

Posterior resin-based composite: review of the literature

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Abstract

The use of direct posterior resin-based composite has increased primarily due to patient esthetic desires and product improvements. Other factors (substantiated or not) contributing to increased use of resin-based composite are environmental and health concerns with dental amalgam.¹ New visible light cured resin-based composite products are introduced yearly, as manufacturers continue to improve this tooth-colored restorative material. This paper will characterize current posterior resin-based composite materials (hybrid, microfill, flowable, and packable), review recent in vitro and clinical research, and recommend indications for these materials. In addition, the literature on compomers will be reviewed and recommendation made for their use. The data indicates that composite resin is a technique sensitive restorative material that can be used in large preparations if proper manipulation and isolation can be maintained. Compomers may also be used as an esthetic posterior restorative if proper isolation is provided. (*Pediatr Dent.* 2002;24:465-479)

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Since the 1990s, resin-based composite (RBC) sales have increased. The ability to mimic tooth structure gave RBC a distinct advantage for patients and dental professionals. As differences between amalgam and RBC properties narrowed, resin-based material was placed in larger preparations. Wear was an early concern with posterior RBC restorations, but improvements in silane application, filler loading, and sizing improved wear. RBC is available in different shades and opacities and various filler particle sizes using different polymerization methods, multiple viscosities, delivery systems, and ion leachability.

Compomers or polyacid modified composite resins

A compomer is a polyacid-modified, resin-based composite with constituents derived from composite and glass ionomer. Compomers are derived from composite resin with glass ionomer components, the etchable glass fillers which provide fluoride release. The wear resistance and mechanical properties of compomers are less than composite resin, but the fluoride release and uptake are greater. Ease of handling is a compomer's greatest asset, which led to its popularity.

Materials classified as compomers have substantial differences. Compomers such as Dyract AP (LD Caulk); Compoglass (Ivoclar North America); F2000 (3M, St. Paul,

Minn) and Hytac (ESPE, Norristown, Pa) are composed primarily of bis-GMA, modified monomers and fluoride-releasing fillers.²⁻⁴ These single-component, light-cured materials contain no water. Water is sorbed into compomers after they contact saliva and produces the small acid-base setting reaction. The auxiliary setting reaction produces increasing strength and setting expansion of all compomers as they age. All compomers require an adhesive bonding agent to bond to the tooth, reducing fluoride released^{5,6} from the restoration into the prepared tooth.

The fluoride release and mechanical properties of compomers vary considerably.^{7,8} Hytac has low fluoride release and high mechanical properties similar to composite resin, whereas others (Compoglass, Dyract and F2000) have properties more like resin-modified glass ionomers. Since Dyract and Compoglass were introduced earlier than F2000, or Hytac, more in vitro data are available on these products.

According to the manufacturer, a hydrophilic monomer, TCB, with 2 methacrylate and 2 carboxyl groups has been added to Dyract so that 50% of the reactive groups on each molecule consists of carboxylic acid groups. These groups are responsible for the bond of Dyract to the tooth. Although Dyract will bond to tooth structure without prior etching and without a bonding agent, this bond is too weak to be clinically useful. A single component bonding system, Prime and Bond NT, is supplied with Dyract. Although

early directions stated that this material did not require etching prior to placement, one clinical study has shown a low retention rate when no etchant was used.⁹

The filler in the original Dyract compomer is a 2.5 μm strontium-aluminum-fluoro-silicate glass filler which provides fluoride release. Dyract AP has a reduced filler size of 0.8 μm , which improves fluoride release and polish compared to Dyract.

Compoglass is a single-component, light-cured fluoride-releasing compomer composed of silanized barium fluorosilicate glass and ytterbium trifluoride fillers. With a mean filler particle size of 1.6 μm , Compoglass is 56% filled by volume and 79% filled by weight. Compoglass releases fluoride from the ytterbium trifluoride and barium aluminum fluorosilicate glass fillers. It is supplied with a single component bonding material.

Although classified by the manufacturer as a compomer, Hytac has physical and mechanical properties like fluoride-releasing composites and should be classified as a fluoride-releasing composite resin. Hytac contains bismethacrylate and acid-modified bismethacrylate resins and is 81% filled by weight (66% is glass filler and 15% is ytterbium trifluoride, a radiopaque and fluoride-releasing agent), with a mean filler particle size of 5 μm . The glass filler is zinc-calcium-aluminum-fluoro-silicate glass, a typical glass ionomer glass and provides an additional source of fluoride release.

F2000 is the most recent addition to the family of compomers and has a mean fluoro-aluminosilicate glass filler particle size of 3 μm (maximum of 10 μm) and added colloidal silica to produce filler loading of 84% by weight. F2000 has an acidic primer/adhesive system based on the Vitremer (3M, St. Paul, Minn) primer and maleic acid.

Resin-based composite composition and improvement

Resin-based composite consists mainly of a resin matrix surrounding inorganic filler particles. The primary constituents of the resin matrix are resin monomers and an initiator/catalyst system for polymerization. The first dental RBC monomer developed in the 1960s is still used today. Based on the reaction product of bisphenol-A and glycidyl methacrylate (bis-GMA), it is a bulky monomer with methacrylate groups at each end of the molecule (dimethacrylate). Polymerization occurs through a free radical addition reaction. The double-bonded carbons of the methacrylate groups at each end of the active site on the monomer cross-links during the polymerization process, producing initially a linear polymer; then by reacting with the second site, a highly cross-linked polymer is produced.¹⁰

Since bis-GMA is quite viscous, it must be thinned by using shorter, more flexible diacrylate monomers, eg, ethyleneglycol dimethacrylate (EGDMA) and triethyleneglycol dimethacrylate (TEGDMA). In the 1970s another diacrylate monomer, urethane dimethacrylate (UDMA) was adopted for dental use. The molecular weight is similar to

bis-GMA, but more flexible. UDMA may be used alone or in combination with other diacrylate monomers.¹¹

Other base monomers are utilized besides bis-GMA and urethane dimethacrylate, however, none has proven to be clinically superior; and these 2 monomers still predominate.

