REVIEW

The use of glass ionomer cements in both conventional and surgical endodontics

M. A. A. De Bruyne & R. J. G. De Moor

Department of Operative Dentistry and Endodontology, Dental School, Ghent University, Ghent University Hospital, Gent, Belgium

Abstract

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The capacity to bond to dental tissues, especially to dentine, their long-term fluoride release and their biocompatibility make glass ionomer cements (GICs) advantageous for use in endodontics, as well as in restorative dentistry. This review provides information on the basic properties of GICs, such as adhesion, antimicrobial effects and biocompatibility, particularly as they relate to use in endodontics. Indications for the use of GICs in endodontics are orthograde root canal sealing, root-end filling, repair of perforations and root resorption defects, treatment of vertical fractures and maintenance of the coronal seal. The paper includes a review on each of these indications. It is concluded that in spite of the critical handling characteristics and the inconclusive findings regarding sealing ability and antimicrobial activity, there is substantial evidence to confirm their satisfactory clinical performance. Both soft tissue and bone compatibility make them suitable for use during endodontic surgery.

Keywords: glass ionomer cement, root canal sealer, root-end filling, surgical endodontics.

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Introduction

Glass ionomer cements (GICs) were developed in the late 1960s and were a product of an acid–base reaction between a basic fluoro-alumino-silicate glass powder and polycarboxylic acid in the presence of water (Wilson & Kent 1971, 1972). Since then, many modifications and improvements to the original formulation have been made. Present-day conventionally setting GICs (conventional GICs) are hybrid materials with both organic and inorganic constituents. These materials are composed of calcium fluoro-alumino-silicate glass powder and aqueous solutions of homo- and copolymers of acrylic acid-containing tartaric acid (Smith 1990). As stated by McLean *et al.* (1994), a more accurate term for this type of material is glass polyalkenoate cement, because these cements are not true ionomers in the chemical sense. However, this term has not been used as widely as the name GIC.

GICs have been widely used in medicine, mainly in otologic and reconstructive surgery and orthopaedics. Because these cements generate no heat while setting, they will not cause thermal damage to tissues and will not affect heat-labile drugs incorporated in the matrix phase of the cement (Wilson & McLean 1988, Wittwer *et al.* 1994). Unset GICs bind to bone (apatite) and metals (McLean 1988, Wilson & McLean 1988) and do not undergo appreciable shrinkage while setting (McLean 1988, Wilson & McLean 1988, Hill *et al.* 1995). Their main use in medicine is the stabilization of implanted devices and bony fragments and reconstruction or obliteration of bony defects (Geyer & Helms 1990, Babighian 1992, Geyer 1992, Ramsden *et al.* 1992, Geyer & Helms 1993, Muller *et al.* 1993, Babighian *et al.* 1994, McElveen 1994, Muller *et al.* 1994, Ramsden 1995).

In order to reinforce conventional GICs, the addition of metals to the filler component has been proposed (Simmons 1983, McLean & Gasser 1985). The powder then

Correspondence: Mieke De Bruyne, Department of Operative Dentistry and Endodontology, Dental School, Ghent University, Ghent University Hospital, De Pintelaan 185 P8, B-9000 Gent, Belgium (Tel.: +32 9 240 40 00; fax: +32 9 240 38 51; e-mail: mieke.debruyne@UGent.be).

contains fluoro-alumino-silicate glass and a silver alloy (Miracle Mix; GC-Corporation, Tokyo, Japan; Simmons 1983), or the glass is sintered with silver (Ketac-Silver; Espe, Seefeld, Germany; McLean & Gasser 1985). The latter product is called a cermet cement (*cer*amics and *met*al). Metal-reinforced GICs have been proposed for restorations and core build-up (McLean 1990).

Another modification of conventional GICs, suggested as an alternative to amalgam for posterior preventive restorations, is the highly viscous GIC (Wilson & McLean 1988): examples of present-day formulations are Fuji IX (GC-Corporation, Tokyo, Japan) and Ketac-Molar (Espe, Seefeld, Germany).

Resin-modified GICs (RMGICs) were introduced in the late 1980s in order to widen the range of clinical applications (Antonucci *et al.* 1988, Sidhu & Watson 1995). Resin modification of GIC was designed to produce favourable physical properties similar to those of resin composites and resin cements while retaining the basic features of the conventional GIC (Yoshii *et al.* 1992). The RMGIC is defined as a material that undergoes both a polymerization reaction and an acid–base reaction.

