Published in final edited form as:
Acta Biomater. 2014 March ; 10(3): 1050–1063. doi:10.1016/j.actbio.2013.11.015.

Ability of New Obturation Materials to Improve the Seal of the Root Canal System – A Review

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Abstract

Objectives—New obturation biomaterials have been introduced over the past decade to improve the seal of the root canal system. However, it is not clear whether they have really produced a three-dimensional impervious seal that is important for reducing diseases associated with root canal treatment.

Methods—A review of the literature was performed to identify models that have been employed for evaluating the seal of the root canal system.

Results and Significance—*In-vitro* and *in-vivo* models are not totally adept at quantifying the seal of root canals obturated with classic materials. Thus, one has to resort to clinical outcomes to examine whether there are real benefits associated with the use of recently-introduced materials for obturating root canals. However, there is no facile answer because endodontic treatment outcomes are influenced by a host of other predictors that are more likely to take precedence over the influence of obturation materials. From the perspective of clinical performance, classic root filling materials have stood the test of time. Because many of the recently-introduced materials are

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so new, there is not enough evidence yet to support their ability to improve clinical performance. This emphasizes the need to translate anecdotal information into clinically relevant research data on new biomaterials.

Keywords

leakage models; root canal; root filling materials; sealability; treatment outcome

1. Introduction

There is increasing need for the medical and dental professions to base their clinical judgement on evidence-based knowledge [1,2]. The requisite for integrating biologically-based knowledge with the advent of new biomaterials designed to improve root canal treatment has been well conceded even before endodontics became a specialty [3]. Because diseases of the dental pulp are predominantly infectious in nature [4], development of new root filling materials should be targeted at improving the ability and efficacy for endodontists to eliminate infections and prevent recontamination [5,6]. As early as 1925, Dr. Walter Hess and his student Dr. Ernst Zürcher showed that root canal systems have exceedingly complex morphologies that may not be amendable to complete shaping and cleaning [7]. Contemporary non-destructive imaging such as micro-computed tomography further reinforced this notion from a three-dimensional (3-D) perspective [8,9]. Between then and now, knowledge of root canal infections has also improved. Apical periodontitis, as it is now known, is not caused by fluid stagnation within unfilled canal spaces [10]. Rather, it is an inflammatory reaction of the periapical tissues and an immunological response of the host defense system to microbes that have infected the root canal system [11,12]. Successful root canal treatment, therefore, depends critically on controlling pulp space infection [13–15]. Root canal infection, like many other infections, is predominantly a biofilm-induced disease [16–18]. The association between bacterial biofilms and apical periodontitis has been confirmed by more recent histobacteriological studies [19,20].

Success in root canal treatment was founded upon the triad of thorough canal débridement, effective disinfection and obturation of the canal space [21]. Historically, a significant share of this triad had been allocated to obturation of the canal space. Obturation of the canal space to the working length [22] has been depicted as the most critical component of root canal treatment for sealing and isolating the canal space from irritants that remain after appropriate shaping and cleaning, and for eliminating subsequent leakage from the periradicular tissues or oral cavity into the filled canal space [23,24]. Results from these early works are supported by recent outcome studies that highlight the contribution of root filling quality to the success of primary and secondary root canal treatment [25–28]. Nevertheless, contemporary research attests that shaping and cleaning are strategically more significant than obturation of the canal space for eliminating root canal infections [29]. Apical periodontitis has been shown to coronal seal [30]. It is indubitable that a high quality coronal seal is heal in teeth with unfilled canals following meticulous shaping and cleaning, and placement of a important for endodontic success [31]. However, insisting that healing reliably occurs in the presence of a defective root filling is to have created a very narrow view [32] on the important roles played by canal obturation in preserving the environment created by shaping and cleaning and preventing microbial reinfection of the canal space [33], both of which are essential for securing long-term periradicular heath.

New obturation materials have been introduced into the endodontic market over the last decade. Some of these are modifications of materials developed for restorative dentistry. Others may be considered as new breeds, embracing radically new concepts that have not been employed before in the field of endodontics. These seemingly unrelated new

developments share a bona fide feature: their promotions are accompanied by impressive case reports. It is beyond doubt that those clinical cases are performed by outstanding clinicians who, in every way, have demonstrated their “conscientious adherence to high (professional) ideals” [34]. Those cases are demonstrations of the results of excellent shaping and cleaning, and perhaps of sound obturation techniques. On further reflection, do they really demonstrate the superiority of one particular new filling material? The present review highlights and analyzes how the quality of seal is determined for the classic root canal obturation materials. This will provide the background for clinicians to determine, based on the best available evidence to date, whether the recently-introduced root canal obturation materials have improved the seal of the root canal system. Search of the literature on the seal of the root canal system was accomplished via the MEDINE (Ovid) database on *in vitro* and *in vivo* studies published between 1981 and 2013, using key words “root filling” OR “obturation” OR “leakage” OR “seal”. Four journals (Journal of Endodontics, International Endodontic Journal, Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontology, and Endodontics and Dental Traumatology) and the bibliography of all relevant articles and review articles were also manually searched.

2. The Classics (Traditional Gutta-percha and Sealer)

Historically, gutta-percha, the trans-isomer of polyisoprene, has been the material of choice as a solid, inert core filling material for root canal obturation, beginning with Bowman's introduction of the material into endodontics in 1867 [35]. Contemporary gutta-percha–based root filling materials utilizes approximately 20% of the raw polymer, with the remaining composition consisting of zinc oxide, wax/resin and metal sulphates [36,37]. Different gutta-percha obturation techniques have been employed, including single-cone technique, solvent softening techniques, cold or warm lateral compaction, warm vertical compaction, continuous wave compaction, thermoplastic injection techniques, thermomechanical compaction techniques, as well as core-carrier techniques [38,39]. Of notable mention is that the single-cone obturation technique, developed in the 1980s for standardization of endodontic instruments and filling points [40], has been revived with the introduction of some contemporary filling techniques [41].

Although gutta-percha is not the ideal filling material for root canals, it has satisfied most of the criteria for an ideal root filling material. In particular, gutta-percha exhibits minimal toxicity, allergenicity and tissue irritability when it is retained within the canal space [42]. Gutta-percha is predominantly non-resorbable and is well tolerated in cases of inadvertent overextension into the periradicular tissues [43], when the overextended material is present in bulk instead of fine particles [44]. Gutta-percha is degradable by bacteria species associated with the *Nocardia* genus [45]. However, such species have not been identified as endodontic pathogens, despite the vast diversity of microbial flora reported in untreated teeth and root-filled teeth with apical periodontitis [46–49]. Although gutta-percha retrieved from retreatment cases had been reported to degrade chemically over time via a slow oxidative process [50], there was no associated loss of texture or disappearance of the material from the obturated canal space. Moreover, those root fillings are defective by default as the internal milieu of the canal space should be predominantly anaerobic if the latter is appropriately sealed.