The first improvement in the resin matrix was developed 30 years after the original Bowen formula. In 1998, the first RBC was introduced based on the ormocer chemistry (Definate, Degussa, Germany).¹²

Multifunctional urethane and thioether(meth)acrylate alkoxy silanes as sol-gel precursors have been developed for the synthesis of inorganic-organic copolymer ormocer composites.¹³

Ormocers (organically modified ceramics) have inorganic-organic copolymers in the blend that allow the RBC to be manipulated like any other RBC. This material seems promising in that mechanical properties were similar to Tetric Ceram (Ivoclar/Vivadent) and the wear was significantly better.¹³

The initiator/catalyst system for direct RBC may be chemically activated, light activated, or both. With chemically activated polymerization, benzoyl peroxide is the initiator (or sulfinic acid may be used as the initiator), and a tertiary amine (eg, dihydroxyethylparatoludine—DHEPT) is the activator.¹⁴ Once the 2-paste, chemically-cured RBC is mixed, the initiator and activator contact and polymerization begins. After a few minutes, the polymerization produces a gel (solid) where the polymer is cross-linked enough to form a cohesive mass which may be finished and polished. In the 1980s, visible light-cured (VLC), resin-based composites were introduced to the dental profession. These resin systems became very popular and are now the dominant, directly-placed esthetic material.

Visible light-cured RBCs are single-paste materials polymerized with visible light energy. VLC RBCs allow the operator to control setting time, require no mixing, and have fewer voids, greater strength, greater fracture toughness, better shade selection, better color stability and higher surface polymerization conversion rates than chemically activated RBC. VLC RBC polymerizes by free radical polymerization and has a photoinitiator and accelerator/catalyst system. The photoinitiator absorbs light energy (photons) emitted from the curing light and directly or indirectly initiates polymerization. Photoinitiators are diketones, such as camphoroquinone, activated by visible light, in the presence of an amine accelerator/catalyst (eg, dimethylamino ethylmethacrylate—DMAEM). The activated diketone/amine complex initiates the polymerization of the dimethacrylate resin monomers.

VLC RBC contains a lower concentration of amine accelerators than chemically cured RBC, which increases the color stability of VLC RBC compared to chemically activated RBC.¹⁵⁻¹⁷ Camphoroquinone is a commonly used photoinitiator with major absorption of visible light wavelengths in the 460-480 nm (blue) range. RBCs may contain a combination of photoinitiators, each requiring its own

specific wavelength for maximum reactivity. Camphorquinone has a maximum absorption spectrum of 468 nm, which is close to the peak spectral output of the LED curing lights.¹⁸

Since different composite resins have different photoinitiators, the light wavelength range absorbed by the photoinitiator for maximum polymerization should be placed on the composite syringe.¹⁹ Percent conversion or the ratio of double bonds converted to single bonds indicates the extent of polymerization. Composites with higher percent conversion have greater mechanical properties, greater wear resistance, better color stability and are more biocompatible, which contributes to increased restoration longevity.²⁰

Visible light-curing units should indicate the spectral emission (wavelength) of the unit, as well as the power density (intensity) of the light output. The spectral emission of the light-curing unit must be wider than the spectral photo polymerization requirements (the maximum absorption) of the photo initiators in the RBC to achieve maximum conversion.¹⁹

During polymerization of resin-based composite, the distance between the monomers decreases as the carbon atoms bond together and molecular movement decreases. With present-day RBCs, this shrinkage ranges from 2%-3% per volume.²¹⁻²³ Clinically, composite resin placed in a cavity preparation is confined by the preparation. Shrinkage of the composite resin transfers stress to the cavity walls. Polymerization shrinkage can tear the adhesive bond to the tooth²⁴ or pull the opposing cusps together by deforming the tooth.²⁵

Shrinkage of the RBC can fracture marginal tooth structure, tear the adhesive, or cause tooth structure to deform, which increases microleakage, postoperative sensitivity, staining and recurrent caries. Increasing the filler content of RBC minimizes resin content, reduces the shrinkage, and increases the stiffness (or modulus of elasticity).

The magnitude of the contraction stress is related to the cavity configuration,²⁶ the compliance of the composite and the surrounding tooth structure,²⁷ the composite resin degree of conversion and the conversion rate of the composite, which is related to the modulus of the composite.²⁸ As RBC polymerizes, the amount of stress generated to the surrounding tooth depends, in part, upon the rate of modulus development. High modulus composites with rapid conversion rates transfer stress to the surrounding tooth structure more rapidly than lower modulus materials with slow conversion rates.

The ceramic filler particles of VLC resin-based composites provide radiopacity and reduce polymerization shrinkage, water sorption, and the coefficient of thermal expansion, while increasing the mechanical properties.²⁹ Generally, increased filler volumetric percentage (filler loading) improves the physical and mechanical properties of RBC. Most filler particles are silicon dioxide based and are either crystalline silica (quartz), silica with metals (silicate

glass), or amorphous silica (colloidal or fumed silica). Fillers range in size with a distribution that averages less than 0.1 μm to a distribution that averages between 10-100 μm .³⁰ Resin-based composites are classified according to their filler size, because filler size affects polishability/esthetics, polymerization depth, polymerization shrinkage, and physical properties. Knowing the range of filler size and percent filler in a specific composite will provide clues to the strength and polishability of the specific composite resin. Macrofilled, resin-based composites developed in the 1960s have fillers that range from 10-100 μm . These were the first products called traditional or large-particle, resin-based composite.

In the 1970s, microfilled resin-based composite was introduced with an inorganic filler particle size averaging less than 0.1 μm . Microfilled RBCs can be polished to an extremely smooth surface, but generally have lower fracture toughness and mechanical properties compared to hybrid RC. These materials contain prepolymerized particles which are bis-GMA resin with silica fillers that have been polymerized and ground to particles of about 20 μm . The prepolymerized particles are then placed into more bis-GMA; it is this mixture that comprises microfilled composites.

A thorough classification system, which classifies composites by the size of their filler particles, was developed.³¹ Midsize-filled (also called, midifil, fine or small particle) particles range from 1.0-10 μm . This particle size was an attempt to provide higher strength than a microfilled RBC and better polishability than a macrofil. *Minifilled* (also called, all-purpose, submicron, or microfine) particles range from 0.1-1.0 μm . These materials still had relatively high strength and better polishability than midfilled RBC.

