Resin Materials for Root Canal Obturation

Cornelis H. Pameijer, DMD, MScD, DSc, PhD[a,b,*],
Osvaldo Zmener, DDS, Dr Odont[c]

KEYWORDS

• Methacrylate resins • Obturation • Biocompatibility
• Leakage • Cytotoxicity

DEVELOPMENT LEADING TO RESIN SEALERS

The concept of resin bonding in dentistry was introduced in the mid-1950s by Buonocore,[1] who advocated the use of an acid to demineralize enamel. Skepticism slowly gave way to general acceptance. However, bonding materials and techniques have completely changed over the course of 50 years. During the initial development only hydrophobic resins were available; these have been replaced by hydrophilic resins over time. Furthermore, about 30 years of research resulted in a change from using 85% phosphoric acid liquid for 60 seconds to etch enamel to 35% phosphoric acid gels for 15 seconds to etch dentin and enamel. Although early attempts were strictly focused on preventive and restorative dentistry, it was only a matter of time before orthodontics and then endodontics embraced this concept. Usually, when new materials and techniques are introduced, there is an initial reluctance on the part of practitioners to abandon trusted and proven methods until evidence that is sufficiently convincing to change established techniques is generated.

The objective of this article is to provide information about methacrylate-based resin sealers (MBRS) on which practitioners can base their decision to consider changing established techniques and embrace a new one. This decision cannot be made by presenting empiric data, but by offering an analysis of scientific evidence from ex vivo and in vivo research. Based on their successful long-track record, gutta-percha and zinc oxide, eugenol, and other conventional sealers, have served as the gold standard for comparison.

[a] Department of Reconstructive Sciences, University of Connecticut, Health Center, Farmington, CT 06030, USA
[b] DLC International, 10 Highwood, Simsbury CT 06070, USA
[c] Post Graduate Program for Specialized Endodontics, Faculty of Medical Sciences, School of Dentistry, University of El Salvador, Buenos Aires, Argentina
* Corresponding author. Department of Reconstructive Sciences, University of Connecticut, Health Center, Farmington, CT 06030.
E-mail address: cornelis@pameijer.com

Dent Clin N Am 54 (2010) 325–344
doi:10.1016/j.cden.2009.12.004 **dental.theclinics.com**
0011-8532/10/$ – see front matter

One of the factors that was instrumental in the development of resin-based sealers was the recognition that gutta-percha does not bond to dentin or to any conventionally used sealer, such as zinc oxide-eugenol (ZOE)-based cements and epoxy resins such as AH-26 or AH Plus. Although these materials are being used successfully, an ideal root canal sealer should be capable of bonding to root canal dentin and to gutta-percha, thus preventing microleakage. Recent advances in adhesive technology have led to the introduction of a new generation of endodontic sealers and filling materials, that are based on adhesive properties and polymer resin technology. These materials are capable of forming a hybrid layer and penetrating deep into dentinal tubules by virtue of their hydrophilic properties.

Early attempts at using resins were reported in 1978 by Tidmarsh,[2] who suggested that a low-viscosity resin could have the potential to be used in root canal obturation. Of the bonding agents that were used in restorative dentistry, the early generations did not use an acid to remove the smear layer and therefore bonded to it. This resulted in a weak bond and did not prevent bacterial leakage. Later generations that used 35% phosphoric acid gels for the removal of the smear layer were more promising. Furthermore, the early resins were hydrophobic and therefore their interaction was adversely affected by moisture in the dentin. The latest bonding agents are hydrophilic and they derive their adhesive properties from micromechanical interlocking by penetrating into dentinal tubules, thus creating an attachment mechanism along with an intimate hybrid layer when they come in direct contact with the surrounding collagen fibrillar intertubular network. The latter requires careful treatment and it has been shown that the collagen network of dentin can be best preserved using 17% to 19% EDTA[3] or low concentrations of citric acid solution as the final rinse. Effective removal of the smear layer before filling the canals will enhance the ability of these bonding agents to enter the dentinal tubules and improve the sealing of the root canal system by increasing the contact surface area. The presence of organic debris along with bacteria within the matrix of the smear layer represents an undesirable interface between filling material and dentin. Furthermore, the sequence of the irrigating solutions has been shown to be a factor. A 5% sodium hypochlorite (NaOCl) solution followed by 17% EDTA or 50% citric acid seems to be the most effective combination.[4,5]

Zidan and El Deeb[6] were among the first to attempt to establish adhesion to dentin walls in vitro with the use of Scotchbond (3M ESPE, St Paul, MN, USA). Apical microleakage with gutta-percha and the bonding agent was significantly less than in root canals obturated with gutta-percha and Tubli-Seal (SybronEndo, West Collins, Orange, CA, USA), a ZOE-based root canal sealer. Handling properties, radiopacity, and the difficulty of removing the sealer in case of retreatment were some of the drawbacks that were experienced. Other possible bonding systems have subsequently been reported in the literature. Leonard and colleagues[7] compared the effectiveness of a combination of the dentin bonding agent 4-methacryloyloxyethy trimellitate anhydride (4-META) and the resin C&B Metabond (Parkell Inc, Edgewood, NY, USA), which was commercialized a few years later as MetaSEAL (Parkell Inc, Edgewood, NY, USA), and the glass ionomer cement Ketac-Endo (3M ESPE, St Paul, MN, USA) for sealing of the root canal system. The coronal and apical seals were tested by means of dye penetration, and both materials showed some evidence of dye leakage. However, the sealing ability of the bonding agent and resin was significantly better. This was further supported by scanning electron microscopy (SEM) of the interface sealer and dentin, indicating the presence of a hybrid layer and resin tags penetrating into the dentinal tubules. Despite these positive features, the materials seemed to be technique sensitive. Nikaido and colleagues,[8] Morris and colleagues,[9] and Erdemir and colleagues,[10] showed that the use of sodium hypochlorite and hydrogen peroxide

or a combination of both irrigants, decreased the bond strength to dentin by adversely affecting the tensile bond strength to bovine dentin. Hydrogen peroxide breaks down to water and oxygen, whereas the combination of sodium hypochlorite and hydrogen peroxide allows for the formation of oxygen, which inhibits polymerization of the adhesive materials. However, irrigation with chlorhexidine did not exhibit these adverse effects.

ALL-BOND 2 adhesive (Bisco, Itasca, IL) and Scotchbond Multi-purpose Plus adhesive in combination with gutta-percha and an epoxy resin–based root canal sealer AH-26 (Dentsply-Maillefer, Switzerland) was also tested for leakage with a 2% methylene blue solution.[11] It was reported that root canals that had the combination of bonding agents with gutta-percha and the epoxy resin sealer leaked significantly less than the controls in which the root canals were obturated with gutta-percha and AH-26. Although no problems were experienced with respect to the working time of the bonding agents, the complexity of the technique (it required many steps) made the use of bonding agents impractical for root canal obturation. Of additional concern is the use of bonding agents containing 2-hydroxyethyl methacrylate (HEMA), which, when extruded beyond the apex into bone, could sensitize patients, particularly if they are from Nordic countries or have genetic make-up that originates there.

Ahlberg and Tay[12] tested a methacrylate-based bone cement normally used in orthopedic surgery, in which the monomer from *N*-butyl methacrylate was changed to tetrahydrofurfuryl methacrylate with 1% *N'N'*-dimethyl *p*-toluidine as the activator. The powder consisted of poly(ethyl methacrylate) with a molecular weight of 150,000 to 1,500,000 and a particle size of 15 to 100 μm. They used this formulation to obturate in vitro root canals of human teeth with gutta-percha cones; the control canals were filled with gutta-percha only. The root canals filled with the resin and gutta-percha leaked significantly less than the controls. Scanning electron microscope observation of the interface revealed a bond not only between the resin-based sealer and the root canal walls but also between the sealer and gutta-percha. With respect to their handling properties, the material was found to be easy to place in the root canal and the working time was approximately 50 minutes. The investigators postulated that, because the smear layer was not effectively removed, bonding to the root canal walls may be attributed to the low viscosity of the resin itself, whereas the ability to bond to gutta-percha was attributed to dissolution of the gutta-percha surface.