A shortcoming of gutta-percha-based root filling materials is their lack of adhesiveness to canal wall dentin. Because of this limitation, a sealer or cement has to be used with gutta-percha to attain a fluid-tight seal, and to fill the space between the canal wall dentin and the obturating material interface. Sealers also fill voids and irregularities in the root canal, lateral and accessory canals, and spaces between gutta-percha points used in lateral condensation techniques. Different types of sealers are currently available, including zinc

oxide eugenol and noneugenol sealers, calcium hydroxide sealers, glass ionomer sealers, epoxy resin–based sealers, silicone sealers, medicated sealers, and the more recently introduced methacrylate-resin-based sealers and calcium silicate-based sealers. Penetration of sealers and even gutta-percha into dentinal tubules has been demonstrated when the canal wall smear layer is removed [51–53]. The extent of penetration of root canal sealers into dentinal tubules [54–56] has often been utilized for demonstrating the improvement of sealability to root canals during the launch of new root filling materials and techniques. However, studies have shown that there is no correlation between sealer penetration into dentinal tubules and sealability in non-bonded [57] or bonded [58] root fillings. Along the same line of thought, a small puff of sealer extending through the apical ramifications [22] or lateral canals [59–61] has been considered by some clinicians to be indicative of an optimally-obturated canal space with a well-sealed apical constriction or lateral portal of exit. The need to force filling materials into these regions to enhance treatment outcome is not supported by a recent histopathological study [62]. In that study, pulp tissues within those ramifications were not removed by contemporary chemomechanical preparation techniques. Forcing materials into those ramifications in teeth with vital pulps resulted in tissue damage and inflammation. The radiographic appearance of filling materials within those ramifications, while visibly appealing, could not guarantee optimal sealing or disinfection. In large ramifications of necrotic pulps where microbes could reach sufficient quantity to cause or maintain disease, the authors opined that alternative strategies that enable thorough disinfection of those regions should be sought to enhance treatment outcome.

Over the last couple of decades, endodontics has benefited from ground breaking advancements in imaging capabilities, better magnification, more accurate working length determination technology, more efficient canal shaping armamentarium, more advanced canal irrigation solutions, and radical changes in tissue dissolution and disinfectant delivery techniques. All of these improvements have contributed to enhanced obturation of the canal space. However, even in countries with highly-developed economies and advanced technological infrastructures, the majority of teeth that require non-surgical root canal treatment are obturated today with the same classic material that was introduced more than 160 years ago, using classical filling techniques that were established in the 1940s and 1950s, with a relatively high and predictable degree of success [25–28]. Despite the paucity of high-level, evidence-based studies [63,64], randomized control clinical trials remain the gold standard in evaluating treatment outcomes. Nevertheless, they suffer from the limitation of not being able to discern whether failure is caused by the material or by the operator. Considering that root canal treatment in teeth without previous histories of apical periodontitis has over 90% success, it is logical to assume that the use of classic obturation materials, from which the majority of those studies were based, should result in an excellent seal of the canal space. Paradoxically, regardless of the technique or delivery system employed for these classic materials, the literature is replete with *in-vitro* studies indicating that they do not routinely provide an impervious seal of the root canal system. Thus, it is appropriate to briefly review how leakage is evaluated for these classic endodontic obturation materials. Specifically, it is important to understand how clinically relevant the currently available laboratory methods are in evaluating the seal of filled root canals.

2.1 *In–vitro* leakage models

Because of the prevailing thinking of opinion leaders from academia in the early 1990s that incomplete filling of the root canal is the major factor in endodontic failure [23,24], different laboratory-based models have been designed to evaluate the sealability of endodontic filling materials and techniques, either in the form of leakage from the root apex (apical leakage) or the coronal aspect of the root canal filling (coronal leakage). Many of these models measure

the penetration of a tracer along the root canal filling, including dyes, radio-isotopes, bacteria and lipopolysaccharides. Other models have been employed apart from the tracer penetration/extraction techniques. Fluorometry measures the fluorescence emitted by a fluorescent tracer around the root fillings. The electrochemical technique measures the passage of an electrical current through electrolyte-filled voids along the root filling. The fluid transport method evaluates the passage of water or saline across through-and-through voids along the root filling. Capillary flow porometry measures the displacement of a wetting liquid from pores that extend along the entire root filling by applying a gas at increasing pressure. The glucose penetration test quantifies the amount of glucose that can be forced under hydrostatic pressure applied from the coronal aspect of the root filling using an enzyme detection method. The results from all *in-vitro* leakage models unanimously show that no canal obturation material/technique can achieve or maintain a long-term seal under the most ideal conditions in extracted teeth.

The major limitations of *in-vitro* leakage studies are their lack of reproducibility, small sample size and inadequate statistical power, absence of standardization and absence of correlation among different leakage models [65–68]. There are also limitations associated with individual models, particularly those involving dye leakage evaluation [69–73]. Even the most logical model for examining reinfection of root-treated teeth, the microbial leakage model, suffers from severe criticism in that most of the studies published to date lack an appropriate control that takes into account the leakage between the root surface cementum and the sticky wax coating [74,75]. This model also does not distinguish between sealability of the root filling from the antimicrobial effects of the obturating material [76]. For example, an *in-vitro* bacteria leakage model was used to confirm the seal of obturated root canals by the absence of turbidity in the culture broth-containing lower reservoir, after 120 days of testing against the ingress of *Enterococcus faecalis*, a bacteria species frequently identified from canals with recalcitrant periradicular lesions. However, subsequent histologic analysis of demineralized sections prepared from the corresponding teeth demonstrated abundant bacteria within the obturated root canals and dentinal tubules [77]. The results of that study re-emphasize the need to utilize histology to validate the routes of microbial leakage in the classical two-chamber microbial leakage model to avoid generation of erroneous results. Another “apparently relevant” leakage model, the glucose leakage model, which is supposed to measure the availability of nutrients to bacteria, has been found to produce inaccurate results due to reaction of glucose with some root canal sealers [78].

Although *in-vitro* leakage models have been adopted by manufacturers for initial screening of new materials and techniques for canal obturation and to justify their superiority for clinical applications, these models have limited clinical relevance. Dr. Thomas Pitt Ford was among the first in 1983 to alert the specialty that the value of *in-vitro* leakage testing has been overemphasized [79], after he found no correlation between apical leakage of root-filled teeth immersed in eosin dye and the tissue response of roots of dogs' teeth filled with the same materials. Similarly, Oliver and Abbott observed that treatment outcome could not be predicted from the results of dye leakage studies, after they identified no statistical significant difference in apical dye leakage between clinically successful and unsuccessful human teeth that had been root-filled for at least 6 months prior to extraction [80]. In that study, the methylene blue dye penetrated 99.5% of the specimens under the effect of a vacuum. The authors concluded that the presence of dye in the canal is a poor indicator of whether the obturation material or technique will result in a successful treatment outcome. More recently, Susini *et al*. also concluded that evaluation of apical leakage using the dye extraction method has no predictive value for the development of periradicular lesions [81]. In that study, the authors immersed extracted human teeth that had been root-treated clinically for at least 4 years into methylene blue dye and then extracted the dye with 65%

nitric acid. They reported no statistically significant difference in the amount of extracted dye in teeth that exhibited an apical radiolucency and those without an apical radiolucency.

