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Biological considerations of dental materials as orifice barriers for restoring root-filled teeth

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ABSTRACT

There is ample published literature regarding the technical aspects of restoring root-filled teeth, but little concerning the biological impacts, consequences, and criteria for the selection of direct restorative materials following endodontic treatment. The provision of an effective coronal seal in addition to a sound root filling is known to be important in the prevention of root canal infection. This review seeks to explore the evidence concerning the selection of dental materials in the restoration of root-filled teeth, specifically with a close examination of the properties of commonly used materials as orifice barriers. © 2023 Australian Dental Association.

Keywords: Coronal seal, endodontic materials, endodontics, review, restorative continuum.

Abbreviations and acronyms: AP = apical periodontitis; CHX = chlorhexidine; CSC = calcium silicate-based cement; GIC = glass ionomer cement; GP = gutta percha; HEMA = 2-hydroxyethyl methacrylate; MTA = mineral trioxide aggregate; OB = orifice barrier; OPG = orthopantomogram; RC = resin composite; RMGIC = resin-modified glass ionomer cement; ZOE = zinc oxide eugenol; ZPC = zinc polycarboxylate cement.

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CLINICAL RELEVANCE

The persistence or emergence of root canal infection and the associated development of apical periodontitis normally requires complex and expensive specialist-managed non-surgical retreatment and/or apical surgery for resolution. Such poor outcomes can impose significant costs on patients, health insurance or healthcare providers through restorative or replacement treatments. The evidence-based selection of dental materials is critical to the restoration of root-filled teeth and should be considered in order to achieve a sound coronal seal.

INTRODUCTION

The impact of microorganisms on pulpal and periapical disease is well-established;[1, 2] despite the identification of fungi, archaea and viruses, bacteria are known to be the most prevalent and dominant microorganisms in endodontic infections.[3] Apical periodontitis (AP) is 'inflammation, usually of the apical or periradicular periodontium, that is of pulpal origin, which may produce clinical symptoms including a painful response to biting and/or percussion or palpation. It may or may not be associated with a radiographic apical radiolucent area'.[4] A systematic review and meta-analysis has reported the global prevalence of AP as being high, with 52% of pooled samples reporting at least one tooth with AP.[5]

Modern non-surgical root canal treatment can deliver high success rates, although the measurement of successful outcomes varies from approximately 92.6%–95% for tooth survival (teeth not radiographically healed but asymptomatic and functional) to 82%–86% with teeth demonstrating radiographic healing.[6–8]

The goal of endodontic treatment is to eliminate and prevent the return of pulpal and periradicular pathosis. This is achieved, not only through the effective chemo-mechanical cleaning of the root canal system and its subsequent filling, but also through ensuring that an effective coronal restoration is placed which creates a durable fluid-tight seal, and where appropriate, cuspal coverage to prevent their fracture.[9–11] The American Association of Endodontists' White Paper on Treatment Standards indicates that placement of a definitive coronal restoration must be considered part of the root filling process to prevent 'recontamination'.[12]

A recent systematic review and meta-analysis reported that root canal treatment is a relatively common procedure throughout the world, suggesting that the prevalence of root-filled teeth worldwide is greater than 8% among the population on average.[13]

There is a plethora of literature published on the technical aspects of restoring root-filled teeth, but little concerning the biological impacts, consequences, and selection criteria. This review article discusses current considerations from a biological perspective for the restoration of root-filled teeth.

THE RESTORATION OF ROOT-FILLED TEETH

Cuspal coverage restorations

There is ample published evidence demonstrating the value of cuspal coverage in the restoration of root-filled posterior teeth in preventing catastrophic tooth fracture, owing in part, to the structural weakening and decreased stiffness of teeth caused by loss of one or both marginal ridges,[14] and the additional internal weakening potentially caused by endodontic access.[15] However, a pragmatic approach should be taken to identifying the ideal restorative requirements for a root-filled tooth. For example, a heavily restored and root-filled lower second molar tooth with multiple cracks present in the marginal ridges and with fractured cusps in a parafunctioning patient might have a different restorative treatment need to an otherwise unrestored lower premolar tooth with root canal treatment resulting from dens evaginatus, where both marginal ridges are still present. Thus, the restoration of every root-filled tooth should be considered with respect to diagnostic and prognostic criteria including, but not limited to, assessment of the periodontal condition, restorability, endodontic condition, structural integrity, and the position and strategic value of the tooth, in addition to patient-level factors.[16] This is particularly critical when considering that root-filled teeth might have already lost significant structure through deep caries, fractures, or trauma if one considers the work of Edelhoff and Sorensen[17, 18] where the removal of as much as 75.6% of posterior and 76% of anterior tooth structure was shown for conventional metal ceramic full crown preparations. In general, the preservation of sound coronal enamel and dentine and the use of minimally invasive bonded onlay restorations is advocated when cuspal coverage is required, wherever possible.[19]