Kataoka and colleagues[13] analyzed the coronal and apical sealing properties of a newly developed resin-based root canal sealer composed of vinylidine fluoride/hexafluoropropylene copolymer, methyl methacrylate, zirconia, and tributylborane as the catalyst, used in conjunction with gutta-percha cones in root canals, which were pretreated with dentin conditioners and primers. They also analyzed the tensile bond strength and used SEM to analyze the interfaces. The test material revealed a significantly higher sealing ability than Pulp Canal Sealer EWT (Sybron Kerr, Romulus, MI, USA) and Sealapex (Sybron Kerr, Romulus, MI, USA), which were used as controls. When the canal walls were pretreated with EDTA and further application of glutaraldehyde/2-hydroxyethyl methacrylate primers, higher bond strength values were recorded. SEM observation revealed the presence of a hybrid layer approximately 2 μm thick, formed by the penetration of the resin into the dentin with only a few gaps at the interface between the sealer and the root canal walls. Based on these observations, the investigators suggested that the tested resin-based sealer had many useful properties for root canal obturation, such as adhesiveness to dentin and gutta-percha while exhibiting good sealing properties.

According to the above information these experimental formulations have the potential to bond to the root canal walls provided the smear layer is removed.

METHACRYLATE-BASED RESIN SEALERS

MBRS are new in endodontics and are derived from polymer chemistry technology initially developed for adhesive restorative dentistry, albeit in modified formulations and viscosities as determined by the specific demands in endodontics. This article focuses on 2 systems as they dominate the market:

1. EndoREZ (Ultradent Products Inc, South Jordan, UT, USA) and
2. RealSeal (Sybron Dental Specialties, Orange, CA, USA).

Pentron Clinical Technologies (Wallingford, CT, USA) was recently acquired by Sybron Dental Specialties, which includes the Resilon-Epiphany system, now marketed as RealSeal. Therefore products such as SimpliFill (LightSpeed Technology Inc, San Antonio, TX, USA), InnoEndo (Heraeus Kulzer, Armonk, NJ, USA), and Resinate (Obtura Spartan, Fenton, MO, USA) and Resilon-Epiphany are now all categorized under the name RealSeal.

ENDOREZ

EndoREZ (ER) is a hydrophilic, two-component (base and catalysts), dual-curing self-priming sealer. The formulation can be described as follows:

The EndoREZ base contains:
- a bismuth compound as the radiopaque filler
- small amounts of other fillers
- diurethane dimethacrylate
- triethylene glycol dimethacrylate
- a peroxide initiator
- a photo initiator (not chamfer quinone).

The EndoREZ catalyst contains:
- a bismuth compound as the radiopaque filler
- small amounts of other fillers
- diurethane dimethacrylate
- triethylene glycol dimethacrylate.

The sealer can be used with gutta-percha or with resin-coated gutta-percha cones, the latter with the objective of establishing continuous adhesion (uniblock or monobloc) between all materials. The sealer is supplied in a double barrel auto mixing and delivery syringe and meets the basic requirements of an endodontic sealer. The manufacturer recommends that after preparation the root canal walls should remain slightly moist to take maximum advantage of the hydrophilic properties of the sealer, thus allowing for resin tags to penetrate into the dentinal tubules and the formation of a hybrid layer with the collagen fiber network.[14] However, too much water can cause water permeation during the polymerization process and results in the entrapment of water droplets in the sealer, resulting in bond disruption and an increase in leakage.[15] Delivery through the tiny opening and the hydraulics involved when using a NaviTip (Ultradent Products Inc, South Jordan, UT, USA) produces a sealer free from air bubbles that fills the canal with a homogeneous layer. The sealer is radiopaque and has favorable low viscosity properties. Low viscosity plays a significant role in the handling properties and makes it useful for placement in wide or narrow root canals; it provides a good adaptation to the intricacies of the dentin walls. EndoREZ bonds well to root canal walls but not to gutta-percha, which constitutes a potential weakness, as a path for bacterial leakage may exist.[16] To address this issue and to establish

a bond between sealer and dentin and between sealer and gutta-percha, resin-coated gutta-percha cones (RCGP) cones (Ultradent Products Inc, South Jordan, UT, USA) were introduced.

The combination of these materials establishes the so-called monobloc and is the reason for the superior sealing properties of the system. The objective of the EndoREZ sealer is to establish a hermetic seal, rather than high bond strength adhesion, that is, optimum softness or hardness while providing a maximum seal.

The RCGP cones can be used with an accelerator, which serves a dual purpose. The polymerization reaction of the EndoREZ is accelerated (within 4–5 minutes) allowing for immediate continuation of the restorative phase should the practitioner choose to do so and bonding of the EndoREZ to the RCGP cones is promoted, thus establishing a monobloc.

REALSEAL (RESILON/EPIPHANY)

Resilon is composed of a polymer-based resin (polycaprolactone), bioactive glass, bismuth oxide, barium sulfate and coloring agents. The sealer is a dual-cure sealer, composed of urethane dimethacrylate (UDMA), poly dimethacrylate (PEGDMA), ethoxylated bisphenol A dimethacrylate (EBPADMA) and bisphenol A glycidyl methacrylate (BIS-GMA), barium borosilicate, barium sulfate ($BaSO_4$), bismuth oxychloride, calcium hydroxide, photo initiators, and a thinning resin. In addition the system comes with a self-etching primer. The premise behind the material is the formation of a monobloc, that is, the primer forms a hybrid layer with dentin, which bonds to sealer, and then bonds to the Resilon core. The ability of Resilon to bond to methacrylate-based root canal sealers has also been questioned because the amount of dimethacrylate in the thermoplastic composite may not be optimum for chemical coupling.[17] However, when surface roughness was established, the micromechanical interlocking increased the mean bond strength significantly.

BIOCOMPATIBILITY

Several early publications (2001 and 2003) have reported on the biocompatibility and adhesiveness of EndoREZ.[18–20] Since then numerous publications have appeared, testing different MBRS formulations and using a variety of techniques, which to a large extent have caused more controversy and confusion than answering the following basic questions:

1. Are resin-based sealers safe?
2. Can they be used successfully in patients?
3. Will they ultimately replace gutta-percha and conventional sealers?
4. Will they last as long as conventional materials?
5. Are they easier to use than conventional materials?

TOXICOLOGY STUDIES IN VITRO

One of the requirements of any dental material for use in humans is that it should be biocompatible. Numerous investigators have conducted cytotoxicity studies ex vivo using cell cultures and in vivo in laboratory animals. The results between investigators are contradictory. Huang and colleagues[21] showed that the elution compounds from MBRS, zinc oxide-eugenol and calcium hydroxide-based sealers were cytotoxic to primary human periodontal ligament cultures and V79 cells, with calcium hydroxide being the least toxic. Huang and co-workers,[22] reported that the highest level of

DNA damage was induced by epoxy resin–based sealers, in this case Topseal (Dentsply, Konstanz, Switzerland), AH-26, and AH Plus. Koulaouzidou and colleagues[23] reported similar results. AH-26 had a severe cytotoxic effect, whereas Topseal and AH Plus had markedly lower effects. These findings are surprising as the basic formulation of AH-26 and Topseal is the same. Bouillaguet and colleagues,[24] reported that: ''Most materials pose significant cytotoxic risks and that cytotoxicity generally decreased with time.'' At 72 hours, GuttaFlow became significantly less toxic than AH Plus, Epiphany sealer, and Resilon. Other investigators, such as Key and colleagues[25] found Epiphany to be less toxic than Grossman's sealer. However, Epiphany was more cytotoxic than Sealapex after 1 hour, but less after 24 hours. Epiphany was more cytotoxic than conventional materials. In a more recent publication[26] similar findings were reported. According to Lodiene and colleagues[27] the multi-methacrylate-based resin (Epiphany) root canal sealer was significantly more toxic to L-929 cells than the silicone-based RoekoSeal and the single methacrylate-based EndoREZ root canal sealers. AH Plus showed intermediate toxicity.