Although the use of methylene blue dye has been criticized in a subsequent study for its futility as a tracer for dye penetration studies due to its chemical reaction with some sealers [73], the endodontic academia at large is skeptical of the clinical implications of currently available *in-vitro* sealability models, and the absence of evidence associated with studies utilizing these models. As an illustration, Shanahan and Duncan recently published a review paper on root canals obturated by a recently-introduced root filling material that has been introduced into the market as a replacement for gutta-percha [82]. The authors identified 46 leakage studies, of which 16 studies (34.5%) demonstrated that the recently-introduced root filling material was statistically superior to gutta-percha in preventing apical or coronal leakage. Nineteen out of the 46 studies (41.3%), on the other hand, demonstrated no statistical difference between the two materials, while 11 studies (23.9%) demonstrated gutta-percha was statistically superior to the recently-introduced material in preventing apical or coronal leakage! This exemplifies the chasmic discrepancies in leakage study findings that do not permit one to support or refute the value of nearly any endodontic material. This has led the Journal of Endodontics [83], and subsequently the International Endodontic Journal [84], to publish position statements in not accepting future studies that are related to comparative appraisals of root filling materials or techniques using *in-vitro* leakage models alone.

2.2 *In-vivo* canine models

Most of the materials for root canal obturation may be classified as class II medical devices according to the U. S. Food and Drug Administration [85]. Class II devices are defined as those which are considered as having “moderate risk” in terms of their risk to the patients and how the risks are mitigated. Class II materials are tested for toxicity and physical properties, not clinical performance. There is no functional test that goes into classification and quality control requirements for these materials. Nevertheless, from a research perspective, the lack of a standardized, clinically relevant *in-vitro* methodology that permits comparative evaluation of functional efficacy has prompted research scientists to develop animal models for comparing the functional efficacy of classic obturation materials in creating an impervious seal of the root canal system.

In endodontics, the most relevant animal model adopted for such a purpose is the *in-vivo* canine model. Two versions of the *in-vivo* model have been employed. The first model was designed to examine the effect of root filling materials in preventing post-treatment periradicular infections via a coronal route [79,86–93]. In this version, dogs were anesthetized using general anesthesia and their premolars were shaped, cleaned and obturated with different materials/techniques, with appropriate positive and negative controls. After canal obturation and temporization, the pulp chamber and access cavity of those teeth were restored. In other studies, the access cavities were subsequently re-accessed and left exposed to the oral environment, or inoculated with dog's plaque and re-sealed. The dogs were humanely sacrificed after a determined period of time and tissue blocks containing the root-filled teeth were fixed, demineralized, laboratory-processed, sectioned and stained to examine the extent of periapical inflammation as well as soft and hard tissue responses, and, occasionally, the presence of bacteria within the intraradicular dentin.

The second version of the *in-vivo* canine model was designed to evaluate the effects of classic endodontic filling materials on the healing of pre-existing apical periodontitis [94–98]. The experiments were similar to the first version, with the exception that the root canals were first exposed to the oral environment to induce the formation of periapical lesions over time [99] prior to shaping, cleaning and obturation of the canal spaces. The examination

criteria were similar to the first version, but with the addition of assessment of the lesion size at designated time periods.

While it is undeniable that the results generated by *in-vivo* animal models are more clinically relevant than those produced by *in-vitro* leakage models, it must be pointed out that data derived from animal studies do not represent the result of the seal of the root canal system *per se*. Rather, those results are the combined effects of: a) the sealability of the root filling materials; b) tissue responses to the short- or long-term cytotoxicity of the materials [100,101]; c) antimicrobial properties of the materials [76]; d) innate antimicrobial and immune-regulatory responses by host defense peptides (defensins and cathelicidins) [102]; and e) the effect of dentinal tubule occlusion on microbial contamination of the root canal space [75]. It has previously been reported that tubular sclerosis (i.e. sclerotic radicular dentin or transparent root dentin [103]) impedes dye penetration into the dentin of instrumented root canals [104]. The more recent work by Rechenberg *et al*. [75] further attests that leakage of microbes through filled root canals occurs through dentinal tubules and their anastomoses instead of along the interface between the root filling material and the canal wall. When leakage occurs, bacteria permeate the tubular aspects of root-filled teeth while sclerotic dentin remains bacteria-tight. This phenomenon should be applicable to both *in-vitro* and *in-vivo* models. Thus, in comparing the “sealability” of different materials using an *in-vivo* animal model, it is unclear if one is evaluating the real sealability or the variability of sclerotic root dentin in different teeth or animals.

One can see that both *in-vitro* and *in-vivo* models are not totally reliable in quantifying the seal of root canals obturated with classic materials. Although *in-vitro* leakage models are not useful as predictors of treatment outcomes, it should be emphasized that they still play an important role as a first simple screening test prior to the commercialization of a new material. The purpose of an initial screening test is to ensure that the new material meets the standards established by pre-existing techniques prior to its application on animals or patients. Until there is a better initial screening test, all *in-vitro* leakage models described in the previous section still have validity. This is because the clinical validity of the in vivo canine model is questionable in terms of the different apical anatomy in the root apices of dog's roots, compared with the roots present in human teeth. Moreover, it is questionable whether sacrificing dogs for the sake of examining the sealability of root canal fillings is really justifiable. Nevertheless, the succeeding question to be answered is whether the new obturation materials/techniques recently introduced into the market are capable of improving the seal already achieved by classic materials/techniques of the root canal system.

3. Recently-introduced Materials

Commercial presentations and glossy advertising have never been more prominent when it comes to the introduction of new dental products into a highly competitive market. Controversies and disputes have emanated, dividing practitioners into philosophical cults [105]. It is not the intent of this review to associate brand names with any individual product or category of products. Rather, they will be discussed in terms of their purported functions or generic compositions. Accordingly, the new commercially-available root filling materials which claim betterment of their seal of the root canal system may be classified by function into those that:

- **I.** Adhere to canal wall dentin and root filling materials to eliminate interfacial gaps;
- **II.** Attempt to self-seal gaps by setting or hygroscopic expansion;
- **III.** Enhance flow and adaptation of the root filling material to canal walls; and
- **IV.** Utilize bioactive reaction products to salvage a compromised seal.

3.1 Adhere to canal wall dentin and root filling materials to eliminate interfacial gaps

This category is by far the most extensively studied. As envisioned by Dr. John Ingle in 1995 [106], one of the recent trends in endodontics has been the development of obturating materials that are capable of bonding to canal wall dentin in order to eliminate interfacial gaps coronally and apically [107]. Dentin adhesive technology has been adapted from restorative dentistry and applied to obturating materials. As far as adhesion to intraradicular dentin is concerned, the same mechanism of hybrid layer formation that has been reported for bonding to crown dentin is recapitulated in intraradicular dentin with the use of etch-and-rinse adhesives [108,109], or methacrylate resin-based sealers that utilize a separate self-etching primer component or self-adhesive sealers that incorporate acidic resin monomers [110]. Likewise, glass ionomer cements which chemically bond to dentin via ion exchange and formation of an intermediate layer along the dentin-material interface [111] have been adopted to produce glass ionomer root canal sealers [112].