Most modern posterior RBCs use a combination of particle sizes to achieve superior strength and improved esthetics over traditional macrofils. In the 1980s, hybrids containing midsize (1-10 μm) or minifilled (0.1-1.0 μm) particles and 7%-15% microfilled (<0.1 μm) particles began to be used in posterior load bearing surfaces.¹⁵ The heavy filler loading (50%-70% by volume)²⁹ possible with hybrids provided the strength and wear resistance for Class I and II restorations. Today, minifilled (all-purpose, submicron, microfine, or micro-) hybrids are the most popular, because they may be used in anterior or posterior areas since they are available in a variety of shades and a range of translucencies and opacities, permitting excellent esthetics. Minifilled hybrids have superior strength compared to most microfils, however, microfils still have better polishability.

Microfill RBC contains amorphous silica particles less than 0.1 μm in size, averaging approximately 0.04 μm . Amorphous silica is radiolucent, and, unless radiopacifiers are present, microfill RBCs are radiolucent. Adding small amounts of other fillers, eg, ytterbium trifluoride (Heliomolar RO, Ivoclar-Vivadent) and barium glass (Tetric Ceram, Ivoclar-Vivadent), will provide radiopacity for microfilled-composite resins. The microscopic size of amorphous silica particles permits microfills to be highly polished.

Since the particles are less than the wavelength of light, the eye sees them as smooth.¹⁵ Unfortunately, this particle size increases the surface area of the fillers and only a relatively small amount of filler can be suspended in the monomer, limiting the amount of filler loading (25%-50% by volume.) Therefore, microfills are generally not as strong as hybrid RBCs and have lower fracture toughness than materials with a higher volumetric percentage of filler.²⁹ Microfills are routinely used in non-stress areas or in a sandwich technique where the microfil veneers a stronger hybrid material. The exception to this is a microfill designed for use as a posterior restorative material, Heliomolar RO (Ivoclar-Vivadent). The microfill, Heliomolar, has consistently shown excellent wear rates and longevity compared to other resin-based composite, including hybrids.³²

Most hybrid RBCs contain a small amount of microfill particles to improve the handling properties (flow) and control stickiness. The minifilled and midfilled particles commonly contain silicate glass with metals, such as barium, strontium, zirconium, aluminum, ytterbium, boron, zinc and fluoride. Barium, strontium, zirconium, boron and ytterbium provide most of the radiopacity of resin-based composites. Once RBC began to be placed in posterior teeth, radiopacity was necessary to diagnose recurrent decay, voids, and overhangs. The current American Dental Association Council of Scientific Affairs recommends that posterior resin-based composites should be radiopaque.³³ The International Standards Organization (ISO) does not require RBC to be more radiopaque than enamel or dentin but bases the standard for radiopacity for composite resin as equivalent to 2 mm of aluminum, which approximates the radiopacity of dentin.

A 2-mm thickness of dentin is equivalent to approximately a 2.5-mm thickness of aluminum, while a 2-mm thickness of enamel is equal to approximately 4 mm of aluminum. By comparison, a 2-mm thickness of amalgam is equivalent to 10 mm of aluminum.³⁴ Espelid and others reported that optimum radiopacity for evaluating recurrent decay is just slightly more radiodense than enamel.³⁵ In a study assessing the radiopacity of posterior tooth-colored restorative materials, Bouschlicher reported that all 9 posterior RBCs in the study were more radiopaque than enamel. In general, flowables have significantly less radiopacity compared to highly filled posterior composite resins.³⁶

Shrinkage

The polymerization of visible light-cured, resin-based composite is affected by 4 factors: (1) constituents of the resin-based composite material, (2) configuration of the cavity preparation, (3) spectral distribution and power of the visible light-curing unit, and (4) clinician's technique. As polymerization proceeds, there is a change in state from a viscous liquid to a solid. As the monomer cross-links to other monomers, the previously mobile monomer molecules are now covalently bonded to other monomers, resulting in shrinkage. Part of the shrinkage occurs before solidification

(gel point) while the material has the ability to flow. After solidification (post-gelation), there is a rapid increase in the stiffness of the material, and further polymerization will apply stress to the bonded surfaces.³⁷ The amount of linear shrinkage by volume has been measured in a number of studies with the following results: 1%-2%,²¹ 1%-3%²² and 1%-3%.²³

If the adhesive bond to tooth structure is insufficient, shrinkage of the VLC RBC pulls the composite away from the cavity walls, forming an opening. This opening at the restoration margins may allow microleakage, staining, sensitivity, and/or recurrent decay.³⁸⁻⁴⁰ Conversely, if the bond to tooth structure is strong enough, as the composite material shrinks, stress is applied to the tooth.^{41,42} This may result in fractured cusps, movement of cusps, and/or postoperative sensitivity.^{43,44}

It is further theorized that, if the tooth structure and adhesive bond are unyielding, the amount of stress generated is dependent on the: (1) volumetric shrinkage, (2) modulus of elasticity (stiffness) of the RBC, and (3) configuration factor of the cavity preparation.⁴² Filler loading (filler content) and volumetric shrinkage play an important role in the contraction stress of composite material. Versluis and others reported proportional interfacial stress with an increase in shrinkage and a nonlinear increase with an increase in the modulus of elasticity.⁴⁵ The higher the modulus of elasticity, the greater the stress transferred to tooth structure if the bonding remains intact.⁴⁰

Hybrid VLC RBCs, with high filler loading, have approximately twice the modulus of elasticity of microfilled composites.³⁴ Although controversial, it is suggested that microfilled composite resin may be appropriate for Class V restorations because of their low shrinkage stress (low modulus and low shrinkage), low fracture toughness, and low wear resistance.⁴⁰

Configuration factor, or C-factor, is the ratio of the bonded area of the restoration to the unbonded area. It is thought that VLC RBC shrinkage and attendant stress can be partially compensated by flow of the composite material.⁴⁶ The areas of the restoration that are not bonded to cavity walls can flow freely during the early portion of the polymerization process. The composite moves or sags at the unbound surface, allowing the composite to stay bonded and reduce the RBC stress.⁴⁷ As the bonded areas increase in relation to the unbonded areas, the ability to flow and compensate for shrinkage is reduced, generating more stress (Choi and others, 2000). The higher the C-factor, the greater the stress on the bonded surfaces.^{26,48} The higher shrinkage stress with higher C-factor is thought to reduce the RBC bond to tooth structure. Yoshikawa and others reported a 21%-35% reduction in microtensile bond strength with C=3 samples compared to C=1 samples, showing that polymerization shrinkage can reduce bonding to tooth.⁴⁹