Based on the these findings it seems that no sealer is universally accepted as being nontoxic. Furthermore, the investigators mentioned earlier have reported completely opposite findings, which makes selection of a sealer without drawbacks difficult, if not impossible. Therefore it is necessary to conduct a careful and critical analysis of the various ex vivo research methodologies to reach a consensus. It is also important to correlate the results of the various techniques with the clinical performance of the same material or materials. Oliver and Abbott[28] reported that clinical and in vitro data frequently contradict each other.

TOXICOLOGY STUDIES IN VIVO

The early studies on which the launch of EndoREZ was based were conducted by Louw and colleagues[18] and Becce and Pameijer[20] who reported that EndoREZ was mildly irritating, but within acceptable standards (1.5° is the acceptable limit). Further evidence of biocompatibility was published by Zmener[29] and Zmener and colleagues.[30] In other related studies (Pameijer, 2002, unpublished data), EndoREZ and Epiphany/Resilon reacted more favorably than the control AH Plus. Preoperative and postoperative radiographs were made and root canal treatment was performed according to a standardized protocol using a rubber dam in subhuman primates. Histologic observations were made at various time periods: 30 days to determine an early reaction and from 3 months to 6 months posttreatment for long-term reactions. The results can be summarized as follows. Ten EndoREZ root canal treated teeth scored a mean inflammatory reaction after 26 days of 1.5°. After 90 days, out of 21 root fills, 4 had extruded sealer with an inflammatory mean of 0.8°. Good apical adaptation scored a lower mean inflammation of 0.4°. None of the periapical areas of the roots at either time period showed bone resorption. The control sealer (AH Plus) had a mean inflammatory reaction of 1.3° after 26 days and 1.0° after 90 days. Epiphany, which was tested according to the same protocol, scored a mean inflammatory reaction of all root fills of 1.2° after 120 days (13 teeth), whereas the inflammation of bone was 0.4°. Control teeth (AH Plus) had a mean inflammatory reaction of 2°, and a bone inflammation of 1°.

Both materials clearly reacted more favorably than the control AH Plus.

These results were confirmed by Zmener.[29] The severity of the reaction decreased over time. Zmener and colleagues[30] conducted a histologic and histometric study in which silicone tubes filled with EndoREZ were implanted in the tibias of rats for a period of 10 days and 60 days. At the 10-day observation period, the number of inflammatory

cells in contact with the sealer was significantly higher. After 60 days, the initial inflammatory reaction was resolved and newly formed healthy bone was observed surrounding the implants. Thus, after early mild irritation the material reacted in a biocompatible fashion allowing healing of bone. In contrast Sousa and colleagues[31] tested AH Plus, EndoREZ, and Epiphany in guinea pigs over 4 and 12 weeks. They reported a severe reaction for EndoREZ; AH Plus was also severe after 4 weeks and moderate after 12 weeks. Only Epiphany showed intraosseous biocompatibility.

EXAMPLES OF SEALER AND POINT BIOCOMPATIBILITY TESTING

The periapical tissues can react to extrusion of a sealer and/or point in several ways:

1. It can cause an inflammatory reaction
2. It can be regarded as a foreign body and be encapsulated
3. A sealer can be present without causing inflammatory reactions and is not encapsulated
4. The sealer can be resorbed over time, with or without an inflammatory reaction.

As mentioned earlier, a material causing an inflammatory reaction is not necessarily bad and the outcome depends on the intensity and duration of the inflammatory process and the ability of the natural defense mechanisms of the body to manage the reaction. Biocompatibility should be construed in a broader sense. If over a reasonable period of time (30–60 days) healing occurs after an initial irritating reaction, a material can still be considered biocompatible. None of the endodontic sealers that are currently being used are totally nonirritating, yet without doubt they are being used with clinical success.

If over a short period of time (up to 30 days) a mild inflammation is present and it diminishes over time, a material with otherwise favorable properties can be considered biocompatible.[29] Eluation of components was recognized by Ferracane and Condon[32] and the inflammatory process as a result of this is the body's response to irritation. Fibrous encapsulation without inflammation is the body's response to isolate an otherwise biocompatible material. Furthermore, a material, usually small size particles, can be present in periapical tissues, cause no inflammation, and be present without encapsulation.

Fig. 1 is a representative radiograph of experimental sealers in 4 central incisors. After 113 days 2 reactions were observed for 2 different experimental sealers. **Fig. 2** is an example of extrusion (intentional to determine biocompatibility) of the sealer into periapical tissues. The sealer particles are not encapsulated and no inflammatory reaction was observed. The periapical tissues reacted differently to the other sealer. After 113 days the histologic features of the apical area (**Fig. 3**) showed slight extrusion into the periapical tissues. A fibrous encapsulation of the material can be observed, however, without the presence of inflammatory cells (magnification $\times$64, hematoxylin and eosin stain).

LEAKAGE STUDIES

Leakage of MBRS, whether coronal or apical, has been studied by numerous investigators, resulting in the publication of contradictory data that have generated more questions than answers.

It has been established that selection of an appropriate sealer will influence the outcome of endodontic therapy.[33,34] For that reason many investigators have focused on this important aspect using techniques such as fluid filtration, dye penetration, and

Fig. 1. At 113 days post treatment, the endodontic radiograph of 4 central incisors shows extrusion of sealer (intentional) into the periapical tissues.

bacterial leakage tests. Frequently AH Plus or AH-26 are used as control materials. In one of the first published leakage tests using India ink, Zmener and Banegas[35] reported no statistically significant difference between EndoREZ and AH Plus. Orucoglu and colleagues,[36] using the fluid filtration method, reported that Diaket with cold lateral condensation leaked less apically than EndoREZ and AH Plus. However,

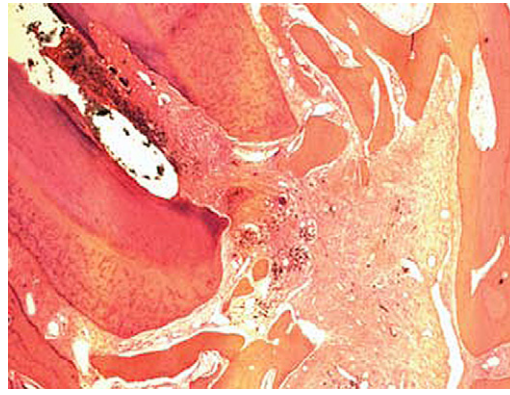

Fig. 2. Histologic reaction of an experimental sealer (*black*) extruded into periapical tissues. The white space was occupied by the Resilon point and disappeared during processing for histology. Ingrowth of connective tissue into apical root space adjacent to the point can be observed. Despite the presence of numerous sealer particles beyond the apex, no inflammatory cells were present (hematoxylin and eosin stain, original magnification ×64).