In the early-2000s, there was a surge of enthusiasm among manufacturers of endodontic obturation materials to produce, via adhesive mechanisms, a continuum of bonded interfaces from dentin to sealer to the core obturation material, and from the coronal to apical aspects of the canal space, including the canal fins, cul-de-sacs and isthmuses. This hypothetical concept results in creating a monoblock in the root canal [113] which, if successful, should completely eliminate interfacial gaps, produce perfect coronal and apical seal, and prevent post-treatment re-infection of the canal space [114]. As gutta-percha does not adhere well to root canal sealers, one way to achieve this goal is to chemically bind or mechanically impregnate a coating over the surface of gutta-percha cones so that the chemistry and surface energy of the coating is akin to the sealer. Examples of this strategy includes resin-coated gutta-percha with functional methacrylate groups for use with a hydrophilic self-priming methacrylate resin-based sealer system [115], and bioactive glass power-impregnated gutta-percha cones for use with a glass ionomer-based sealer [116] or a premixed calcium silicate-based sealer [117]. Theoretically, this type of intracanal bonding strategy produces a tertiary monoblock with three adhesive interfaces: dentin-sealer, sealer-coating and coating-gutta-percha [113]. As demonstrated by finite element analysis modeling, the magnitude of stress created within the root canal during force application increases with the number of interfaces, from 1.67 to 8.33 MPa, in hypothetical monoblocks created by the sealers [118]. There are manufacturing difficulties in creating a uniform coating over the entire surface of a gutta-percha cone. It is not infrequent to see denuded gutta-percha with incomplete resin coating (Figures 1A and 1B) or non-uniform distribution of glass particles (Figures 1C and 1D). It is known that an oxygen inhibition layer is not required for immediate bonding of fresh resins that cure by a free radical polymerization mechanism, due to the presence of active free radicals within the material [119]. However, bonding does not occur once the free radicals are depleted [120]. Thus, it is hard to envisage how adhesion of methacrylate resin-based sealers to non-sticky, commercially-packaged resin-coated gutta-percha can occur even if a continuous resin coating exists.

Another strategy to achieve an intracanal monoblock is to incorporate a cross-linkable difunctional methacrylate into an alternative thermoplastic polymer to render the root filling material bondable to self-etch or self-adhesive root canal sealers. This strategy was brought to fruition by the introduction of a biodegradable, polycaprolactone-based thermoplastic root filling material that is currently marketed as a replacement for gutta-percha [121]. Ideally, this type of intracanal bonding strategy produces a secondary monoblock with two adhesive interfaces: dentin-sealer and sealer-root filling material [113]. However, the dimethacrylate is not miscible with the polycaprolactone in the commercialized version of the material, and phase separates into discontinuous droplets within the bulk of the filling material (Figure 2). As there is no catalyst and co-initiator in the root filling material, polymerization of the surface droplets can only occur if they are exposed on the surface of the root filling material

to enable diffusion of free radicals from the resin sealer. Unfortunately, the dimethacrylate resin droplets are usually covered by the polycaprolactone polymer and are only exposed after laboratory differential etching of the polycaprolactone. This probably explains why adhesion of a methacrylate resin sealer to this root filling material is low [122]. In a recent review on this root filling material, the authors concluded that the material cannot presently be considered an evidence-based alternative to gutta-percha, the current gold standard for root filling material [82]. Nevertheless, because the system requires no changes in the techniques of canal preparation or obturation, it provides an alternative for patients suffering from natural rubber allergy, who, despite reassurance of the lack of cross-reactivity between natural rubber and gutta-percha [123,124], are apprehensive in having their root canals obturated by gutta-percha.

An important issue that jeopardizes the seal of root canals that are filled with these relatively rapid-polymerizing, resin sealer systems is their extended setting shrinkage behavior [125], and the inability of the long narrow root canals to cope with the relief of polymerization shrinkage stresses created by these systems on the bonded interfaces (i.e. dentin, resin-coating or bondable core material) [126–128]. This is particularly so when manufacturers recommend light-curing through the canal orifices to create an immediate coronal seal. Although there may be partial relief of shrinkage stresses as the resin sealer flows into patent dentinal tubules, gaps are still formed along the interfaces despite the presence of long resin tags in the hydrophilic self-priming methacrylate resin sealer system [58]. Similar results can be seen in root canals obturated with the polycaprolactone-based filling material and its accompanying self-etching resin sealer, either by destructive or non-destructive evaluation methods. Using micro-computed tomography, intracanal voids were found to be significantly fewer in canals that are obturated with gutta-percha and accompanying sealers [129]. Using confocal laser scanning microscopy (CLSM), gap distribution was significantly higher, and gap thickness were significantly larger in canals that were obturated with the polyacaprolactone-based filling material and its accompanying sealers, when compared to roots obturated with gutta-percha and an epoxy resin-based sealer (Figure 3) [130]. Another CLSM study came to the same conclusion that obturation of root canals with gutta-percha using non-bonding techniques resulted in significantly more gap-free regions, when compared with the use of the polycaprolactone-based material and its accompanying self-etching sealer [131]. Unlike leakage, interfacial gaps are clinically relevant because as little as 1% shrinkage of root canal sealers can result in gaps that are large enough for bacteria penetration [132]. Although epoxy resin also shrinks during polymerization [133], commercially available epoxy resin-based root canal sealers set slowly enough to permit the shrinkage stresses to be relieved through resin flow. Subsequent water sorption from incompletely desiccated dentinal tubules further contributes to relief of residual shrinkage stresses via hygroscopic expansion [132,134].

Another route of interfacial void formation is the potential biodegradation of the core filling material itself. There are no published reports indicating that this phenomenon occurs in gutta-percha to the extent that permits bacteria penetration. However, there are continuing anecdotal discussions that such a phenomenon occurs in polycaprolactone-based root filling materials when there is a breach of the coronal seal, so that bacteria can penetrate the root filling and propagate. Development of apical periodontitis has been noted in teeth obturated with polycaprolactone-based material, in which there was no evidence of pre-operative periodontitis [135], with occasional disappearance of the filling material (Figure 4, a–d). A more common observation in cases that require re-treatment, is the loss of structural integrity of the polycaprolactone-based root filling material “from the rigid state to a pliable, almost gelatinous form” [135]. Also, black material was sometimes identified during retreatment, in canals previously treated with this filling material. The color change from pink to black was clarified by the manufacturer to be due to bismuth sulphide, a reaction

product between bismuth oxychloride, the radiopacifier, and proteins derived from leaked body fluids. Contrary to what the manufacturer claimed, a similar color change was identified after exposure of the polycaprolactone-based root filling material to bacteria present in root canal infections [136]. This potential degradation process requires several years before it can be detected in a radiograph. A possible cause of such a phenomenon is enzymatic degradation of the polycaprolactone component of the root filling material [137,138] by remnant microbes from infected root canals. Under starvation, these bacteria are capable of producing inducible enzymes to use polycaprolactone as an alternative source of nutrients [139]. The polycaprolactone-based obturation concept was originally marketed as a better product than gutta-percha for preventing coronal leakage [140]. Results of the recent endodontic microbiota-related biodegradation studies [135,136] suggest that should coronal leakage occur, root canals obturated with the polycaprolactone-based material are more likely to leak than those obturated with gutta-percha. Further work should be performed to clarify this potential biodegradation phenomenon. It would be interesting also to see if the seal of the root canal system can be improved when polycaprolactone is replaced by polybutylene [141].

3.2 Attempt to self-seal gaps by setting or hygroscopic expansion

Expansion of obturation materials to improve the seal of root-filled canals has been reported even for classic obturation materials. Gutta-percha expands in the presence of eugenol [142,143] which may help to reduce gaps within canals obturated with zinc oxide-eugenol sealer-filled canals caused by the release of eugenol from the set sealer [144], shrinkage [132, 145] or dissolution of sealer over time [146]. Apart from eugenol-induced expansion, closure of interfacial gaps in gutta-percha-filled root canals may also occur by slow, hygroscopic expansion of gutta-percha [147], due to sorption of incompletely removed moisture present within the canal space [148].

