/resin composite and the resin composite was 2.7% and 4.1% respectively, resulting in a total failure frequency of 3.3%. There was no statistical difference between the two groups. Reasons for failure were: One tooth with evaluated restorations in each group developed pulpitis. Both cavities were of large size and the tooth in the resin composite group had symptoms before the restoration was placed. One resin composite restoration in a bruxing patient showed a fracture at 36 months. Secondary caries was observed contiguous to one restoration in each group at the 36 months recall. The caries activity estimation performed showed that 51.7% of the patients were regarded as high-caries-risk patients. No loss of retention was observed during the 3 years. No significant difference was seen between the groups at the different recalls. For marginal adaptation a significant change occurred after 6 months in both groups (baseline vs 6months, p = 0.013; baseline vs 3years, p = 0.000) and for marginal discoloration after 6 months in the sandwich group (baseline vs 6months, p = 0.025; baseline vs 3years, p = 0.001) and after 36 months in the RC-group (p = 0.008). A significant difference in color match was observed in both groups after 24 months (p = 0.018). All these changes were in the acceptable range. Over all, there were only small changes over time in both groups. Except for the patients with pulpitis, none of the other patients reported post-operative sensitivity.
Curing depths of a universal hybrid and a flowable resin composite cured with quartz tungsten halogen and light emitting diode units (paper III)

The curing depths are given in Table 8. Generally, prolonged curing yielded higher values of depth of cure, but statistically significant differences between the mean values were found only in five out of the ten cases. However, a statistical analysis of the increases in depth of cure obtained as a result of prolonged curing showed that prolonged curing significantly increased the depth of cure ($p < 0.0005$). Generally, a higher depth of cure values was obtained with Tetric Flow than with Tetric Ceram, but statistically significant differences between the mean values were found only in one out of the eleven cases. A statistical analysis of the differences in depth of cure between the two materials showed that Tetric Flow yielded significantly higher depth of cure values than Tetric Ceram ($p < 0.0005$).

In order to compare the curing units, the curing times of $3 + 10$ s and of $3 + 30$ s for the Bisco VIP curing unit, were compared with curing times of the other curing units of 20 s and 40 s, respectively. At a curing time of 20 s, the curing units fell into three groups: Luxomax resulted in the significant lowest depth of cure, Demetron 2000, Ultralume, and Bisco VIP, yielded higher and statistically similar depths of cure, and Astralis 7 yielded the significantly highest depth of cure. At a curing time of 40 s, Luxomax resulted in significantly lower depth of cure than all curing units except Demetron 2000, and Astralis 7 yielded significantly higher depth of cure than did Luxomax and Demetron 2000. At both curing times, a significant linear correlation was found between the determined irradiances of the curing units and the pooled depth of cure values obtained (20 s: $r = 0.89$, $p < 0.025$; 40 s: $r = 0.91$, $p < 0.01$).
Table 8. Depth of cure. For each curing unit separately, depth of cure values characterized by same letter are not statistically different at $p \leq 0.05$.