The work of Opdam and others[20–22] has shown that resin composite and amalgam perform well as large posterior restorations, with relatively low annual failure rates and are worthy of consideration where patients do not possess the means to undergo more expensive indirect procedures. Indeed, the provision of a 'one-size-fits-all' approach to teeth with lower restorative demands following root canal treatment might be more conservatively managed with less aggressive direct restorative procedures where appropriate. Dawson *et al*.[23] found no difference in the rate of AP in teeth restored with laboratory-made crowns, amalgam or resin composite provided that the quality of the restoration was adequate. A recent narrative review pointed to the lack of evidence determining the type of restorative materials required for restoring root-filled teeth, agreeing that while indirect restorations might be required for some root-filled teeth, there is a degree of selection bias in the literature, in that 'dentists and patients are less likely to choose indirect restorations for teeth with uncertain prognosis', and that preserving tooth structure in conjunction with an optimal seal and protection of the tooth should be assessed in each individual case when deciding on direct or indirect materials.[24]

The importance of the coronal seal

The literature is replete with evidence that endodontic 'failure', i.e., the return or persistence of intraradicular infection,[25] might be attributed to loss of the coronal seal, with some authors suggesting that the quality of the coronal restoration is at least as important as the technical quality of the endodontic treatment underlying it.[26] A study looking at restorative and endodontic treatment quality between two Canadian populations found that teeth with adequate root fillings and inadequate restorations had three times the odds risk of developing AP than those with both adequate root fillings and coronal restorations.[27] A meta-analysis looking at the quality of coronal restorations found that the odds of success were significantly higher in teeth with satisfactory restorations than those with unsatisfactory restorations.[28] Root-filled teeth of a high technical standard are still at risk of failure if the integrity of the coronal seal fails through marginal caries, deficiencies, leakage or fractures.[29] Segura-Egea *et al*.[30] reported the quality of endodontic treatment to be of greater importance than the coronal restoration but found that teeth with inadequate root canal treatments and inadequate coronal restorations had an increased prevalence of AP, while the converse was true for those with adequate root canal treatments and adequate coronal restorations. Similarly, Tronstad *et al*.[31] found the quality of root canal treatment to be of more importance than that of coronal restorations but expounded that teeth with good quality coronal restorations had success rates improved by 10%.

However, the significance of these findings has been disputed by the work of Ricucci and others,[32, 33] who showed that well-filled root canal systems tended to resist bacterial leakage for some time, limiting bacteria to the coronal portion of the root canal for several months following exposure to the oral environment. Interestingly, these studies identified bacterial invasion through staining and histological analysis, but the authors stated that the potential leakage of bacterial by-products and endotoxins was not assessed and might have played a role in causing the inflammation observed in the studies. An earlier study showed that both bacteria and endotoxins were able to penetrate the root-filling materials in post-prepared canals, but that endotoxin penetration was faster than bacterial penetration.[34] This raises the possibility that rapid penetration of endotoxin could lead to an early periapical reaction developing, with subsequent AP and the need for retreatment or periapical surgery.

Nonetheless, other published studies have downplayed the significance of the quality of coronal restorations on endodontic outcomes.[35, 36] It is important to note that there is considerable heterogeneity in the study designs observing AP related to both root canal treatments and coronal restorations. Some studies were undertaken prospectively,[36] but a greater number were retrospective and cross-sectional in design based on assessment of the radiographic appearance of both root canal treatment and coronal restorations[37] and correlating their technical standards to the presence of AP. The retrospective nature of these studies often revealed a paucity of diagnostic information prior to root canal treatment having been performed on the teeth included in the study, e.g., the presence or absence of a periapical radiolucency prior to treatment, whether endodontic treatment was carried out by an endodontist or a general dentist, which practitioner placed the final restoration and precise details of the restoration, for example, the restorative material used, type of bonding or design of the restoration. Often in these studies, the technical quality of the root canal treatments and coronal restorations were performed radiographically, sometimes based on orthopantomograms (OPGs) alone.[37] While larger approximal defects and caries might be relatively easy to diagnose radiographically, the diagnosis of more discreet lesions or defects would be compromised in other areas of the coronal aspect of teeth, and more easily discerned on clinical examination in combination with radiographic examination. Some studies looked at coronal restorations both radiographically and clinically.[36, 38, 39] It is important to consider that retrospective studies capturing radiographic information on teeth at a single point in time might be unable to determine accurately the healing or disease progressions of periapical lesions, and might not be able to show 'causation' over 'association' with respect to the quality of endodontic treatment or coronal restorations.[40]

A systematic review aimed to discern whether adequate root canal treatments combined with inadequate coronal restorations performed better than inadequate root canal treatments combined with adequate coronal restorations.[41] The authors found that the quality of coronal restorations was not more important than the quality of root canal treatments and that perhaps the clinical significance of coronal leakage might be less than that indicated by *in vitro* studies. However, there was limited investigation into the substance of the papers reviewed. The authors reported in fact, that they were unable to identify significant and relevant information and acknowledged that the wide variability of criteria resulted in considerable heterogeneity between studies. They also acknowledged that data from the majority of the studies were based on subjective radiographic examination and that information on preoperative periapical status was lacking, as was that of the duration between root canal treatment completion and placement of the coronal restoration. The authors concluded, logically, that the combination of both adequate root canal treatments and adequate coronal restorations produced better treatment outcomes in preventing bacterial ingress.