Some of the recently-introduced materials also utilize expansion of the sealer or obturation points as a mechanism to compensate for or self-seal gaps inside the canal space. The first is a polydimethylsiloxane-based sealer than contains gutta-percha particles. This sealer has been reported to expand by less than 1% (0.44–0.76% at 37°C) after setting [125,149]. Although *in-vitro* leakage studies are common, they are of limited value, as discussed in Section 2. The second expansion method is a cold lateral condensation technique that utilizes single or multiple cones of a new water-expandable obturation material together with an epoxy resin-based or a calcium silicate-based sealer [150]. This new obturation point employs technology derived from water-expandable polymers utilized in contact lens [151], and is designed to radially expand as it absorbs water that is resident in the instrumented canal space and dentinal tubules. The manufacturer claims that the lateral expansion occurs non-isotropically, with the expansion relying on the extent to which the hydrophilic polymer is pre-stressed (i.e. expansion will be reduced when it is in contact with the canal wall) [152]. This non-uniform expansion is said to enhance the sealability of root canal fillings by pushing the sealer into close contact with the canal wall during the initial setting of the sealer. The obturation point consists of an inner radiopaque nylon core and an outer radiopaque polymer coating of a cross-linked hydrophilic copolymer of acrylonitrile and vinylpyrrolidone [150]. A recent study showed that the expansion of the new hydrophilic obturation points is complete within 20 minutes, a time period in which most root canal sealers still exhibit flow during setting [153]. The magnitude of linear or volumetric setting expansion was not included in that study; based on the data presented, linear expansion is estimated to be in the range of 11.5–14%. This high value undoubtedly exceeds the standard set by the American National Standards Institute, which states that the mean linear expansion of the sealer shall not exceed 0.1% [154]. However, results from that study [153] were obtained by direct immersion of obturation points directly in water. The

amount of available water for causing lateral expansion was much more than what would be expected from residual moisture in intraradicular dentin, after the root canal was blot-dried with paper points or from naturally occurring intra-radicular moisture. Moreover, no sealer was employed for coating, which might have impeded diffusion of water into the obturation points.

To date, very limited information is available on this novel obturating point. Further work should be performed to identify whether over-swelling into the gaps may generate high enough positive root strains, or produce intraradicular microcracks that slowly propagate with time during intraoral functioning to result in vertical root fracture [155,156]. It cannot be overemphasized that while crack initiation may be rapid, fatigue crack growth in dentin caused by the generation of initial flaws is a slow process and may take years to result in catastrophic failure [157,158]. Although there have been anecdotal reports of short-term clinical success in teeth filled with these water-induced expandable non-gutta-percha obturation points, the results cannot be acceptable without long-term clinical validation.

3.3 Enhance flow and adaptation of the root filling material to canal walls

Coating metal cores such as gold wire, silver points and endodontic files with heat-softened gutta-percha for three-dimensional obturation of the canal space has long existed before the commercialization of different prefabricated gutta-percha core-carrier systems that are claimed to enhance adaptation of the gutta-percha to the canal wall, and flow of the guttapercha into lateral canals. Due to the difficulties encountered in retreatment and in the preparation of post spaces, the original metal carriers were subsequently replaced by plastic obturators [159,160]. Although the core-carrier technique has been regarded as the only genuine warm gutta-percha technique for adaptation to the apical third of the canal space, voids could not be completely eliminated when canals obturated with this technique were examined using impression casts (Figures 5A and 5B) or 3-D non-destructive investigation techniques [161,162]. As discussed in Section 1, the need for gutta-percha to flow into the dentinal tubules (Figure 5C and 5D) or lateral canals has also been challenged [62]. In terms of clinical outcome, results from two separate retrospective studies were unanimous in that there was no significant difference in the success rate achieved using the core-carrier technique or the cold lateral condensation technique for primary root canal treatment [163,164].

There are two recent modifications to the classic core-carrier systems. The first modification involves replacement of the gutta-percha carrier with a coating of the polycaprolactone-based filling material described in Section 3.1 [165], which is chemically united with a resin-based core. Removal of this modified obturator during retreatment may be achieved by mechanical means or softening with chloroform as the resin-based core is soluble in this organic solvent. The second modification involves replacing the Vectra or polysulphone plastic carriers in a classic gutta-percha-based system with cross-linked thermoset gutta-percha that does not melt by heat used in an obturator oven, and is insoluble in common organic solvents employed for root canal retreatment [166]. Removal of this modified obturator during retreatment is achieved by mechanical trephining through the core. To date, there are no peer-reviewed studies on the clinical efficacy of this new core-carrier system.

3.4 Utilize bioactive reaction products to salvage a compromised seal

A new category of root canal sealers based on mineral trioxide aggregate (MTA) has recently been commercially available. These sealers are an outgrowth of the popular MTA materials, which are based on tricalcium silicate, a hydraulic (water-setting) powder used for various surgical and vital pulp therapy treatments [167]. This type of root canal sealer is attractive because of its hydrophilicity [168] and bioactivity that has been reported for

MTA-type materials [169,170]. Calcium silicate-based sealers include some of same hydraulic compounds found in Portland cement, primarily tricalcium silicate and dicalcium silicate powder [168]. They set by reaction with water and form a highly alkaline (pH ~ 12) cement composed of a rigid matrix of calcium silicate hydrates and calcium hydroxide [171]. These hydrates form on the surface of the original calcium silicate particles and hydration gradually penetrates inward. When these sealers set, the dimensional change is less than 0.1% expansion, which helps in creating a barrier that is important for sealing the canal space [172]. For the tricalcium silicate particles to contribute to sealing, they must become hydrated by water from the sealer liquid or in the root canal.

Although some calcium silicate-based sealers do not contain phosphate, they react with phosphate ions derived from tissue fluids to form needle-shaped carbonated apatite crystallites (Figure 6) [169]. Others reported formation of an interfacial layer between MTA and dentin that stems from a similar apatite formation reaction [162,173]. Theoretically, when obturated root canals come into contact with tissue fluids in the apical region, or when there is ingress of tissue fluids via a defective coronal restoration, these intracanal bioactive reactions may contribute to salvaging a compromised seal.

Four calcium silicate-based sealers are currently commercially available [174–177]. To date, no peer-reviewed papers have been published to establish the benefits of incorporate tricalcium silicate powders in sealers in clinical studies. All studies are based on *in-vitro* testing and *in-vivo* animal models on tissue responses after implantation of set sealers in subcutaneous tissues.

4. *In-vivo* animal studies involving the recently-introduced materials

All published studies were conducted on root fillings using methacrylate resin-based sealers. Two of the studies were performed using the hydrophilic self-priming methacrylate resin-based sealer described in Section 3.1. The first study compared the sealability of the hydrophilic self-priming methacrylate resin-based sealer and two other sealers, when root canals of dog's premolars were obturated with gutta-percha and one of three sealers after post-space preparation [178]. That study was essentially a dye leakage study as the teeth were extracted after exposure to the oral environment and immersed in India ink, and thus the results had limited value. The second study compared tissue reactions of the hydrophilic self-priming methacrylate resin-based sealer in root fillings that were prepared short of, or beyond the apical foramen-like apical communication in dogs' teeth [179]. The conclusion that “limiting the sealer short of the communication resulted in a better treatment outcome” was not different from what is already known from earlier clinical studies using classic root canal sealers [24].