<table>
<thead>
<tr>
<th>Depth of cure (mm)</th>
<th>mean ± sd</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 2000, 20 s, Tetric Ceram</td>
<td>2.7 ± 0.27</td>
<td>A</td>
</tr>
<tr>
<td>Demetron 2000, 20 s, Tetric Flow</td>
<td>2.8 ± 0.27</td>
<td>A</td>
</tr>
<tr>
<td>Demetron 2000, 40 s, Tetric Ceram</td>
<td>3.4 ± 0.42</td>
<td>AB</td>
</tr>
<tr>
<td>Demetron 2000, 40 s, Tetric Flow</td>
<td>3.8 ± 0.27</td>
<td>B</td>
</tr>
<tr>
<td>Luxomax, 20 s, Tetric Ceram</td>
<td>2.1 ± 0.22</td>
<td>A</td>
</tr>
<tr>
<td>Luxomax, 20 s, Tetric Flow</td>
<td>2.4 ± 0.22</td>
<td>A</td>
</tr>
<tr>
<td>Luxomax, 40 s, Tetric Ceram</td>
<td>3.0 ± 0.00</td>
<td>B</td>
</tr>
<tr>
<td>Luxomax, 40 s, Tetric Flow</td>
<td>3.2 ± 0.27</td>
<td>B</td>
</tr>
<tr>
<td>Bisco VIP, 3+10 s, Tetric Ceram</td>
<td>3.0 ± 0.00</td>
<td>A</td>
</tr>
<tr>
<td>Bisco VIP, 3+10 s, Tetric Flow</td>
<td>3.1 ± 0.55</td>
<td>AB</td>
</tr>
<tr>
<td>Bisco VIP, 3+30 s, Tetric Ceram</td>
<td>3.9 ± 0.42</td>
<td>BC</td>
</tr>
<tr>
<td>Bisco VIP, 3+30 s, Tetric Flow</td>
<td>4.5 ± 0.00</td>
<td>C</td>
</tr>
<tr>
<td>Astralis 7, 20 s, Tetric Ceram</td>
<td>3.5 ± 0.50</td>
<td>A</td>
</tr>
<tr>
<td>Astralis 7, 20 s, Tetric Flow</td>
<td>3.9 ± 0.42</td>
<td>A</td>
</tr>
<tr>
<td>Astralis 7, 40 s, Tetric Ceram</td>
<td>4.3 ± 0.27</td>
<td>A</td>
</tr>
<tr>
<td>Astralis 7, 40 s, Tetric Flow</td>
<td>4.7 ± 0.45</td>
<td>A</td>
</tr>
<tr>
<td>Ultralume, 20 s, Tetric Ceram</td>
<td>2.8 ± 0.27</td>
<td>A</td>
</tr>
<tr>
<td>Ultralume, 20 s, Tetric Flow</td>
<td>3.1 ± 0.22</td>
<td>AB</td>
</tr>
<tr>
<td>Ultralume, 40 s, Tetric Ceram</td>
<td>3.5 ± 0.35</td>
<td>AB</td>
</tr>
<tr>
<td>Ultralume, 40 s, Tetric Flow</td>
<td>4.2 ± 0.27</td>
<td>B</td>
</tr>
<tr>
<td>Elipar Trilight, 40 s, Tetric Ceram</td>
<td>3.8 ± 0.27</td>
<td>A</td>
</tr>
<tr>
<td>Elipar Trilight, 40 s, Tetric Flow</td>
<td>4.5 ± 0.00</td>
<td>B</td>
</tr>
</tbody>
</table>
A Fourier Transform Raman spectroscopy analysis of the degree of conversion of a universal hybrid resin composite cured with light-emitting diode curing units (paper IV)

Table 9 shows the degree of conversion values for both 0 and 7 mm light-tip - resin composite distances at depths of 0, 2 and 4 mm depth levels. Zero (0) represents the top surface of the specimens, 2 represent the bottom of the 2 mm specimens, and 4 represent the bottom of the 4 mm specimens. The Elipar FreeLight showed a significantly lower degree of conversion for both light-tip – resin composite distances at all depths compared to the other curing units (p < 0.05). Significant differences between the other curing units were only found at the 4 mm depth level with a 7 mm light guide tip-resin composite distance: Demetron 400 versus Elipar FreeLight 2 and LEDemetron; and Ultralume 2 versus Elipar FreeLight 2 and LEDemetron (p < 0.05). Significant differences for the individual curing units between the top surface and the increasing depth levels were found for the Elipar FreeLight at 4 mm depth and for Ultralume at 2 and 4 mm depths when cured with a light-tip – resin composite distance of 7 mm (p < 0.05).

The conversion ratios of the DC value at 4 mm depth with a light-tip – resin composite distance of 7 mm for each curing unit compared with the highest conversion found at 0 mm depth and 0 mm light-tip – resin composite distance (LEDemetron 0/0) are shown in Table 10. These indicate the decrease in degree of conversion for each unit compared to the most optimal value measured. The effect of the light- tip – resin composite distance is shown in Table 11. The reduction in degree of conversion was ≤ 9% when the light-tip – resin composite distance was increased from 0 to 7 mm.
**Table 9.** Degree of conversion in percent (mean) for the Z100 specimens cured with a 0 mm or 7 mm light-tip - resin composite distance on top surface (0) and at 2 and 4 mm depths.