In a recent review article, Gulabivala and Ng[42] identified some of the problems with many of the studies classifying restorations as either satisfactory or unsatisfactory, in that criteria were not standardised, and pointed to the lack of reference to the presence or absence of an inner core restorative material. In addition, there is no clear consensus on choice of core material. The European Society of Endodontology's 2021 position statement on 'The restoration of root filled teeth' states 'Clinicians have a number of choices for core placement prior to cuspal coverage restoration. Unfortunately, there are currently no randomized controlled clinical trials comparing amalgam, composite, or other materials, such as glass ionomer cements, as core materials for root filled teeth restored with crowns'[19]

Indeed, many retrospective studies assessing the survival and success of root canal treatment are unable to quantify a multitude of pre- and post-operative factors. A recent narrative review highlighted a wide variety of potential factors that might affect the success or survival of root-filled teeth, including, but not limited to, patient factors such as age, systemic health, tooth type, timing of the restoration, amount of remaining tooth structure, the expected function of the tooth, and the presence of cracks, among others which could affect treatment outcomes.[24] The authors also alluded to the concept of 'functional retention', reporting a prevalence of approximately 40% of root-filled teeth having AP in cross-sectional studies.[24] A study investigating endodontic and periapical status in an Australian population with similar findings suggested that this might 'imply stability in a closed microbiological system',[43] further reinforcing the need for both establishing and maintaining both an endodontic and coronal restorative seal.

Limitations of root filling materials

Whilst contemporary endodontic treatment employs chemo-mechanical root canal preparation, it has been shown that microorganisms can penetrate up to 150 μm into dentinal tubules,[44] and that the root canal system cannot be rendered fully free of microbes via mechanical preparation[45, 46] or chemical irrigation.[47, 48] In practice, the goal is to gain access to the site of infection to reduce the microbial load sufficiently, so that the number of any residual microorganisms is minimised, if not completely eliminated.[49] This requires adequate compaction of the root filling and minimisation of gap formation, particularly between the root filling and the root canal walls.

Furthermore, the ability of gutta percha (GP) and endodontic sealers to fill all voids within a root canal system is imperfect.[50, 51] Notwithstanding the challenges created by naturally occurring voids and aberrations within the root canal anatomy that are difficult or impossible to gain access to, endodontic sealer materials should ideally have excellent flowability, wettability and adaptability, and excellent resistance to shrinkage and erosion/dissolution after placement. It is known that some sealers might experience shrinkage after placement, while others might expand.[52–54] The mode of use of GP has changed over time[55] with heated materials being in common use, and these too might also experience significant dimensional change after initial placement, potentially reducing the sealing ability at the dentine-gutta percha interface.[56,57] Some sealers show antimicrobial activity, but many do so for a relatively short period of time.[58–61] Degradation of polymer-based root filling and sealer materials has been observed.[62]

Thus, instead of viewing the root filling and final coronal restoration as being distinct from one another, the concept of a restorative continuum should be applied, using whichever materials function best in a given area of the tooth, and applying a selection of materials capable of adequately adapting to and sealing the root canal system from root apex to crown, whilst providing the required aesthetic and mechanical properties coronally. The properties required of a material as an indirect restoration placed coronally to resist fracture of the tooth under occlusal loading are clearly distinct from those required from root filling materials intended to seal a complex three-dimensional root canal system, as would be a core material or a post system. In bridging the junction between root filling and coronal restoration, it is critical that the material selected can adequately penetrate and adapt to the coronal-most aspect of the root canal system, whilst also functioning as a foundation for the final coronal restoration. It is also recommended that a 'leak-proof' restoration be placed as soon as possible after endodontic treatment.[63]

ORIFICE BARRIERS

In considering the coronal restoration of root-filled teeth, it is imperative that the dental materials selected are capable not only of rendering a seal that prevents microbial ingress and a nutritional source for any remaining microorganisms but also possess physical properties capable or resisting dislodgement, wear and/or fracture. In practice, this might indicate the use of multiple materials to achieve such goals in the final coronal restoration. Saunders and Saunders[64] showed *in vitro* that extensive leakage through root fillings with Indian ink was prevented by the presence on the pulp chamber floor of either copal ether varnish and amalgam, Ketac Bond (GIC) or Ketac Silver (Cermet), recommending that excess GP and sealer should be cleared from the pulp chamber floor prior to the restoration being placed.

An orifice barrier (OB), also reported as 'intra-orifice barrier', 'coronal plug' or 'orifice plug', is a restorative material placed into the root canal orifices and as a base covering the pulp chamber floor, following completion of root canal treatment.[65] A variation includes limiting the material to a level at or just below orifice level. It is normally placed as a separate material to the core/foundational/final restorative material. This is distinct from an amalgam style 'Nayyar Core', where the final (core) restorative material is placed into the root canal orifices.[66] Figure 1 shows a schematic representation of an OB, while Figures 2 and 3 show zinc polycarboxylate cement and glass ionomer cement OBs respectively, radiographically.