The rest of these *in-vivo* canine studies were related to the use of the polycaprolactone-based root filling material and its proprietary bondable methacrylate resin root canal sealers. All of these studies utilized the first model version (Section 2.2) to compare the seal of root fillings in preventing post-treatment periradicular reinfections via a coronal route. Histopathological data generated by these *in-vivo* studies were as conflicting as leakage results derived from *in-vitro* models [82]. Whereas earlier studies indicated that dogs' teeth obturated with the polycaprolactone-based material using different obturation techniques produced more favorable periapical tissue responses than gutta-percha filling techniques [180–182], more recent studies indicated no difference between the two root filling materials [183–185].

As discussed in Section 2.2, tissue responses are not equivalent to the seal of the root canal system. Other factors, not necessarily related to the seal, could have contributed to the *in-vivo* responses. When teeth were left exposed to the oral environment to induce bacteria

leakage, differences in antimicrobial activity between the classic and the recently-introduced root canal sealers could have accounted for the difference in tissue responses [186]. Another issue that has not been considered in most *in vivo* canine studies is the role played by over-instrumentation or overfilling in the tissue response, in particular between what may be classified as “no inflammation” versus “mild inflammation”. For example, in the study by Shipper *et al*. [180], 82% of the dog's teeth that were obturated with gutta-percha and an epoxy resin-based sealer exhibited had mild periapical inflammation and 18% had no inflammation. By contrast, 19% of the dog's teeth that were obturated with the polycaprolactone-based root filling material and its accompanying self-etching sealer exhibited mild periapical inflammation and 81% had no inflammation. Without stratifying those teeth into under-filled, fully-filled or over-filled, it is dubious if differences between those two root filling materials are meaningful. Conversely, when the dogs' teeth were stratified and allocated to the two root filling material groups with approximately equal numbers in the study performed by Brasil *et al*. [184], there were no significant differences in both the extent and the intensity of inflammatory reaction in teeth obturated with either root filling material.

5. Clinical studies: classic *vs* recently-introduced materials

The outcome of root canal treatment depends on a multitude of factors and not simply on materials or techniques of obturation [187]. While specific filling materials have been ardently promoted, there is little, if any, clinical data that supports the superiority of one material over another. In the past, treatment outcome studies have rarely vigorously examined the contribution of obturation materials to clinical success. Even for obturation techniques (vertical *vs* lateral condensation), their contribution to treatment outcome is weak and of questionable significance, and then only in cases with preoperative apical periodontitis [26,188].

Traditionally, non-surgical root canal treatment has enjoyed an excellent track record. Epidemiological studies based on insurance records indicated that 92.1% of these treatments remained functional after a 3.5 year period [189]. Using the same concept of functionality as a less stringent method for assessing treatment outcome, other authors showed that 97% of cases remained functional in the oral cavity after an 8-year period of primary root canal treatment. [190], while 89% of the teeth were retained in the oral cavity after endodontic retreatment [191]. For meta-analyses of treatment outcomes, Friedman reported that 90–97% of the cases remained functional. When a more stringent method of assessment based on definitive radiographic healing was used for examination, 88–97% of the cases without apical periodontitis were successful, while 74–91% of the cases with apical periodontitis were successful [192]. A similar trend was also reported by Ng *et al*. in that the presence of pre-operative apical periodontitis reduces the success of primary root canal treatment [193]. Using functionality as a less stringent method of assessment, successful outcomes were identified in 87–93% of the cases without apical periodontitis, and 76–87% of the cases with apical periodontitis. When definitive healing was employed as a more stringent criterion for success, 73–92% of the cases without apical periodontitis were successful, while 61–78% of the cases with apical periodontitis were successful. These results are also supported by those derived from a prospective cohort study by Ricucci *et al*. [194]. Using definitive healing as the yardstick for assessment, successful outcome was observed in 89.5% of the cases without apical periodontitis and 82.7% of the cases with apical periodontitis. Taken together, results from these classical studies predicate that the future of new obturation material lies in its potential to improve specifically the healing of apical periodontitis, and not simply improving the overall outcome of root canal treatment. As all treatment outcome studies rely on the use of radiographs in quantifying success [195], a confounding variable that affects the quality of future clinical studies for the recently-introduced materials is their ability to

demonstrate healing of apical periodontitis from a 3-D perspective [196,197]. For comparisons among materials or techniques, however, conventional 2-D radiography of low sensitivity, but high specificity, may still be valuable.

For the different categories of recently-introduced obturation materials described in Section 3, clinical studies could be identified for only those materials that promote adhesion to canal walls. Between 2004 and 2012, Zmener and Pameijer conducted a longitudinal series of retrospective cohort studies on the clinical performance of root canals obturated with gutta-percha and the hydrophilic self-priming methacrylate resin-based sealer, using 2-D radiographic and clinical evaluation criteria. Although the success data were initially categorized into cases with or without apical periodontitis, with an overall success rate of 91.3% at 14–24 months [198], only cumulative probabilities of success were reported at 5-year recall (86.3%) [199], 8-year recall (86.5%) [200] and 10-year recall (92.1%) [201]. These studies generated valuable information on the clinical performance of a particular obturation material for marketing to general practitioners who desire a simpler obturation technique. Nevertheless, there was no comparison with existing materials or techniques. The authors concluded that the hydrophilic self-priming methacrylate resin-based sealer has similar performance as conventional root canal sealers reported in the literature. The corollary to that statement is that the use of a self-priming, bondable resin-based sealer does not improve the clinical performance over the use of classic, non-bondable root canal sealers.

There are four additional clinical studies that reported the use of the bondable polycaprolactone-based root filling material in conjunction with its proprietary self-etching sealers. The first study is a prospective case series study that examined 21 cases using 2-D radiographic and clinical assessment criteria at 1-year recall, but without a gutta-percha comparison group. Results were reported qualitatively and no conclusion can be reached apart from anecdotal impressions [202]. The second study by Conner *et al*. [203] is a retrospective case series study conducted using radiographic and “clinical impression of healing” quantification procedures, without a gutta-percha comparison group. This study reported that 89.4% of cases were healed or healing after at least one year of root canal treatment. The authors concluded that root canals obturated with the recently-introduced material has a similar healing rate as gutta-percha obturated canals reported in the literature. The corollary to that statement is that the use of the polycaprolactone-based root filling material does not improve the clinical performance over the use of gutta-percha.

The third study by Cotton *et al*. [204] is a retrospective cohort study that compared the clinical outcome of root canals obturated with gutta-percha and a zinc oxide eugenol-based sealer with those obturated with the polycaprolactone-based root filling material and its accompanying self-etching methacrylate resin-based sealer. The study was conducted using 2-D radiographic and clinical evaluation criteria, with a recall period between 12–25 months. Similar to previous studies, the presence of a preoperative periradicular lesion was found to be statistically significant in predicting treatment outcome. However, there was no statistically significant difference between the two obturation materials when outcomes were evaluated by combining teeth with or without periradicular lesions. Even when those cases were stratified by examination of only teeth with pre-operative periradicular lesions, there was still no statistically significant difference in treatment outcome between the two obturation materials.

