

Critical Review on Methacrylate Resin–based Root Canal Sealers

Young Kyung Kim, DDS, PhD,* Simone Grandini, DDS, PhD,[†] Jason M. Ames, DMD,[‡] Li-sha Gu, DDS, MS,[§] Sung Kyo Kim, DDS, PhD,* David H. Pashley, DMD, PhD,^{||} James L. Gutmann, DDS, PhD,[¶] and Franklin R. Tay, BDS (Hons), PhD^{||#}

Abstract

Introduction: Four generations of methacrylate resin–based sealers have been available commercially. Three of these were introduced during the last 5 years when the concept of simultaneous bonding of root canal sealers to root filling materials and dentin was popularized. **Methods:** This article presents an overview of methacrylate resin–based sealers, with the objectives of clarifying the behavior of these materials and delineating their limitations in clinical application. **Results:** The first generation sealer was introduced in the mid-1970s. The initial enthusiasm associated with its use eventually diminished as a result of its suboptimal physical, biologic, and clinical properties. With advances in self-etching adhesive technology acquired from adhesive dentistry, methacrylate resin–based sealers were reintroduced in the beginning of the 21st century to support the introduction of bondable root canal filling materials. Three different generations of these sealers have since been available commercially. Although some *in vitro* studies on the sealing ability, self-etching potential, biocompatibility, and removability of the sealers showed better potential over conventional nonbonding sealers, accomplishing the ideal goal of a monoblock in the root canal space with these materials is still regarded as a major challenge. **Conclusions:** On the basis of the *in vitro* and *in vivo* data available to date, there appears to be no clear benefit with the use of methacrylate resin–based sealers in conjunction with adhesive root filling materials at this point in their development. (*J Endod* 2010;36:383–399)

Key Words

Biocompatibility, evidence-based, fracture resistance, methacrylate resin–based sealers, monoblocks, removability, sealing ability, self-etching potential

Although predictable clinical results have been reported with the use of nonbonding root canal sealers (1, 2), there has been a continuous quest for alternative sealers or techniques that bond simultaneously to canal wall dentin as well as filling materials (3–8). Before the advent of contemporary methacrylate resin–based sealers that are specifically designed for endodontic application (9, 10), there had been sporadic attempts on the use of low viscosity resin composites and dentin bonding agents as sealers for root filling materials, with favorable *in vitro* results (11–16). Indeed, using a citric acid–ferric chloride etchant known as 10:3 solution, Leonard et al (11) were the first to demonstrate the formation of a hybrid layer in radicular dentin with C&B-Metabond (Parkell Inc, Edgewood, NY) in 1996, an adhesive resin composite for bonding of indirect restorations and prostheses. Nevertheless, claims made by research scientists on the potential advantages in bonding to root canals were modest during that era. After the marketing of self-priming, self-etching, and self-adhesive resin luting technologies in restorative dentistry (17, 18), functionally analogous, low viscosity methacrylate resin–based root canal sealers have since been available for use in endodontics after the commercialization of a root filling material that claims to adhere to methacrylate resins. This genre of bondable root canal sealers has been aggressively promoted with the highly desirable property of creating monoblocks within the root canal space (19). The term *monoblock* refers to the scenario wherein the canal space becomes perfectly filled with a gap-free, solid mass that consists of different materials and interfaces, with the purported advantages of simultaneously improving the seal and fracture resistance of the filled canals (3, 4). The most recently introduced self-adhesive type bondable root canal sealers (20–22) are also associated with the additional benefits of reduced application steps and overall improvements in their user friendliness. Accordingly, the objectives of this review were to clarify the behavior of these sealers and to identify, if possible, evidence-based support on the merits of their clinical use.

Methacrylate Resin–based Root Canal Sealers Chronological Classification

To date, 4 generations of methacrylate resin–based sealers have been introduced. The first generation Hydron (Hydron Technologies, Inc, Pompano Beach, FL) appeared in the mid-1970s (23–25) when scientific foundations behind dentin bonding were at their infancy stage of development (26). The use of poly[2-hydroxyethyl methacrylate] (poly[HEMA]) as the major ingredient (27) rendered the sealer very hydrophilic.

From the *Department of Conservative Dentistry, School of Dentistry, Kyungpook National University, Daegu, Republic of Korea; [†]Department of Endodontics and Restorative Dentistry, University of Siena, Siena, Italy; [‡]Private Endodontic Practice, Warner Robins, Georgia; [§]Department of Operative Dentistry and Endodontics, Guanghua School of Stomatology, Sun Yat-sen University, Guangzhou, China; ^{||}Department of Oral Biology, School of Dentistry, Medical College of Georgia, Augusta, Georgia; [¶]Department of Endodontics, Baylor College of Dentistry, Texas A&M University System Health Science Center, Dallas, Texas; and [#]Department of Endodontics, School of Dentistry, Medical College of Georgia, Augusta, Georgia.

Address requests for reprints to Dr Franklin Tay, Department of Endodontics, School of Dentistry, Medical College of Georgia, Augusta, GA 30912-1129. E-mail address: ftay@mcg.edu.

0099-2399/\$0 - see front matter

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doi:10.1016/j.joen.2009.10.023

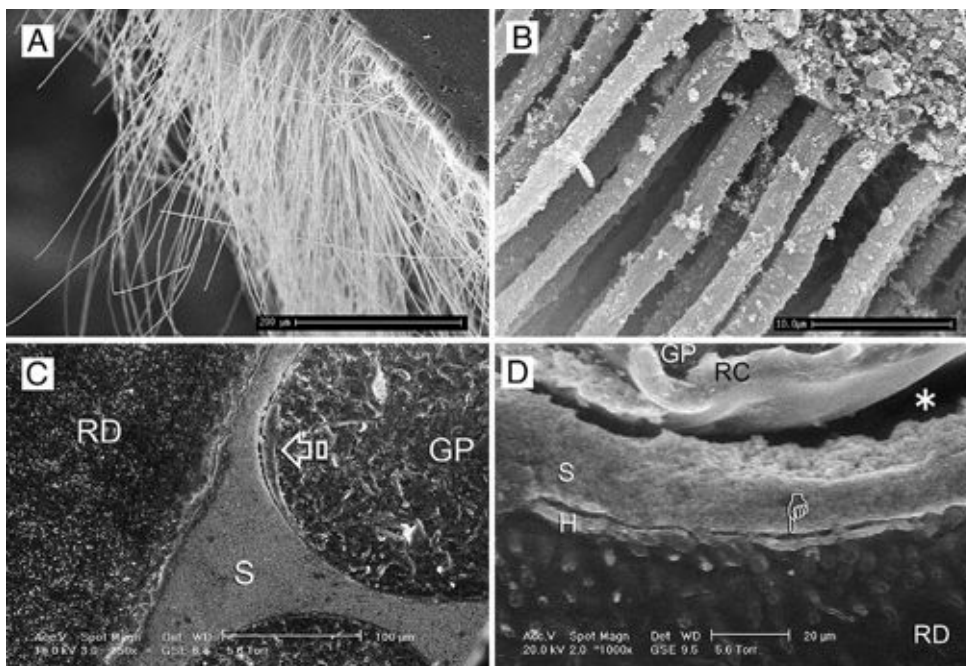


Figure 1. (A) Scanning electron microscopy (SEM) image (150 \times) taken from the coronal third of a NaOCl/EDTA-irrigated root canal. The latter was filled under moist conditions (43) with the EndoREZ sealer. The radicular dentin was demineralized and deproteinized to expose the extent of resin infiltration into the dentinal tubules. (B). High magnification SEM (2000 \times) of the resin tags shown in the previous image. (C) Environmental SEM (ESEM) image (350 \times) taken from a non-dehydrated root section that was filled with EndoREZ sealer (S) and resin-coated gutta-percha (GP). Only a fraction of the circumference of the gutta-percha cone was surrounded by the resin coating (open arrow). RD, radicular dentin. (D) High magnification ESEM image (1000 \times) of the previous image showing the presence of a thin hybrid layer (H) along the surface of the radicular dentin (RD) that was created after the use of 17% EDTA as the final irrigant. Despite the presence of profuse resin tag formation, a gap (pointer) could be seen between the hybrid layer and the sealer (S). Likewise, a larger gap (asterisk) could be identified between the sealer and the resin coating (RC) of the gutta-percha (GP) cone.