Reduction of stress during polymerization has been an area of intense research. Bases/liners with lower modulus of

elasticity and higher compliance to accommodate contraction stress have been a subject of interest. A flexible liner can stretch to relieve the force of polymerization shrinkage.⁵⁰ Resin-modified glass ionomer, glass ionomer, and adhesive resins have been used as stress modifiers with mixed results.⁵¹⁻⁵³ Some manufacturers are currently providing more viscous (thicker) bonding agents by increasing filler loading in the area with the idea that a thicker adhesive layer will accommodate contraction stress and provide a stronger bond. Resin inlays and ceramic inserts have been advocated to reduce the problems of polymerization shrinkage.⁵⁴⁻⁵⁶

Another method to reduce polymerization stress is the "directed shrinkage" technique using self-cured RBC in the first increment. The polymerization begins at the tooth surface due to body temperature, then VLC RBC fills the remainder of the cavity preparation.^{57,58} However, improved marginal adaptation with the directed shrinkage technique was not confirmed in follow-up studies.^{59,60}

Recently, visible light-curing unit manufacturers have attempted to decrease the amount of contraction stress or slow the polymerization process by introducing curing lights that initially have a low intensity and/or a short duration of cure. It is thought that this slower set permits movement of the polymer chains, allowing stress relief and improved marginal integrity. By far, the most common source of light for dental light curing units is a quartz-tungsten-halogen (QTH) bulb. Most of the energy produced by QTH bulbs is in the form of heat and wavelengths of light other than the 400-525 nm range. VLC units have filters that absorb heat and permit the appropriate wavelengths of light (bluish) to be transmitted through the light guide. The amount of light energy per unit area or "power density" (PD) is expressed as milliwatts/cm² (mW/cm²). The minimum recommended power density to adequately polymerize 2 mm of resin-based composite has increased to the current recommendation of 400 mW/cm².⁶¹

Recently, researchers have taken a slightly different view of the power density necessary for adequate polymerization. Lower power density lights may be used initially, as long as the total energy reaches a threshold for complete polymerization.

In 1996, over a 4-minute period while controlling the output of the curing unit with a rheostat, Goracci slowly polymerized composite resin and showed fewer marginal gaps with this slow polymerization technique.⁶² Although verified, the technique required too much time to polymerize composite resin clinically. The commercial development of that technique increased polymerization rates and shortened the time for polymerization to make it clinically useful. The ESPE Highlight curing light was the first curing light with a "soft cure." This unit started at a low output of 180 mW/cm² which, after 10 seconds, increased to 750 mW/cm² to complete the 40-second cure. The Highlight was replaced with the 3M ESPE Elipar Trilight curing light, which had an exponential output mode in which the output

ramps from low to high output. Curing lights with variable output (softstart-polymerization curing units) reduce and/or delay the amount of polymerization stress. These methods of "soft curing" include step-curing, ramp-curing, and pulse-delayed curing.

Many researchers have found improved marginal integrity with these techniques.⁶³⁻⁶⁶ However, not all researchers have had positive results with these methods.⁶⁷⁻⁷⁰ In 2 studies, we found no significant difference using this technique and bulk curing.^{71,72} Another technique, advocated to decrease stress associated with the shrinkage of composite resin is the pulse delay, or the pulse cure technique.⁶⁶ This technique places increments of composite resin and cures each increment. The final enamel replacement increment is cured with a brief burst of energy for 2 to 3 seconds. A 3-minute delay is then given to allow the composite time to flow and shrink while the restoration is finished and polished. After finishing, the restoration is cured at a high intensity to totally polymerize the material. Research has shown that soft-curing techniques do not affect the final mechanical properties of the composite resin; however, the effectiveness of the soft cure in decreasing leakage and stress at the margins of Class II restorations is not clear nor has it been proven clinically.

To provide enough energy for optimum polymerization (EOP) at a specified depth in the composite, the composite must be exposed to light for an appropriate duration and at the proper wavelength range and power density (mW/cm²). The power density (mW) multiplied by seconds yields mW(sec)/cm² or mJoules/cm², abbreviated as mJ/cm². A 40-second exposure with a power density of 400 mW/cm² yields 16,000 mJ/cm². The EOP at a specified depth (EOP@D) of each composite may be determined by measuring the energy necessary to achieve optimum mechanical properties at a specified depth of cure. Manufacturers should specify the EOP@D for each composite. Once clinicians know the EOP@D and the power density of the light-curing unit, the curing time may be determined by dividing the power density into the EOP@D. If the EOP@2 mm of shade C1 is 8000 mJ/cm² and the light-curing unit has a power density of 400 mW/cm², then the duration of light curing should be 20 seconds to achieve EOP @2 mm (8000 mJ/cm²/400 mW/cm² = 20 seconds).¹⁹

The surface of the composite material near the light source is ordinarily polymerized thoroughly and the conversion percentage is high; but at a depth of 2 mm, the conversion percentage drops significantly.⁶¹ Activation of the photoinitiators (CQ) declines exponentially as a function of the distance from the surface^{73,74} due to light absorption and scattering. The absorption and decline of light energy as it passes through composite is a function of the shade/translucency of the resin, filler particle size, make-up, loading percentage, and photoinitiator concentration, as well as the resin/particle index of refraction.⁷⁵ Caughman recommended curing composite in increments no larger than 2 mm, and for dark opaque shades 1 mm depth may be advisable.⁷⁶

High intensity QTH lights and plasma arc curing (PAC) lights have greater power density than conventional QTH curing lights, 1000-2500 mW/cm² vs 300-800 mW/cm². Argon lasers also have greater effective power density due to their coherence and directional nature.⁷⁷ High intensity lights were developed to polymerize RBC in less time than conventional QTH lights. If the power density of a high-intensity light is twice as great as a conventional light, then the curing time will be reduced by half. Curing depths do not increase as power density increases since there is an exponential decrease in light energy as it travels through RBC or dentin. At a 2 mm depth in RBC, only 9%-17% of light is transmitted, and at 3 mm only 2%-8% of light is transmitted. For all types of curing lights, light transmission through wet dentin at 2 mm is 13% and at 3 mm it is 6%.⁷⁸ With appropriately reduced exposure times (to match their effective power density), high intensity lights are not significantly different from conventional lights in curing depth, flexural strength, or flexural modulus.⁷⁹ Also, some plasma arc lights, light-emitting diodes (LED), and all lasers have a narrow spectral range, so certain RBC with a combination of photoinitiators may not reach optimum polymerization.⁸⁰ Therefore, composite resin may be polymerized more quickly with high-powered curing lights, but large increments cannot be cured thoroughly even with powerful curing lights.