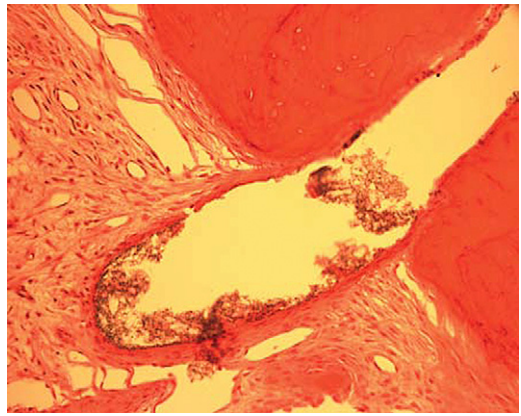

Fig. 3. At 113 days post endodontic treatment, the sealer (*dark brown*) is surrounded by a fibrous capsule in the periodontal ligament space. No inflammatory reaction is present as a result of the extruded material, point, and sealer (hematoxylin and eosin stain, original magnification ×200).

others[37] reported that AH Plus leaked less than EndoREZ and AH-26 using a single cone technique. Compared with zinc oxide-eugenol,[38] MBRS was found to be more effective in sealing. These investigators also used the fluid filtration method. Using similar techniques,[39] it was found that the apical seal of Epiphany and Resilon was not different from AH Plus and gutta-percha, AH Plus and Resilon, and Epiphany and gutta-percha. In contrast, using a fluid-transport method, Tunga and Bodrumlu[40] concluded that Epiphany and Resilon leaked significantly less ($P<.05$) than gutta-percha and AH-26. Others reached a similar conclusion when comparing Resilon and gutta-percha and AH Plus,[41] and in bacterial leakage tests[42,43]; Epiphany and Resilon were superior to gutta-percha and various other sealers. Pitout and colleagues[44] also used a bacterial leakage test and a dye penetration method and Biggs and colleagues[45] did not observe a difference between Resilon and gutta-percha. Several investigators have used the dye penetration technique to demonstrate that MBRSs are superior or inferior to conventional materials.[46–48] One explanation for the difference in results between the various MBRS materials can most likely be attributed to the presence or absence of moisture in the root canal at the time of obturation.

To put leakage studies in context, in 2001 Oliver and Abbott[28] conducted a study to determine if there was a correlation between apical dye penetration and clinical performance of root fillings. They tested the length of apical dye penetration using a vacuum technique ex vivo in 116 human roots that had been root-filled at least 6 months before extraction. Endodontic treatment was classified as clinically successful or unsuccessful and the results for these groups were compared using an analysis of variance and the Student *t*-test. Positive and negative controls were used to test the experimental system. In unsuccessful cases the dye penetrated significantly further although the raw data suggested little difference. Overall, the dye penetrated in 99.5% of the specimens, and this indicates that the presence of dye in a canal is a poor indicator of whether a technique or material will succeed clinically. However, the extent of dye penetration may be related to the clinical outcome. The investigators concluded that clinically placed root canal fillings do not provide an apical seal that prevents fluid penetration and therefore the outcome of treatment cannot be predicted based on the results of apical dye leakage studies. In 1993 Wu and Wesselink[49] reviewed the

shortcomings of various tests reported in the literature. However, dye leakage studies may be useful to determine the performance of a new material or technique by conducting comparative studies with existing systems. An electrochemical technique that seems to be sensitive and has generated findings that correlate with bacterial leakage tests, has been published by von Fraunhofer and colleagues.[50] **Fig. 4** illustrates a comparison between resin sealers and conventional sealers.

Independent of the technique used (fluid filtration or bacterial leakage test or other tests), there is no general agreement on whether there is reduced or more leakage when using MBRS. In addition ex vivo tests frequently do not correlate with clinical performance.

WHEN TO DRY AND WHEN NOT TO DRY

The contradictory data of several of the leakage studies can be explained and are most likely the result of the ingrained belief in endodontics that root canals after a final rinse need to be dried thoroughly. Many articles reviewed stated in the materials and methods section that "the canals were dried" (eg, Biggs and colleagues[45] and Kardon and colleagues[51]). Several of the articles did not specify in sufficient detail the condition of the root canal. Based on established endodontic techniques we can speculate with a fair amount of certainty that the canals were thoroughly dried. Thorough drying will create a hydrophobic environment while a hydrophilic material is being used. Field emission scanning electron microscopy (FESEM) and SEM have provided excellent examples of the potential of EndoREZ when proper moist conditions are adhered to and the recommended insertion technique is followed (**Fig. 5**) and show what happens when the canal is thoroughly dried according to well-established endodontic techniques (**Fig. 6**). The concept of moist bonding has always been difficult to explain in restorative dentistry, and endodontics has not been exempt from the same misinterpretations and misconceptions. For MBRS, whether EndoREZ or Epiphany, to establish a proper seal, the dentin needs to be moist to allow for the penetration of resin tags into the opened dentinal tubules and the formation of a hybrid layer, thus taking advantage of the hydrophilicity of these materials, whether bonding agent or sealer. In the case of EndoREZ this allows for deep penetration of resin tags, up to 500 to 1000 μm and more, and for Epiphany it allows bonding of the adhesive by means of a hybrid layer and resin tags into the dentin. Unlike restorative dentistry, where a reflection

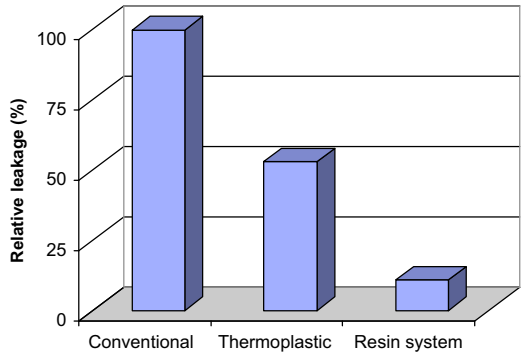

Fig. 4. Relative leakage behavior of endodontic obturation techniques. (*From* Von Fraunhofer JA. Dental materials at a glance. Oxford: Wiley-Blackwell; 2009; with permission.)

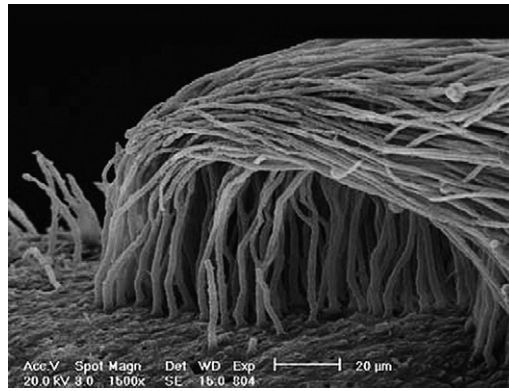

Fig. 5. FESE micrograph of EndoREZ tags extruding from the root filling material extending distances of at least 400 to 600 μm. The foreground shows fractured resin tags (caused by polymerization shrinkage) or resin tags that have partially entered the dentinal tubules. (*From* http://www.ineedce.com. Pameijer CH, Barnett F, Zmener O, Schein B. Methacrylate based resin endodontic sealers: a paradigm shift in endodontics? ENDO0710DE; 2008:1–11; with permission.)

of light from the moisture on the surface of a preparation can be visualized, in a root canal this is not possible, thus making clinical judgment more difficult.

In a study by Zmener and colleagues[14] 4 scenarios of dentin wetness or dryness were tested for apical and coronal dye leakage. In Group 1, 95% ethanol was used followed by paper points to dry the canals. In Group 2, the canals were blot dried with several paper points. In Group 3, a luer vacuum adaptor with low vacuum for 5 seconds followed by 1 paper point for only 1 to 2 seconds was used. In Group 4, the root canal remained flooded and no effort was made to remove excess distilled water. It was theorized that perhaps the hydrophilic properties of EndoREZ with the scenario in Group 4 would displace excess water.