The concept of a discrete OB to reduce the risk of coronal leakage is not new,[65, 67] and it is generally accepted that the presence of an additional coronal restorative barrier is valuable in at least slowing the leakage of fluids or microorganisms into the underlying endodontic treatment.[68] An advantage of this procedure is that the operator can place a restorative material immediately after the endodontic treatment is completed while the tooth is still under isolation, in

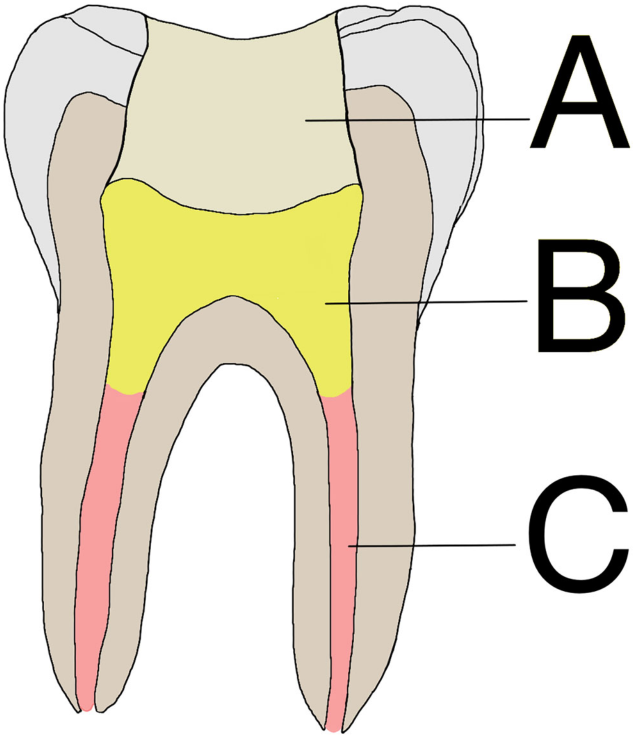

Fig. 1 Schematic of an orifice barrier in a root filled molar tooth. (a) intracoronal restoration; (b) orifice barrier; (c) root filling.

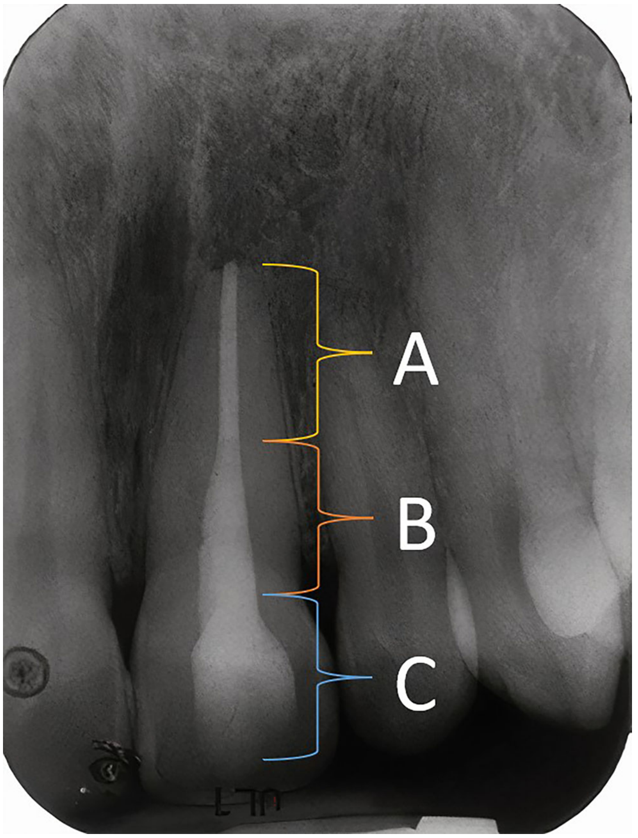

Fig. 2 (a) Gutta percha; (b) zinc polycarboxylate cement orifice barrier; (c) resin composite intracoronal restoration (Courtesy Professor Peter Parashos).

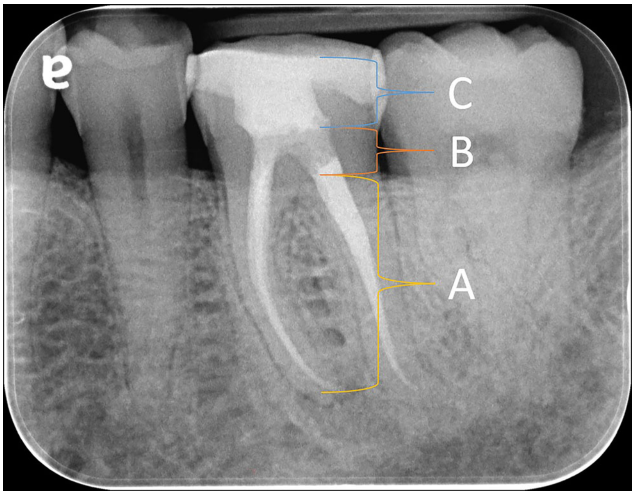

Fig. 3 (a) Gutta percha; (b) glass ionomer cement orifice barrier; (c) resin composite intracoronal restoration (Courtesy Dr Monique Cheung).

order to prevent leakage through a potentially defective interim or temporary restoration prior to placement of a final restoration.[69, 70] Additionally, the complexity involved in placing an appropriate direct or indirect restoration requiring properties suitable for aesthetics and function under load, for example, is not married to the seal at the coronal aspect of the endodontic treatment, and a more effective and perhaps technically simplistic technique or material can be applied. Figures 4–6 show the immediate placement of a zinc polycarboxylate OB after root filling completion, overlaid with a glass ionomer cement prior to restoration with a resin composite overlay.

