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Root perforation repair concepts and materials: A review

Key words  Bioceramics, matrix techniques, MTA, repair materials, perforation repair

Perforation of the root canal is a serious complication of root canal treatment that may even result in tooth loss. Many different concepts and materials for perforation repair have been described and investigated over the decades. This article reviews the literature and summarises the relevant research findings on this subject.

Introduction

Root perforation, once regarded as one of the most unpleasant complications of root canal treatment\textsuperscript{1,2}, is one of the most common causes of endodontic failure\textsuperscript{3}. Root perforation is an artificial communication between the root canal system and the supporting tissues of the teeth and/or oral cavity in the affected parts of the periodontium\textsuperscript{4}. Its causes may be iatrogenic (e.g. root canal preparation, post space preparation) or pathologic (e.g. resorption)\textsuperscript{5}.

According to reports in the literature, the incidence of root perforation during root canal treatment ranges from 2\% to 12\%.\textsuperscript{1,2,6,7,8} In 1961, Ingle\textsuperscript{9} estimated that approximately 10\% of all endodontic failures can be attributed to root perforation. In a study by Kvinnsland et al.\textsuperscript{10}, 53\% of all iatrogenic root perforations occurred during post insertion, and the remaining 47\% during routine root canal treatments. These complications occurred in the maxilla in more than 74.5\% of cases investigated in their study, and the buccal and mesial root surfaces and middle root segments were the most commonly observed sites of occurrence of perforation. Tsesis et al.\textsuperscript{7}, on the other hand, detected a significantly higher incidence of root perforation in the lower molars (54.3\%).

Root perforations in the “critical zone” at the level of the alveolar crest and epithelial attachment have the worst prognosis due to their potential for microbial contamination and consequent periodontal destruction\textsuperscript{11}. Crestal root perforations often lead to epithelial migration, which significantly reduces the chances of regeneration\textsuperscript{11}.

More coronal root perforations can be safely repaired by using adhesive materials or by definitive replacement of teeth without periodontal involvement. The prognosis of perforations apical to the critical zone may also be good if adequate endodontic treatment can be performed with sufficiently bacteria-tight perforation repair\textsuperscript{11}.

Perforation repair materials

In the past, the prognosis for root perforation repair based on orthograde coverage used to be unpredictable\textsuperscript{10} because the available repair materials frequently led to the development of periodontal defects\textsuperscript{12}, i.e. to the formation of a fibrous connective tissue capsule bordering on directly adjacent bone. Amalgam, Cavit, zinc oxide eugenol (ZOE) and gutta-percha were commonly used perforation repair materials in those times\textsuperscript{13}.

Benenati et al.\textsuperscript{14} reported that amalgam achieves better results than the warmer, vertically condensed gutta-percha, whereas Lantz and Persson\textsuperscript{15} claimed...
the reverse. Harris\textsuperscript{16} recommended Cavit, but his claim that it achieves an 89.3\% success rate could not be confirmed by Jew et al.\textsuperscript{5}. Weine\textsuperscript{17} favoured the use of zinc oxide eugenol cement, whereas Martin et al.\textsuperscript{18} recommended the use of calcium hydroxide, Ca(OH)$_2$, for hard tissue regeneration.

Technological advancements such as the operating microscope (OPMI) have reduced the need for surgical perforation repair interventions, and new materials such as mineral trioxide aggregate (MTA) are continuously increasing the long-term predictability of perforation repair procedures. MTA remained the repair material of choice for most indications until the introduction of bioceramics\textsuperscript{11}.

The choice of repair material is determined by the technical accessibility of the perforation site, the ability to control the leakage of fluids, and aesthetic factors\textsuperscript{19}.