Hydron was designed to be injected into a root canal and to be polymerized *in situ* for en masse root filling. It was reported to be (1) easy to use because of its injectability, (2) nonirritating, (3) highly adaptable to the canal walls, (4) non-supportive of bacterial growth, and (5) able to be calcified in the event of inadvertent extrusion of the sealer into the periapical regions (24, 28). However, the sealer came to a disastrous end and became obsolete in the 1980s because discrepancies between the manufacturer's claims and laboratory/clinical findings on its physical/clinical properties and biocompatibility became apparent soon after its commercialization (29–32). The sealer caused severe inflammatory reaction (29), absorption of the material (30), severe leakage (31), as well as water sorption and swelling (32).

The second generation of bondable sealer (33–35) is nonetching and hydrophilic in nature and does not require the adjunctive use of a dentin adhesive. It is designed to flow into accessory canals and dentinal tubules to facilitate resin tag formation for retention and seal after smear layer removal with NaOCl and ethylenediaminetetraacetic acid (EDTA) (36). EndoREZ (Ultradent Products Inc, South Jordan, UT) is a dual-cured radiopaque hydrophilic methacrylate sealer (34–37) that might be used in the wet environment of the root canal system and is very effective in penetrating dentinal tubules and adapting closely to the canal walls (Fig. 1A and B). Although EndoREZ is recommended for use with either a conventional gutta-percha cone or with specific EndoREZ points (resin-coated gutta-percha) (Fig. 1C and D), low bond strength to the dentinal wall was reported with conventional uncoated gutta-percha (38). To facilitate rapid cure of EndoREZ, an accelerator that is compatible with EndoREZ has recently become available (39).

To simplify bonding procedures, new generations of self-etching (third generation) and self-adhesive (fourth generation) luting resin composites have been introduced to restorative dentistry during the

last 5 years. Similar generations of root canal sealers became commercially available shortly after the introduction of those luting resin composite systems. The third generation self-etching sealers contain a self-etching primer and a dual-cured resin composite root canal sealer. The use of self-etching primers reintroduced the concept of incorporating smear layers created by hand/rotary instruments along the sealer-dentin interface (40–42). An acidic primer is applied to the dentin surface that penetrates through the smear layer and demineralizes the superficial dentin. The acidic primer is air-dried to remove the volatile carrier, and then a dual-cured, moderately filled flowable resin composite sealer is applied and polymerized. Provided that these materials are sufficiently aggressive to etch through thick smear layers (43), the technique sensitivity of bonding to root canals might be reduced when smear layers are inadvertently retained in the apical third of instrumented canal walls.

FibreFill R.C.S. root canal sealant (Pentron Clinical Technologies, Wallingford, CT) is an example of a third generation methacrylate resin-based sealer that is designed for filling canals with fiber-reinforced obturators that are attached to thermoplastic root filling material tip. The resin sealer is used in combination with a self-cured, self-etching primer system (FibreFill Primer A and B). Bonding between adhesive systems and dentin depends on the penetration of monomers into the conditioned dentin surface to create micromechanical interlocking between the dentin collagen and resin, forming a hybrid layer. FibreFill R.C.S. is reported to have good sealing (10, 44, 45) and adhesive properties (46) to radicular dentin.

Another third generation methacrylate resin-based sealer that incorporates the use of self-etching primers became commercially available with the introduction of Resilon (Resilon Research LLC, Madison, CT), a dimethacrylate-containing polycaprolactone-based

thermoplastic root filling material (47). For the Epiphany (Pentron Clinical Technologies), RealSeal (SybronEndo, Orange, CA), Resinate (Obtura Spartan Corp, Fenton, MO), and Smart (Discus Dental, Culver City, CA) systems, the self-etching primers are further reduced from a 2-bottle system to a single-bottle system. These self-etching primers/adhesives mostly contain 2-acrylamido-2-methyl-propanesulfonic acid (AMPS) as the functional acidic monomer (48). In the single-bottle type self-etching primer, the functional acidic monomers, solvents, water that is necessary for ionization of the acidic monomers, and self-cured catalysts are incorporated into “one-component” (ie, incorporated inside a single bottle). This is similar to the so-called one-component type all-in-one adhesives that are currently available in restorative dentistry. By combining self-etching adhesives and methacrylate resin-based sealers with Resilon, the manufacturer introduced what they advertised as “a new era” in root canal obturation (4, 49, 50). An ethoxylated bisphenol-A-dimethacrylate (EBPADMA)-based resinous solvent (eg, RealSeal Thinning Resin, SybronEndo) is also included in these systems to adjust the sealer viscosity. However, addition of the thinning solvent to the sealer without photoactivation did not increase adhesion to dentin (51).

The fourth generation methacrylate resin-based sealers (eg, MetaSEAL, Parkell Inc; RealSeal SE, SybronEndo) are functionally analogous to a similar class of recently introduced self-adhesive resin luting composites in that they have further eliminated the separate etching/bonding step (52). Acidic resin monomers that are originally present in dentin adhesive primers are now incorporated into the resin-based sealer/composite to render them self-adhesive to dentin substrates. The combination of an etchant, a primer, and a sealer into an all-in-one self-etching, self-adhesive sealer is advantageous in that it reduces the application time as well as errors that might occur during each bonding step. MetaSEAL is the first commercially available fourth generation self-adhesive dual-cured sealer (53, 54). The inclusion of an acidic resin monomer, 4-methacryloyloxyethyl trimellitate anhydride (4-META), makes the sealer self-etching, hydrophilic, and promotes monomer diffusion into the underlying intact dentin to produce a hybrid layer after polymerization. The sealer purportedly bonds to thermoplastic root-filling materials as well as radicular dentin via the creation of hybrid layers in both substrates. MetaSEAL is also marketed as Hybrid Bond SEAL (Sun Medical Co Ltd, Shiga, Japan) in Japan and had been reported to produce similar or slightly inferior sealing properties as conventional nonbonding epoxy resin-based sealers (55, 56).

The idea of incorporating 4-META as a resin monomer component for root canal sealers is not new. Endoresin-2 was similar to Hydron because it was designed to be used as an injectable type of en masse root filling material rather than a root canal sealer (57, 58). SuperBond RC Sealer (Sun Medical Co Ltd) is a liquid-and-powder type sealer. Its polymer powder consists of the same constituents as the commercialized Polymer (L-Type radiopaque) in Super-Bond C&B resin (Sun Medical Co Ltd). Reports claim that it possesses reasonable sealing ability when compared with conventional root canal sealers (59, 60).

RealSeal SE is the simplified dual-cured version of RealSeal and uses a polymerizable methacrylate carboxylic acid anhydride (ie, 4-META) as the acidic resin monomer (20–22). It might be used with Resilon cones or pellets by using cold lateral or warm vertical techniques or with the more recently introduced RealSeal 1 (SybronEndo), a carrier-based Resilon obturator system (61).

Reality Check on Contemporary Methacrylate Resin-based Sealers

The predominant adhesive mechanism of methacrylate resin-based sealers to radicular dentin is micromechanical retention of resins

that infiltrated the partially demineralized collagen matrix. Thus, effective bonding in the root canal environment remains a challenge. This is due to the limited vision and access even with the use of an operating microscope, the preponderance of sclerotic dentin along the apical part of the root canal (62), differences in regional bond strengths (63), debris on the canal wall (64–66), and high cavity configuration factor (C-factor) (3, 63, 67, 68) inside long narrow canals. Under these circumstances, the sealing performance of thin films of low viscosity resin sealers might be severely jeopardized (38, 69). Therefore, a number of issues are raised in this review to highlight the problems that might be expected in application of methacrylate resin-based sealers.

Can Methacrylate Resin-based Sealers Create Adequate Retention in Radicular Dentin to Prevent Disruption of Sealing Integrity During Polymerization?

Recent studies regarding the limited aggressiveness of contemporary self-etch and self-adhesive resin composites (33, 70, 71) raised similar concerns on the true self-etching potential of self-etching and self-adhesive sealers to hybridize intact radicular dentin. Mechanically prepared canals contain areas that are inaccessible by currently used endodontic instruments (72). Moreover, canal irrigants might not reach all parts of the canal space (73, 74). This results in retention of debris and smear layers along the apical third of the canal walls and isthmi (75–77). Thus, the true etching potential of self-etching and self-adhesive sealers is an important criterion for achieving adequate bonding to radicular dentin in the absence of adjunctive demineralization of canal wall dentin contributed by calcium chelating root canal irrigants (72, 78) (Fig. 2).