<table>
<thead>
<tr>
<th>Distance/depth level (mm)</th>
<th>0/0</th>
<th>0/2</th>
<th>0/4</th>
<th>7/0</th>
<th>7/2</th>
<th>7/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 400</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Elipar FreeLight</td>
<td>58.8</td>
<td>56.3</td>
<td>53.8</td>
<td>56.6</td>
<td>55.1</td>
<td>52.5</td>
</tr>
<tr>
<td>Elipar FreeLight 2</td>
<td>53.8</td>
<td>52.5</td>
<td>50.8</td>
<td>52.3</td>
<td>50.4</td>
<td>46.4</td>
</tr>
<tr>
<td>Ultralume</td>
<td>58.5</td>
<td>56.4</td>
<td>55.7</td>
<td>58.2</td>
<td>56.1</td>
<td>54.6</td>
</tr>
<tr>
<td>LEDemetron</td>
<td>59.0</td>
<td>57.9</td>
<td>55.3</td>
<td>57.5</td>
<td>56.0</td>
<td>52.0</td>
</tr>
</tbody>
</table>

**Table 10.** Conversion ratios (C ratio), for the highest measured degree of conversion value (=LEDemetron 0/0), related to degree of conversion for each curing unit observed at 4 mm level using a light tip - resin composite (LT – RC) distance of 7 mm.

<table>
<thead>
<tr>
<th>Curing unit</th>
<th>LT-RC Distance / mm</th>
<th>C ratio: 4 mm depth compared with 0mm (LEDemetron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demetron 400</td>
<td>7</td>
<td>0.87</td>
</tr>
<tr>
<td>Elipar FreeLight</td>
<td>7</td>
<td>0.77</td>
</tr>
<tr>
<td>Elipar FreeLight 2</td>
<td>7</td>
<td>0.91</td>
</tr>
<tr>
<td>Ultralume 2</td>
<td>7</td>
<td>0.88</td>
</tr>
<tr>
<td>LEDemetron</td>
<td>7</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Table 11. Influence of light-tip - resin composite distance for the curing units. Conversion ratios for degree of conversion values at 7 mm light-tip – resin composite distance compared to direct contact degree of conversion values at the different depth values (0, 2 and 4 mm) for each light curing unit.

<table>
<thead>
<tr>
<th>Distance(mm)/depth (mm)</th>
<th>7/0 : 0/0</th>
<th>7/2 : 0/2</th>
<th>7/4 : 0/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elipar FreeLight</td>
<td>0.97</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>Demetron 400</td>
<td>0.96</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>Elipar FreeLight 2</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>Ultralume 2</td>
<td>0.97</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>LEDemetron</td>
<td>0.98</td>
<td>0.99</td>
<td>0.97</td>
</tr>
</tbody>
</table>

In vivo interfacial adaptation of Class II resin composite restorations with and without a flowable resin composite liner (paper V)

Interfacial adaptation was evaluated for all restorations with flowable resin composite liner (FRC) and without liner (TRC) (Fig 7-10). Gap-free adaptation to the cervical enamel (CE) was observed in 96.2% for FRC and in 90.2% for TRC. For the dentin (D) the corresponding percentages were 63.6% and 64.9% respectively and for occlusal enamel (OE) 99.7% and 99.5%. The difference between the two restoration groups was not statistically significant. Significant better adaptation was observed to OE than CE and D (p < 0.01), and to CE than D (p < 0.01). Gap free adaptation with the soft start, 500 and 700 mW/cm² continuous curing modes, respectively, was observed to CE: 88.7%, 92.7%, 97.9% (ns); OE: 99.8%, 98.7%, 100% (ns); and D: 64.0%, 63.9%, and 64.6% (ns). The gap free scores to occlusal enamel (OE) for both groups were statistically significant better than to cervical enamel and dentin, OE > CE > D (p < 0.01). Cervical enamel fractures parallel to the margins were observed in 21.7% for the FRC group and 20.8% for the TRC (Fig 11). For the occlusal enamel the values were 2.4% for both groups. No dentin fractures were observed.
Figure 7. Excellent interfacial adaptation to the occlusal enamel part of a resin composite restoration. Original magnification x200.

Figure 8. Higher magnification of Fig 7. Original magnification x1000.
Figure 9. Gap formation to the dentin part of a resin composite restoration. Original magnification x200.

Figure 10. Good interfacial adaptation to dentin in a resin composite restoration. Long tags can be observed in dentin tubules. Original magnification x1000.
Discussion