The following perforation repair materials are described in the literature:

- Amalgam\textsuperscript{20};
- Cavit\textsuperscript{21};
- Composite;
- Dentine chips;
- Foils (Teflon and indium foil, etc.);
- Geristore: a resin-modified glass-ionomer-cement (compomer) especially developed for the repair of severe cervical defects based on its good adhesion to dentine;
- Glass ionomer cement (GIC)\textsuperscript{3};
- Gutta-percha: A study of the effects of a mixture of resin, gutta-percha and chloroform on 24 perforation repairs on human teeth by Strömberg et al.\textsuperscript{22} in the 1970s showed that it achieved good results in all cases except furcation perforation repair, which may be impaired by epithelial ingrowth;
- Hydroxyapatite (HA);
- Zinc oxide-eugenol (ZOE) cement reinforced with plastic additives such as polymethyl methacrylate polymers, polystyrene, and polycarbonate; product example: IRM
- Calcium hydroxide\textsuperscript{23};
- Freeze-dried bone;
- Mineral trioxide aggregate (MTA) with collagen\textsuperscript{24,25};
- Plaster of Paris (calcium sulfate/burnt gypsum);
- Tricalcium phosphate;
- Zinc oxide eugenol cement (ZOE);
- Zinc oxide eugenol cement reinforced by replacing a portion of the eugenol with 2-ethoxybenzoic acid (EBA) and a portion of the zinc oxide with inorganic fillers, especially alumina (Al$_2$O$_3$); product example: Super-EBA.

### Material requirements of repair materials

The material requirements of perforation repair materials vary depending on whether the perforation is located inside (intraradicular) or outside the root canal (extraradicular).

Requirements of root perforation repair materials used in the canal:

- Ability to induce bone and cementum formation; Biocompatible;
- Ability to provide a fluid-tight seal;
- Bacteriostatic;
- Radiopaque;
- Non-resorbable;
- Non-carcinogenic;
- Readily available;
- Easy-to-use and relatively inexpensive\textsuperscript{23,25,27,28}.

Additional requirements:

- Ability to provide a bacteria-tight seal;
- Unaffected by blood;
- It should be possible to prevent extrusion of the material into the surrounding tissues\textsuperscript{11,13}.

Before the introduction of MTA, the flow properties of perforation repair materials also used to be an important factor. The more flowable a repair material, the better it adheres to the perforation walls\textsuperscript{29}.

Amalgam, Cavit, glass ionomer cement, gutta-percha and sealers as well as zinc oxide cements meeting the biocompatibility and insolubility requirements have been available since 1992. The materials available at that time did not meet the other requirements, however\textsuperscript{11,13}. The matrix material must be:

- Biocompatible;
- Sterile or sterilisable;
- Resorbable;
- Must not induce inflammatory reactions.
Products meeting the above material requirements have been available since the early 1990s; these include freeze-dried bone, demineralised bone, calcium phosphate materials, and hydroxyapatite (HA)\textsuperscript{13}.

Resorbable membranes were first used in periodontology. Salman et al.\textsuperscript{30} investigated their utility as matrix material for root perforation repair in an animal model and found that the placement of a resorbable barrier at the pulp chamber aspect of a furcal perforation did not result in healing superior to that achieved through the use of resin-modified glass ionomer cement (RMGIC) alone.

\section*{Amalgam}

Amalgam used to be the most commonly used perforation repair material\textsuperscript{12}. Grossman recommended the use of this alloy as a repair material back in 1957\textsuperscript{31}. A major advantage of amalgam is its fast curing time of only 4 min\textsuperscript{32}. However, amalgam has poor sealing properties which lead to the development of inflammatory processes and insufficient periodontal tissue regeneration, as Balla et al.\textsuperscript{23} pointed out in 1991. In 1992, Lemon introduced the “internal matrix concept of perforation repair”, in which he recommended to condense amalgam against an extraradicular hydroxyapatite barrier with light pressure\textsuperscript{13}.

In agreement with many other authors, Mehrvarzfar et al.\textsuperscript{33} found that amalgam is associated with microleakage and thus no longer meets modern standards for perforation repair materials. Souza et al.\textsuperscript{34} concluded that although amalgam is known to release toxic elements, its cytotoxicity is lower than that of glass ionomer cement. Copper and zinc are the main contributors to the cytotoxicity of amalgam, whereas pure silver and mercury play a significantly less important role\textsuperscript{35}.

\section*{Geristore}

Geristore (DenMat, Santa Maria, CA, USA) is a resin-modified glass-ionomer-cement (compomer) specifically developed for the repair of severe cervical defects due to its good adhesion to dentine. Before a subgingival defect can be repaired with Geristore, dentine surfaces must be pretreated with phosphoric acid conditioner. Furthermore, the use of an adhesive technology followed by light curing of the material is required.