Removal of the smear layer with EDTA as the final rinse is recommended by manufacturers of methacrylate resin-based sealers to reduce leakage and improve the seal of filled canals. Thus, the retention mechanisms suggested by the manufacturers of methacrylate resin-based root canal sealers (ie, dentin hybridization and profuse resin tag formation) are likely to be contributed by the combined dentin demineralization effects of EDTA (78) and the sealer system. MetaSEAL (20, 21) and RealSeal SE (20, 22) are unable to etch beyond thick smear layers created by rotary nickel-titanium instruments into the underlying intact radicular dentin in the absence of the adjunctive use of EDTA as a calcium chelating irrigant. Conversely, RealSeal possesses mild etching ability on smear layer-covered radicular dentin (22). When EDTA was used as the final rinse, the smear layer was completely dissolved, and a thin layer of partially demineralized dentin could be identified on the intact dentin surface, irrespective of whether the sealer is non-etching (EndoREZ) or self-etching (RealSeal, MetaSEAL, and RealSeal SE) (20–22). Contrary to the manufacturers' claims, neither the second nor the fourth generation sealers are likely to bond well to radicular dentin if EDTA is not used to remove the smear layer and smear plugs, or when EDTA does not reach the apical third of the canal walls. Inadequate dentin hybridization might also occur in the calcospherite-containing noninstrumented dentin for those clinicians who elect to use NaOCl as the only active root canal irrigant.

How Strong Is Resin Adhesion Inside Root Canals?

A major problem associated with bonding inside root canals is the challenge to relieve the shrinkage stresses created on the canal walls of these long narrow “cavities” during polymerization of resin sealers (79–81). Polymerization shrinkage, which is more severe in sparsely filled, low viscosity root canal sealers, can disrupt the close initial contact between the sealer and the surrounding dentin and create shrinkage gaps where microorganisms can penetrate and multiply. In view of the high probability for imperfect dentin bonding in root canals

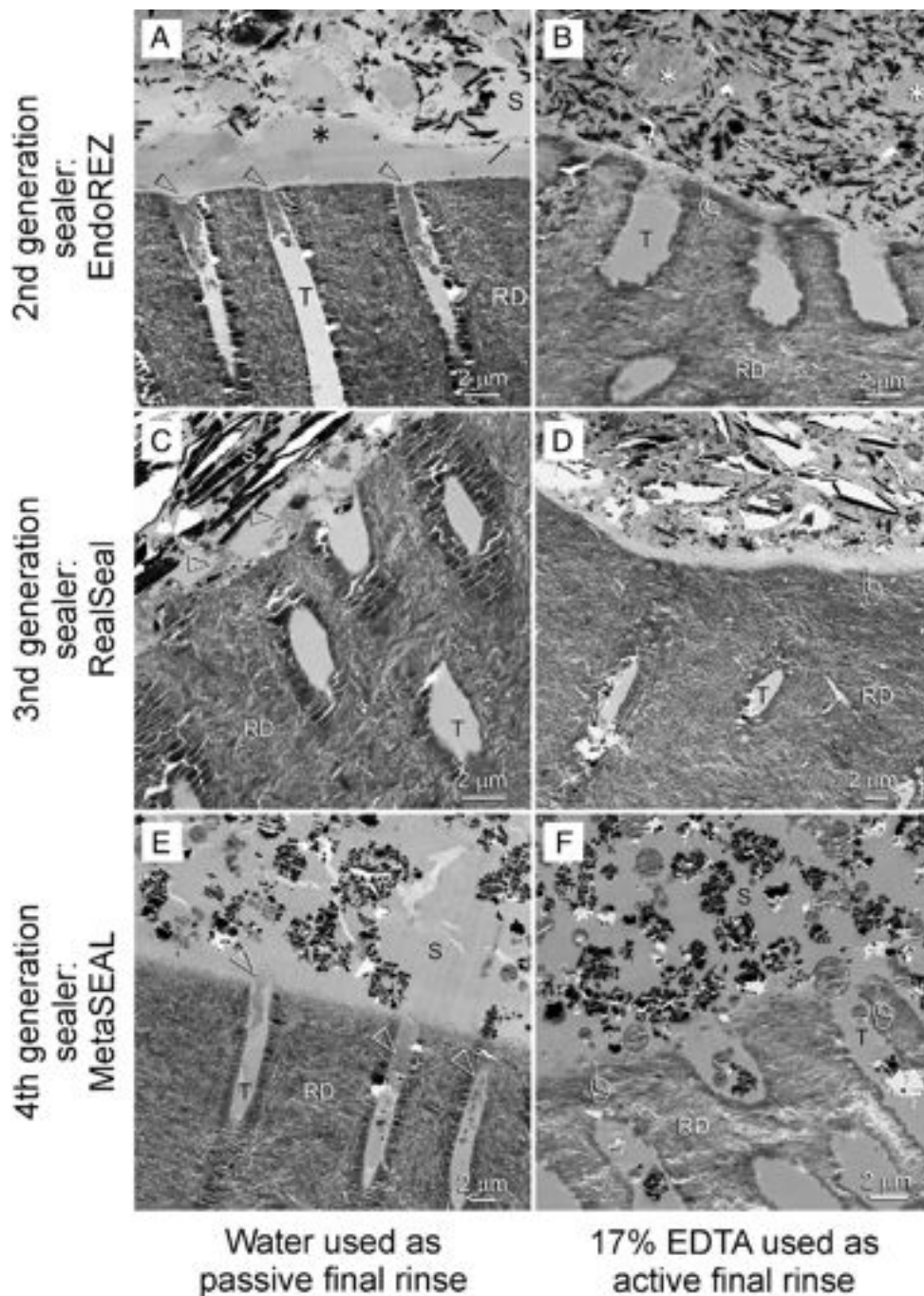


Figure 2. Transmission electron microscopy images of radicular dentin (2000 \times) that had been rinsed with 6.15% NaOCl as the initial irrigant. For images in the left column (A, C, and E), the dentin was rinsed with distilled water as the passive final irrigant. For images in the right column (B, D, and F), the dentin was rinsed with 17% EDTA as the active final irrigant. S, sealer; T, dental tubule; RD, radicular dentin. (A) Without EDTA, application of EndoREZ (second generation) to moist dentin did not remove smear plugs (open arrowheads), and hence no resin tags were produced. The sealer separated from the dentin surface, creating an artifactual gap (asterisk). Part of the smear layer could be seen on the surface of the separated sealer (arrow). (B) Smear plugs were effectively removed after the use of EDTA, enabling EndoREZ to form resin tags within the dentinal tubules. A hybrid layer (pointer) was produced on the dentin surface. Application of EndoREZ to moist dentin resulted in phase separation of the hydrophobic resin component (asterisk). (C) Without EDTA, the use of a separate self-etching primer in RealSeal (third generation) resulted in partial dissolution of the smear layer (open arrowheads) and smear plugs. No hybrid layer could be seen. (D) A 2- μ m-thick hybrid layer was created by the combined effect of EDTA irrigation and application of the RealSeal primer. (E) Without EDTA, the mild, self-etching MetaSEAL (fourth generation) did not completely dissolve the smear layer and smear plugs (open arrowhead). (F) After dissolution of the smear layer and smear plugs by EDTA, MetaSEAL created a thin hybrid layer (pointers) and penetrated patent dental tubules to produce filler-containing resin tags.

and the high volumetric shrinkage (80), slow polymerization of the dual-curable sealers would improve the chance for the relief of shrinkage stress via resin flow. Indeed, the manufacturers of methacrylate resin-based sealers have taken this issue into consider-

ation. The slow self-curing mechanism of some of these sealers is supposed to promote stress relief via prolonged gelation time during the initial setting stage. However, *in vitro* studies comparing the push-out strengths of various root filling materials to radicular dentin

invariably showed that roots obturated with bondable root filling material/methacrylate resin–based sealer combinations had, surprisingly, significantly lower push-out strengths than gutta-percha/conventional nonbonding sealer combinations (8, 53, 82–86). Resilon/Epiphany (RealSeal)-filled canals also contained significantly more voids and gaps than those filled with gutta-percha and conventional sealers (87) (Fig. 3). More importantly, when filled canals were subjected to occlusal loading that simulated the behavior of the sealer-dentin interface under cyclic functional stresses, Resilon/RealSeal obturated canals exhibited significantly greater interface disruption when compared with unloaded controls (88). Several factors could have accounted for the suboptimal sealing properties of methacrylate resin–based sealers inside root canals. Pulling of resin sealer tags out of the tubules during polymerization shrinkage of the sealer might create gaps along the sealer-dentin interface (89). Heat generation during warm vertical compaction and searing of the sealer from the canal orifices with a heat source could have expedited the setting of the sealers, defeating the purpose of incorporating delayed polymerization mechanisms and preventing relief of polymerization stresses by slow flow (53, 83). The manufacturer's instruction for immediately light-curing the coronal part of the root filling to create a coronal seal might also limit flow of resin sealer (90). In addition, manipulation of the partially polymerized sealer during compaction of the root filling materials might disrupt the developing bonds between a self-etching primer and radicular dentin (91).