The interest in the clinical use of GICs arises mainly from their behaviour as adhesive – bioactive materials with therapeutic action (Wilson & McLean 1988, Davidson & Mjör 1999). As the capacity to bond to dentine (Wilson & McLean 1988), the fluoride release without loss of strength of the material (Cattani-Lorenti *et al.* 1994, Mitra & Kedrowki 1994) and the biocompatibility (Sidhu & Schmalz 2001) make GICs advantageous for use in restorative dentistry, these characteristics also contribute to their indicated use in endodontics. Moreover GICs possess antibacterial properties against many bacterial strains (Tobias *et al.* 1985, Chong *et al.* 1994b, Heling & Chandler 1996, Herrera *et al.* 1999).

Use of GICs in endodontics

The use of GIC in root canals was first introduced by Pitt Ford (1979) in a laboratory study. Using a single cone technique (gutta-percha or silver cones in combination with a GIC), he found that the working time was too short to be used in conjunction with the lateral compaction technique. Stewart (1990) proposed two other formulations in order to prolong the working time, and added barium sulphate to increase radiopacity. Ray & Seltzer (1991) developed a usable experimental formulation with adequate working time, radiopacity and adhesion to the root canal wall. These modifications led to the commercialization of Ketac-Endo (Espe, Seefeld, Germany) in 1991.

Apart from the conventionally hardening cements, RMGICs were also tested. Saunders *et al.* (1992) tested Vitrebond (3M, St Paul, MN, USA) in combination with gutta-percha and showed that there was good adaptation of the sealer to the root canal.

Good adhesion and a strong material contribute to the strength of the tooth. In an *in vitro* study, Trope & Ray (1992) found an increased resistance to vertical fracture when obturating canals in conjunction with a glass ionomer sealer.

More recent developments are two experimental GIC sealer formulations: KT-308 (GC-Corporation, Tokyo, Japan; Lalh *et al.* 1999a), which is a conventional GIC with an increased radiopacity and an extended working time, and 'ZUT' (University of Toronto, Canada; Lalh *et al.* 1999a), consisting of KT-308 combined with an antimicrobial agent, a silver-containing zeolite (0.2–20% weight). 'ZUT' demonstrated an effective suppression of adherent *Enterococcus faecalis* over a 12-week period (Patel *et al.* 2000), which may promote its efficacy as a root canal sealer.

The proven clinical efficacy of GICs in medical applications (Geyer & Helms 1990, Babighian 1992, Geyer 1992, Ramsden *et al.* 1992, Geyer & Helms 1993, Muller *et al.* 1993, Babighian *et al.* 1994, McElveen 1994, Muller *et al.* 1994, Ramsden 1995) also suggests potential advantages for the field of surgical endodontics: minimal irritation of periradicular tissues may be expected and it is known that the fluoride release may contribute to bone mineralization (Tencer *et al.* 1989).

General properties – endodontic perspective

Adhesion and bonding to dental tissue

The adhesion of GIC to dental tissue relies primarily on chemical interaction and, to a lesser extent, on micromechanical interlocking (Wilson *et al.* 1983, Akinmade & Nicholson 1993, Shen 1996). Lalh *et al.* (1999a) investigated the bond strength of two experimental GIC sealers ('KT-308' and 'ZUT') and Ketac-Endo to bovine dentine conditioned with the most common irrigants. Bond strength appeared to be lowest after treatment of dentine by 17% ethylene diamine tetra-acetic acid (EDTA) and 2.6% sodium hypochlorite (NaOCl). Irrigation with NaOCl or even with distilled water resulted in a higher bond strength (Lalh *et al.* 1999a) and the formation of a hybrid layer between the GIC and the dentine (Lalh *et al.* 1999b). This research suggested that the smear layer should be preserved. In a more recent study (Timpawat

et al. 2001), contradictory results were obtained. Conditioning with phosphoric acid or citric acid, which was also more effective in removing the smear layer, resulted in higher bond strengths than conditioning with EDTA and NaOCl or conditioning with polyacrylic acid. Bonding to dentine without smear layer removal (5.25% NaOCl) was too low to be measured in the testing apparatus (Timpawat *et al.* 2001). According to this study, the smear layer should be removed. Apart from this, Ketac-Endo demonstrated a lower shear bond strength than 'KT-308' or 'ZUT' (Lalh *et al.* 1999a, Chung *et al.* 2001).