By far, the most convincing study was the one performed by Tehrany [205] at the University of North Carolina at Chapel Hill. This retrospective case series study examined periapical healing of teeth with asymptomatic apical periodontitis only, after root canal treatment with gutta-percha or the polycaprolactone-based root filling material. Radiographic and clinical

outcomes of root canal treatments completed by undergraduate dental students under direct supervision of an endodontic faculty member for a minimum of 12 months were evaluated separately. Teeth filled with gutta-percha or the polycaprolactone-based root filling material did not differ statistically in their radiographic outcome (81.1% versus 78.4%, respectively), when the cases were evaluated using 2-D periapical radiographs. Likewise, teeth obturated with gutta-percha or the polycaprolactone-based root filling material did not differ statistically in their clinical success (90.1% versus 89.6%, respectively), which was defined as absence of all clinical signs and symptoms associated with persistent inflammation or infection.

6. Conclusion

Over the past decade, there has been an exceptionally fine harvest of novel root canal obturation materials that are designed to improve the seal of the root canal system. Without doubt, sealing of root canals three-dimensionally contributes to the success of root canal treatment. However, the quest for a clinically relevant model for evaluating the seal of the root canal system has evolved along a topsy-turvy path of intellectual discourse to become an intangible philosophical ideal. As the genre of currently available *in-vitro* and *in-vivo* models is not totally suitable for quantifying the seal of root canals obturated with classic materials, one has to resort to clinical outcomes to infer if there are patient-related benefits associated with the use of the recently-introduced materials for obturating root canals. Yet, there is no facile answer; essays on endodontic treatment outcome are confounded by a host of other predictors that are more likely to take precedence over the influence of obturation materials [28].

From the perspective of clinical performance, classic root filling materials have substantiated what Aristotle expressed as `historical truth' [206] and have stood the test of time. Because many of the recently-introduced materials are so new, there is not enough evidence yet to support their ability to improve clinical performance. For those recently-introduced materials they may be comparable to, but do not exceed outcomes already achieved by the use of classic biomaterials.

As elegantly expressed by Dr. John Whitworth [38], improvements in technological possibilities in root canal obturation may have met needs other than healing more disease: “As no single obturation technique or material can claim superior evidence of a better seal, decisions may be based on factors such as speed, simplicity, economics or `how it feels in my hands'. For some, there may be other issues at stake, such as the desire to keep `up to date,' to demonstrate `mastery,' to keep ahead of referring colleagues, or to enliven the working day by `the thrill of the fill'”. Within that agenda, the choice of the practitioner may be pragmatically justified based on a merger of individual preference, experience and practice circumstance, or simply, as partisan to the encomium delivered by a master storyteller. While such a stance may appear errant to a health care profession that has consistently envisioned the importance to base clinical judgement on evidence-based knowledge, it emphasizes the need to transl ate anecdotal opinions into analyzable research data to provide stronger evidence to support the launch of new biomaterials for improving patient care. It is often the lack of relevance of the currently available testing techniques, rather than the willingness of the manufacturers to perform pre-clinical testing, that limits the empirical rationale for adopting or rejecting new endodontic materials. Consequently, anecdotal evidence is what has been adopted as critique of new endodontic materials. It makes sense to get oneself acquainted with one or two commonly used techniques and materials, respecting the principles of good root canal treatment, in order to create consistent, radiographically well-adapting, homogeneous root canal filling at the right

length. It is important to realize that no filling material or technique can compensate for inadequate asepsis and disinfection procedures.

Acknowledgments

This work was supported by grants R01 DE015306-06 from the National Institute of Dental & Craniofacial Research (PI: David H Pashley) and National Key Basic Research Program of China grant 2012CB526704 (PI: Jihua Chen). The authors thank Mrs. Michelle Barnes and Mrs. Marie Churchville for their secretarial support.

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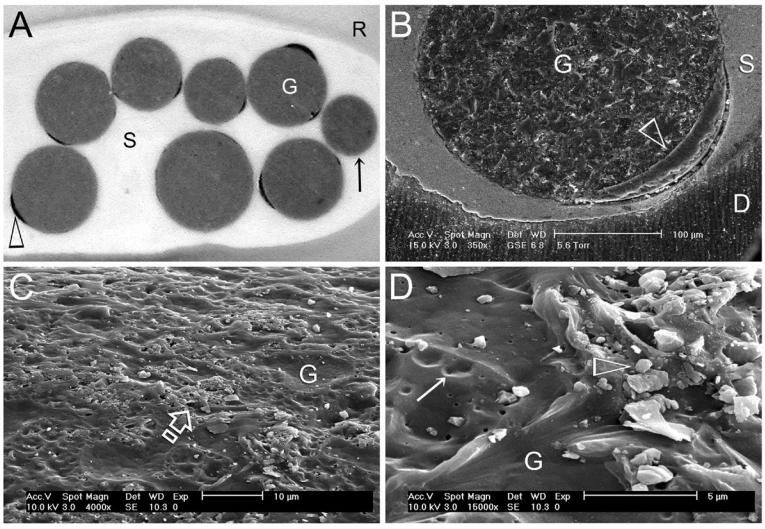

Figure 1.

A. Stereoscopic microscope image of incomplete coating (open arrowhead) of resin-coated gutta-percha points (G) that are used with a hydrophilic self-priming methacrylate resin-based root canal sealer (S). Some obturation points are devoid of resin coating (arrow). **B**. Environmental scanning electron microscopy (ESEM) image of a partially resin-coated gutta-percha point (G), taken at 95% relative humidity, showing a gap between the resin coating (open arrowhead) and sealer; D: root dentin. **C**. SEM of the surface of a bioactive glass particle-coated gutta-percha point (G) that is used with a glass ionomer-based root canal sealer. Distribution of the glass particles is limited to some areas only (open arrow). **D**. High magnification of Figure 1C. Area on the left is devoid of glass particles (open arrowhead). Areas previously occupied by glass particles (open arrowhead) are denoted by depressions on the gutta-percha surface (arrow).

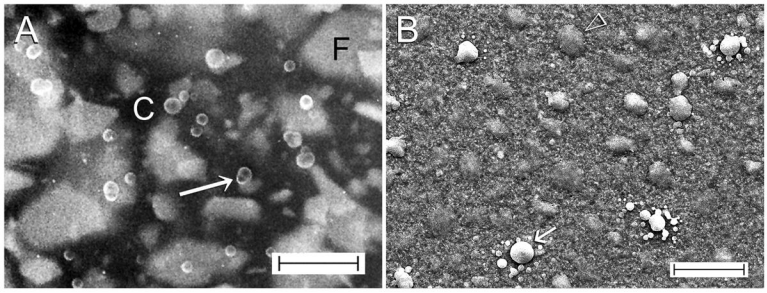

Figure 2.

A. SEM image of the heat-pressed surface of thermoplastic polycaprolactone-based root filling material (C) showing phase separation of the methacrylate resin component (arrow) from the polycaprolactone. F: fillers. Bar = 5 μm. **B**. SEM image of the polycaprolactone-based root filling material after surface etching of the polycaprolactone root filling material with 0.1 N NaOH revealing exposed, partially-coalesced methacrylate resin droplets (arrow). Open arrowhead: unexposed fillers. Bar = 20 μm.