Although unfavorable laboratory results have been reported in some studies on the use of methacrylate resin–based sealers, other studies have demonstrated that they showed significantly higher bond strength to dentin and more consistent sealer penetration into the dentinal tubules than zinc oxide–eugenol (ZOE)–based sealers (92, 93). Patel et al (94) compared the dentinal tubule penetration of RealSeal and Tubliseal (Sybron Kerr, Orange, CA) with rhodamine B isothiocyanate dye labeling. The authors found that laterally-compacted RealSeal had significantly more sealer penetration into dentinal tubules than Tubliseal in all canal thirds. Longer sealer tag formation, however, cannot be taken as an indicator of a better seal. Rather, the length of the sealer tags is a function of their chemical and physical characteristics (95, 96).

Different experimental modifications have been designed for improving the adhesion of methacrylate resin–based sealers to radicular dentin. For example, an adhesive-modified technique has been proposed to improve the adhesive strength of EndoREZ to dentin (97, 98). The adjunctive use of a dual-cured self-etch adhesive for simultaneously etching and priming dentin before the application of the EndoREZ sealer was found to create more definitive hybrid layers, higher tensile bond strength to dentin, and less leakage. Another experimental modification is the adaptation of indirect dentin bonding techniques used for bonding inlays and crowns to bonding within root canals (8). A self-etching adhesive was first polymerized inside the root canal with the aid of a Teflon plugger. Because there was no bonding between the Teflon plugger and the adhesive, stress relief was achieved by unlimited flow, in spite of the extremely high C-factor within a root canal. The acrylic point was then bonded in a manner analogous to the bonding of an inlay by using additional adhesive resin.

Do Methacrylate Resin–based Sealers Prevent Leakage?

Leakage continues to be a major reason for failure in root canal therapy. Although the clinical relevance of *in vitro* leakage studies has been severely challenged, these studies constitute a significant part of the current literature on methacrylate resin–based sealers and cannot be ignored in a review article, particularly in view of the

scarcity of evidence-based clinical outcome studies on this topic. A summary of the different types of leakage studies (9, 10, 34, 49, 55, 91, 98–129) used to examine leakage in roots filled with methacrylate resin–based sealers is listed in Table 1. The data are also graphically represented in Fig. 4.

Ideally, a root canal filling material should provide a barrier that prevents bacterial ingress from the oral cavity. The Resilon/Epiphany system is reported to establish an immediate coronal seal after light-curing of the dual-cured sealer at the canal orifices. An immediate coronal seal is clinically advantageous because there are situations in which filled root canals might be exposed to the oral environment and subject to bacterial recontamination (34). Indeed, Resilon/Epiphany sealer group leaked significantly less than all groups in which AH 26 was used as a sealer for gutta-percha or Resilon (49). Both EndoREZ/resin-coated gutta-percha and Epiphany/Resilon were found to provide better coronal seal when the respective sealer was used on moist canal wall dentin when compared with the use of a ZOE-based sealer/gutta-percha (34). However, these findings are in contrast with the results that demonstrated the Resilon/Epiphany system exhibited more leakage than the use of a glass ionomer intraorifice barrier (127) and was not better than gutta-percha/conventional sealers in preventing coronal leakage (110). It is known that polymers degrade over time through physical and chemical processes (130). As the bond degrades, interfacial leakage increases, which resembles *in vivo* aging (124, 129). In addition, Resilon is susceptible to alkaline (131) and enzymatic (132) hydrolysis. Therefore, biodegradation of Resilon by bacterial/salivary enzymes (133) and endodontically relevant bacteria might occur in the event of apical or coronal leakage, further compromising the seal achieved after root canal treatment. Bacterial degradation of gutta-percha also occurs with the bacteria using poly(trans-1,4-isoprene) as the sole carbon and energy source for growth (134). However, such a process is seen only in the genus *Nocardia* (128), which is found mostly in soil and is not a recognized endodontic pathogen. Gutta-percha can be decomposed by the heat generated with the use of warm vertical compaction techniques (135). However, decomposition of gutta-percha components had only been detected by using chemoanalytical methods. The decomposition of gutta-percha is a slow oxidative process that has been detected chemically from gutta-percha retrieved from 5- to 15-year-old retreatment cases (136). Apart from chemical detection of breakdown products, there was no radiographic documentation of the disappearance of gutta-percha from filled canals.

Does Adhesion Exist between Core Materials and Sealers to Create a Monoblock?

The entrepreneurial concept of creating a root canal monoblock to achieve a total bond and hence a total seal of the canal space has been hampered by the lack of chemical union between the polyisoprene component of gutta-percha and methacrylate-based resins. To circumvent this problem, several strategies have been used. The first commercialized strategy was introduced by coating gutta-percha cones with a polybutadiene-diisocyanate-methacrylate adhesive (137). This proprietary adhesive resin includes a hydrophobic portion that is chemically compatible with the hydrophobic polyisoprene substrate and a hydrophilic portion that is chemically compatible with a hydrophilic methacrylate resin. With the use of this adhesive resin coating, a strong chemical union is achieved between the gutta-percha and the methacrylate resin–based sealer. This thermoplastic resin-coated gutta-percha cone is recommended for use with the EndoREZ system (39).

The second commercialized strategy uses a polycaprolactone and dimethacrylate-containing resin blend to form a filled thermoplastic