An OB material should be both easily identifiable and easily removed in the event of orthograde retreatment being required in order that iatrogenic damage is minimised. Wolcott *et al.*[71] investigated pigmentation of OB materials to establish the sealing ability of three materials in addition to their visibility and ease of removal. They reported that, among three glass ionomer-based materials, a blue-pigmented Vitrebond (Resin-modified glass ionomer cement) OB was significantly better ($P < 0.05$) at preventing leakage than those without OBs, where the pink glass ionomer material was easily identified but did not significantly reduce leakage.

Many studies have investigated the efficacy of OBs, testing a variety of materials including amalgam, conventional glass-ionomer cements, resin-modified glass-ionomer cements, resin composites, zinc polycarboxylate cements (ZPC), mineral trioxide aggregate (MTA) and calcium silicate-based cements (CSC).[72–80] A recent systematic review and meta-analysis concluded that various materials placed as OBs are effective in the prevention of microleakage *in vitro*.[81] However, insufficient data prevented statistical comparisons

Fig. 4 Zinc polycarboxylate cement (ZPC) orifice barrier placed immediately after root filling completion, prior to placement of glass ionomer cement (GIC) interim restoration.

Fig. 5 Restorative appointment 1 week later following cutback of glass ionomer cement (GIC) to create space for overlay restoration. *Note* GIC is still covering zinc polycarboxylate cement (ZPC).

Fig. 6 A direct resin composite (RC) overlay restoration was placed with sectional matrices, finished and polished.

from being made. In fact, the heterogeneity and weak design of this type of study have led several prominent journals to refuse publication of studies based on assessment of microleakage[82, 83] due to inconsistency of study design and the lack of clinical relevance.[84, 85]

Nonetheless, there is some *in vitro* evidence linking the penetration of bacteria along marginal gaps associated with cyclic loading. Khvostenko *et al.*[86] shown that with marginal gaps between tooth and resin composite materials of 15–30µm, cyclic loading promoted bacterial leakage. Hollanders *et al.*[87] have suggested that occlusal loading might cause greater gap deformation and might increase hydrodynamic flow and the rate of secondary caries at restorative margins. There are, however, challenges in relating *in vitro* findings of leakage to clinical outcomes.[88]

There is also limited *in vivo* evidence to support the use of OBs. This is, in part, due to study design. The studies by Ng *et al.*[89, 90] and Kumar *et al.*[91] were unable to show the effect of OBs as the primary seal was not compromised during the study period. Several clinical animal studies have shown limited evidence for the use of OBs or the maintenance of a coronal seal over root-filled teeth in split-mouth designs comparing various root-filling materials either sealed or left exposed to the oral environment.[92–95] However, such studies are time-limited by ethical and cost constraints, so the long-term effect of exposed root fillings versus those sealed by OBs clinically is challenging to show.

The provision of an OB should be best regarded as the creation of a 'sub-seal'[42] to protect a root filling in the event of future coronal restoration loss or leakage. Such a seal might prevent the perceived need by clinicians to undertake endodontic retreatment in the event of the primary coronal restoration becoming compromised,[96] where the OB remains unimpacted.

ORIFICE BARRIER MATERIALS

In decoupling the properties required of a root-filling material, or a coronal restorative material, the best-fit properties of an OB material can be idealised and are presented in Table 1. A summary of the relevant properties of various material groups is presented in Table 2 and is discussed in more detail below.

Resin composite

For resin composite materials, it is well-established that enamel bonding is preferable to dentine bonding from the point of view of technical complexity and expected durability of restorations.[97] Despite significant improvements to dentine bonding systems over recent decades,[98] the bonding interface remains a clinical problem. This is in part due to the challenges encountered in bonding a hydrophobic material in resin composite to a hydrophilic substrate in dentine. In order to promote the formation of the hybrid

Table 1. Desirable properties of an ideal orifice barrier material

Property	Description/Reasoning
Aesthetics	Placed cervically, materials might create discolouration or shadowing in anterior or visible posterior teeth
Adaptation	Able to adapt intimately to root canal/cavity walls without porosities or marginal defects
Adhesion	Improve integrity of material in root canal space and avoid dislodgement if primary coronal restoration is lost
Sealing ability	Able to resist leakage of fluids, microorganisms and their nutrients and by-products
Fast setting	Photocuring/command set or rapid self-setting to allow placement of coronal restorative material
Ease of placement	Simplified technique for placement in prepared root canal space if at sub-orifice level
Ease of removal	Material should be easily removed to minimise iatrogenic damage if root filling requires retreatment later
Antimicrobial activity	Able to resist aggregation or penetration of microorganisms
Resistance to degradation	Able to resist fluid or chemical degradation, or resist physical or fluid/chemical wear if primary coronal seal is compromised
Remineralising/repair	Able to remineralise adjacent dentine or aid repair of collagen in dentine
Physical properties	Mechanical and thermal properties similar to dentine