Positive and negative controls were also tested. Dye leakage as determined by methylene blue, showed that EndoREZ and Epiphany/Resilon in Groups 2 and 3

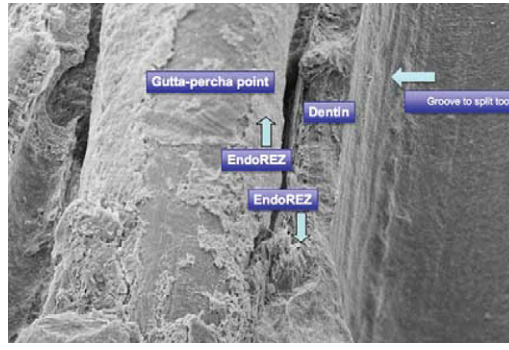

Fig. 6. Scanning electron micrograph of a gutta-percha point partially covered with EndoREZ. The space between point and adjacent dentin wall is filled with EndoREZ; however, no penetration into the dentinal tubules was observed. This is the result of over drying. (*From* Becce, C, Pameijer CH. SEM study of a new endodontic root canal sealer. J Dent Res 2001;79(AADR issue):abstract #866; with permission.)

exhibited significantly less coronal and apical leakage ($P<.05$) than Groups 1 and 4. The method with a low vacuum luer adaptor and paper point drying for 1 to 2 seconds (Group 3) scored the lowest leakage. There was no statistically significant difference between EndoREZ and Epiphany/Resilon. Another clinical technique to maintain moist dentin is to make sure that when excess water (or EDTA, saline or chlorhexidine) is removed with paper points, the last paper point shows at least 3 mm of moisture.

OXYGEN-INHIBITED LAYER

When conducting biocompatibility studies using subcutaneous implantation or intraosseous bone implants, specimen preparation of MBRS may result in the formation of an oxygen-inhibited layer, which depends on the method of sample preparation. The presence of an oxygen-inhibited layer plays a significant role in the outcome of tissue reactions, because resin, whether chemical, light, or dual cured, does not polymerize at its surface when in contact with air. This surface layer contains unreacted monomers that are highly toxic. However, this does not mean that polymerized sealers cannot cause irritation. Conversion of monomer in a typical polymerization reaction is at best less than 70%.[52] It is important to thoroughly flush the root canal with EDTA after using NaOCl, followed by an optional final flush with sterile saline or 2% chlorhexidine (Consepsis, Ultradent Products Inc), because oxygen left behind from the NaOCl inhibits polymerization, thus forming an oxygen-inhibited layer. The effect of this was demonstrated by the following study dealing with irrigation.

IRRIGATION PROTOCOL

Bond strength values of MBRS using different intracanal irrigation scenarios vary depending on the sequence of rinses and the composition of the last rinse. To determine the importance of an irrigation protocol that does not interfere with dentin bonding of a sealer, an experiment using a modification of the thin-slice push-out test design was used by Pameijer and Zmener.[53] Intact human teeth were instrumented according to a standardized protocol and subsequently prepared to produce 18 standardized dentin tubes (n = 6 per group for 3 groups), with a 3 mm internal diameter. The irrigation protocol was as follows:

Group 1 (n = 6): irrigation for 1 minute with 10 mL of 17% EDTA to remove the smear layer followed by a continuous flow of 10 mL of 5.25% NaOCl. The canal was then dried with a luer low vacuum tip for 2 seconds followed by sterile cotton pellets leaving the dentin slightly moist with NaOCl.

Group 2 (n = 6): irrigation with a continuous flow of 10 mL of 5.25% NaOCl followed by 10 mL of 17% EDTA (1 minute each) followed by drying with a luer low vacuum tip for 2 seconds followed by sterile cotton pellets leaving the dentinal walls slightly moist with EDTA.

Group 3 (n = 6): irrigation with a continuous flow of 10 mL of 5.25% NaOCl followed by 10 mL of 17% EDTA (1 minute each) and a final 2-minute rinse with 10 mL sterile distilled water. The canals were dried with a luer low vacuum tip for 2 seconds followed by sterile paper points leaving the dentinal walls slightly moist with distilled water.

All samples were then obturated with EndoREZ as per the manufacturer' instructions and prepared for the push-out test. **Fig. 7** shows the setup of the custom-made equipment used. Data were recorded in megaPascals (**Table 1**). The results of the push-out tests revealed that all groups had measurable adhesive properties. Group 1 showed the lowest bond strength values, whereas the values for Groups 2 and 3 were much higher. Although the results in Group 3 were slightly better, no statistically significant differences were demonstrated compared with Group 2 ($P>.05$).

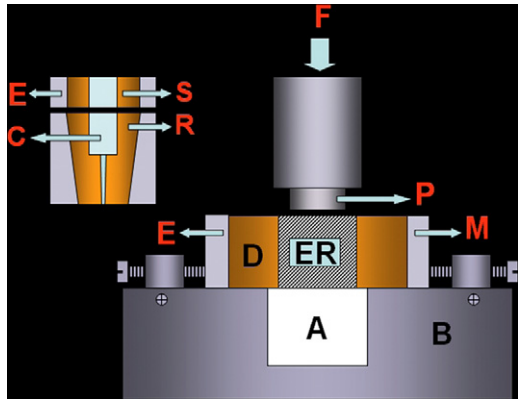

Fig. 7. The push-out test setup. A, space for displaced sealer; B, metal base of apparatus for sample fixation; F, direction of force; P, cylindrical plunger; D, 3 mm high root dentin cylinder; ER, EndoRez sealer; E and M, lateral sides of acrylic resin; R, remaining root; C, cylindrical preparation of the root canal (6 mm long with a 3 mm internal diameter); S, 3 mm high root section embedded in acrylic resin. The black line below E and S represent the cut through the samples perpendicular to the long axis of the tooth. (*From* http://www.ineedce.com. Pameijer CH, Barnett F, Zmener O, Schein B. Methacrylate based resin endodontic sealers: a paradigm shift in endodontics? ENDO0710DE; 2008:1–11; with permission.)

Visualization of the presence or absence of an oxygen-inhibited layer at the interface of dentin and EndoREZ sealer was demonstrated in cross sections (**Figs. 8** and **9**). **Fig. 8** shows a sample of Group 1. The light blue color represents dentin, the narrow gold colored band is the oxygen-inhibited layer, and the dark blue color represent fully polymerized EndoREZ. A photograph of Group 2 is significant (see **Fig. 9**) for the absence of a halo of unpolymerized resin. The dentin is light blue in color, and the dark blue represents fully polymerized EndoREZ. When EDTA was used as a final rinse, only polymerized (dark blue) EndoREZ was present at the dentin (light blue) interface and the cross sections were similar to the Group 2 samples.

It is obvious that unpolymerized resin at the interface dentin and sealer offers a pathway for leakage and has to be prevented at all cost.

CLINICAL EVIDENCE

More reports of reasonably long-term clinical studies have appeared in the literature that make it easier for the practitioner to evaluate the benefits and success of MBRS. EndoREZ was first reported on by Zmener and Pameijer.[54,55] One intermediate clinical study on Epiphany/Resilon[56] followed by a long-term clinical study have been published by Barnett and Debelian.[57]

Table 1
Mean push-out bond strength value

Group	n	Mean Bond Strength, MPa (SD)	Range
1	6	1.33 (0.45)	0.69–1.73
2	6	7.95 (0.60)	8.67–7.11
3	6	8.09 (0.49)	8.67–7.28

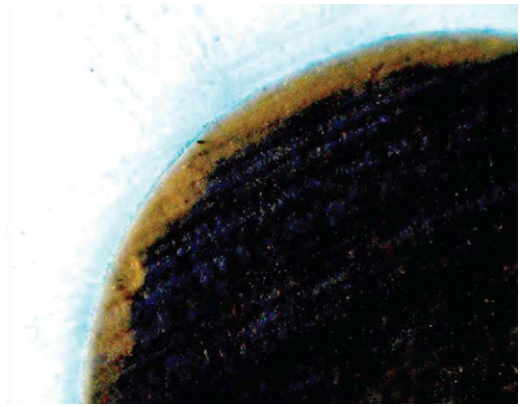

Fig. 8. Group 1 showing a cross section of dentin (*light blue*), an oxygen-inhibited layer (*gold colored halo*) and polymerized EndoREZ (*dark blue*).