Anti-microbial effects

Conventionally setting glass ionomer cements

Several studies have demonstrated that conventionally setting GICs are able to reduce bacterial growth (Tobias *et al.* 1985, Meryon & Johnson 1989, Scherer *et al.* 1989, Palenik *et al.* 1992, Prati *et al.* 1993). Although bacterial inhibition associated with GICs is measurable (Tobias *et al.* 1985), variations in techniques make it difficult to make comparisons among studies. It is important to note that the extent of bacterial inhibition differs between and among materials (Forss *et al.* 1991, Seppä *et al.* 1993), as well as between the different strains of bacteria and the methods used (Meryon & Johnson 1989). The mechanism of the antibacterial activity of GICs is not clear, and several theories have been put forward. The most documented one suggests that fluoride ions released from GICs are responsible for bacterial inhibition. The fluoride release alone, however, may not be the only antimicrobial mechanism (Seppä *et al.* 1993). There may be an added antimicrobial effect because of acidity (Palenik *et al.* 1992), related to the polyalkenoic acid (Seppä *et al.* 1993). Yet another theory points to the zinc component; it is known that zinc exhibits a stronger antibacterial activity than fluoride (de Rosas & Chan 1996). In this respect, it has been shown that GICs without zinc did not have effective antibacterial properties (Tobias *et al.* 1985). It has been hypothesized that the combined release of zinc and fluoride may be responsible for the antimicrobial activity (Sidhu & Schmalz 2001).

Studies on the antibacterial activity of GICs related to their use in endodontics are few, although the bacterial inhibition of Ketac-Endo endodontic sealer has been reported. Abdulkader *et al.* (1996) found that Ketac-Endo inhibited all the bacteria used in their study. The antimicrobial action, according to the authors, was related to the low pH, when freshly prepared (Mount 1994), and the potential to release fluoride ions (Tobias *et al.* 1985, Meryon & Johnson 1989). The possibility that other components were involved was not excluded. Heling & Chandler (1996) found antibacterial activity only after 7 days for Ketac-Endo and none at 24 h, whereas all other sealers compared in the study showed antibacterial activity at 24 h. In another study, Shalhav *et al.* (1997) concluded that Ketac-Endo possessed a very potent but short-acting antibacterial activity.

Two experimental GIC root canal sealers ('KT-308' and 'ZUT') were tested in different studies for antibacterial activity against *E. faecalis*. Depending on the experimental design, different results were obtained. 'ZUT' demonstrated a significant reduction in bacterial growth in contrast to 'KT-308' (Patel *et al.* 2000), whereas it could not provide more resistance to bacterial ingress compared to 'KT-308' or AH 26 (De Trey, Zürich, Switzerland; Padachey *et al.* 2000). In another *in vitro* study, 'KT-308' effectively prevented penetration of *E. faecalis* into root canals, whereas 'ZUT' did not (McDougall *et al.* 1999).

Resin-modified glass ionomer cements

The most investigated RMGIC is Vitrebond (3M, St Paul, MN, USA). Freshly mixed Vitrebond revealed a significantly greater antimicrobial activity than the conventional cement Aquacem (De Trey, Zürich, Switzerland). The inhibitory properties were similar when the material was light-cured or chemically cured. This suggests that antibacterial agents dissolved rapidly (Coogan & Creaven 1993). On one hand, it was suggested that the antibacterial activity was associated with low pH of the freshly mixed RMGIC combined with the release of fluoride ions above a threshold value (De Schepper *et al.* 1989). Furthermore, HEMA (2-hydroxyethyl methacrylate) was also considered to contribute to the antimicrobial action (Coogan & Creaven 1993). In case of Vitrebond, the marked antibacterial activity may be because of high levels of toxic agents released during curing, such as benzine bromine and benzine iodine (Geurtsen *et al.* 1998).

Biocompatibility

Conventionally setting glass ionomer cements

Research on the biocompatibility of GICs in conventional and surgical endodontics has focused mainly on conventionally setting GICs. The latter exhibit good biocompatibility for three main reasons (Nicholson *et al.* 1991): (i) they set with minimal exotherm; (ii) neutralization is generally sufficiently rapid that any potential irritation because of the presence of free acid is minimal; and (iii)

the substances leached from the set cement are generally either benign or beneficial to the tissue in which the cement is placed.

Crisp *et al.* (1978) measured setting exotherms and found that GICs gave the smallest setting exotherm of any other dental cements examined, making them unlikely to cause any thermal damage or necrosis. This is in marked contrast with other biomedical cements and is a feature that contributes to the biocompatibility of GICs.