\section*{Glass ionomer cement (GIC)}

An \textit{in vitro} study of the sealing quality of MTA vs modified resin-glass ionomer cement (RMGIC) by Daoudi und Saunders\textsuperscript{36} showed that significantly less leakage occurred in furcal perforations repaired with mineral trioxide aggregate. Moreover, the use of an operating microscope had no significantly positive effect on the quality of the perforation repair with GIC or MTA.

Alhadainy and Hime\textsuperscript{37} reported that the sealing ability of light-cured glass ionomer cement was superior to that of Cavit and amalgam, and that amalgam produced the worst results. It was also found that the sealing ability of light-cured RMGIC (Vitrebond) and Ca(OH)\textsubscript{2} was better than that of conventional chemically cured glass ionomer cement (Ketac Fil) and Ca(OH)\textsubscript{2}\textsuperscript{37, 38}.

Himel and Alhadainy\textsuperscript{39} confirmed that light-cured RMGIC resisted methylene blue dye penetration significantly better than light-cured composite resin, regardless of whether dentine preparation and acid etching was performed. However, the RMGIC-treated surfaces with dentine preparation and acid etching showed significantly less dye penetration than those without dentine preparation and acid etching.

Fuss et al.\textsuperscript{40} demonstrated that the sealing ability of silver glass ionomer cement (Chelon Silver, ESPE, Seefeld, Germany) is significantly better than that of amalgam. After studying bacterial contamination of the pulp chamber of extracted teeth by \textit{Streptococcus sobrinus}, Jantarat et al.\textsuperscript{41} concluded that the sealing ability of Ketac Silver was significantly better than that of amalgam; however, all of the materials studied showed complete leakage of bacteria within 22 days. Mittal et al.\textsuperscript{42} compared the sealing ability of amalgam, glass ionomer cement, composite, IRM and AH\textsubscript{26} in 90 extracted teeth. The sequence in which the materials are listed reflects the order of their sealing ability, from worst to best. In other words, amalgam proved to be the least suitable material for perforation repair. Chau et al.\textsuperscript{43} compared the sealing ability of light-cured glass ionomer
cement and calcium phosphate cement (CPC) alone and in combination, and found no significant difference in the mean extent of dye leakage between the three groups. Souza et al., who tested the cytotoxicity of several different perforation repair materials, found that GIC clearly had the highest cytotoxicity because of its dose-dependent inhibition of cell development. Geurtsen found that numerous unbound resin components may leach from GIC after polymerization in an aqueous environment.

**Hydroxyapatite (HA)**

In 1994, Balla et al. reported a histological study of furcal perforations repaired with hydroxyapatite (HA), amalgam and tricalcium phosphate, which showed no signs of tissue regeneration but rather, of variably severe inflammations in all specimens. Specimens dressed with hydroxyapatite generally exhibited better tissue responses, but severe necrosis was observed in one sample. New bone formation was not observed in any of the specimens.

**Calcium hydroxide**

Before the introduction of MTA, calcium hydroxide, \( \text{Ca(OH)}_2 \), was used to induce the re-calcification of extraradicular tissue, for example, in indirect or direct pulp capping or apexification. After extensive shaping and cleaning, \( \text{Ca(OH)}_2 \) paste was applied to fill the root canal until the desired degree of calcification was achieved (this step was repeated as needed). Light-cured calcium hydroxide produced far better results in lateral root perforation repair than chemically cured class ionomer cement or amalgam. However, calcium hydroxide caused moderate to severe inflammation of the furcal bone.

**Plaster of Paris (calcium sulfate, burnt gypsum)**

Historically, plaster of Paris (PoP) originates from a large gypsum quarry in the Montmartre district of Paris. It consists of calcium sulfate, or burnt gypsum. Plaster of Paris is a biocompatible material with hemostatic properties. It is resorbed within approximately 4 weeks after placement and is thus a suitable matrix material.

**Zinc oxide eugenol (Super-EBA)**

Before MTA became available, Super-EBA (Keystone Industries, Gibbstown, NJ, USA) was considered a good alternative to silver amalgam for perforation repair. Weldon et al. confirmed that when used as a furcation repair material, Super-EBA has good sealing ability comparable to that of MTA. Compared with MTA, Super-EBA showed a significantly better sealing ability, but only up until the 24-h follow-up. The combination of MTA below with Super-EBA on top resulted in significantly more leakage than MTA or Super-EBA alone. Compared with glass ionomer cement, the cytotoxicity of Super-EBA can be classified as moderate. Previous studies indicate that the cytotoxicity of Super-EBA can be attributed to the release of zinc ions into aqueous solutions.