Resin composite restorations have been used in dental practice regularly since the 1970s. For the first decade they were predominantly used instead of silicate cement for Class III, IV and V cavities. Since the mid 1990s, they have also been used in stress-bearing posterior areas, i.e. for Class I and Class II restorations. This was a result of the patient’s fear for mercury in dental amalgam and their demand of aesthetic, tooth-colored restorations, but also as a result of the introduction of better functioning dentin bonding systems and improved resin composites. New filler types, reduced filler sizes and increased filler loading resulted in reduced wear of the restoration (113,114). The bonding systems became amphiphilic and better suitable for the wet dentin substrate. Recent bonding systems are simplified and easier to handle for the dentist (104). Still there is one important problem that not has been solved yet. During polymerization of resin composites, the resin part shrinks as a result of monomer conversion into a rigid polymer by a radical addition reaction. This results in a shrinkage stress in the bonded resin composite.
restoration, which may weaken or disturb the interfacial adaptation (24). The largest stress is generated directly during curing and before the maximal strength of the bonding system to the cavity walls is established. Chewing forces will further stress the bonding surface (23). Marginal and interfacial integrity is crucially important for the durability of a restoration. Adhesive failures may cause hypersensitivity, recurrent caries and pulpal injury (14). Hodges et al (50) studied the relation between gap width and recurrent caries in occlusal margins of amalgam restorations and found a direct correlation. This may also be valid for resin composite restorations. However, others were not able to show a good correlation.

The conventional way to restore a cavity with resin composite has been by using the horizontal incremental technique. Each increment should not exceed 2 mm and it should be light-cured for at least 40 s. It has been stated that the resin composite shrinks towards the light and for curing the first layer in a deep cavity the curing time has to be increased because the light intensity drops with the inverse square of the distance between the light source and the resin (72). Versluis et al (109) questioned the statement that an incremental restoration technique reduces the stress caused by composite shrinkage. Simulated stress fields in a tooth restored using different incremental techniques were studied with a finite element analysis method. Their analysis showed that in a restoration with a good bond to the cavity the incremental restoration techniques increased deformation of the restored tooth as a result of the volumetric contraction of the resin composite during polymerization. This was explained by a shrinkage deformation of the cavity walls caused by each individual increment layer, which all together decreases the size of the cavity during the filling process.

The shrinkage of resin composite towards the light has been studied by Versluis et al (110) and Asmussen and Peutzfeldt (5). Versluis et al used a finite element technique and concluded that resin composite does not shrink toward the light, but that the direction is predominantly determined by the shape of the cavity and the bond quality of the resin composite to the tooth tissues. Asmussen and Peutzfeldt concluded that the direction of shrinkage is a result of the interplay
between the direction of the light, the bonding and the thickness of the resin composite.

Different curing and restoration techniques have been proposed to reduce the shrinkage stress. Among these are light-curing techniques, such as three-sited curing technique, soft-start and pulse-curing, and incremental oblique insertion and different sandwich restorations. Lösche (64), however, showed that the effect of three-sited light-curing technique was not attributed to the guided polymerization but more to the reduction of light intensity. In general, a more rapid polymerization and a higher degree of conversion will result in increased shrinkage stress. A reduced initial irradiance as in soft-start and pulse-cure techniques has been suggested to result in a slower development of stiffness of resin composite and prolong the compensating flow during polymerization (39, 56, 106).

It has been shown that resins with low modulus of elasticity, when used in a thin layer as a liner in combination with resin composite, reduced the formation of cervical gaps and marginal leakage (57). In studies I and II, a polyacid-modified resin composite was used in an open sandwich restoration with a universal resin composite. Since polyacid-modified resin composite include resins with a modulus of elasticity value lower than those of resin composite (7), the material applied as a bottom layer, may work as a stress-absorbing barrier between the tooth and the resin composite. The higher water sorption of the polyacid-modified resin composite may result in improved adaptation and in combination with its fluoride release may prevent secondary caries (68). In study V, a flowable resin composite was used with the same purpose. Because of its lower modulus of elasticity (6), the flowable resin composite has also been proposed for open sandwich restorations (19, 32, 78).

Marginal integrity and interfacial adaptation is mostly studied with dye microleakage tests. These tests, using extracted teeth, are relatively easy and cheap to perform (100). The technique is difficult to standardize, and the large standard deviations make this test method difficult to interpretate (30). Roulet (87) argued that although the marginal integrity of restorations is an important parameter, because marginal gap formation is associated with recurrent caries and
pulpal disease, both in vitro and in vivo testing have severe limitations, and the scientific community have to accept that materials will be misjudged during evaluation processes. In papers I and V, the interfacial adaptation was studied with a SEM replica technique, another method widely used to evaluate marginal and interfacial adaptation. Direct observation by SEM is difficult due to the presence of the liquid phase in the tooth tissues. The vacuum procedure used during microscopy causes artifacts, such as cracks, if the liquid is not removed in a proper way. These may resemble true gap-formation (75). By using a replica method, artificial gap-formation can be avoided. Grundy showed a high degree of agreement comparing directly by SEM observed specimens with replica models (43). Teeth planned to be extracted for orthodontic reasons were used in study I and V. These make it possible to study marginal and interfacial adaptation of restorations after different functioning times in situ (25). The SEM-analysis used is both qualitative and quantitative. A similar method has been described earlier by Roulet et al (86) and has also been used in several earlier published in vivo investigations (29). The quality of the interfacial border between the restoration and the tooth structures was analyzed according to an ordinal scale with increasing degree of marginal deficiencies. Since the scoring system is dependent on the operator’s degree of reproducibility, calibration between and within the authors was regularly performed. The inter-examiner reliability gave a kappa value of 0.77. The qualitative and quantitative character of the analysis is represented by different scores measured on a SEM-picture and transformed to percentages of the total length measured.