Visible light energy and polymerization of resin-based composite increase the intrapulpal temperature.⁸¹ Although controversial, one study has reported pulpal histological changes with a 5.5°C increase in temperature and significant irreversible pulpal damage with an 11°C increase.⁸² As the intensity and duration of light curing increases, the pulpal temperature increases. Increasing dentin thickness mediates the temperature rise, and air lowers the pulpal temperature.⁸³ High-intensity, light-curing sources or defective infrared filters could cause significantly higher pulpal temperatures compared to conventional curing lights. Clinicians should be aware of the potential thermal hazard from high-intensity, visible light curing.⁸⁴

The intensity of light-curing can be affected by the distance the light guide is held from the curing site. As the distance from the light source to the composite increases, there is a linear decrease in the power density.⁸⁵ Mehl changed the distance of the light guide to vary the intensity of soft-polymerization and found that 10 mm from the composite reduced the intensity by 50%.⁶⁵ Similar reductions in intensity were found by other researchers.^{75,86}

However, Hansen and Asmussen reported that an irradiation distance of 12 mm reduced the depth of well-cured resin only by about 1 mm compared with close contact to the resin surface.⁸⁷ Since attenuation of light intensity occurs in air, it is best to position the light guide close to the RBC during curing. Incremental curing is recommended to fully polymerize the resin-based composite.⁶¹ Whether light-curing in increments reduces stress or microleakage is less clear.⁸⁸⁻⁹³ Bulk-curing is desirable because of its efficiency.

The transenamel polymerization (TEP) technique⁹⁴ does not provide adequate polymerization in the center of the restoration.^{71,72} This may or may not affect the long-term success of the restoration. This area needs further research.

Many conventional QTH curing lights have interchangeable light guides of varying diameters. Commonly 11-13 mm light guides are used since this size will cure an entire restoration. The relationship of the exit port diameter of the light-curing unit to the curing tip diameter will affect the curing unit's power density. If the exit port is 11 mm and the light guide tip is 7 mm, the light output is concentrated into a smaller area, increasing the power density. This is the mechanism of increasing the power density with the "turbo tip." High-intensity curing lights (eg, plasma arc, high-intensity QTH) have smaller diameter exit ports and light guide tips, so the advantage of less curing time is somewhat diminished by more exposures per restoration or increasing the distance from the restoration. Neo and others reported that light curing with a 13-mm diameter light with the spot or overlap method for 60 seconds achieved the highest mean hardness. Wide tip size resulted in greater hardness than narrow tip size when using the overlap or spot-cure method. Tips narrower than the specimen size should not be used with the spot cure method.⁹⁵ The output of quartz tungsten halogen visible-light-curing units decreases with time due to degradation of components such as the bulb, reflector, filter, and optic bundle.⁹⁶

The output intensity of curing lights in a significant number of dental offices (45%) is less than the recommended level.⁹⁷ Light-curing at lower power density levels (250 mW/cm²) will decrease the mechanical properties of some resin-based composites compared to light-curing at higher levels (450 mW/cm²).⁹⁸ The best method for evaluation of the output is a radiometer.⁹⁹ Manufacturers have recognized the importance of monitoring the power density and they are now including radiometers in the curing-light units. Newer curing QTH units have a power density range from 500-800 mW/cm² compared to the previous standard of 300-500 mW/cm².

Flowable resin-based composite

VLC flowable resin-based composites are conventional composites with the filler loading reduced to 37%-53% (volume) compared to 50%-70% (volume) for conventional minifilled hybrids.¹⁰⁰ The fillers of most flowable RBC are usually minifilled size, although some products are microfilled. The amount of fluidity varies significantly from one product to another. Bayne and others measured the flow of 5 flowables and found that the most fluid, Ultraseal XT Plus (Ultradent), had 5 times the flow of the least fluid, AELITEFLO (Bisco). Compared to conventional hybrids, AELITEFLO exhibited the same amount of flow as Z-100 (3M-ESPE) and half the flow of Prodigy (Kerr).¹⁰¹ As a result of differences in viscosity, flowable RBC varies considerably in polymerization shrinkage, stiffness, and other physical properties.¹⁰²

Bayne compared mechanical properties of 8 flowables and 2 minifilled hybrids. In general, the flowables had inferior mechanical properties, although a few approached the properties of hybrids.¹⁰¹ In vitro abrasion wear tests have produced contradictory results^{101,103,104} and the clinical wear resistance of flowable RBCs has yet to be determined. However, because of the decreased filler content and reduced physical properties, it is recommended that flowables only be used in low-stress areas, or very conservative occlusal restorations. Flowable RBCs are recommended for the initial increment in Class II restorations. This thin increment serves as a liner for the proximal boxes of Class II restorations, and the less viscous flowable material adapts to sharp angles and surface irregularities. With this technique, a flowable layer is placed initially to fill the internal irregularities of the preparation, then a posterior RBC is placed on top to provide strength and wear resistance. The in vitro microleakage and gap formation studies on this technique are contradictory.¹⁰⁵⁻¹⁰⁷ Leakage does not seem to be reduced when flowables are placed in the proximal box.¹⁰⁸ Since no clinical trials have been reported on this technique, it is unclear if this flowable/posterior RBC Class II technique is clinically superior to using a posterior RBC only. However, these materials may be useful in preventing voids at the line angles when old amalgam restorations are replaced and filled with RBC.¹⁰⁹