**Mineral trioxide aggregate (MTA)**

Mineral trioxide aggregate is still a widely accepted and commonly used repair material for perforations at bone level. MTA improves the prognosis of
perforated teeth that would otherwise be classified as compromised\textsuperscript{12,25}.

**Physical and chemical properties of MTA**

MTA consists of two components: hydrophilic powder and sterile water. The powder is composed of tricalcium silicates, tricalcium aluminates and tricalcium oxides as well as silicate, mineral and bismuth oxides. The original MTA formulation was grey in colour, which occasionally resulted in tooth discoloration. White MTA was developed later. It differs from grey MTA in that it contains no iron and has a lower bismuth oxide content. When hydrated, the powder turns into a gel that hardens within about 4 h. MTA has a compressive strength of up to 67 MPa\textsuperscript{32}.

MTA has antibacterial and antifungal properties. It is a bioactive material that regulates cytokine production. Moreover, MTA triggers cell differentiation and the immigration of hard tissue-producing cells. The calcium ions released from MTA promote cell attachment and proliferation, and its basic pH of about 12.5 creates an antibacterial environment\textsuperscript{32}. Ca(OH)$_2$ forms at the surface of MTA, and root cementum grows over MTA under ideal conditions\textsuperscript{56}.

**New tissue formation with MTA**

Regarding the response of the periodontal ligament to different repair materials (amalgam, Super-EBA and MTA), Sarkar et al.\textsuperscript{57} found that MTA induces the best tissue response in terms of new cementum formation. Conversely, the results of Moretton et al.\textsuperscript{58} not only suggest that MTA is not osteoinductive, but also indicate that it is osteoconductive. On contact with pulp or periradicular tissue, MTA stimulates hard tissue formation\textsuperscript{25,59}. In turn, the regeneration of cementum facilitates the regeneration and re-attachment of periodontal tissues\textsuperscript{25,32}. Additionally, MTA induces the proliferation of undifferentiated pulp cells as well as of osteoblast-like cells and fibroblasts of the periodontal ligament. This proliferation is the prerequisite for wound healing in the bone, dentine and cementum.

Tziafas et al.\textsuperscript{60} conducted an animal study which demonstrated that MTA causes functional and cytological changes in pulp cells. A uniform layer of crystalline structures formed along the pulp-MTA contact interface. Bone-like hard tissue deposits accumulated in this layer in all teeth studied. This study demonstrated the ability of MTA to induce the formation of repair dentine. Torabinejad et al.\textsuperscript{32,61} found that MTA promotes the regeneration of cementum, resulting in more effective perforation closure than the other repair materials studied.

**Biocompatibility of MTA**

The absence of pathological effects following the extrusion of MTA into the surrounding tissues can be considered as proof of the biocompatibility this material. Another advantage of MTA is its lack of mutagenicity. It is non-neurotoxic and is one of the least cytotoxic dental materials\textsuperscript{62}. After comparing the biocompatibility and cytotoxicity of amalgam, glass ionomer cement, Super-EBA, N-Rickert, MTA, and gutta-percha, Souza et al.\textsuperscript{44} confirmed that MTA was the least cytotoxic of the perforation repair materials studied. Glass ionomer cement, N-Rickert and amalgam caused significant changes in the number and development capacity of the tested cells and were rated as the most cytotoxic, Gutta-percha, Super-EBA and MTA, on the other hand, proved to be less cytotoxic.

Pitt Ford et al.\textsuperscript{25} compared the responses of perforations in dog teeth repaired with mineral trioxide aggregate vs amalgam and found histological signs of inflammation in all specimens repaired with amalgam, but in only one of six canine teeth repaired with MTA. An animal study in which MTA was implanted in the mandibular and tibial bone of guinea pigs also verified the biocompatibility of MTA\textsuperscript{63}. Another study established that MTA has no significant effect on the bacterial growth of facultative or anaerobic bacteria\textsuperscript{64}. No difference in biocompatibility between white MTA and grey MTA has been detected in any study to date\textsuperscript{65,66}.

Figures 1 to 5 demonstrate the use of MTA for perforation repair in the coronal third of a root.