Friedl et al (40) studied in vitro the same restorations as those investigated in studies I and II. They obtained no differences in dentin marginal adaptation and a slightly, but not significantly, improved enamel marginal adaptation for the resin composite restoration compared with the sandwich restoration. This was also confirmed in study I, which showed no statistical significant difference in interfacial adaptation between the two techniques studied. There may be different reasons for this.

- Significance could not be obtained due to insufficient sample size.
The functioning time was too short for the difference to become significant. Meyer (68) stated that the polyacid-modified resin composite (PMRC) absorbs water for a long time and that hygroscopic expansion will continue. As an example, Dyract showed a volumetric expansion of 2% after 5 months of immersion in water.

Earlier studies of open sandwich restorations with GIC showed improved marginal adaptation but a high clinical failure rate due to a continuous erosion loss of the GIC (28,59). In study II the durability of the PMRC/RC open sandwich restoration was compared intra-individually to a direct RC restoration in a clinical 3 years study. The intra-individual design was chosen to eliminate patient variability. At the three-year recall all but one patient showed up, resulting in a recall rate of 98.6%. The cumulative failure frequency was 2.7% for the PMRC/RC and 4.1% for the RC There was no statistical difference between the groups. The caries activity estimation performed showed that 51.7% of the patients were regarded as high caries risk patients. Rasmusson et al (85) investigated restorations of six different resin composite resins and showed a 14% cumulative failure rate at the 5 years recall, while Köhler et al (62) showed 28% failures after 5 years. The main reasons for failures were secondary caries, fractures and poor marginal adaptation. Their restorations were made with earlier types of composites and dentin bonding systems. Geurtsen and Schoeler (42) placed 1209 Class I and II restorations, also with an inferior dentin bonding system, and evaluated 234 restorations after 4 years. They showed a 13 % failure rate. Only few clinical evaluations have been performed with newer amphiphilic dentin bonding systems. Perry et al (76) evaluated 50 Class II restorations of the same composite as in the study in paper I and II. After 2 years, only 29 of the 50 restorations could be evaluated. No failures were reported. Schoch et al (98) investigated the same resin composite as that used in study I and II, but with a different bonding system, in Class II cavities. They concluded after a one year follow-up that the material displayed good clinical durability. Wucher et al (112) evaluated Dyract, Spectrum-TPH and a sandwich combination in which Dyract was covered by the resin
composite TPH in Class II restorations in 23 patients. At the 3-year recall the restorations of 20 patients were evaluated, and it was concluded that all three types of restorations performed well clinically. No post-operative sensitivity was reported by the patients, indicating proper bonding and sealing. Only one Dyract/TPH sandwich restoration had to be replaced after 2.5 years due to root caries. The Dyract restorations exhibited significantly more occlusal wear than the TPH and the Dyract/TPH sandwiched restorations. The marginal integrity was also found to be significantly better for the TPH and Dyract/TPH restorations compared to Dyract restorations, while no significant difference could be demonstrated between TPH and Dyract/TPH restorations. The authors concluded that the low failure rate suggested that Dyract and TPH are reliable restorative materials for use in permanent Class II cavities and the results confirm those of the study II.

There is a great need of long-term clinical trials of resin composite restorations. In view of the modifications and expected improvements in resin composites and dentin-bonding systems a follow-up time of three years is too short to allow discrimination between various materials and restorative techniques. For amalgam failure rates between 15 – 17 % have been reported after 13 – 15 years (44,63,60), and we also need these kinds of follow-up times for modern resin composites and bonding systems. In 1999, Raskin et al (84) published a clinical study where they evaluated 100 Class I and II resin composite restorations (Occlusin) after 10 years. At the 10-years recall only 37 restorations were reviewed and the failure rate was estimated to be between 40 and 50%. van Dijken (31) compared resin composite inlays (Brilliant) with direct placed resin composite restorations (Fulfil). Thirty-seven of the original forty patients attended the 11-year recall. van Dijken showed a failure rate of 17.7% for the inlays and 27.3% for the resin composite restorations. Pallesen and Qvist (74) compared five different inlays and direct resin composite restorations (Brilliant Dentin, Estilux Posterior, SR-Isosit). After 11 years, 27 of the original 28 patients were examined. The failure rate was 16% for the direct restorations and 17% for the inlays.
The fact that only few long-time follow-ups of resin composite restorations have been published reflects the problems with clinical longitudinal studies.