A comparative radiopacity study of flowable, resin-based composites reported that, of the 8 flowable RBCs tested, only 3 were equal or greater in radiopacity than enamel: Tetric-flow, (Ivoclar-Vivadent), Flow-it, (Jeneric/Pentron), and Crystal-Essence (Confi-Dental).¹⁰⁰ Bouschlicher and others reported similar results with Tetric-flow and Flow-it, while 4 other flowables were less radiopaque than enamel.¹¹⁰

Packable resin-based composite

One of the difficulties with conventional RBC material for Class II restorations is its lack of condensability. This quality would help achieve good internal adaptation to the cavity walls and adequate interproximal contact with adjacent teeth. Unfortunately, the low viscosity of conventional RBC compared to amalgam prevents it from being condensable. Also, unlike amalgam, conventional RBC has a stickiness that may interfere with condensation. During condensation, the RBC may stick to the condenser and draw away from the cavity walls. "Packable," or "condensable," RBCs were introduced with the expectation that they would handle and condense like amalgam, thereby improving proximal contacts. Since their filler loading was high and their filler distribution was different than other RBCs, they had a different handling and consistency. Early claims by manufacturers that these RBC could be bulk cured stirred the interest of many clinicians. Due to the filler loading and distribution, improved handling properties and wear resistance were expected.¹¹¹

It was thought that a highly filled RBC with minifilled to macrofilled particles and viscous resin matrix would be more condensable and adapt the matrix band against the adjacent tooth, permitting better contact. A variety of products were manufactured, some with modified resin chemistry compared to conventional posterior RBC. Much of the change in viscosity is due to changes in the fillers: ALERT (Jeneric/Pentron) has the usual hybrid filler, but also has microglass fibers greater than 20 μm in length; Solitaire (Heraeus Kulzer) has agglomerated particles reaching 10-15 μm ; and Surefil, (Dentsply/Caulk) has trimodal sized fillers that improve filler loading.¹¹² These products were introduced as "condensable" RBC designed for use as Class I and II restorative materials; some products claimed to simulate the condensability of amalgam. Since 1998, at least 6 other products have entered the market in this category.

Condensable RBCs, also called high-density or packable RBCs, varied greatly in their particle size, filler loading, and, consequently, viscosity. At best, the most viscous product approaches the viscosity of a spherical alloy amalgam, and this viscosity decreases as the material warms to mouth temperature.¹¹³

Brackett and Covey evaluated the consistency of 2 condensable RBCs, 2 conventional RBCs, 2 spherical amalgams, and 2 admixed amalgams. They reported that the compression forces for condensable RBCs (Solitaire and Surefil) were significantly less than all 4 amalgams.¹¹⁴ Because of condensable RBCs' failure to simulate the properties of amalgam, the dental profession has come to call the condensable RBCs "packable." Many packable products are more viscous than conventional RBCs and less sticky, but less than the viscosity of an admixed amalgam. While their handling properties are an improvement for larger Class I and Class II restorations, packable resin-based composites did not fully solve the difficulty in achieving interproximal contact. In an in vitro Class II study, Bagby and others found that packable RBC had smaller interproximal gaps than one hybrid, but were not comparable to the amalgam (Tytin, SDS Kerr) tested.¹¹⁵ Peumans et al, also reported that the packability of the composite resin did not influence the tightness of the contact area.¹¹⁶

The physical properties of packable RBCs are not superior to conventional hybrid RBCs and their large particles have shown increased wear.¹¹³ Manhart and others reported different in vitro results indicating that packables—ALERT (Jeneric/Pentron) and Surefil (Dentsply, Detrey)—had slightly higher flexural strength, modulus, and fracture toughness than a conventional hybrid—Tetric Ceram (Vivadent). While another packable, Solitaire (Heraeus Kulzer), had significantly lower mechanical properties than all three RBCs.¹¹⁷ Leinfelder and others reported that, overall, the mechanical properties of packable composites are not substantially better than most conventional minifilled hybrids.¹¹²

In vitro wear comparisons between conventional RBC and packables vary from study to study. Some studies show better wear resistance for certain conventional RBC while others show better results for certain packables.^{104,119-122} Perry's 2-year clinical study of 25 Class II restorations reported that Surefil demonstrated clinical acceptability in all categories.¹²³ The data currently available on condensable RBC as a posterior restorative material is encouraging but guarded. Once longer-term clinical trials are reported, a clearer picture will become evident. Because packable RBC was designed for posterior use, handling properties dominate over esthetics. Packables generally exhibit good handling properties—low stickiness and slump—however, the shade selection is limited.¹²⁴ Packables with larger particles will not polish as well as conventional RBC (Z-100, 3M).¹²⁵ Since packables are used almost exclusively in posterior areas, adequate radiopacity is a prerequisite. Of 4 packable RBCs, only one Solitaire (Heraeus Kulzer) had radiopacity less than 2 mm of aluminum.¹²⁶

The depth of cure for condensable RBC is similar to other composite resins. Cobb and others reported that ALERT cured to a depth of 3.2 mm with 500 mW/cm² light source for 40 seconds.¹²⁴ This study used the scrape test to determine the depth of cure of RBC. In this test, a sample is light cured, the soft uncured material is scraped away, and the remaining polymerized material is measured and divided by 2. Dividing by 2 gives a more accurate assessment of the depth that is adequately polymerized. In another study, Choi and others used the ISO standard for evaluating depth of cure. In this test, the bottom of a 2-mm sample should achieve 80% of hardness of the top of the sample. With 2 mm samples of shades A1 and A2, 3 packables were light cured adequately with 1080 mW/cm² for 40 seconds, while Solitaire (Kulzer) and Pyramid-Enamel (Bisco) were not cured adequately.¹²⁶ Using a 700-mW/cm² light source for 40 seconds, Manhart and others adequately cured 4 shade A2 packables to depths ranging from 2.5-3.5 mm.¹¹⁷ All of the previous studies indicate that packable RBCs are no different than conventional RBCs in their depth of cure and that depth of cure, depends primarily upon the level of photoinitiator in the composite.