Table 2. Comparison of properties of orifice barrier materials

Material	Notes	Subtype	Adhesive	Antimicrobial	Aesthetics	Handling	Setting time	Increment depth	Ease of removal
RC	Polymerisation shrinkage Inhibition by eugenol-based sealers and peroxide-based bleach Degradation of dentine bond over time	Paste	Yes	No	Very good	Incremental placement required (max 2mm)	Command Set	Maximum 2 mm	Poor
		Flowable	Yes	No	Very good	Simple (max 2mm DOC)	Command Set	Maximum 2mm	Poor
		Bulk fill	Yes	No	Very good	Simple (4–5 mm DOC)	Command Set	4-5mm	Poor
		Self cured	Yes	No	Very good	Simple	Variable	No limit	Poor
		Dual cured	Yes	No	Very good	Simple	Command Set	Ideal polymerisation might be depth-limited	Poor
GIC	Potential for bubble entrapment with encapsulated systems	CGIC	Yes	Some	Good	Simple	2-6mins	No limit	Moderate
		RMGIC (Light cured)	Yes	Some	Good	Simple	Command Set	Resin DOC limited	Moderate
		RMGIC (Self cured)	Yes	Some	Good	Simple	4 min	No limit	Moderate
ZPC	Solubility		Yes	Minimal	Fair	Complex	2–6 min	No limit	Good
Amalgam	Poor aesthetics		No	Yes	Poor	Simple	24 h; initial set <10 mins	Minimum 2 mm	Moderate
Cavit	Hygroscopic Poor physical properties		No	No	Fair	Simple	15–30 min	Preferably >3.5 mm	Good
ZOE-based cements	Eugenol inhibits RC systems		No	Yes	Fair	Simple	2–6 min	No limit	Good
Zinc Phosphate	Solubility		No	Minimal	Fair	Simple	2.5 min–8 min	No limit	Good
MTA	Very long setting time Can cause discolouration		No	Yes	Poor	Complex	2 h 45 min	No limit	Poor
CSC	Complex handling Long setting time		No	Yes	Fair	Complex	12 min	No limit	Moderate

CGIC, conventional glass ionomer cement; CSC, calcium silicate-based cement; DOC, depth of cure; GIC, glass ionomer cement; MTA, mineral trioxide aggregate; RC, resin composite; RMGIC, resin-modified glass ionomer cement; ZOE, zinc oxide eugenol; ZPC, zinc polycarboxylate cement.

layer,[99] removal or penetration of the smear layer and demineralisation of the superficial dentine layer must occur to allow infiltration of monomers. In 'etch and rinse' adhesive systems, following acid-etching to remove the smear layer, HEMA (2-hydroxyethyl methacrylate) present within a solute is commonly used as an amphiphilic bridge to improve wettability and to infiltrate the collagen network, thus allowing subsequent addition and polymerisation with methacrylate-based resin composite materials. In the 'self-etch' adhesive systems, acidic functional monomers such as the commonly used 10-MDP (10-methacryloyloxydecyl dihydrogen phosphate) monomer are capable of penetrating the smear layer and etching mineralised structure, in addition to infiltrating collagen and chemically bonding to hydroxyapatite. However, both HEMA and 10-MDP are susceptible to problems such as water sorption and hydrolytic degradation, and hydrolysis is a key reason for resin degradation within the hybrid layer, leading to water penetration and resin elution, and reducing bond strength over time.[100] It is also postulated that breakdown of collagen fibrils occurs as a result of proteolytic degradation caused by the release and activation of endogenous enzymes such as MMPs (matrix metalloproteinases) and cysteine cathepsins, and it has been demonstrated *in vitro* that agents including chlorohexidine (CHX) might inhibit such enzymes, promoting longer preservation of the hybrid layer.[101]

Additional problems arise in the adhesion to dentine and polymerisation of resin composite materials at or apical to the coronal root canal orifice,[10,102] due to alteration of dentine or contamination of the smear layer with endodontic materials, chlorine[103] or hydrogen peroxide-based[104] bleaching agents, depth of photocuring[105] or higher configuration factor (C-Factor) and associated polymerisation shrinkage stress.[106]

The use of indirect bonded glass-ceramic restorations usually indicates bonding with resin-based cements. Placing such restorations on teeth with extensive coronal enamel loss and without the presence of an OB or base material essentially leaves the resin composite-dentine bond as the 'weakest link' if the coronal seal becomes compromised.

With respect to the use of resin composite materials as OBs, with such a wide range of product choices, it is critical that the clinician is aware of the limitations of the materials for a given purpose. For example, some of the newer variants include 'bulk fill' materials, advertised to cure up to 4-5 mm depth, but such claims should be regarded with scepticism as inferior depth of photocuring and degrees of polymerisation have been demonstrated.[107] Injectable or flowable materials still generally have a 2 mm maximum depth of photocuring, and this varies depending on the opacity and filler content of the material and the radiant power, irradiance, tip distance and angulation associated with the light curing unit being used. Resin composite materials capable of dual curing often contain tertiary amines which are known to discolour over time and are perhaps best avoided in anterior teeth where aesthetics are critical.[108]