- It is difficult to “keep” the number of drop-outs low. The higher the drop-out frequency, the more difficult it is to draw conclusions.
- After a long term follow-up, the investigated materials are seldomly still on the market but have been replaced.

Still, a clinical follow-up is the final test for a restorative system.

At the Portland Composites symposium Sakaguchi (96) discussed whether controlled clinical studies of posterior composites are truly representative of practice-based performance and the inherent variability between clinicians. At the same symposium, Sarrett (97) asked for more hypothesis-driven clinical research to define clinical relevance of laboratory tests. There seems to be a symbiotic relationship between the laboratory and the clinical research. To be able to perform good clinical studies there have to be good laboratory research to base the studies on. But the laboratory results can’t stand alone without have been proven clinically.

Adequate curing of resin composite is crucial for the performance of the resulting restorations. A lot of research has been done to show how physical properties and biocompatibility are affected by the degree of conversion (4,71). Caughman et al (17) showed a significant correlation between degree of conversion and cellular toxicity of resin composites: The higher degree of conversion, the lower the cellular toxicity. On the other hand a higher degree of conversion also results in increased shrinkage (90). Adaptation studies which do not report how the restorations were cured are therefore of low value. Good adaptation could be caused by low degree of conversion of the resin composite. Several in vitro studies have investigated the effect of the use of a flowable resin composite liner on marginal seal of resin composite restorations, but the results are contradictory (9,19,20,37,53,78). In study III, a universal resin composite was compared with its flowable version from a depth of cure point of view. A light-tip – resin composite distance of 6 mm was used in order to imitate curing of the bottom layer in a Class
II cavity. The results showed that Tetric Flow yielded statistically significantly higher depth of cure than Tetric Ceram. This may be explained by the higher filler content in the universal version of the resin composite, which results in an increased scattering of the light (93). It can be assumed that the results are applicable for all combinations of universal/flowable resin composites.

Rueggeberg et al. (89) recommended that increments not thicker than 2 mm should be used when a resin composite is cured for 60 s with a QTH unit. Prati et al (80) discussed what happens in a clinical situation when a 2 mm increment is inserted in an 8 mm deep cavity. Considering the reduction of irradiance through air and through resin composite they estimated that only 4% of initial irradiance will reach the deeper layer of resin composite placed in contact with the dentin walls. Their results were in contrast with the results in study III. All the curing units used in the present study were able to cure more than the recommended 2 mm, despite a light tip distance of 6 mm and a curing time of 20 s. For a curing time of 20 s the depth of cure was found to vary between 2.1 and 3.9 mm and for a curing time of 40 s between 3.0 and 4.7 mm.

Both LED curing units studied in paper III showed irradiances that were lower, as measured by the hand-held radiometer, compared to the QTH units. The LED Ultralume and the QTH Demetron 2000 units differed by 140 mW/cm², but showed depths of cure of similar magnitude. This is in agreement with the findings of Hofmann et al (51) and may be explained by the fact that the higher irradiance registered for the QTH unit includes spectral ranges that do not activate camphorquinone (61). Still there was a statistically significant linear correlation at both curing times, between the determined irradiances of the curing units and the pooled depth of cure values obtained. It has to be emphasized that the depth of cure results of study III is applicable for the curing units and the resin composites used in this study and can not be assumed to apply to all kinds of light-curing units and all brands and shades of resin composite. This was corroborated by Price et al (83) who showed that depth of cure values differ for different brands of resin composites when cured with the same curing unit.
In study IV the degree of conversion, of a universal hybrid resin composite cured with LED curing units of low and high irradiance irrespectively and with a 510 mW/cm² QTH unit, was investigated with Fourier Transform Raman (FT-Raman) spectroscopy. Three curing depths (0, 2, 4 mm) and two (0 and 7 mm) light-tip – resin composite distances were tested. FT-Raman spectroscopy was chosen since it is possible to make the measurements directly on the resin composite specimen. By FTIR analysis, conversion is measured on a thin film of resin composite, 50 – 70 µm, produced between Mylar strips (46). To simulate different depths of the resin composite, pre-cured wafers of different thickness and of the same resin composite have to be positioned between the Mylar strip, covering the thin film of uncured resin composite, and the light guide of the curing unit. Using FTIR, Hackman et al (46) studied the degree of conversion of Z100 cured with a QTH curing unit (600 mW/cm²) according to curing modes. Following a 40 s cure they measured a 54% degree of conversion at top of the specimen and 46% at a depth of 2 mm. These values can be compared with the degree of conversion found in the present study with the QTH Demetron 400 (510 mW/cm²) of 58.8% on the top surface and 53.3% at 2 mm. The decrease of degree of conversion between top surface and 2 mm depth in Hackman et al’s study was 14.8% compared to our 9%. The difference may be caused by differences between batches of the resin composite, between ways of measuring the irradiance and/or between the methods used to simulate a depth of 2 mm.