In a retrospective study on 180 patients a total of 295 root canals were treated with laterally condensed gutta-percha cones in conjunction with EndoREZ. Root canal therapy was performed in 1 visit using standardized techniques. The results were assessed clinically and radiographically 14 to 24 months postoperatively[54] and after 5 years.[55] A comparison with baseline radiographs was made. Parameters for success were based on the absence of clinical symptoms, a normal or slightly widened periodontal ligament, and resolution of periapical radiolucencies with an absence of pain in patients who had pre-existing lesions associated with pain. After 2 years the overall success rate was 91.03%. In the subsequent 5-year follow-up that examined the same pool of patients, 129 responded to a recall request. Root canals had been adequately filled to the working length in 92 teeth (76.66%) and short in 13 (10.83%). Fifteen cases (12.50%), filled flush at the initiation of the experiment, showed slight resorption of the filling material at the apex within the lumen of the root canal. Of the 10 roots with extrusion, none had radiographic evidence of sealer in the periradicular tissues after 5 years. All patients were free of clinical symptoms. A life table analysis revealed a cumulative probability of success of 86.3% at the 5-

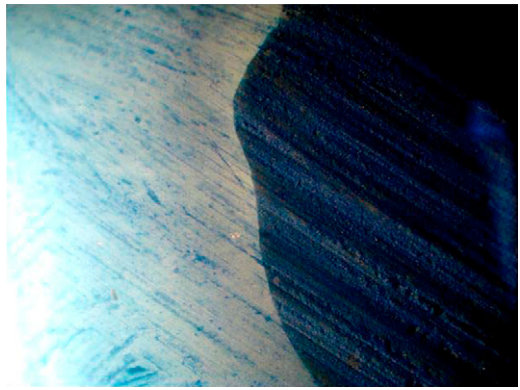

Fig. 9. A cross section of dentin (*light blue*), adjacent to fully polymerized ER (*dark blue*). No oxygen-inhibited layer is present.

year recall with a 95% confidence interval of 79.7 to 91.0. This percentage compares favorably with the literature[34,58,59] on the use of conventional sealers.

An example from the 5-year study is shown in the following 3 radiographs. Preoperative (**Fig. 10**A) and immediate postoperative view (**Fig. 10**B), and a 5-year follow-up (**Fig. 10**C) on tooth number 8 filled with EndoREZ and gutta-percha. Extruded sealer was resorbed during the interim and new bone was deposited. The patient has been free of symptoms since completion of treatment.

The results of Resilon/Epiphany in a 2-year prospective study have been reported by Debelian.[56] A total of 67 vital teeth were treated in 1 visit and 53 necrotic pulps in 2 visits (n = 120). After 2 years 108 cases were evaluated by 3 evaluators and the mean of the Periapical Index Scores (PAI) was calculated. When PAI 1 and 2 were combined (PAI 1 = healed; PAI 2 = in the process of healing), the success rate after 24 months was 91.6% (a similar success rate, ie, 91.3%, was reported by Zmener and Pameijer).[54]

Results after 4 years:

86 of 102 teeth (93.1%) were scored as successful (PAI 1, 2). 53 of 56 teeth (94.6%) that were without preoperative apical periodontitis were scored as successful.

42 of 46 teeth (91.3%) that were diagnosed as nonvital pulps with apical periodontitis were scored as successful.

Comparison between EndoREZ and Resilon is not feasible here because of the difference in evaluation periods (4 and 5 years, respectively). However, the

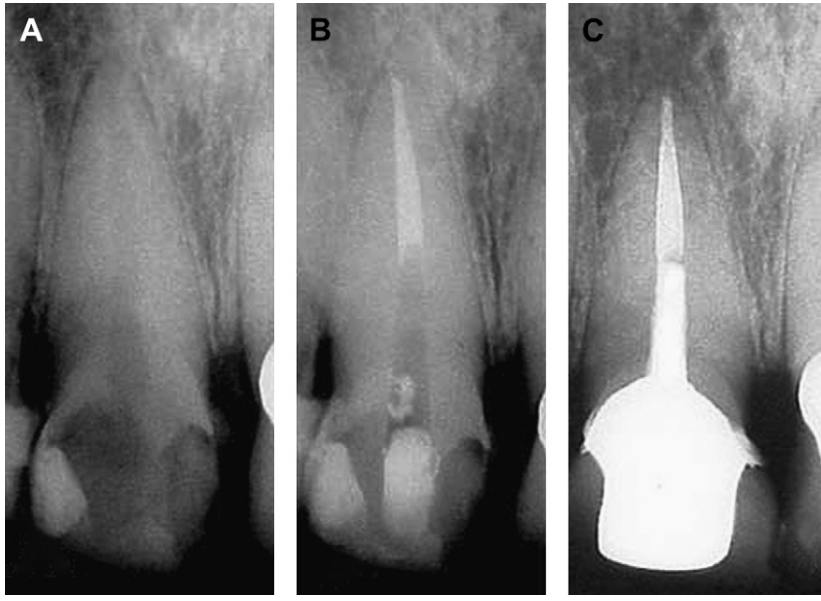

Fig. 10. (*A*) Upper incisor with pulpal involvement caused by leaking anterior restoration. (*B*) Immediate postoperative view. (*C*) After 5 years, the incisor, restored with a post and core and porcelain fused to metal is functional and completely asymptomatic. (*From* http://www.ineedce.com. Pameijer CH, Barnett F, Zmener O, Schein B. Methacrylate based resin endodontic sealers: a paradigm shift in endodontics? ENDO0710DE; 2008:1–11; with permission.)

percentages seem to indicate that both perform equally well and compare favorably with conventional sealers that have been reported in the literature.[60–62]

Ideally, more prospective clinical studies are needed to confirm these studies.

DO RESIN-BASED SEALERS REINFORCE ROOTS?

Intraradicular dentin bond strength tests have been conducted by means of a push-out test evaluating various sealers and combinations of sealers and points.

Some investigators reported higher values with resin-based sealers,[63,64] whereas others reported a lack of reinforcement.[65,66] Furthermore some experimental designs are suspect because of the drying of the root canal technique that has been discussed previously or the lack of standardization of the samples. Optimum standardization by Grande and colleagues[66] led to the following conclusion: the currently available endodontic filling materials and their recommended adhesive procedures are not able to influence the mechanical properties of root canal dentin. The flexural properties of Resilon and gutta-percha or EndoREZ and gutta-percha are too low to reinforce roots.

RETREATMENT OF MBRS

One of the requirements of a root canal sealer is that, in case of failure, the root canals can be retreated. According to de Oliveira and colleagues[67] and Ezzie and colleagues,[68] Epiphany/Resilon could be removed faster and with less residual filling material when K3 files,[67] or ProFile 0.06 combined with heat and chloroform[68] were used compared with gutta-percha and AH Plus. Automated[69] instrumentation can also be used to remove resin-based, zinc oxide, and eugenol endodontic sealers when retreating root canals. Straight canals obturated with gutta-percha and sealer may be negotiated with engine-driven stainless steel Anatomic Endodontic Technology (Ultradent Products Inc) instruments. The flute design with sharp cutting edges resulted in efficient cutting of the gutta-percha, aided by the softening of the material caused by frictional heat. Each individual instrument was discarded after instrumentation of 2 teeth, thus reducing the possibility of instrument breakage. The recommendation to use new instruments had been reported previously.[70] However, only teeth with straight canals were tested and consequently no conclusions can be drawn about the retreatment efficacy of AET instruments in curved root canals.