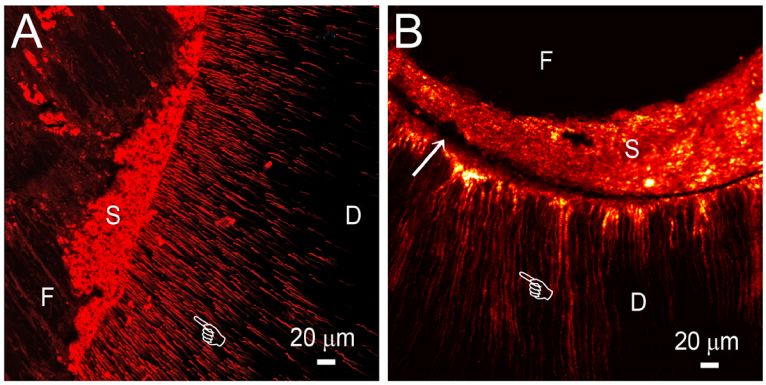

Figure 3.

A. Subsurface confocal laser scanning microscopy of a gap-free region of a root canal that is obturated by a root filling material and sealer. **B**. Subsurface confocal laser scanning microscopy of a gap-containing region (arrow) of a root canal that is obturated by a root filling material and sealer. In both specimens, penetration of the root canal sealer into the dentinal tubules is evident (pointer), irrespective of the presence or absence of gaps. F: root filling material; S: root canal sealer; D: root canal dentin.

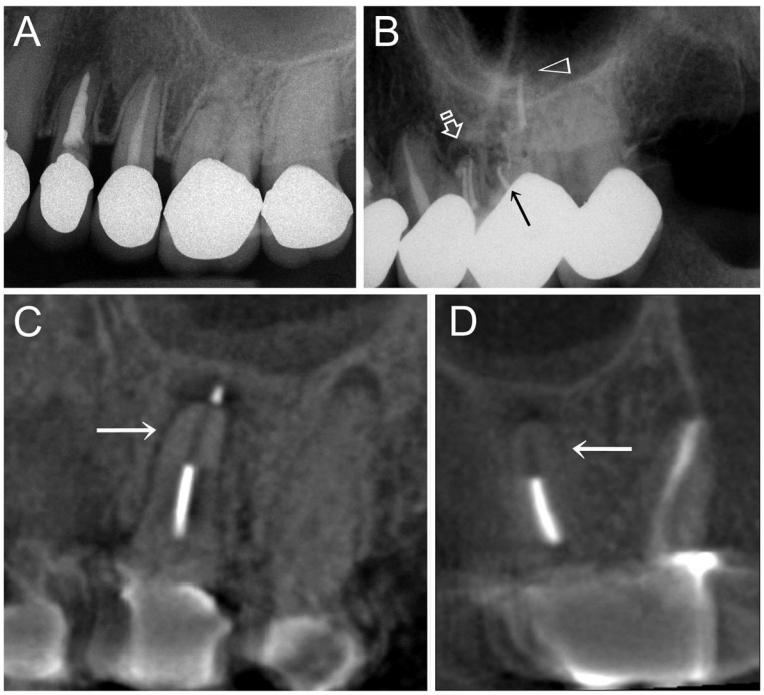

Figure 4.

A. Pre-operative periapical radiograph of the upper left first molar (second tooth from the right). Although the tooth was non-vital, there was no periapical radiolucency associated with the palatal root. **B.** Post-operative periapical radiograph of the upper left first molar after root canal treatment and obturation with a polycaprolactone-based root filling material and accompanied resin-based sealer. Four radiopaque filled canals can be identified: 2 canals in the mesiobuccal root (open arrow), one canal in the distobuccal root (arrow) and one canal in the palatal root (open arrowhead). **C.** Three-year post-treatment cone beam computer tomography image (sagittal projection across the palatal root) of the same root-treated upper left first molar showing partial disappearance of the polycaprolactone root filling material (arrow) and the development of a periapical lesion at the root tip of the palatal root. **D.** Three-year post-treatment cone beam computer tomography image of the same tooth taken along an oblique coronal projection, revealing the palatal root and the distobuccal root. Disappearance of the polycaprolactone root filling material from the apical third of the root canal (arrow) is also evident from this angulation.

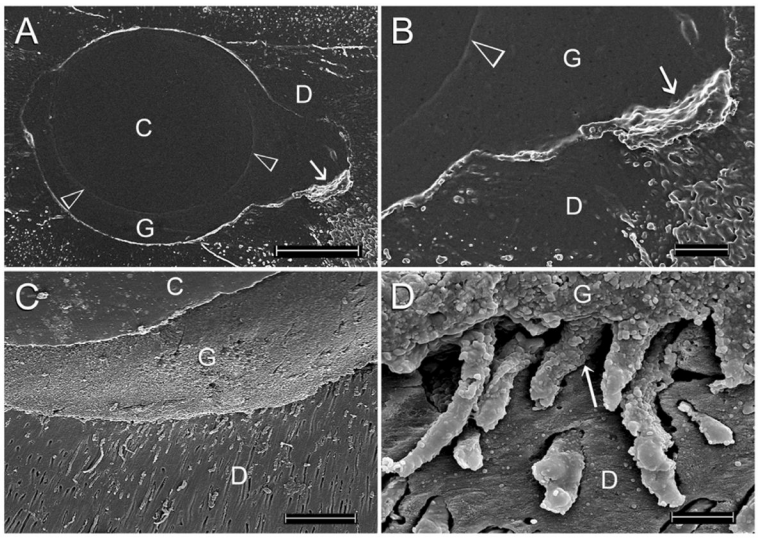

Figure 5.

A. SEM of a polyvinylsiloxane impression negative replica of a section of a single-rooted canal that was obturated using a gutta-percha-based core-carrier technique. The gap-free interface between the plastic core (C) and the gutta-percha (G) can be seen (open arrowheads). A gap is evident within the canal fin (arrow). D: root dentin. Bar = 200 μm. **B.** High magnification of Figure 5A showing the aforementioned gap as a protruded piece of impression material (arrow) between the gutta-percha (G) and root dentin (D). Open arrowhead: interface between the obturator core and gutta-percha. Bar = 50 μm. **C.** SEM image obtained by direct observation of a single-rooted canal obturated using a gutta-percha-based core-carrier technique. Extension of the root filling material and sealer into patent dentinal tubules can be seen. C: plastic core; G: gutta-percha; D: root dentin. Bar = 200 μm. **D.** High magnification of Figure 5C showing extension of highly granular gutta-percha (G) into the dentinal tubular orifices (arrow). The rest of the tags that occupied the dentinal tubules is contributed by the root canal sealer. D: root dentin. Bar = 5 μm.

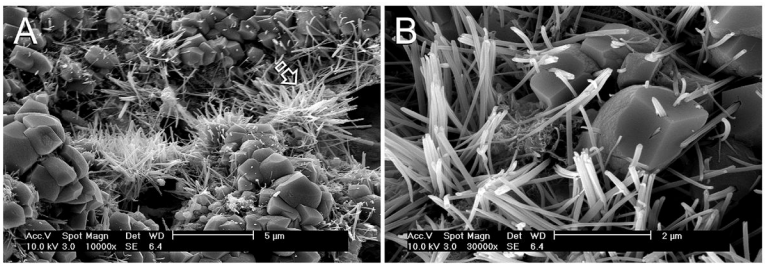

Figure 6.

A. SEM image of the surface of a bioactive calcium silicate-based root canal sealer showing the presence of apatite crystalline clusters (open arrow) after exposure to a phosphate ion-containing simulated body fluid for 24 hours. **B.** High magnification of Figure 6A showing the needle-shaped apatite crystallites, some of which were sprouting from the calcium silicate filler particles.