To get as high energy as possible it is recommended that the light guide tip is placed close to the surface of the restoration during curing. In the clinical situation this will not always be achievable, especially when curing material in deeper parts of Class II cavities. Price et al (81), showed that the mean distance of the light guide tip to the gingival floor of Class II molar cavities was 6.3 mm. Harrington et al reported (47) that the irradiance at the resin composite surface decreased to approximately 1/3 when the light-tip was moved from being in contact with the resin composite to a distance of 7 mm. Consequently we evaluated light-tip – resin composite distances of 0 and 7 mm. Meyer et al (69) found that the LED Elipar FreeLight decreased 83% in irradiance when used at a distance of 10
mm from the radiometer, while the QTH Optilux decreased only 44%. The authors expressed concern about the use of LED units in long light-tip – resin composite distance situations. In this study the Elipar FreeLight showed significantly lower degree of conversion than the control Demetron 400 QTH unit. The Elipar FreeLight, in contrast to the other investigated LED devices, belongs to an earlier generation of LED units with low irradiance. The newer LED units evaluated showed equal or higher degree of conversion than the control QTH unit.

Depth of cure can be determined in different ways. One way is described in ISO 4049. With this method, a sample of resin composite is made in a stainless steel mold and is cured from one side. Then the sample is removed from the mold and the soft uncured material at the bottom of the sample is gently scraped off with a plastic spatula. The length of the remaining, cured material divided by 2 is the depth of cure. Another way of estimating depth of cure was used in study III, where we used a 25% decrease in hardness as a threshold value for determination of depth of cure.

A common way to calculate depth of cure is by measuring hardness on the top and bottom surfaces of resin composite samples. In 1992, Pilo and Cardash (79), suggested that the ratio between hardness on the top surface and hardness on the bottom surface of a resin composite specimen should be 0.8 – 0.9 for an acceptable cure of resin composite. The 0.8 ratio value has also been used by other authors, i.e. Ernst (36) and Price al (83). Bouschlicher et al (11), studied the relation between hardness ratio and degree of conversion ratios and found that the hardness ratio of 0.80 corresponded to a degree of conversion ratio of 0.90. Soh et al (102) investigated the effectiveness of two LED units. They calculated a hardness ratio of 0.97 of a 2 mm thick Z100 specimen after cure with the Elipar FreeLight for 40 s at a light-tip – resin composite distance of 1 mm. In study IV, we calculated conversion ratio (bottom/ top), using Elipar FreeLight and found values comparable to those of Soh et al’s. However, the conversion ratio of a specimen cured with one curing unit does not necessarily express the quality of the unit. A curing unit that result in a low degree of conversion at the top surface may have a conversion ratio similar to that of a curing unit that results in a higher top
degree of conversion. Therefore, we also used another way of expressing the conversion ratio by using the highest measured degree of conversion value as a reference. Comparing the conversion ratios for the most difficult situation (4 mm depth and 7 mm distance), we found the lowest conversion ratio for the Elipar FreeLight curing unit (0.77). The unit which also showed the lowest irradiance, Demetron 400 and Ultralume 2 also showed values lower than 0.9 which indicates that these units were not capable of curing a 4 mm resin composite from a distance of 7 mm. In contrast Elipar FreeLight 2 and LEDemetron showed conversion ratios higher than 0.9.