FUTURE EXPECTATIONS

It is anticipated that the MBRS will continue to appeal to the dental profession. New techniques and modifications of existing ones will be developed and introduced. For instance, the EndoREZ system recommends harpooning of catalyst-coated accessory cones after placement of the master cone into the sealer. This not only accelerates the setting reaction but also reduces the amount of sealer, thus reducing polymerization shrinkage; consequently a reduction in leakage can be accomplished. Because the accessory cones are placed after the master cone has been seated, there is no risk of pressing unreacted catalyst beyond the apex potentially causing damage to the periradicular tissues.

Bonding in endodontics is gaining recognition as reflected in a statement by Mounce[71]: ''Given the long-term trends in dentistry there can be little, if any, doubt that the future of endodontics is bonded. The goal of being able to bond a canal from the minor constriction to the canal orifice to the occlusal surface is a desirable one.''

On the challenging side of the positive ex vivo and in vivo studies and clinical success are publications that underscore the complexity of chemical compositions and their biologic interaction of currently available dental materials; these publications cannot be ignored. Material composition seems to be a critical factor.[72,73] It has been established that the co-monomer triethylene glycol dimethacrylate (TEGDMA) causes gene mutations in vitro. Formation of micronuclei indicates chromosomal damage and the induction of DNA strand breaks detected with monomers, such as TEGDMA and HEMA. New findings indicate that increased oxidative stress results in impairment of the cellular pro- and antioxidant redox balance caused by monomers. Monomers reduce the levels of the natural radical scavenger glutathione (GSH), which protects cell structures from damage caused by reactive oxygen species (ROS). Depletion of the intracellular GSH pool may then significantly contribute to cytotoxicity, because a related increase in ROS levels can activate pathways leading to apoptosis. Neither EndoREZ nor Epiphany contain these components.

After a thorough review of the available data and despite the contradicting ex vivo and in vivo tests, it seems that MBRS are here to stay. EndoREZ and Resilon are now being used successfully, about 10 years after their inception. The only conclusive evidence is long-term clinical success. Therefore more long-term data are needed to determine whether they will eventually replace conventional sealers or will be used in parallel as an alternative choice when filling root canals.

REFERENCES

1. Buonocore MG. A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. J Dent Res 1955;34:849–53.
2. Tidmarsh BG. Acid-cleaned and resin sealed root canals. J Endod 1978;4: 117–21.
3. Osorio R, Erhardt MC, Pimenta LA, et al. EDTA treatment improves resin-dentin bonds' resistance to degradation. J Dent Res 2005;84:736–40.
4. Yamada R, Armas A, Goldman M, et al. A scanning electron microscopic comparison of a high volume final flush with several irrigating solutions. Part 3. J Endod 1983;9:137–42.
5. Baumgartner JC, Mader CL. A scanning electron microscopic evaluation of four root canal irrigation regimens. J Endod 1987;13:147–57.
6. Zidan O, El Deeb ME. The use of a dentinal bonding agent as a root canal sealer. J Endod 1985;11:176–8.
7. Leonard JE, Gutmann JI, Guo IY. Apical and coronal seal of roots obturated with a dentine bonding agent and resin. Int Endod J 1996;29:76–83.
8. Nikaido T, Takano Y, Sasafuchi Y, et al. Bond strengths to endodontically treated teeth. Am J Dent 1999;12:177–80.
9. Morris MD, Lee KW, Agee KA, et al. Effects of sodium hypochlorite and RC-Prep on bond strengths of resin cement to endodontic surfaces. J Endod 2001;27: 753–7.
10. Erdemir A, Eldeniz AU, Belli S, et al. Effect of solvents on bonding to root canal dentin. J Endod 2004;30:589–92.
11. Manocci F, Ferrari M. Apical seal of roots obturated with laterally condensed gutta-percha, epoxy resin cement and dentin bonding agent. J Endod 1998; 24:41–4.
12. Ahlberg KM, Tay WM. A methacrylate-based cement used as a root canal sealer. Int Endod J 1998;31:15–21.

13. Kataoka H, Yoshioka T, Suda H, et al. Dentin bonding and sealing ability of a new root canal resin sealer. J Endod 2000;26:230–5.
14. Zmener O, Pameijer CH, Serrano SA, et al. The significance of moist root canal dentin with the use of methacrylate-based endodontic sealers: an in vitro coronal dye leakage study. J Endod 2008;34:76–9.
15. Wong Y, Spencer P. Continuity etching of an all-in-one adhesive in wet dentin tubules. J Dent Res 2005;84:350–4.
16. Zmener O, Pameijer CH. Resin-coated gutta-percha cones coupled with a resin-based sealer: a new alternative for filling root canals. Endod Prac 2007;10:21–5.
17. Tay FR, Hiraishi N, Pashley DH, et al. Bondability of Resilon to a methacrylate-based root canal sealer. J Endod 2006;32:133–7.
18. Louw NP, Pameijer CH, Norval G. Histopathological evaluation of root canal sealer in subhuman primates. J Dent Res 2001;80(Special issue):654 [abstract #1019].
19. Becce C, Pameijer CH. SEM study of a new endodontic root canal sealer. J Dent Res 2001;79(AADR issue) [abstract #866].
20. Becce C, Pameijer CH. Biocompatibility of a new endodontic sealer. J Dent Res 2003;81(IADR Special issue):B321 [abstract #2483].
21. Huang TH, Lee H, Kao CT. Evaluation of the genotoxicity of zinc oxide eugenol-based, calcium hydroxide-based, and epoxy resin-based root canal sealers by comet assay. J Endod 2001;27:744–8.
22. Huang FM, Tai KW, Chou MY, et al. Cytotoxicity of resin-, zinc oxide-eugenol-, and calcium hydroxide-based root canal sealers on human periodontal ligament cells and permanent V79 cells. Int Endod J 2002;35:153–8.
23. Koulaouzidou EA, Papazisis KT, Beltes P, et al. Cytotoxicity of three resin-based root canal sealers: an in vitro evaluation. Endod Dent Traumatol 1998;14:182–5.
24. Bouillaguet S, Wataha JC, Tay FR, et al. Initial in vitro biological response to contemporary endodontic sealers. J Endod 2006;32:989–92.
25. Key JE, Rahemtulla FG, Eleazer PD. Cytotoxicity of a new root canal filling material on human gingival fibroblasts. J Endod 2006;32:756–8.
26. Eldeniz AU, Mustafa K, Ørstavik D, et al. Cytotoxicity of new resin-, calcium hydroxide-and silicone-based root canal sealers on fibroblasts derived from human gingiva and L929 cell lines. Int Endod J 2007;40:329–37.
27. Lodiene G, Morisbak E, Bruzell E, et al. Toxicity evaluation of root canal sealers in vitro. Int Endod J 2008;41:72–7.
28. Oliver CM, Abbott PV. Correlation between clinical success and apical dye penetration. Int Endod J 2001;34:637–44.
29. Zmener O. Tissue response to a new methacrylate-based root canal sealer: preliminary observations in the subcutaneous connective tissue of rats. J Endod 2004;30:348–51.
30. Zmener O, Pameijer CH, Banegas G. Bone tissue response to a methacrylate-based endodontic sealer: a histological and histometric study. J Endod 2005; 31:457–9.
31. Sousa CJ, Montes CR, Pascon EA, et al. Comparison of the intraosseous biocompatibility of AH Plus, EndoREZ, and Epiphany root canal sealers. J Endod 2006; 32:656–62.
32. Ferracane JL, Condon JR. Rate of elution of leachable components from composite. Dent Mater 1990;6:282–7.
33. Spångberg LS. In vitro assessment of the toxicity of endodontic materials. Int Endod J 1981;14:27–34.
34. Orstavik D, Kerekes K, Eriksen HM. Clinical performance of three endodontic sealers. Endod Dent Traumatol 1987;3:178–86.