Proximal contacts

Since posterior RBC were introduced, other devices were developed to improve proximal contact areas with Class II RBCs. Since circumferential matrix bands surround the tooth, the wedge must not only compensate for the thickness of the matrix band, but also for the RBC shrinkage. If a 2-surface restoration is being placed, the wedge must compensate for sectional matrix bands like Palodent Plus (Caulk), Compositight (Garrison), and the Contact Matrix (Danville Materials). Sectional matrices are placed on one proximal surface only and wedged, and a spring steel ring is opened and placed in the interproximal area. This ring separates the teeth effectively and allows a better contact

area to be developed. Hand instruments have also been developed to improve proximal contact areas by pushing the soft RBC against the matrix and the adjacent tooth and then curing it in that position.

Wear

Although in vitro wear testing has limitations, these tests are necessary to predict the clinical success of new formulations of RBC. In 1975, Powell et al, designed a wear testing machine that tested specimens in a sliding and impact contact with human enamel. Using this machine, they reported that amalgam had greater wear than a conventional composite resin.¹²⁷ Likewise, others have developed wear machines that have not related to the clinical performance of composite resin.^{128,129} More recently wear testing systems have developed which have better correlation of laboratory and clinical wear.¹³⁰⁻¹³² The system developed by de Gee, Pallav and Davidson (1986) is a 3-body wear test that uses poppy seeds as a food substitute. Wear figures generated with this system compare well with the wear generated during clinical trials.¹³³ Another system, using polymethylmethacrylate beads for the food bolus, has been used to measure wear¹³⁴ with reasonable success. The de Long and Douglas wear-testing machine was very sophisticated, with contact time and sliding wear paths precisely controlled. This system is commercially available as the Bionix Test System (MTS, Eden Prairie, Minn). It also simulates clinical wear closely, but not precisely.¹³⁵ In short, these and many other systems have been used to measure and predict RBC wear, some more accurately than others. In general, the wear of composites has improved¹³⁶ and the wear of posterior formulations are approaching enamel, 31 $\mu\text{m}/\text{y}$ at the occlusal contact areas.¹³⁷

In vivo wear has been measured in multiple ways, beginning with early categorical data collection forms, progressing to the rapid, inexpensive Leinfelder-calibrated cast measurement system and then utilizing the M-L scale.¹³⁹ The Leinfelder cast method of measuring wear is the most widely accepted method for measuring wear in clinical research studies. This method uses a series of 6 calibrated clinical cast models exhibiting wear in 100- μm increments. The M-L scale uses 18 standard models that differ by 25- μm increments. The Vivadent scale combines elements of the Leinfelder and the M-L scales and has greater precision in measuring clinical wear. Later, laser scanning and profilometric analysis determined more precise measures of wear than the previous visual methods.

The most recent method of measuring wear is the 3-dimensional laser digitizer.¹⁴⁰ Williams et al,¹⁴¹ were the first to describe a laser technique for wear measurement from replica models. The same year, DeLong and Douglas¹⁴² described a 3-D imaging method using computer graphics. More recently, Willems et al,¹⁴³ have used a 3-D measuring technique on epoxy models to calculate the differentiated wear between enamel and composite.¹⁴⁴ Measuring wear of

composite resin in clinical trials is difficult and time consuming. As the wear resistance of composite resin has improved, fewer studies have concentrated on this aspect of composite resin restorations.

Clinical trials

The earliest reports of composite resin clinical evaluation reported significant wear with Class II composite resins (Table 1).¹⁴⁵ The American Dental Association's guidelines for provisional and complete acceptance for posterior composite resin have changed since the guidelines were first published in 1981. In 1989, for complete acceptance, the study duration was reduced to 4 years from the earlier 5-year design. Reflecting the improvement in the durability of the RBC for posterior applications, wear was reduced from the 1981 level of 150 μm at 3 years and the maximum of 250 μm at 5 years to 50 μm at 2 years and 100 μm at 4 years. The results of clinical trials using resin composite as a direct restorative material for posterior restorations have shown increasing success with newer, more highly filled products.¹⁴⁶

In the 1970s and 1980s, posterior RBC restorations had poor wear resistance, and the subsequent loss of anatomical form in these restorations was a leading cause of failure. Improvements in filler loading, sizing, and modifications in silane application, as well as improvements in the monomer, have produced better restorative materials. With these improvements, changes in the failure mechanisms of posterior-resin-composite restorations have occurred. Now, marginal deterioration, discoloration, and secondary caries are the primary reasons for the replacement and failure of posterior resin composite restorations.¹⁴⁷ Microfilled composites had more fracture in Class II restorations compared to hybrid resin composites,¹⁴⁶ perhaps due to their lower mechanical properties.

The high incidence of poor marginal integrity, marginal discoloration, and recurrent caries is due to polymerization shrinkage of the composite resin, poor bonding agents and faulty application techniques. Despite improvements in adhesive systems, perfect marginal adaptation is impossible to achieve, and leakage results.

As resin composites and adhesives have improved, preparations have become smaller. Conservative preparations reduce occlusal stresses on the restorative materials, preserve tooth strength and reduce the total shrinkage of the composite. About 60% of all operative dentistry is due to the replacement of failing restorations.¹⁴⁸ Many composite resin restorations are replacements for amalgam restorations, and, since the size of the restoration is essentially predetermined by the size of the amalgam preparation, composites placed in these preparations may have a shorter lifespan due to increased functional loading. In addition, the preparation must be extended to include all the corrosion products of the amalgam covering the enamel and dentin. Corrosion products interfere with bonding and should be eliminated before applying the bonding agent.

Composite resins in primary teeth

A number of studies have evaluated the success of posterior composite resins and other restorative materials in primary teeth.^{150,151,155,156,164,169} Holland evaluated the success of amalgam restorations in primary teeth over a 7-year period and reported several interesting facts. The 1139 amalgam restorations in primary molars were placed mainly by undergraduate dental students with supervision. The data was stratified by age into 5 different 2-year age groups. Restoration longevity was significantly different between age groups, with younger patients having shorter restoration lifetimes. Class II restorations had shorter longevity than Class I restorations in primary molars. A surprising fact reported was that restoring a previously restored tooth decreased the life span of the second restoration in all ages. The first restoration of a given type will last longer than its replacement in the same tooth in primary molars. The authors reported that restoration longevity was based on patient age, tooth type, complexity of the restoration and the number of times the restoration was placed. All restorations placed in first primary molars had shorter survival times than those in second primary molars. This study emphasizes the benefit of preventive measures in delaying the restoration of teeth. If the restoration can be delayed to a later time, then the older patient will have increased longevity from that restoration.