**Disadvantages of MTA**

The main disadvantages of MTA are its potential for tooth discoloration (greying), long setting time, and high cost, difficult handling, and difficulty of removal.
The mode of action of MTA is based on the following mechanisms:

- Formation of Ca(OH)$_2$ and its release of calcium ions;
- Alkaline pH of about 12.5;2
- Effects on cytokine production;
- Promotes the differentiation and migration of cells involved in hard tissue formation;
- Formation of hydroxyapatite on the surface of MTA.

Pitt Ford et al. demonstrated that the results described above can only be achieved if the perforation is repaired quickly. Late repair with MTA was associated with inflammation despite the good properties of the material. De-Deus et al. compared the sealing ability of MTA with that of Portland cement and found no significant difference between the two materials. Al-Hezaimi et al. evaluated the antibacterial effects of grey vs white MTA on Enterococcus faecalis and Streptococcus sanguis and found that grey MTA completely prevented bacterial growth, whereas white MTA had a lower antibacterial effect on E. faecalis.

Soluti et al. compared the sealing ability of mineral trioxide aggregate, IRM and amalgam in vitro. In comparison with the other materials, MTA led
to significantly better sealing results and exhibited the lowest overfilling tendency, while IRM showed the least underfilling tendency. Two studies of the sealing ability of various perforation repair materials demonstrated that blood contamination has no negative effect on the sealing ability of MTA, but does impair that of amalgam, Super-EBA and IRM. Mente et al. conducted a long-term study of the treatment outcome of orthograde perforation repair of 64 teeth and found that repair with MTA yielded a success rate of 86% over a mean 4 to 9 years of follow-up. Most failures occurred within the first 4 years after MTA repair.

Further results of studies on perforation repair with MTA are shown in Table 1.

### Bioceramics

Bioceramics are non-metallic inorganic materials that were already well-known for their applications in the medical field (e.g. for joint replacement) before they were introduced in endodontics around 2008. They can be used as sealers as well as for orthograde and retrograde root canal filling, root perforation repair, pulp capping and apexification. Their enhanced biocompatibility gives new bioceramic materials an edge over conventional sealing materials. One in vitro study demonstrated the adhesion, proliferation and survival of human bone marrow mesenchymal stem cells, periodontal ligament cells, and dental pulp stem cells on the surface of a newly developed bioceramic material. Another advantage is that, in contrast to MTA, bioceramics do not lead to coronal tooth discoloration.

TotalFill BC RRM is bioceramic root repair material (RRM) which, according to the manufacturer (FKG Dentaire, La Chaux-de-Fonds, Switzerland), is composed of calcium silicate, zirconium oxide, tantalum oxide and calcium phosphate. Bioceramics require the presence of fluid for setting and thus are very hydrophilic. The setting time for TotalFill BC RRM Putty is approximately 2 h according to data provided by the manufacturer. FKG Dentaire’s Fast-Set Putty has a shorter setting time (20 min), which gives it an additional advantage over MTA because this enables the dental practitioner to repair a root perforation while filling other parts of the root canal with two materials (gutta-percha and bioceramic sealer). The extreme hardness of bioceramics can be a disadvantage as this makes them extremely difficult to remove after hardening.

### Matrix techniques

The greatest challenge to root perforation repair is to achieve hemostasis on the one hand and controlled placement of the repair material on the other. Retentive preparation of the external perforation wall was the method used to prevent overfilling in the 1960s and 1970s. In later years, matrix techniques were developed to prevent the extrusion of repair materials. In 1969, Auslander and Weinberg proposed the use of indium foil as a matrix to be applied prior to the orthograde filling of furcation perforations with amalgam. However, radiological and histological findings presented by Aguirre et al. in 1986 indicated that furcation perforation repair with amalgam and gutta-percha led to significantly better treatment outcomes than indium foil. A variety of different resorbable materials (e.g. collagen, freeze-dried demineralised allogeneic bone, hydroxyapatite, gel foam and calcium sulfate) are available for matrix concepts of root perforation repair, but collagen and calcium sulfate are most commonly used because of their ease of handling. Collagen is cut into tiny pieces and inserted with a hand plugger or an MTA gun system one piece at a time up to the periodontal ligament, where it is resorbed within 4 to 6 weeks.