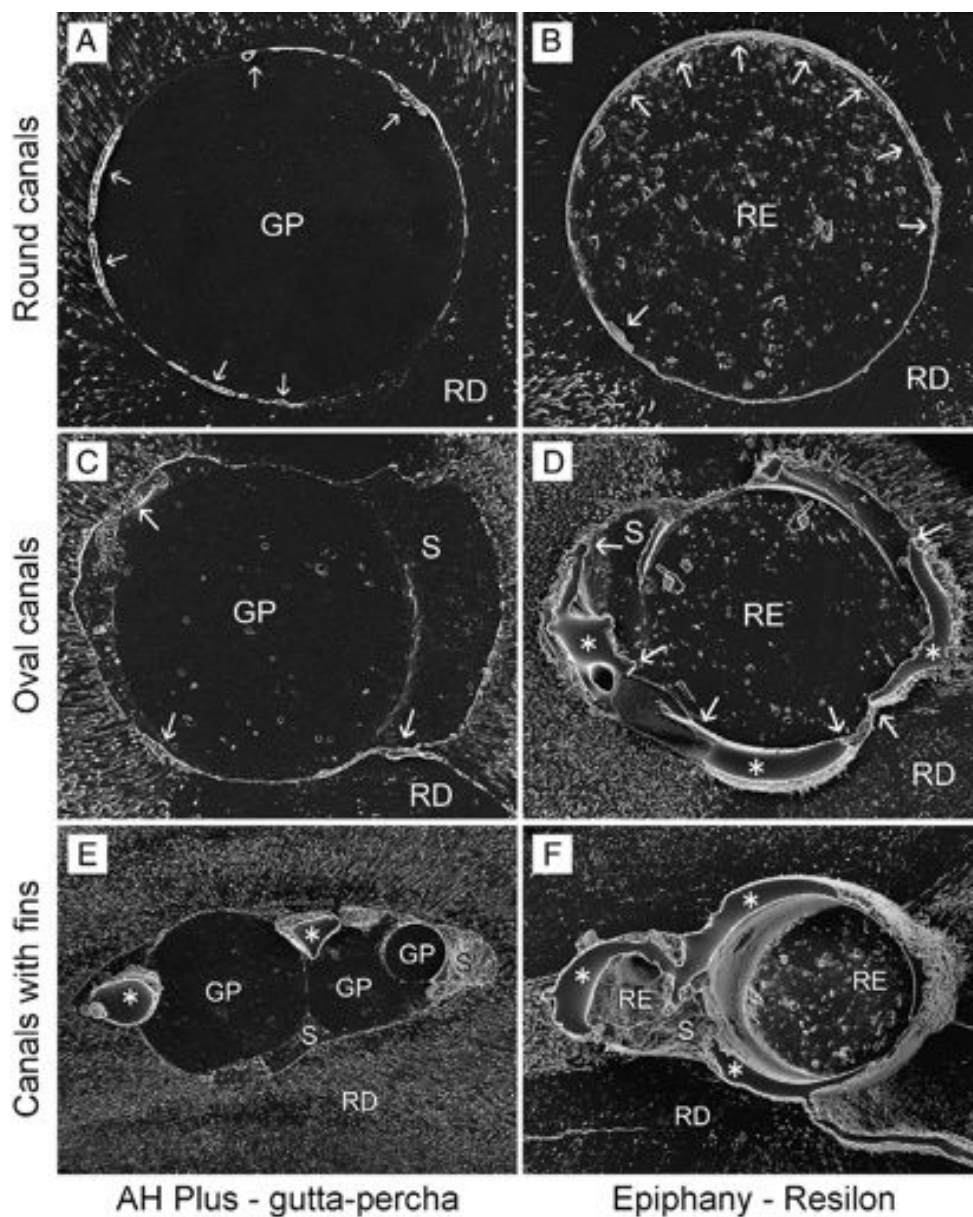


Figure 3. SEM images taken from polyvinylsiloxane impressions of root canal sections of round canals (A and B), oval-shaped canals (C and D), and roots containing postinstrumentation canal fins (E and F) that were filled with AH Plus/gutta-percha (left column) or Epiphany/Resilon (right column) by using a cold lateral compaction technique. Sections were taken at 5 mm coronal to the anatomic apex of each canal and were brought into relief with a 2-minute application of EDTA before impression taking. With the use of a negative replica technique, gaps could be recognized as impression materials that protruded from the impression surface. GP, gutta-percha; RE, Resilon; S, sealer; RD, radicular dentin; arrows, gaps between the sealer and dentin; pointer, gaps between the sealer and the filling material; asterisk, more extensive gaps in which the impression material appeared blunted because the latter could not penetrate the entire depth of the gap in a root canal section.

composite (Resilon) that replaces gutta-percha as an alternative root filling material (47). An experimental strategy has also been developed by using a zinc oxide-filled thermoplastic polyurethane composite root canal-filling material and a light-cured urethane-acrylate/tripropylene glycol diacrylate root canal sealer (138, 139). Another experimental system uses ethylene vinyl acetate (EVA) as the major thermoplastic component of an alternative root filling material (140) together with a dimethacrylate-conjugated fluorene monomer (141) for potential bonding to methacrylate resin-based sealers.

The introduction of adhesive endodontics offers promise of adhesion to root dentin but also creates problems (3). For the second gener-

ation EndoREZ system, gaps and silver leakage were identified between the gutta-percha resin coating and the EndoREZ sealer, even though a thin layer of hybridized dentin created by EDTA demineralization could be identified together with long resin tags (36). When considering that the interface between the gutta-percha resin coating and the resin sealer is the only truly bondable interface in this system, this interface is a weak link that failed during polymerization shrinkage of the sealer. The chemical union between the polyisoprene component of the gutta-percha and the polybutadiene end of the resin coating molecule appears to be stronger than the coupling between the methacrylate end of the molecule to the resin sealer (Fig. 1D). Removal of the oxygen

TABLE 1. *In vitro* Leakage Studies Associated with the Use of Methacrylate Resin–based Sealers

Results claimed by authors	Studies (reference)	Type of leakage	Sample size	Period of aging	
Methacrylate resin–based sealers seal better than conventional sealers	Economides et al (10)	Fluid filtration	60	2 months	
	Shipper et al (49)	Bacterial leakage	156	30 days	
	Shipper et al (99)	Bacterial leakage	56	14 weeks	
	Zmener et al (100)	Dye leakage	45	7 days	
	Aptekar and Ginnan (101)	Dye leakage	105	3 months	
	Tunga and Bodrumlu (102)	Fluid filtration	66	Immediate	
	Sagsen et al (103)	Fluid filtration	36	Immediate	
	Stratton et al (104)	Fluid filtration	140	Immediate	
	Adanir et al (105)	Fluid filtration	80	Immediate	
	Wedding et al (106)	Fluid filtration	46	90 days	
	Verissimo et al (107)	Dye leakage	70	7 days	
	Bodrumlu et al (108)	Fluid filtration	72	Immediate	
	Zmener et al (34)	Dye leakage	76	7 days	
	Shin et al (109)	Bacterial leakage	160	4 weeks	
	Tay et al (91)	Dye leakage	20	3 hours	
	No difference between methacrylate resin–based sealers and conventional sealers	Pitout et al (110)	Dye leakage, bacterial leakage	110	72 hours, 3 months
		Biggs et al (111)	Fluid filtration	96	Immediate
Shemesh et al (112)		Fluid filtration, glucose penetration	70	Immediate, 4 weeks	
Kaya et al (113)		Glucose penetration	156	30 days	
De-Deus et al (114)		Bacterial leakage	70	9 weeks	
Baumgartner et al (115)		Bacterial leakage	36	50 days	
Raina et al (116)		Fluid filtration	22	Immediate	
Belli et al (55)		Fluid filtration	24	24 weeks	
Lyons et al (117)		Bacterial leakage	80	28 days	
Williamson et al (118)		Bacterial leakage	70	40 days	
Methacrylate resin–based sealers seal worse than conventional sealers	Kardon et al (9)	Fluid filtration	64	Immediate	
	Bouillaguet et al (119)	Dye leakage	20	48 hours	
	Sevimay and Kalayci (120)	Dye leakage	55	7 days	
	Orucoglu et al (121)	Fluid filtration	45	Immediate	
	Gillespie et al (98)	Fluid filtration	55	Immediate	
	Onay et al (122)	Fluid filtration	70	Immediate	
	da Silva Neto et al (123)	Fluid filtration	60	60 days	
	Paqué and Sirtes (124)	Fluid filtration	90	16 months	
	Gernhardt et al (125)	Dye leakage	72	7 days	
	Pasqualini et al (126)	Bacterial leakage	88	47 days	
	Jack and Goodell (127)	Fluid filtration	34	Immediate	
	De-Deus et al (128)	Fluid filtration	40	14 months	
	Kokorikos et al (129)	Fluid filtration	96	12 months	

These studies were used for preparing the pie chart in Fig. 4.

inhibition layer (142) from the surface of resin-coated gutta-percha cones during packaging has been hypothesized for their weak adhesion to the methacrylate resin–based root canal sealer, resulting in their frequent delamination from the sealer after root canal obturation. Hiraiishi et al (143) attempted to improve the shear strength of the resin-coated gutta-percha to the EndoREZ sealer by generating active free radicals for chemical coupling via *in situ* application of a dual-cured dentin adhesive to the resin-coated gutta-percha. They observed a 5-fold increase in shear strength after adhesive application, with complex interfacial failures instead of complete sealer delamination from the resin coating.

The adhesive strength of Resilon to a third generation methacrylate resin–based sealer was 4–5 times lower than the bond strength of a composite resin to the same sealer (144), suggesting that the coupling of methacrylate resin–based sealers to Resilon is very weak. Indeed, as surface roughness of the Resilon root filling material increased, the contribution by micromechanical retention eventually exceeded the contribution by chemical coupling (145). This occurrence might be attributed to the phase separation of the emulsified dimethacrylate

phase within a continuous polycaprolactone phase (145). Likewise, the amount of dimethacrylate incorporated in Resilon might not yet be optimized for effective chemical coupling to methacrylate resin–based sealers (144, 145). Surprisingly, the bond strength of Epiphany to Resilon was reported to be lower than the bond strength of AH 26, an epoxy resin–based sealer to Resilon (146).

The fourth generation self-adhesive type root canal sealers are still relatively new, and detailed information on their adhesive properties to root filling materials is limited or lacking. For the 4-META containing sealer MetaSEAL, a recent report identified a hybrid layer-like structure along the gutta-percha–sealer interface (147). However, no data are currently available on the adhesive strength of MetaSEAL to gutta-percha via this hybrid layer-like interface.

Taken together, these data suggest that the chemical coupling between contemporary methacrylate resin–based sealers to root filling materials is generally weak or insufficiently optimized. In view of the extremely high C-factor encountered in long, narrow root canals (68), it is doubtful whether the core material–sealer bond is capable of resisting polymerization shrinkage stresses that develop during the

Do methacrylate resin-based sealers provide better apical/coronal seal over conventional non-bonding root canal sealers?