The aqueous polymeric acids used for the preparation of GICs are relatively weak acids. Polyacrylic acid has a pK_a of 4.5–5.0, depending on the concentration. This value rises to between 6 and 7.5 as full neutralization is approached (Mandel 1983). After the initial step of neutralization, which is reasonably rapid, the process slows down, and 1000 min after the start of mixing, it is still incomplete (Cook 1982). This implies that the material remains slightly acidic for some time. However, the pH rises sufficiently quickly in a way that there is no attack on the tooth surface as such, neither does the initial mismatch of the pH of the cement and the bone structure lead to problems either of cement failure or of loss of biocompatibility (Jonck *et al.* 1989a).

The species leached from a GIC are dependent on the initial constituents of the cement. Little or no organic species have been found to be leached out of GICs (Kuhn *et al.* 1983), the components described so far being all inorganic, as follows:

- Silica: The precise role of silica in the human metabolism is unclear, although it appears to lower the cholesterol levels in blood (Iler 1979). This, in combination with its low toxicity, suggests that the leaching of silica either in the teeth or in the bone is likely to be benign to the body (Nicholson *et al.* 1991).
- Aluminium: In some respects, aluminium is the least biologically acceptable of all the leached elements. However, in endodontic applications, the release of aluminium would not be expected to cause problems. First, the amount released has been shown to be very small (Crisp *et al.* 1980, Brookman *et al.* 1986); secondly, any release that does occur, takes place in close proximity to mineralized tissues, either teeth or bone. The main constituent of this mineralized tissue is hydroxy-apatite, and because of its size, the Al^{3+} ion would be expected to occupy suitable vacancies in the surface of this material (Atkinson & Witt 1985).
- Calcium: Is released in very small amounts (Crisp *et al.* 1980, Brookman *et al.* 1986) and is beneficial to mineralized tissues. As the main inorganic constituent of teeth and bone is calcium phosphate mineral hydroxy-apatite, calcium can be incorporated in the hydroxy-apatite during remodelling of the bone (Atkinson & Witt 1985).
- Phosphate: Ionomer glasses do not necessarily contain phosphate, although most of the commercially available ones do. Its most important physiological use is the formation of the mineral hydroxy-apatite (Nicholson *et al.* 1991).
- Fluoride: The fluoride ions fit better than the hydroxyl ions into the hydroxy-apatite lattice of the teeth, which, afterwards, is more resistant to the attack of acids produced in the mouth (Atkinson & Witt 1985). The fluoride ions can be incorporated into bone, which is less easily resorbed and does not undergo ion exchange as readily as nonfluoridated bone (Atkinson & Witt 1985).

Root canal sealer

One of the requirements of an ideal root canal sealer is that it should be non-irritating to the periapical tissues and should be compatible with living connective tissues (Grossman 1982). Although specific research on GIC root canal sealers is limited, GICs in general are believed to be biocompatible. Subcutaneous implantation in rats caused a mild inflammatory reaction on the fifth day, which diminished progressively, compared with a zinc oxide–eugenol-based sealer, Tubli-Seal (Kerr Manufacturing Co., Romulus, MI, USA), which caused a severe reaction and remaining irritating (Kolokuris *et al.* 1996). Jonck *et al.* (1989a,b) and Jonck & Grobbelaar (1990) conducted a series of experiments on baboons and then on humans: GICs were nontoxic in bulk, and allowed, as well as promoted, normal haemopoetic and osteoblastic activities on the cement surface. The cement had no inhibitory effect on bone tissue development and there was a total absence of fibrous tissue envelopment with the cement being effectively incorporated into the bone. Osteoblastic activity has also been demonstrated in cell cultures in the presence of Ketac-Endo (Snyder *et al.* 1997).

Sealing material (perforation, root-end filling) in surgical endodontics

The use of GICs in the periradicular region implies that the material will have direct contact with the healing bone. Direct contact will take place between the mineralized bone and root dentine, as well as the cementum (Craig & Harrison 1993, Torabinejad *et al.* 1995). Bone implantation studies confirmed good tolerance to different kinds of GICs (Zmener & Dominguez 1983, Lehtinen 1986, Blackman *et al.* 1989, Jonck *et al.* 1989a,b, DeGrood *et al.* 1995). Unfortunately, the interpretation of these bone implantation studies is difficult (Mjör 1980).

However, more relevant clinical studies confirm the biocompatibility (Callis & Santini 1987, Zetterqvist *et al.* 1987). This intimate bond between GIC and living bone seems to be enhanced by fluoride leaching from the GIC (Brook *et al.* 1991).