We also investigated the reduction of degree of conversion due to an increase in light-tip – resin composite distance from 0 to 7 mm. Price et al (82) investigated the effect on irradiance on increasing the light-tip – resin composite distance from 2 mm to 9 mm and showed a decrease between 20% and 78% depending on the light curing unit. The authors concluded that the design of the light guide affected the dispersion of the light. This was in contrast to our results as we found the reduction to be less than 10% for all curing units tested. The development of LED curing units has been fast during the last decade. The first versions on the market showed very low power densities and narrow spectral ranges. Thus they were, only able to cure resin composite with camphorquinone and to cure to a limited depth. Today, high power LEDs are on the market with irradiances of more than 1000 mW/cm² and broad spectral ranges that allow for activation of other photoactivators than camphorquinone.

In study V, the replica scanning electron microscope method was used to evaluate interfacial adaptation in class II resin composite restorations:

1. placed with and without a flowable resin composite liner and
2. cured with three different curing modes: soft-start and 500 or 700 mW/cm² continuous irradiation.

The adaptation to dentin of the resin composite restorations in this study was 63.6%, which is inferior compared to earlier reported interfacial adaptation results evaluated with the same method (paper I,27,29). This is probably caused by poorer
bonding capacity of the dentin bonding system used (Syntac Single-Component). Vargas et al (105) demonstrated that single bottle adhesives produced hybrid layers of varying thickness, ranging from no discernible layer for Syntac Single-Component to a 50 µm thick layer when using filler primer systems. They also showed low shear bond strength for the one-bottle adhesive system Syntac Single-Component. Manhart et al (67) investigated marginal quality and microleakage of several restorative systems in Class V cavities and showed statistically higher dentin leakage with Syntac Single-Component than for a filled single bottle adhesive. The inferior interfacial adaptation of the adhesive in the study in paper V was also observed recently in a similar SEM evaluation (101).

The use of a flowable composite in addition to conventional resin composite has been studied in vitro by Ernst et al (32) and Peutzfeldt & Asmussen (78) and found to have a beneficial effect. These results were not supported by Chuang et al (19,20), who examined the effect of flowable composite liner on marginal microleakage of class II restorations and found no improvement in cervical marginal seal. Also in a two-year clinical study, Ernst et al (33) could not repeat their positive in vitro results. No statistically significant difference was found between the Class II restorations with and without a flowable liner.

It is possible that the result of study V would have been different if another dentin bonding system had been used. The shear bond strength for the one-bottle adhesive system, Syntac Single Component, could not withstand the forces from the polymerization shrinkage. With a more potent dentin bonding system, the ability of the flowable resin composite to function as a stress absorbing layer might have been more noticeable.

In this study the influence of three different curing modes was evaluated, conventional curing (500 mW/cm²), high power curing (700 mW/cm²) and soft-start curing (650 mW/cm²). The use of soft-start curing has been suggested to prolong and increase the compensating flow of the resin composite during the initial polymerization (34,39,56,106). However Hofmann (52) and Sahafi et al (95) showed that soft-start did not improve the marginal adaptation of resin composites bonded to dentin cavities compared with conventional curing. Amaral et al (2)
found no statistical significant difference regarding marginal leakage and gap formation between soft-start, pulse-delay and conventional curing techniques. These findings were confirmed in the present study, which found no statistical significant differences between the three curing modes.

Based on the results of the papers I - V and articles in the reference list, it is possible to give the following recommendations.

- The use of a poly-acid modified resin composite or a flowable resin composite in open sandwich restorations did not improve the interfacial adaptation of Class II resin composite restorations. In deep cavities, which may be difficult to keep dry, a resin modified glass ionomer/resin composite open sandwich restoration should be used.
- Be sure to have a light curing-unit of good quality and check the irradiance regularly, preferably every day.
- Check the depth of cure obtainable with a specific light-curing unit and resin composite brand and shade according to the method described in ISO 4049.
- When you have to replace an old QTH light-curing unit, chose a later version of an LED. Ensure that irradiance and the spectrum of the emitted light covers all resin-based materials used in the clinic.
Conclusions

- Neither the sandwich restoration with polyacid-modified resin composite nor the flowable resin composite improved the interfacial adaptation of the restorations.
- No difference in durability was found between the sandwich restorations with polyacid modified resin composite or the resin composite restorations. A low failure rate was observed after a clinical observation time of three years.
- The depth of cure of the flowable resin composite was higher than the depth of cure of the resin composite. It was found that the curing time of the resin composite studied could be reduced or the increment layer thickness increased compared to earlier recommendations.
- LED curing units of the latest generation were able to cure resin composites to a higher degree of conversion than the control QTH unit.
- The use of soft-start curing did not improve the interfacial adaptation of neither of resin composite restorations tested.
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