Glass-ionomer cements

Glass-ionomer cements (GIC) are ion-releasing materials formulated for various uses, based on an acid-base setting reaction in which a fluoroaluminosilicate glass reacts with a polyalkenoic acid to form a composite material made up of unreacted glass particles embedded in a polyalkenoate salt matrix.[109] The resulting material adheres chemically to hydroxyapatite through an ion exchange layer and releases fluoride. Although the majority of fluoride release occurs as an early burst, there is a low level of sustained release, which increases when under acid attack.[110] The effectiveness of fluoride-releasing materials in caries control, however, is still uncertain.[111] *In vitro* testing found the impact of various endodontic materials on the bond strength of GIC to dentine not to be significant.[112]

Resin-modified glass-ionomer cements (RMGIC) undergo a similar acid-base reaction, but with the addition of resins such as 2-hydroxyethyl methacrylate (HEMA) and bisphenol A-glycidyl methacrylate (Bis-GMA), permit a command set and higher earlier strength than GICs.[113] The use of RMGICs in deeper cavity configurations created by the removal of coronal root filling materials, however, creates the risk of leaving unpolymerized HEMA beyond the reach of photocuring.[114] The more recent self-curing RMGICs might offset this risk.

As GIC and RMGIC systems are often encapsulated for predictable mixing and ease of delivery via injection, great care must be taken to avoid air entrapment during placement into root canals, which could lead to void formation if used as OBs.

Zinc polycarboxylate cements

Zinc polycarboxylate cements (ZPC), although a precursor to GICs, are based on the reaction of oxides of zinc, magnesium, tin, bismuth and/or alumina and polyacrylic acid, and have a history as liners due to good biocompatibility.[115] ZPC can bond chemically to dentine via a similar ionic mechanism to GIC.[116] ZPCs have been shown to be an appropriate base material, *in vitro*.[117] More recently, ZPCs have been reported to increase mineral density in artificially induced carious dentine, and have outperformed GICs in doing so.[118] As ZPCs are generally hand-mixed chairside, handling can be perceived by clinicians as challenging. To permit optimal material adaptation to canal walls and minimise of void formation, ZPC can be applied to the prepared canal orifices using a Flat Paste Filler instrument, without attempting compaction *per se* due to the risk of creating voids.

MTA and calcium silicate-based cements

Mineral trioxide aggregate (MTA), composed primarily of tricalcium and dicalcium silicate, was first introduced as a root-end filling material in the 1990s,[119] and it has been used widely in endodontics for applications including vital pulp therapy, apexification, and perforation repair,[120] but its prolonged setting time of 2 hours and 45 minutes[121] deems it unsuitable for use as a coronal restorative material.[122] Furthermore, MTA is known for post-operative discolouration of tooth structure,[123] making it less than ideal for use as an OBs in anterior or premolar teeth. Owing to the success of MTA, there has been considerable interest in the development of related calcium silicate cement-based materials for a variety of endodontic applications including indirect pulp capping material in the treatment of deep carious lesions.[124] One such material is Biodentine (Septodont, Saint Maur des Fosses, France), with a much shorter total handling time of 12 min, including mixing and setting.[125] Some of the advantageous properties of the related bioceramic materials include good biocompatibility, a prolonged high pH, favourable responses from host tissues including the ability to stimulate hard tissue repair and antimicrobial properties. Canoglu *et al*.,[126] showed MTA to be significantly superior in dye leakage testing to resin composite and GIC. However, disadvantages of these materials include an imperfect dentine sealing ability, complex handling, a prolonged setting time, inferior physical properties and increased expense, making these materials currently unsuitable for several restorative procedures.[122]

Other materials

Various 'temporary' restorative materials including Cavit (3M, St. Paul, MN) and Intermediate Restorative Material (IRM) (Dentsply, Tulsa Dental, Tulsa, OK, USA) have been evaluated as OBs and coronal sealing materials.[68, 76, 127] Cavit, being relatively inexpensive and easy to use is commonly used in dentistry and is marketed in differing formulations affecting hardness of set, but is a proprietary combination based on zinc oxide, calcium sulphate hemihydrate, zinc sulphate, triethylene glycol diacetate, polyvinyl acetate among other components including barium sulphate and pigments.[128] It is a hygroscopic material that undergoes linear expansion through water absorption on setting, thus providing a restorative seal.[129] However, it has relatively poor physical properties and *in vitro* studies have suggested that 3.5–4 mm thickness is required to effect a seal.[129, 130] Provided Cavit is effectively reinforced by an appropriate overlaying material, its sealing ability and ease of removal with ultrasonic instruments, avoiding iatrogenic damage in the event of retreatment, make it worthy of consideration as an OB material.[65, 68, 127]

IRM is a reinforced zinc oxide-eugenol (ZOE) material, with bactericidal properties due to the presence of eugenol, derived from oil of cloves.[115] As a 'temporary' material, its physical properties outweigh those of Cavit, although *in vitro* studies have suggested that Cavit promotes superior sealing.[68, 127, 131, 132] Additionally, eugenol is known to inhibit the polymerisation of resin-based materials and has been shown to interfere with dentine bonding systems,[133] and ZOE-based restorative materials are perhaps best avoided beneath resin composite-based restorations.