Resin-modified glass ionomer cements

Resin-modified glass ionomer cements contain unsaturated groups and hence may lack the biocompatibility of conventionally setting GICs (Wilson 1990), and concerns have been raised about their use. Moreover, differences in the amounts and patterns of fluoride released (Verbeeck *et al.* 1998) and cytotoxicity amongst RMGICs have been reported (Kan *et al.* 1997). Aluminium is also released from RMGICs in the short term, as well as in the long term (Forss 1993). According to Geurtsen *et al.* (1998), the eluates in RMGICs were the prime causes for cytotoxic reactions. The cytotoxicity of Vitremer (3M, St Paul, MN, USA) has been studied (Yoshikawa *et al.* 1994, Kan *et al.* 1997, Geurtsen *et al.* 1998), and the release of HEMA has been shown to be one of the prime causes. Vitrebond used for pulp capping was more irritating to the pulp tissue than calcium hydroxide (do Nascimento *et al.* 2000). On the other hand, direct pulp capping with Vitremer did not seem to cause pulpal inflammation, and Vitremer implants only caused slight reactions in rabbits (Bazzucchi *et al.* 1995, Tassery *et al.* 1997).

Compared to conventionally setting GICs, RMGICs have easier handling properties; this, in association with their adhesion potential, makes them attractive as root-end filling materials. The low cytotoxicity (Chong *et al.* 1994a) and the pronounced antibacterial activity (Chong *et al.* 1994b), as well as a favourable tissue response when used as a root-end filling material in infected teeth (Chong *et al.* 1997a,b), demonstrate that this material might be used in endodontic surgery.

Root canal sealing

Orthograde root canal sealing

The objectives of root canal treatment are total debridement of the pulpal space, development of a fluid-tight seal at the apical foramen and total obliteration of the root canal (Ingle *et al.* 2002). Complete elimination of microorganisms is impossible (Sjögren *et al.* 1997, Sundqvist *et al.* 1998). The ideal root canal filling would thus be the one which possesses bactericidal properties against remaining microorganisms and which creates a barrier against newly invading microorganisms. Thanks to their properties of chemical adhesion (Wilson *et al.* 1983, Akinmade & Nicholson 1993, Shen 1996) and long-term fluoride release (De Moor *et al.* 1996, Verbeeck *et al.* 1998), GICs appear to have the desirable properties.

Sealing ability

Incomplete obturation of the root canal system is one of the causes of endodontic failure when microorganisms remain in the canal (Petersson *et al.* 1986, Ingle *et al.* 2002). Endodontic filling materials with ability to seal the root canal hermetically are therefore important for successful root canal treatment.

In vitro *evaluation* Research on sealing ability of GICs has mostly been performed *in vitro*. Unfortunately, data from these studies are often clinically irrelevant and contradictory (Wu & Wesselink 1993, Al Ghamdi & Wennberg 1994). GICs have been reported to perform worse (Al Ghamdi & Wennberg 1994, De Gee *et al.* 1994, Smith & Steiman 1994, Ahlberg *et al.* 1995, Horning & Kessler 1995, Şen *et al.* 1996), equal to (Brown *et al.* 1994, Goldberg *et al.* 1995, Holland *et al.* 1995, Horning & Kessler 1995, Malone & Donnelly 1997, Raiden *et al.* 1997, Taylor *et al.* 1997, Kont Çobankara *et al.* 2002) or better than (Koch *et al.* 1994, Wu *et al.* 1997, Friedman *et al.* 2000, Kont Çobankara *et al.* 2002) the conventional sealers based on zinc oxide–eugenol or resin.

Short working time and fast set are both factors that contribute to the fact that GICs are often used in combination with a single cone technique. This is in contradiction to the concept of gutta-percha condensation, of which it is expected that proper condensation and reduced thickness of the sealer enhance the seal (De Gee *et al.* 1994, Wu *et al.* 1994, 1997, Georgopoulou *et al.* 1995, Kontakiotis *et al.* 1997). The single cone technique in combination with GIC might therefore be the reason for the more extensive leakage (Lee *et al.* 1997).

Hence, also for GICs, sealer thickness appears to be a crucial factor in sealing efficacy. As with other sealers, the seal appears to be inversely related to the thickness of the sealer layer (De Gee *et al.* 1994, Wu *et al.* 1994, 1997, Georgopoulou *et al.* 1995, Kontakiotis *et al.* 1997). A thick layer implies more shrinkage and consequently more leakage (Wu *et al.* 1994).