Preparation design has been investigated in primary teeth. Nelson et al, did not use a cavosurface bevel on preparations in a 1980 study, while Paquette et al,¹⁷⁰ did in a 1983 study. In 1985, Oldenburg et al,¹⁷¹ beveled some preparations and left others unbeveled. Oldenburg examined composite resin restorations after 4 years in 3 different cavity designs. Included in this study were conventional amalgam-type preparations, a modified preparation which was the same as the amalgam but with a 1 mm occlusal surface-beveled margin, and a modified preparation in which the 1 mm bevel was placed in preparations in which the enamel was removed for access to caries removal only. At 4 years, the restorations for 42 conventional, 37 beveled and 44 modified preparations with no mechanical retention were evaluated. The failure rate for conventional preparations was 8%, for the beveled preparations it was 7%, and for the modified preparations it was 17%. More than half of all failures occurred in the primary first molar. Class II restorations with the modified cavity preparation had the highest failure rate of 34%, compared to the beveled 8% and the conventional (15%). It is unfortunate that this study has not been repeated with newer adhesives. The results might be surprising.

In conducting this review of the literature, it became obvious that the reporting of clinical trials is woefully inadequate. Often, sample size was reported incorrectly, power analysis was not used, and materials and methods were not listed. Editors may not deem it relevant to list each step in the application of bonding agent or composite resins, for example, but directions change with time and it would be

Table 1. Clinical Studies of Resin-Based Posterior Composites

Year	First author	Observed period (years)	Composite and adhesive used	Sample at recall	Survival rate %	Major failure mechanism
1973	Phillips ¹⁴⁵	3	Adaptic/none	—	—	Wear
1987	Oldenburg ¹⁴⁹	2	Experimental Sybralloy Am	142 120	97 97	Am less wear, failure 4 in each material, composite unacceptable in permanent teeth due to wear
1987	Oldenburg ¹⁵⁰	4	Ful-Fil X-55	62 primary teeth 61 primary teeth	—	Evaluated 3 preparation designs and 2 composites
1988	Wilson ¹⁵¹	5	Occlusion/bonding resin	67	86	Higher failure rate in Class II than Class I
1989	Letzel ¹⁵²	4	Occlusion/bonding resin/amalgam	711	94	Loss of material and recurrent caries
1990	Smales ¹⁵³	3	Visio-Molar P-30	42 251	94 100	Small restorations
1990	Welbury ¹⁵⁴	5	Prisma-Fil and Prisma-Shield	150	95	—
1991	Barnes ¹⁵⁵	5 8	Ful-Fil/ Prisma Bond	32 primary molars 28 primary molars	90 75	Recurrent caries, wear at 8 y premolars=160, molars=213 μm
1991	Barr-Agholme ¹⁵⁶	2	P-30/Scotchbond Dispersalloy	64 primary teeth 55 primary teeth	88 68	Class IIs in primary molars
1992	Wendt ¹⁵⁷	3	Clearfil Photoposterior/ Photobond	60	—	1 recurrent caries all Bravo surface texture
1992	Freilich ¹⁵⁸	3	Heliomolar, Marathon, P-30, experimental composite	105	99	—
1993	Mjör ¹⁵⁹	5	P-10	91	85	—
1993	Dickinson ¹⁶⁰	3	Herculite XR/Bondlite	23	100	Wear, marginal integrity
1995	Wassell ¹⁶¹	3	Brilliant	71	96	—
1997	Geurtsen ¹⁶²	4	Herculite XR/ Bondlite	591 premolars 618 molars	87	Placed in private practice, bulk fracture, 2 nd caries, tooth fracture
1998	Helbig	5	P-50	27	89	Marginal integrity and surface texture
1998	Mair ¹⁶³	10	P-30- Scotchbond, Occlusin (enamel bond), Clearfil Posterior Clearfil Bonding agent + 2 amalgams—New True Dentalloy and Solila Nova	18 20 18	—	P-30 and Occlusin=400 μm wear, Clearfil=300 Clearfil P performed better than the other composites. Am had significantly less wear, placed in dental school, used RD, 1 operator
1988	Vann ¹⁶⁴	4	Ful-Fil	35 primary teeth 44 primary teeth	—	Excessive wear
1999	Raskin ¹⁶⁵	10	Occlusin	100	50-60	Loss of anatomical form and approximal contacts
1999	Scheiben-Bogen ¹⁶⁶	2	Tetric, Pertac-Hybrid Unifil, Blend-a-lux	43	90	Recurrent caries
1999	Wilder ¹⁶⁷	17	Estilux, Nuva-Fil, Nuva-Fil PA, Uvio-Fil	85	76	264 μm wear, most occurred in first 5 y
2000	Manhart ¹⁶⁸	3	Tetric, Pertac-hybrid Unifil, Blend-a-lux	30	87	Recurrent caries
2000	Burgess	5	Z-100/Scotchbond MP	65	92	Margin, fracture
2001	Attin ¹⁶⁹	3	CompoglassTPH-Spectrum/P&B 2.0	46 primary teeth 46 primary teeth	80 86	1 pair of molars in each patient

helpful to have the specific directions used with each study. Bonding agents used should be listed in each report. Failures should be clearly listed and the reasons for the failures examined carefully.

Summary

Resin-based composite is used increasingly for the restoration of defects in posterior teeth. However, these materials are technique sensitive, and overall clinical performance depends upon good case selection and a skilled operator. Properly applying RBC in posterior cavity preparations requires knowledge of adhesives, composites, polymerization kinetics, and the ability to apply those principles to the patient being treated. Composites and their accompanying adhesives are unforgiving compared to silver amalgam. With low- to moderate-carries-risk patients, RBC should be the initial material used to restore a small carious lesion in the posterior region. Flowable or hybrid RBC would be ideal in this situation. Hybrid and packable RBC is indicated for small to large posterior restorations. Compomers should be limited to Class III and Class V restorations in the permanent dentition.

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