Smart materials and antimicrobial materials

Research activity is growing around the development of 'smart' dental materials which have been described based on their degree of interaction with the environment, ranging from 'inert' (no interaction), to 'active' (one-way, uncontrolled release of therapeutics), to 'responsive' (releasing therapeutics in response to specific signals) to 'autonomous' (respond holistically to the microenvironment complexity, adapting to changing conditions).[134] Active or responsive materials might leach antimicrobial agents, e.g., chlorhexidine (CHX), antibiotics, enzymes or other compounds, leading to the depletion of such agents, or impacting the physical properties of the materials.[135]

There has been recent interest in materials with biofilm-inhibiting properties.[136, 137] Two studies observed the effect of zinc-containing materials on the inhibition of Streptococcus mutans biofilm growth with encouraging results.[138, 139] There has also been work on resin materials based on quaternary ammonium methacrylates in the hope that they might yield lasting antimicrobial effects.[140] Two studies have investigated novel endodontic sealers incorporating dimethylaminohexadecyl methacrylate and amorphous calcium phosphate with antibiofilm and remineralization properties, one of which investigated the addition of silver nanoparticles.[141, 142] Another study looked at the antibacterial effect on E. faecalis of Biodentine, a calcium silicate-based material, after incorporation of titanium tetrafluoride.[143]

In attempting to avoid leaching of antimicrobial components from GICs leading to inferior mechanical properties demonstrated in earlier studies,[144, 145] recent *in vitro* studies have investigated the modification of GICs with silver nanoparticles[146] and silver nanowires[147] and demonstrated reduced biofilm aggregation without significant degradation of the materials. Materials capable of resisting microbial leakage without suffering degradation through leaching could potentially prove beneficial if used as an OB.

OTHER INDICATIONS FOR ORIFICE BARRIERS

Cracked root-filled teeth

A cracked tooth with (one or more) cracks extending onto the root surface[148] is often considered to have a guarded prognosis, and extraction might be recommended instead of endodontic treatment by the treating clinician due to a perceived increased risk of failure. The prevalence of cracks in teeth has been reported as high, with a practice-based study reporting 70% of patients presenting with visible cracks in at least one posterior tooth.[149] A recent survey has highlighted a reluctance among dentists in Australia practising outside of metropolitan areas to restore cracked teeth requiring root canal treatment with probing depths of more than 5 mm, favouring extraction over root canal treatment.[150] A survey of American Endodontists revealed a preference to extract teeth with singular 6mm probing depths.[151]

However, a recent prospective study looked at survival of endodontically treated teeth with radicular cracks over 2-4 years, in which teeth were endodontically treated and then obturation materials removed 2-3 mm apical to the deepest extent of the radicular crack, prior to placement of an 'extended orifice barrier'. The authors showed a promising survival rate of 96.6% (improving upon a range of 85.5%-96.8% with 2+ years follow-up in the literature) and suggested that OBs might have particular importance in teeth with radicular cracks, in being able to seal areas of the root internally where extended crown margins might not be feasible.[152]

Sim *et al*. reported an overall survival for cracked root-filled teeth with radicular extension at 81.8%[153] whereas a more recent systematic review and meta-analysis of four articles reported overall five-year survival at 84.1%.[154] The prospects for success with cracked teeth should perhaps trigger conversations with patients about the potential for retaining compromised teeth in preference to implant-supported restorations, where the prevalence of peri-implantitis remains a longer-term concern.[155]

Periodontally involved root filled teeth

Periodontitis is known to be associated with lower survival of endodontically treated teeth,[156, 157] although a cause-effect relationship between periodontitis and AP is unclear.[158] Stassen *et al*.[159] suggested that in root-filled teeth with marginal bone loss resulting from periodontitis, there was an association between the coronal level of the root filling and the risk of AP. The authors recommended reducing the coronal level of the root filling below, or at least at the level of the surrounding marginal bone.

CONCLUSIONS

In order to consider a root-filled tooth well-restored from a biological perspective, the final restorative outcome must be more than the sum of its parts. The underlying root filling must, of course, having been effectively chemomechanically cleaned, be well compacted and as free of voids as possible. However, the potentially permeable nature of root-filling materials obligates provision of a coronal restoration capable not only of resisting fracture, wear and marginal caries, but also providing a lasting secondary seal in the event that the primary seal is compromised. Thus, the provision of an orifice barrier can be regarded as a simple, but essential third seal (i.e., apical to any core and cuspal coverage restorative materials indicated) in the restorative continuum following completion of the root filling, selecting a material that is both easily placed and capable of delivering a durable seal while utilising materials for the coronal restoration with characteristics better suited for fracture and wear resistance. The literature also implies that the location of the orifice barrier ought to be placed in such a fashion that it lies apical to any coronal or radicular cracks, and perhaps also apical to exposed dentine on root surfaces resulting from periodontitis and associated bone loss and/or recession.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Michael E Wylie: Conceptualization; data curation; formal analysis; investigation; project administration; writing – original draft. **Peter Parashos:** Conceptualization; formal analysis; supervision; writing – review and editing. **James R Fernando:** Supervision; writing – review and editing. **Joseph EA Palamara:** Supervision; writing – review and editing. **Alastair J Sloan:** Supervision; writing – review and editing.

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