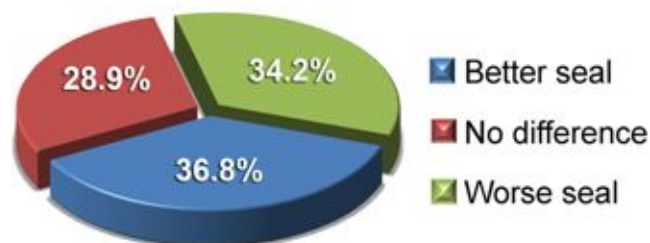


Figure 4. A pie chart summarizing the results of *in vitro* studies (Table 1) that compared the extent of leakage between teeth that were filled with methacrylate resin-based sealers versus conventional nonbonding sealers.

setting of the resin sealer to permit the realization of the goal of creating a monoblock in the root canal system.

Do Methacrylate Resin-based Sealers Strengthen Roots?

The combined use of self-etching or self-adhesive methacrylate resin-based sealers and bondable root filling materials would increase the fracture resistance of filled canals. This hypothesis was tested by Teixeira et al (6). They showed that roots filled with Resilon/Epiphany exhibited significantly higher fracture load values than those filled with gutta-percha/AH 26 when the specimens were subjected to vertical loading forces. This finding was supported by other studies that demonstrated that roots filled with methacrylate resin-based sealers exhibited higher resistance to fracture than those filled with gutta-percha and sealers (148, 149). However, opposing results were reported by other studies showing that bondable root filling materials did not improve the overall mechanical properties of the root dentin (150–159). In those studies, the combined use of Epiphany (RealSeal)/Resilon was unable to reinforce endodontically treated teeth against horizontal fracture forces (150, 152, 154, 155) as well as vertical loading forces (151, 156–158). Wilkinson et al (152) found that mean fracture loads of Epiphany/Resilon and AH Plus/gutta-percha groups were not significantly different from the positive controls, which were instrumented but not obturated with either a sealer or a root filling material.

Two criteria should be considered in analyzing the results of studies on fracture resistance. The first criterion is that comparisons should be made with an appropriate positive control. For example, in the study by Hammad et al (148), Epiphany and EndoRez groups showed significantly higher fracture loads than gutta-percha and Gutta-Flow (Coltène/Whaledent Inc, Cuyahoga Falls, OH) groups. However, it is not clear whether this result indicates obturation with Epiphany/EndoRez sealers, and the respective root filling materials could strengthen instrumented roots with enlarged canals because the comparison with the unfilled control was not performed in that study.

The other criterion is that filled experimental groups should not yield results that are significantly lower than those derived from the positive control (ie, unfilled instrumented roots). In general, instrumentation of root canals significantly weakens the root structure and renders the root more susceptible to fracture (160–162), although Jainaen et al (157) reported that there was no significant difference between sound dentin and prepared dentin in their resistance to vertical root fracture. Thus, only studies showing higher fracture loading in filled roots than the unfilled control should be regarded as demonstrating increased fracture resistance. In a study that investigated the fracture

properties of resin-infiltrated root dentin, roots filled with a methacrylate resin-based sealer resulted in a significantly lower work of fracture (W_f , the work required to form a new surface of unit area in dentin itself) than the positive control in fractures that were initiated from an inner to outer direction. The result implied that the material was unable to reinforce roots against fracture (159). The authors recognized that the reason for this erroneous result was unknown. Presumably, the result reflects more of the operators' error in handling the materials rather than the properties of the material per se. Analyses of the studies on fracture resistance are summarized in Table 2, and the results of those studies satisfying the 2 aforementioned criteria are represented graphically in Fig. 5.

Collectively, currently available methacrylate resin-based sealers and their recommended adhesive procedures are not able to influence the mechanical properties of root canal dentin. This conclusion might be due to the following factors: (1) polymerization that occurred along the sealer-dentin interface in the coronal part of the root is possibly affected by oxygen inhibition (163); (2) creeping of incompletely polymerized resinous sealers, which results in failure along the sealer-dentin interface (164); (3) presence of residual monomers in the root canals (165); and most importantly, (4) the low cohesive, tensile, compressive strengths and modulus of elasticity of the currently available root filling materials when compared with dentin, with the former behaving as elastomers that dissipate instead of transmitting stresses (157, 166). In addition, the extremely unfavorable cavity geometry (ie, C-factor) of root canals causes gaps along the dentin/sealer interface during polymerization of the methacrylate resin-based sealers (19).

Are Methacrylate Resin-based Sealers Biocompatible?

Although root canal sealers are intended to be contained only within the canal space, they might be extruded through the apical constriction or other avenues of communication with the periodontal ligament space during placement (167, 168). The tissue response to these materials might influence the final outcome of root canal treatment (169). Contact of extruded sealers might result in irritation of the periradicular tissues and delayed wound healing (170, 171). Thus, the biocompatibility of root canal sealers is critical to the success of root canal treatment (172).

EndoREZ was found to be well-tolerated by connective tissues (173, 174) and bone tissue (175). Although it is reported to have minimal cytotoxic effects when freshly mixed or after setting (176), these favorable findings were not supported by Bouillaguet et al (119) and Scarparo et al (177). Their results indicated that EndoREZ had a more intense and longer-lasting inflammation in subcutaneous connective tissue of rats than AH Plus sealer. Moreover, the authors found that EndoREZ became more cytotoxic with increased exposure time to the cell culture medium.

The cytotoxicity profile of MetaSEAL revealed that it remained severely cytotoxic during the first week, whereas an epoxy resin-based sealer became only moderately cytotoxic after the same period. Both sealers eventually became non-cytotoxic (54). The same finding was also observed in the Epiphany sealer (178). Generally, the freshly mixed condition might be more relevant to clinical use because unset sealers are placed into the canals.

Other studies that evaluated the cytotoxicity of Epiphany and Real-Seal produced highly variable results. Sousa et al (179) observed bone formation and only minor inflammatory reactions in guinea pigs. However, Epiphany in both freshly mixed and set conditions showed a severe to moderate cytotoxic effect (176), and its cytotoxicity actually increased with time, posing significant cytotoxic risks (180, 181). The

TABLE 2. *In Vitro* Fracture Resistance Studies Associated with the Use of Methacrylate Resin-based Sealers and Bondable Root Filling Materials

Results claimed by authors	Studies	Parameters examined	Compaction methods	First criterion: appropriate positive control (unfilled instrumented roots) included	Second criterion: results were not significantly lower than those derived from the positive control	Additional negative control (noninstrumented roots)?	Range of standard deviations	Comments	Studies that satisfy both first and second criteria (ie, two "Yes")
Improved fracture resistance	Teixeira et al, 2004 (6)	Vertical root fracture	Cold lateral, warm vertical	Yes	Yes	No	16.5%–38.9%	NA	Yes
	Hammad et al, 2007 (148)	Vertical root fracture	Cold lateral, single cone	No	No	Yes	15.4%–38.8%	No positive control	No
	Schäfer et al, 2007 (149)	Vertical root fracture	Cold lateral	Yes	Yes	Yes	11.3%–23.2%	NA	Yes
No difference between methacrylate resin-based sealers and conventional sealers	Stuart et al, 2006 (150)	Horizontal root fracture	Warm vertical	Yes	Yes	Yes	19.4%–29.4%	NA	Yes
	Grande et al., 2007 (151)	Flexural stress	Warm vertical	Yes	Yes	No	25.2%–40.0%	NA	Yes
	Wilkinson et al., 2007 (152)	Horizontal root fracture	Warm vertical	Yes	Yes	Yes	—	No numeric data available	Yes
	Sagsen et al., 2007 (153)	Vertical root fracture	Cold lateral	Yes	Yes	No	6.2%–24.3%	NA	Yes
	Ribeiro et al., 2008 (154)	Horizontal root fracture	Cold lateral	Yes	Yes	No	12.0%–25.5%	NA	Yes
	Hemalatha et al., 2009 (155)	Horizontal root fracture	Warm vertical, single cone	Yes	Yes	No	7.3%–12.5%	Student <i>t</i> test for analyzing 4 data groups	Yes
	Karapinar et al., 2009 (156)	Vertical root fracture	Cold lateral	Yes	Yes	Yes	—	No standard deviation	Yes
Jainaen et al., 2009 (157)	Vertical root fracture, work of fracture, micro-punch shear strength	Single cone	Yes	Yes	Yes	16.4%–42.2%, 39.8%–54.3%, 18.8%–36.5%	NA	Yes	
Lower fracture resistance	Ulusoy et al., 2007 (158)	Vertical root fracture	Cold lateral	Yes	Yes	No	19.6%–23.7%	NA	Yes
	Jainaen et al., 2009 (159)	Work of fracture	Single cone	Yes	No	Yes	Inner to outer direction: 7.2%–55.5% Coronal to apical direction: 39.8%–54.6%	Roots filled with resin-based sealer had lower work of fracture than positive control in an inner to outer direction.	No

NA, not applicable.