Leakage mainly appears between the root canal wall and the sealer, where the presence of a smear layer influences the seal (Saunders & Saunders 1994a, Tidswell *et al.* 1994, Goldberg *et al.* 1995, Holland *et al.* 1995, Raiden *et al.* 1997, Taylor *et al.* 1997). This interface is affected by irrigants and medicaments used during root canal

treatment (Raiden *et al.* 1997, Lalh *et al.* 1999b, Chung *et al.* 2001, Timpawat *et al.* 2001). Removal of the smear layer allowed GIC-based sealers to enter some of the dentinal tubules (Saunders *et al.* 1992), although not as deeply as other sealers (Şen *et al.* 1996). Nevertheless, the literature remains contradictory. Thus, again because of the limitations of the *in vitro* methodology, removal of the smear layer has been reported to reduce leakage significantly (Holland *et al.* 1995, Raiden *et al.* 1997, Taylor *et al.* 1997) or to make no difference (Saunders & Saunders 1994a, Tidswell *et al.* 1994, Goldberg *et al.* 1995).

In vivo *evaluation* To overcome the limitations of *in vitro* investigations, Friedman *et al.* (1997) developed a model to assess the functional efficacy of endodontic filling materials and techniques *in vivo*, in which they evaluated bacterial ingress in mandibular premolars in beagle dogs. According to this model, an experimental GIC sealer (KT-308), used in combination with cold lateral gutta-percha condensation, scored better than Roth 801 cement (zinc oxide–eugenol sealer; Roth International Ltd., Chicago, IL, USA), when the canals of root-filled teeth were inoculated with plaque (Friedman *et al.* 2000).

Retreatment

One of the requirements for an ideal root canal filling material is that it should be removed easily from the root canal if necessary (Grossman 1982). Experience indicates that removing a root filling that consists only of hardened cement is difficult (Lovdahl & Gutmann 1997). Therefore, GIC sealer should be used in combination with gutta-percha: gutta-percha can be dissolved and then the cement can be removed ultrasonically from the canal without leaving excessive amounts of residue on the canal walls (Friedman *et al.* 1992, Friedman *et al.* 1993a, Moshonov *et al.* 1994). Nevertheless, it has been shown that it takes more time to remove a GIC sealer than a conventional sealer during retreatment procedures (Friedman *et al.* 1992, Friedman *et al.* 1993a, Moshonov *et al.* 1994) and for partial removal during dowel space preparation (Raiden *et al.* 1998).

Long-term clinical follow-up

Data on the long-term clinical follow-up of the use of GIC root canal sealers during root canal treatment are scarce, and clinical follow-up is limited to 18 months. In a study performed by Friedman *et al.* (1995), the healing rate for teeth treated with Ketac-Endo was in the range reported in previous studies with other sealers. One of the findings on Ketac-Endo was that, contrary to other sealers (Augsburger & Peters 1990), it was not resorbed after periradicular extrusion (Friedman *et al.* 1995), confirming its low tissue solubility.

Root-end filling material

Conventionally setting, resin-based and cermet GIC formulations have been used as root-end filling materials. As GICs are sensitive to moisture at the start of their set and as avoiding moisture contamination in the periradicular region is not achieved easily, the application of GICs demands precise handling and placement procedures.

In some cases, GICs have also been used at the apical end of extremely shortened root canals, when a post-space is needed after root-end resection (De Moor & De Bruyne 2000).

Sealing ability

In vitro *evaluation* Glass ionomer cements used as root-end filling materials have been tested in various *in vitro* studies, with and without varnish, and have been compared mainly to amalgam (Friedman 1991). Again, because of the limitations of the methodology, the results have been contradictory. GICs provided a better seal (Schwartz & Alexander 1988, Zetterqvist *et al.* 1988, Pissiotis *et al.* 1991, Aktener & Pehlivan 1993, Alhadainy *et al.* 1993, Özata *et al.* 1993, Chong *et al.* 1995, Hosoya *et al.* 1995, Pretorius & van Heerden 1995, Gerhards & Wagner 1996, Wu *et al.* 1998, Sutimantanakul *et al.* 2000), an equal seal (Olsen *et al.* 1990, Friedman *et al.* 1991a, Roth 1991, Danin *et al.* 1994, Sutimantanakul *et al.* 2000, Siqueira *et al.* 2001) or a worse seal (King *et al.* 1990, Danin *et al.* 1992, Biggs *et al.* 1995, Sutimantanakul *et al.* 2000, Siqueira *et al.* 2001, Reister *et al.* 2002) than other root-end filling materials. When conventionally setting GICs were compared after application of a varnish, a better seal was ensured (Barkhordar *et al.* 1989, Aktener & Pehlivan 1993, Özata *et al.* 1993); the resin-modified formulations scored better than the conventional cement, and both rated better than cermet cements (Özata *et al.* 1993, Rosales *et al.* 1996).