### Discussion

The prognosis for teeth with root perforation depends on the time between perforation occurrence and repair, the severity of initial damage to
the periodontal ligament, the location of the perforation relative to the gingival sulcus, the size of the lesion, the sealing ability of the repair material, the quality of repair, and the severity of infection of the perforation\textsuperscript{3,11,84}. Studies comparing the treatment outcome of perforations repaired with MTA vs previously used repair materials are summarised in Table 1. Clinical cases are presented in Figures 6 to 11.

The inadequacy of older repair materials is reflected by their inability to adequately seal endodontic perforation defects so as to prevent communication between the oral cavity and the inside of the affected tooth as well as by their lack of sufficient biocompatibility. No repair material used before the introduction of MTA was able to stop inflammatory processes resulting in attachment loss or to maintain tissue health at the perforation site. Mineral trioxide aggregate, on the other hand, is able to stimulate regenerative processes resulting in tissue attachment and cement formation\textsuperscript{12,25,90}.

Pontius et al.\textsuperscript{74} achieved a success rate of 90\% over a mean recall time of 37 months. Moreover, they observed no significant difference in treatment success for 50 perforations induced by initial root canal treatment vs retreatment in terms of the presence or absence of preoperative apical periodontitis or with regard to the periodontal status at the perforation site. Prognostic factors like the size or location of the perforation, the time until repair, or the type of tooth affected have become less important. In one long-term study with a 1- to 8-year follow-up, only those perforations with a diameter of more than 3 mm had a lower success rate of repair\textsuperscript{72}. However, two other factors that influenced the treatment outcomes were the experience of the dental practitioner and the placement of a post after treatment.
Even with all the advantages described above, it is important to remember that MTA also has disadvantages that must be taken into account. The main disadvantages of MTA are:

- Long curing time (2 h 45 min ± 5 min)\(^3\)^\(^2\);
- Relatively high price and technique-sensitive handling;
- Heavy metal content\(^7\)^\(^6\);
- When used for supracrestal or transgingival perforation repair, there is a risk that MTA might be washed out of the oral cavity by fluids before it has completely set\(^4\)^\(^9\). This can be avoided by using adhesive materials to restore subgingival defects\(^3\)^\(^,\)^\(^1\)^\(^\)\(^1\); and
- Risk of tooth discoloration\(^9\)^\(^1\).

In a biomimetic approach to perforation repair, Alsanea et al.\(^9\)^\(^2\) succeeded in stimulating DPSCs to differentiate into odontoblast-like cells that secreted a matrix for reparative dentine bridging in an animal model through the subcutaneous implantation of dentine wafers containing human dental pulp stem cells (DPSCs) and dentine matrix proteins in mice. This approach appears to hold promise as a future strategy for perforation repair through endogenous tissue regeneration.