Studies satisfying the 2 criteria described in the table were used for preparing the pie chart in Fig. 5.

toxicity of Epiphany might be explained by the presence of unpolymerized hydrophilic monomers (such as HEMA) that can easily diffuse into the cell-culture medium (182) and elicit significant toxicity (183). Epiphany requires body temperature and total elimination of air contact to polymerize. It polymerized within 30 minutes in an anaerobic environment, but in the presence of air, material setting took up to 7 days (184). Forty percent of the sealer remained unpolymerized despite a post-curing time of as long as 2 weeks *in vitro* (185). Consequently, extrusion of a methacrylate resin-based sealer through the periapical foramen would create an uncured surface layer for extended time periods (180, 184). This might alter the toxicity profile of resin-based sealers because more incompletely polymerized, toxic monomers are present in the exposed sealer. A sealer should not hinder tissue repair, but rather, it should stimulate the reorganization of injured tissues. Therefore, these results support the need to continue to develop better endodontic sealers that combine optimal sealing and bonding properties of resins with acceptable biologic properties for endodontic applications.

Can Root Canals Obturated with Methacrylate Resin-based Sealers Be Effectively Re-treated?

Removing as much filling material as possible from inadequately prepared and/or filled root canal systems is essential to uncover the remaining necrotic tissues or bacteria that are responsible for periapical inflammation and persistent infection (186). With the exception of a recently published study (187), there is a general consensus that methacrylate resin-based sealers used with Resilon or gutta-percha were more effectively removed, with less remnant filling material than conventional sealer/gutta-percha combinations (188–194), especially in the apical part of the root canal (190). Remnants and debris were still observed on the middle third and coronal third of the canal walls, irrespective of removal techniques (188–191, 194). On one hand, the difference in the removability of materials might be explained by the adhesion between the core materials and sealers (192, 193). On the other hand, easier removal and less remnant materials would imply that methacrylate resin-based sealers did not bond well to sclerotic dentin that is present in the apical part of the canal walls. Although Resilon is soluble in chloroform and other solvents (188–190), Epiphany is insoluble in the solvents commonly used in dentistry. Thus, removal of resin sealers from fins, accessory canals, or canal isthmi remains a challenge (3).

How Badly Do Methacrylate Resin-based Sealers Absorb Water and Leach?

With the advent of hydrophilic methacrylate resin-based root canal sealers, the issue of water sorption became a concern, because plasticizing of a resinous matrix via water sorption and diffusion precedes and expedites the leaching of the resin components (195). This was demonstrated by the study of Donnelly et al (196), who observed significantly higher solubility (3%–8%) in all 3 methacrylate resin-based sealers (Epiphany, InnoEndo [Heraeus-Kulzer, Inc, Armonk, NY], and EndoREZ), when compared with conventional root canal sealers. This result is in agreement with the finding of another study (197), in which solubility values for Epiphany and AH Plus were 3.41% and 0.21%, respectively. The American Dental Association specifications require less than 3% solubility for root canal sealers (198). Thus, most hydrophilic methacrylate resin-based sealers do not meet this criterion. Water ingress might, however, have belated beneficial effects. Swelling of the resin matrix results in expansion of the composite that compensates for the polymerization stresses that are created during shrinkage (199).

Compared with conventional non-bonding sealers and root filling materials, does the use of methacrylate resin-based sealers and bondable root filling materials improve the fracture resistance of root-filled teeth?

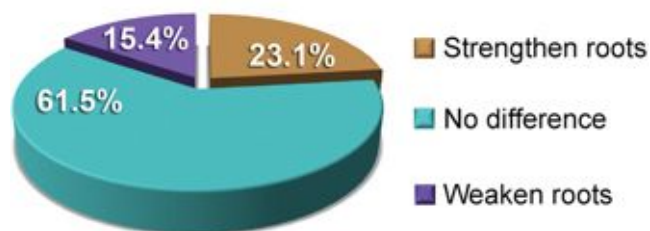


Figure 5. A pie chart summarizing the results of *in vitro* studies (those satisfying both criteria in Table 2) that examine whether the use of methacrylate resin-based sealers and bondable root filling materials is able to improve the fracture resistance of root-filled teeth.

Paradoxically, Smartseal (DRFP Ltd, Stamford, United Kingdom), a resin-based sealer that has not been reported in the peer-reviewed literature, relies on water sorption from dentinal tubules in the canal walls to expand and obtain a tight seal within the root canal (200). It consists of Smartpoint, a radiopaque non-gutta-percha core with a radiolucent hydrophilic polymer coating (copolymer of vinylpyrrolidone and acrylonitrile, methyl methacrylate, or HEMA) and Smart paste, a radiolucent sealer that contains an active polymer. The manufacturer claims that Smartpoint expands only laterally on absorbing water from the tooth, adopting the canal shape. Smart paste also expands on hydration to form a perfect seal. As stated earlier, the most common problem associated with the incorporation of hydrophilic resin monomers is that in the oral environment, these materials can absorb water and elute unreacted monomers. Although the well-polymerized Smartpoint hydrophilic coating might contain much unreacted monomers, leachable monomers from the incompletely polymerized Smart paste sealer can leak through the apical foramen after water sorption and swelling and cause inadvertent harmful detrimental effects on the periodontal tissues (201). Diffusion of water into resin matrices might result in the rapid deterioration of the physical/mechanical properties of a resin (202), compromising the durability of resin-dentin bonds by hydrolysis and microcrack formation (203).

Are There Any Evidence-based Clinical Studies to Support the Merits in Using Bondable Root Canal Sealers?

The American Association of Endodontists has placed heavy emphasis on the concept of evidence-based endodontics during the last few years. According to the Center of Evidence-Based Medicine (www.cebm.net), each study should possess specific design characteristics that would match 1 of the 5 levels of evidence the CEBM recognizes (204). A literature search using the following key words—methacrylate resin-based sealers, sealing ability, self-etching potential, biocompatibility, removability, monoblocks—returned only 4 relevant articles (Table 3). Other web sources yielded 2 additional abstracts.

In 2004, Zmener and Pameijer (174) conducted a preliminary retrospective evaluation of the EndoREZ sealer used in conjunction with laterally condensed gutta-percha. One hundred eighty patients were observed, with a total of 295 root canals. Root canal treatments were performed in single visits with standardized techniques. In this study, the results were assessed clinically and radiographically (14–24 months postoperatively), and only 145 patient records were

TABLE 3. *In Vivo* Outcome Studies Associated with the Use of Methacrylate Resin-based Sealers and Bondable Root Filling Materials

Author (reference)*	Type of Study	Parameters	Cleaning and shaping (C&S)/ obturation material	Compaction method	Evaluation of results	Follow-up period	Control (conventional sealer/gutta-percha group)	Success rate	Dropout rate	Conclusion	LOE [†]
Zmener and Pameijer (174)	Retrospective	Success vs failure	Standardized C&S protocol/ gutta-percha and EndoREZ	Lateral compaction	Radiographic and clinical evaluation	1–2 years	None	91.3%	19.44%	EndoREZ fillings lasted for 2 years	4
Zmener and Pameijer (7)	Retrospective	Success vs failure	Standardized C&S protocol/ gutta-percha and EndoREZ	Lateral compaction	Radiographic and clinical evaluation	5 years	None	86.3% (79.7%–91.0%) confidence interval	33.33%	Continuation of previous 2004 study. EndoREZ fillings lasted for 5 years	4
Conner et al (208)	Retrospective	Healing vs nonhealing	Nonstandardized C&S protocol/ Resilon	No standardized protocol	PAI and clinical evaluation	At least 1 year	None	89.36%	0%	Healing rates for Resilon-filled teeth in private practice were similar to studies performed in university settings with gutta-percha root fillings	5
Cotton et al (209)	Retrospective	Healing vs nonhealing	Standardized C&S protocol/ Resilon and Epiphany sealer	Warm vertical compaction	PAI and clinical evaluation	2–25 months	Gutta-percha and Kerr Pulp Canal Sealer	78.6%	0%	No difference between roots filled with conventional materials and adhesive root filling materials	2

*Two additional abstracts by Debelian (210) and Oya (211) had not been published as full articles and were not included in this summary.