In vivo *evaluation* In general, the performance of GIC has been comparable to that of amalgam (Friedman *et al.* 1991b, Trope *et al.* 1996, Chong *et al.* 1997c), in contrast to the failure of GIC to seal infected root canals in an earlier study (Pitt Ford & Roberts 1990).

Clinical evaluation In spite of the previously mentioned contradictory results, it has been shown that, when periradicular surgery with a root-end filling of Chemfil (De Trey, Zürich, Switzerland) was performed on teeth with necrotic pulps and periradicular pathosis without prior root canal treatment, satisfactory healing 1 year postoperatively occurred (Danin *et al.* 1999). Also Ketac-Silver used as a retrograde filling material performed well on the long term (Bühler 2000).

Follow-up
The long-term success of GIC as a root-end filling material has been confirmed in several studies (Zetterqvist *et al.* 1991, Jesslén *et al.* 1995, Bühler 2000). Compared to amalgam root-end fillings, GICs appear to perform as well. The moist environment does not seem to be detrimental to the surface (Jesslén *et al.* 1995) and GICs seem to be less susceptible to moisture than expected. This has been shown both *in vitro* (De Moor & Verbeeck 1998) and *in vivo* (Friedman *et al.* 1991b).

Repair of perforations and root resorption defects

Perforation repair

Root perforation is an undesirable complication of root canal preparation and often leads to tooth extraction (Fuss & Trope 1996). Successful treatment depends mainly on immediate sealing of the perforation and prevention of infection (Fuss & Trope 1996). In addition to factors related to the perforation itself, such as time elapsed since the perforation occurred and size and location of the perforation (Lemon 1992, Fuss & Trope 1996), the repair material is also of importance (Fuss & Trope 1996).

In vitro *evaluation*
Although *in vitro* studies alone cannot support the clinical choice of materials, a variety of methods and materials for perforation repair *in vitro* (surgical and nonsurgical) successfully tested GICs for sealing perforations (Alhadainy & Himel 1994, Himel & Alhadainy 1995, Chau *et al.* 1997, Manocci *et al.* 1997, Alhadainy & Abdalla 1998).

Clinical evaluation
Goon & Lundergan (1995), Shuman (1999), Behnia *et al.* (2000) and Breault *et al.* (2000) described the successful repair of perforations with GIC. From these cases, GIC appeared to be a suitable material for repair of perforations or near perforations, where it acted as a substitute for dentine.

Repair of root resorption cavities

Thorough debridement and cleaning of the resorption cavity are essential for a good prognosis (Gutmann & Harrison 1994). Moreover, long-term success is also influenced by the use of a biocompatible restorative material (De Moor *et al.* 2002). As previously stated, because of the long setting reaction (setting continues for more than 1 year; Wilson & McLean 1988), hydration of GICs during the initial setting influences the long-term properties through contact with the moist environment (Şen *et al.* 1996, Kontakiotis *et al.* 1997, Taylor *et al.* 1997, Wu *et al.* 1997). Nevertheless, contemporary chemically cured GICs appear to perform well; Ketac-Fil (Espe, Seefeld, Germany) used for the repair of resorption defects gave satisfactory results for at least 4 years (De Moor *et al.* 2002).

Treatment of vertically fractured teeth

Vertical fractures occasionally occur in vital teeth, both intact and those with large restorations, because of excessive occlusal forces or traumatic injuries. In endodontically treated teeth, vertical fractures are more frequent (Bender & Freedland 1983, Sorensen & Martinoff 1984, Hansen *et al.* 1990). In a vertically fractured tooth, the fracture line becomes infected resulting in bone loss along the fracture line (Walton *et al.* 1984). Consequently, to successfully treat a fractured tooth and to eliminate the infection, the fracture line needs to be eliminated or, when a complete fracture is present, the tooth segments must be bonded together. A biocompatible environment should be maintained to obtain reattachment of periradicular tissues (Trope & Rosenberg 1992).