35. Zmener O, Banegas G. Apical leakage of endodontic sealers. Endod Pract 2004; 7:30–2.
36. Orucoglu H, Sengun A, Yilmaz N. Apical leakage of resin based root canal sealers with a new computerized fluid filtration meter. J Endod 2005;31:886–90.
37. Da Silva Neto UX, de Moraes IG, Westphalen VP, et al. Leakage of 4 resin-based root-canal sealers used with a single-cone technique. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2007;104:e53–7.
38. Adanir N, Cobankara FK, Belli S. Sealing properties of different resin-based root canal sealers. J Biomed Mater Res B Appl Biomater 2006;77:1–4.
39. Onay EO, Ungor M, Orucoglu H. An in vitro evaluation of the apical sealing ability of a new resin-based root canal obturation system. J Endod 2006;32:976–8.
40. Tunga U, Bodrumlu E. Assessment of the sealing ability of a new root canal obturation material. J Endod 2006;32:876–8.
41. Stratton RK, Apicella MJ, Mines P. A fluid filtration comparison of gutta-percha versus Resilon, a new soft resin endodontic obturation system. J Endod 2006; 32:642–5.
42. Shipper G, Orstavik D, Teixeira FB, et al. An evaluation of microbial leakage in roots filled with a thermoplastic synthetic polymer-based root canal filling material (Resilon). J Endod 2004;30:342–7.
43. Maltezos C, Glickman GN, Ezzo P, et al. Comparison of the sealing of Resilon, Pro Root MTA, and Super-EBA as root-end filling materials: a bacterial leakage study. J Endod 2006;32:324–7.
44. Pitout E, Oberholzer TG, Blignaut E, et al. Coronal leakage of teeth root-filled with gutta-percha or Resilon root canal filling material. J Endod 2006;32:879–81.
45. Biggs SG, Knowles KI, Ibarrola JL, et al. An in vitro assessment of the sealing ability of Resilon/Epiphany using fluid filtration. J Endod 2006;32:759–61.
46. Gernhardt CR, Kruger T, Bekes K, et al. Apical sealing ability of 2 epoxy resin-based sealers used with root canal obturation techniques based on warm gutta-percha compared to cold lateral condensation. Quintessence Int 2007;38:229–34.
47. Sevimay S, Kalayci A. Evaluation of apical sealing ability and adaptation to dentine of two resin-based sealers. J Oral Rehabil 2005;32:105–10.
48. Aptekar A, Ginnan K. Comparative analysis of microleakage and seal for 2 obturation materials: Resilon/Epiphany and gutta-percha. J Can Dent Assoc 2006;72:245.
49. Wu MK, Wesselink PR. Endodontic leakage studies reconsidered. Part I. Methodology, application, and relevance. Int Endod J 1993;26:37–43.
50. von Fraunhofer JA, Kurtzman GM, Norby CE. Resin-based sealing of root canals in endodontic therapy. Gen Dent 2006;54:243–6.
51. Kardon BP, Kuttler S, Hardigan P, et al. An in vitro evaluation of the sealing ability of a new root-canal-obturation system. J Endod 2003;29:658–61.
52. Kidal KK, Ruyter IE. How different curing methods affect the degree of conversion of resin-based inlay/onlay materials. Acta Odontol Scand 1994;52:315–22.
53. Pameijer CH, Zmener O. The effect of irrigation protocol on the polymerization of resin-based sealers–significance of oxygen inhibition. In: Methacrylate based resin sealers – a paradigm shift in endodontics. South Jordan (UT): Ultradent Press; 2009. p. 135.
54. Zmener O, Pameijer CH. Clinical and radiographic evaluation of a resin-based root canal sealer. Am J Dent 2004;17:19–22.
55. Zmener O, Pameijer CH. Clinical and radiographical evaluation of a resin-based root canal sealer: a 5-year follow-up. J Endod 2007;33:676–9.
56. Debelian G. Treatment outcome of teeth treated with an evidenced-based disinfection protocol and filled with Resilon. J Endod 2006;32 [abstract #PR4].

57. Barnett F, Debelian G. Clinical outcomes of endodontically treated teeth filled with Resilon. In: Methacrylate based resin sealers–a paradigm shift in endodontics. South Jordan (UT): Ultradent Press; 2009. p. 119.
58. Friedman S, Löst C, Zarrabian M, et al. Evaluation of success and failure after endodontic therapy using a glass ionomer cement sealer. J Endod 1995;21: 384–90.
59. Huumonen S, Lenander-Lumikari M, Sigurdsson A, et al. Healing of apical periodontitis after endodontic treatment: a comparison between a silicone-based and a zinc oxide-eugenol-based sealer. Int Endod J 2003;36:296–301.
60. Kerekes K, Tronstad L. Long-term results of endodontic treatment performed with a standardized technique. J Endod 1979;5:83–90.
61. Hoskinson SE, Ng YL, Hoskinson AE, et al. A retrospective comparison of outcome of root canal treatment using two different protocols. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2002;93:705–15.
62. Field JW, Gutmann JL, Solomon ES, et al. A clinical radiographic retrospective assessment of the success rate of single-visit root canal treatment. Int Endod J 2004;37:70–82.
63. Skidmore LJ, Berzins DW, Bahcall JK. An in vitro comparison of the inraradicular dentin bond strength of Resilon and gutta-percha. J Endod 2006;32:963–6.
64. Teixeira FB, Teixeira EC, Thompson JY, et al. Fracture resistance of roots endodontically treated with a new resin filling material. J Am Dent Assoc 2004; 135:646–52.
65. Ungor M, Onay EO, Orucoglu H. Push-out bond strengths: the Epiphany-Resilon endodontic obturation system compared with different pairings of Epiphany, Resilon, AH Plus and gutta-percha. Int Endod J 2006;39:643–7.
66. Grande NM, Lavorgna L, Ioppolo P, et al. Influence of different root canal filling materials on the mechanical properties of root canal dentin. J Endod 2007;33: 859–64.
67. de Oliveira DP, Barbizam JV, Trope M, et al. Comparison between gutta-percha and resilon removal using two different techniques in endodontic retreatment. J Endod 2006;32:362–4.
68. Ezzie E, Fleury A, Solomon E, et al. Efficacy of retreatment techniques for a resin-based root canal obturation material. J Endod 2006;32:341–4.
69. Zmener O, Banegas G, Pameijer CH. Efficacy of an automated instrumentation technique in removing resin-based and zinc oxide and eugenol endodontic sealers when retreating root canals: An in vitro study. Endod Prac 2005;8:29–33.
70. Tronstad L, Niemczyk SP. Efficacy and safety tests of six automated devices for root canal instrumentation. Endod Dent Traumatol 1986;2:270–6.
71. Mounce R. Say what you will: the future of endodontic obturation is bonded. Endod Prac 2007;10:48.
72. Schweikl H, Spagnuolo G, Schmalz G. Genetic and cellular toxicology of dental resin monomers. J Dent Res 2006;85:870–7.
73. Schweikl H, Hartmann A, Hiller KA, et al. Inhibition of TEGDMA and HEMA-induced genotoxicity and cell cycle arrest by *N*-acetylcysteine. Dent Mater 2007;23:688–95.