[†]LOE (205, 206) (clinically related studies only): 1, randomized control trials; 2, low-quality randomized control trials, cohort studies; 3, case control studies; 4, poor-quality cohort and case control studies, case series; 5, case reports, expert opinion without explicit critical appraisal.

available for a follow-up examination; the dropout rate was 19.4%, just below the limit set for a clinical study (205). For the evaluated teeth, 75.9% were considered to be filled to the working length, and 13 (9.0%) cases were judged as failures. Because it is a retrospective case series study, it rates as level of evidence (LOE) 4. It was performed during a relatively short recall period (14–24 months) and had no control group and a dropout rate close to the 20% maximum. Furthermore, the indicator of healing was the periapical radiograph, which is not an absolute indicator of healing and can be a source of bias (positive: periapical lesions in the alveolar bone not affecting the cortical bone and thus invisible on radiographs, and negative: fibrous repair) (206).

The authors continued their work with another radiographic evaluation at 5 years (207), with the same EndoREZ data pool. Of the 180 patients, 120 responded to the 5-year recall. The success of root canal treatments was based on clinical and radiographic parameters. Approximately 76% of the cases presented at the 5-year recall were presented with an adequate filling, and 12.5% of the cases showed slight resorption of the filling material at the apex within the lumen of the root canal. Pulp vitality, absence of periapical radiolucency, and lesion size smaller than 2 mm positively influenced the success rate. Although the study revealed a cumulative probability of success of 86.3% at the 5-year recall, these results should be considered carefully as a result of the bias introduced by the high dropout rate (33.33%) (206). The level of evidence in this study is low (LOE4) because it is a case series that does not feature a control group. Moreover, the indicator for healing is solely dependent on the interpretation of a periapical radiograph by an external examiner.

In another study, Conner et al (208) evaluated the clinical outcomes of nonstandardized root canal treatment carried out in a private practice in which Resilon was used as obturation material. Follow-up radiographs (at least 1 year after the treatment) were compared with immediate postoperative radiographs by 16 dentists from different geographic locations (continental U.S. and Western Europe). The total number of teeth was 82. Periapical index (PAI) and Clinical Impression of Healing (CIH) quantification procedures were used to determine the status and change in the condition of the teeth. The former revealed that 90% of the teeth that were healthy at the initial reading (PAI, 1 or 2) maintained this condition at the follow-up evaluation. Of those teeth that were unhealthy (PAI, 3–5) at the initial appointment, 73.3% were judged as healthy (50%) or improved (23.3%) during the follow-up evaluation. In contrast, the proportion of healthy or healing teeth with the second evaluation criterion (CIH) was 89.4%. Resilon was the only common material used in all the cases; the study evaluated the contribution of a single element to the overall healing process. The authors concluded that Resilon was not in any way detrimental to the success rate achieved in those cases. This study can be considered a case report (LOE5) because it is only a description of cases. Once again, no control group was used for comparison between the outcomes of fillings with conventional nonadhesive materials versus adhesive materials. The follow-up period was also variable.

To date, the best level of evidence available on the subject is in the article by Cotton et al (209). It is a retrospective study that evaluated the treatment outcome of root canal systems filled with Kerr Pulp Canal Sealer (SybronEndo)/gutta-percha and versus those that were filled with Epiphany sealer/Resilon. More than 100 teeth treated by the same operator were included in the study. Clinical outcomes (healed versus unhealed) were assessed by using the PAI index and clinical evaluation at recall appointments. Statistical analysis was applied to determine the magnitude of the association between the obturation materials used and the measured outcome. The analysis indicated that pulp

vitality, presence of a preoperative lesion, and length of recall times were statistically significant in predicting treatment outcome, which were consistent with the results derived from previous works. The study also showed that age, tooth position, and length of recall times were statistically significant in predicting the outcome. This study can be considered a low quality randomized control trial (LOE2). Randomization was performed in patient distribution between groups, and the evaluation was performed by 2 calibrated evaluators and a third operator for data collection. A control group was used (gutta-percha and sealer), and a thorough statistical analysis was performed. However, the study presents some controversial issues because the initial population of patients was not consistent (age, gender, and type of teeth) and recall times vary greatly (2–25 months). Nevertheless, the authors concluded that the type of filling material had no statistically significant difference in the clinical outcome.

The levels of evidence derived from the 2 abstracts (210, 211) are both LOE4. Those abstracts are case series with no control groups. They both concluded that using a methacrylate resin-based filling material is not detrimental to the outcome of the root canal treatment but failed to compare the results with those achieved by using conventional root canal filling materials.

Future Research and Concluding Remarks

Progress in the development of methacrylate root canal sealers does not stop short at striving for a total bond and a total seal of the root canal system. For example, an experimental third generation methacrylate resin-based sealer has adopted a different approach by incorporating sustained antibacterial activity into the polymerized sealer (Dr Satoshi Imazato, personal communication, July 2008). This antibacterial sealer is a 2-step dual-cured system consisting of a 2-bottle primer component and a resin sealer component. Both the primer and sealing resin contain the antibacterial resin monomer 12-methacryloyloxydecyl pyridinium bromide (MDPB) that is found in Clearfil Protect Bond (Kuraray Medical Inc, Tokyo, Japan) (212). The MDPB resin monomer owes its antibacterial properties to the positively charged pyridinium functional group. Before polymerization, the positively charged MDPB attaches to the negatively charged components on the bacteria cell wall and causes bacteriolysis. The antibacterial resin monomer partially retains its antibacterial property via direct contact killing after its polymerization and immobilization within the resin matrix (213). From an endodontic perspective, such a concept is similar to the substantivity conferred by the use of chlorhexidine as a root canal irrigant (214). Experimental chlorhexidine-releasing polymethylmethacrylate-based root canal sealers have been developed with the incorporation of 2–3 wt% chlorhexidine diacetate into the sealer powder (215). It would be interesting to follow the development of future generations of antibacterial methacrylate resin-based sealers.

In the overall scheme of things, the recent development of methacrylate resin-based root canal sealers has been nothing short of phenomenal vis-à-vis the emergence of 3 generations during a 5-year period; some of the sealers introduced 5 decades ago are still available for use today. Does the introduction of methacrylate resin-based root canal sealers really represent a paradigm shift in endodontics (216)? The package deal concept of root canal obturation by using the combination of a sealer and a root filling material has existed for more than a century (217). Except for the fleeting appearance of an experimental vacuum obturation protocol associated with the noninstrumented technique (218), there has not really been any paradigm shift in root canal obturation. In the age of adhesive endodontics, the focus has most often been directed to gutta-percha substitutes. Similar to gutta-percha, the primary function of these gutta-percha substitutes is to occupy space, with the more important issue being the sealer and its properties.

What have changed with the publicizing of adhesive endodontics are the materials and not the techniques of obturation or the biologic principles; failure in root canal therapy is more the operator's responsibility rather than the fault of the materials (219, 220). Are bondable methacrylate resin-based sealers better alternatives for root canal obturation than their nonbonding counterparts? This statement does not appear to be openhandedly supported by the plethora of *ex vivo* studies. Moreover, very few of the currently limited clinical outcome studies have included a control group to support the advantages of these new materials over conventional nonbonding materials. Indeed, the paucity of evidence-based clinical information available on some of these aggressively promoted materials might serve as food for thoughts for clinicians to think twice about adopting these approaches to root canal obturation. The reasons for clinicians who elect to use bondable methacrylate resin-based sealers and adhesive obturating materials are varied. Whereas some might use them as marketing tools for practice growth, others might perceive them as the solution to endodontic failure in cases that were previously filled by using conventional sealers and nonadhesive root filling materials. On further reflection, is it appropriate to hold canal obturation culpable for endodontic failures when it should have been the potential inadequacies of currently adopted canal irrigation principles (74, 221), failure to abide by the philosophy of creating larger apical seats to permit optimal debridement (222, 223), or the failure to provide well-sealed restorations (224, 225)? Under the conditions of well-executed cleaning and shaping and the provision of adequate coronal restorations, it is dubious whether the merits of adhesive methacrylate resin-based sealers might be revealed in future prospective randomized controlled clinical trials, particularly when more stringent criteria for evaluating success are used (206, 226).

Acknowledgments

This study was supported by funds provided by Dental Research Center, School of Dentistry, Medical College of Georgia. The authors are thankful to Mrs Michelle Barnes for secretarial support.

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