In vitro evaluation

As a result of their adhesive properties, GICs have been proposed for bonding root segments. Friedman *et al.* (1993b) described the ability of Ionos glass ionomer bone cement (Ionos, Seefeld/Oberbay, Germany), to bond two segments together, to be less than that of bonding agents and cyano-acrylate cement. Their findings were based on the *in vitro* resistance to the repeated fracturing of roots, which were previously fractured and bonded. Also the use of Ketac-Endo, instead of AH 26, as a sealer did not increase the resistance to root fracture *in vitro* in human maxillary canine teeth, although both were

significantly stronger than roots whose canals were instrumented but not obturated (Cobankara *et al.* 2002). On the other hand, immature roots could be reinforced *in vitro* by placing a RMGIC in the canal after the apical 2 mm of the canal had been filled with gutta percha and AH 26 (Goldberg *et al.* 2002).

Moreover, an advantage of GICs is that they can be used without etching, the latter being detrimental to the cementum and periodontal ligament (Hammarstrom *et al.* 1986). In this respect, it was seen that GICs can maintain a bond in a wet environment and withstand thermocycling better than Gluma (Bayer Dental, Leverkusen, Germany; Sorensen 1991). The biocompatibility of GIC may also offer opportunities for periodontal reattachment (Dragoo 1997). Treatment success depends on this reattachment and on prevention of periodontal tissue breakdown (Trope & Rosenberg 1992).

Clinical evaluation

Stewart (1990) strengthened incompletely fractured teeth by filling the canals with a modified GIC assumed to flow into the fracture line. One-year follow-up showed that the teeth were still comfortable.

Barkhordar (1991) described a case of a mesiodistal fracture in a maxillary first premolar. The fracture was initially treated with calcium hydroxide for 6 months in order to encourage the natural healing of the periradicular area and consequent resolution of the pockets. Silver-reinforced GIC was then used as a root canal sealer and condensed in the root canal. At the 2-year recall, satisfactory healing was present.

Trope & Rosenberg (1992) described a vertical fracture in a maxillary left second molar, which, 1 year after bonding the extracted segments together with a glass ionomer bone cement (Espe, Seefeld, Germany) and replantation, was still functioning normally.

Selden (1996) reported on the repair of incomplete vertical fractures in six teeth. After 1 year, all had failed, whether or not GIC had been used apart from 4-META, and despite elimination of all lateral occlusal contacts.

Coronal seal

The prevention of coronal leakage is an important factor for success and failure of endodontic therapy (Saunders & Saunders 1994b, Ray & Trope 1995, De Moor & Hommez 2000, De Moor *et al.* 2000, Tronstad *et al.* 2000, Hommez *et al.* 2002). Coronal microbial invasion after a successful endodontic treatment can be the reason why endodontic treatment fails on the long term and apical periodontitis develops in spite of an adequate root filling on radiograph (Saunders & Saunders 1994b, Friedman 1998).

In vitro evaluation

Although there is no clinical evidence, GICs perform well as a coronal filling material *in vitro* compared to other materials. Placement of GIC in the canal orifices and on the floor of the pulp chamber in multirooted teeth clearly diminished the coronal ingress of microorganisms from the access cavity of the filled root canals (Carman & Wallace 1994, Chailertvanitkul *et al.* 1997, Barthel *et al.* 1999, Barthel *et al.* 2001). In one study, using the fluid filtration method, GIC microleakage values did not differ significantly from the intact crown values after 8 weeks (Bobotis *et al.* 1989). In another *in vitro* study using an electrochemical technique, Ketac-Fil GIC, placed in conditioned cavities, leaked less than Kalzinol (DeTrey, Zürich, Switzerland) and Cavit-W (Espe, Seefeld, Germany); while placed in unconditioned cavities, Ketac-Fil was almost equally effective as Kalzinol and more effective than Cavit-W after a 1-month experimental period (Lim 1990). Only one study showed a contrary result (Beckham *et al.* 1993).

Conclusion

Glass ionomer cements are bioactive and adhesive materials with a therapeutic action; they act as antimicrobial materials with a high degree of biocompatibility. In spite of their critical handling characteristics, there is substantial evidence for their use as a root-end filling material. Both soft tissue and bone compatibility make GICs suitable as root filling material during endodontic surgery. GICs used as a root canal sealer, however, have mostly been investigated *in vitro* and their use remains a matter of debate as a result of the inconclusive findings on their sealing ability and antimicrobial activity. The use of GICs in the repair of perforations or root resorption cavities and as temporary restoration during endodontic therapy, despite having been extensively investigated with success *in vitro*, requires further *in vivo* and clinical investigation. The repair of vertically fractured teeth with GICs has been described in a limited number of cases. The results remain contradictory and require further substantiation.

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