**Conclusion**

Modern repair materials have significantly improved the management of root perforations, which Seltzer et al.\(^1\)^\(^,\)^\(^2\) described as one of the most grievous endodontic failures back in 1967. Long-term studies have shown that they yield extremely positive results in terms of tooth preservation.
Table 2  Results of studies comparing MTA with older perforation repair materials (as reported by the authors).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>In vivo</th>
<th>In vitro</th>
<th>Number / Location / Species</th>
<th>Parameters studied</th>
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<tr>
<td>Aguirre et al.83</td>
<td>1986</td>
<td>X</td>
<td></td>
<td>48 maxillary molars</td>
<td>Histological, radiographic &amp; clinical findings; Severity of inflammation, bone, dentine, cement resorption, type of healing, epithelial proliferation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Furcation Dogs</td>
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<tr>
<td>Alhadainy &amp; Himel85</td>
<td>1994</td>
<td>X</td>
<td></td>
<td>60 teeth</td>
<td>Dye penetration as measured by stereomicroscopy</td>
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<td></td>
<td></td>
<td>Furcation Humans</td>
<td></td>
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<tr>
<td>Suyk et al.86</td>
<td>1998</td>
<td>X</td>
<td></td>
<td>32 maxillary and mandibular molars</td>
<td>Amount of force required to remove MTA from the hard tooth structure</td>
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<td>Furcation Humans</td>
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<td>Salman et al.30</td>
<td>1999</td>
<td>X</td>
<td></td>
<td>30 mandibular premolars</td>
<td>Histological response to a matrix</td>
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<td>Furcation Dogs</td>
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<tr>
<td>Daoudi &amp; Saunders36</td>
<td>2002</td>
<td>X</td>
<td></td>
<td>46 molars</td>
<td>Dye penetration</td>
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<td>Weldon et al.54</td>
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<td>X</td>
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<td>Main et al.12</td>
<td>2004</td>
<td>X</td>
<td></td>
<td>16 Humans</td>
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<td>Yildirim et al.28</td>
<td>2005</td>
<td>X</td>
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<td>90 mandibular premolars and molars</td>
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<td>Al Hezaimi et al.68</td>
<td>2006</td>
<td>X</td>
<td></td>
<td></td>
<td>Antibacterial effect against <em>E. faecalis</em> and <em>S. sanguis</em></td>
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<tr>
<td>Al-Daafas und Al-Nazhan87</td>
<td>2007</td>
<td>X</td>
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<td>72 posterior teeth</td>
<td>Histologic healing response; Severity of inflammation, type of healing, epithelial proliferation, resorption of bone, dentine, cement</td>
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<td>Dogs</td>
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<td>2008</td>
<td>X</td>
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<td>10</td>
<td>Success rate, clinical and radiographic</td>
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<td></td>
<td>Human</td>
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</tr>
<tr>
<td>Samiee et al.89</td>
<td>2009</td>
<td>X</td>
<td></td>
<td>34 premolars</td>
<td>Histologic response; Severity of inflammation, Epithelial proliferation</td>
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<td>Furcation</td>
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<td></td>
<td>Dogs</td>
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<tr>
<td>Krupp et al.75</td>
<td>2013</td>
<td>X</td>
<td></td>
<td>90 teeth</td>
<td>Success rate, radiographic</td>
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<td></td>
<td></td>
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<td>Human</td>
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<tr>
<td>Pontius et al.74</td>
<td>2013</td>
<td>X</td>
<td></td>
<td>50: all tooth types</td>
<td>Success rate, clinical and radiographic</td>
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<td>Furcation and lateral</td>
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<td>Humans</td>
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<td>Long-term study</td>
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<tr>
<td>Mente et al.72</td>
<td>2014</td>
<td>X</td>
<td></td>
<td>64 teeth</td>
<td>Long-term study; Sealing quality</td>
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<td>Humans</td>
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<tr>
<td>Recall time</td>
<td>Materials used</td>
<td>Results by material</td>
<td>Comments</td>
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<tr>
<td>2 and 6 months</td>
<td>1. Amalgam 2. Gutta-percha 3. Indium foil + amalgam</td>
<td>No significant difference between amalgam and gutta-percha</td>
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<tr>
<td>24 h 72 h</td>
<td>MTA covered with a wet or dry cotton pellet</td>
<td>MTA</td>
<td>No difference between MTA retention with a wet or dry cotton pellet, but moisture in the perforation during placement led to significant better results MTA resisted displacement at 72 h significantly more than at 24 h</td>
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<tr>
<td>3 months</td>
<td>1. RMGIC alone 2. Atrisorb + RMGIC</td>
<td>No difference</td>
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<tr>
<td>72 h</td>
<td>1. MTA 2. RMGI (Vitrebond) with or without an operating microscope (OMPI; 26x magnification)</td>
<td>MTA</td>
<td>Significantly better, but no difference in acceptability of repair with either material with or without an OPMI</td>
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<tr>
<td>30 min 4 h 24 h 1 week 1 month</td>
<td>1 MTA 2. Super-EBA 3. MTA +Super-EBA</td>
<td>No significant difference</td>
<td>MTA: satisfactory sealing only after 4 h or more, Super-EBA: only superior after 24 h</td>
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<tr>
<td>≥ 1 year</td>
<td>MTA</td>
<td>MTA</td>
<td>100% success rate</td>
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<tr>
<td>1 month 3 months 6 months</td>
<td>1. MTA 2. Super-EBA</td>
<td>MTA</td>
<td>MTA: All specimens showed cementum formation at 6 months Super-EBA: Connective tissue formation</td>
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<tr>
<td>1 h 24 h 72 h</td>
<td>1. White MTA 2. Grey MTA</td>
<td>Grey MTA</td>
<td>Antibacterial effect is dependent on the concentration of MTA</td>
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<td>4 months</td>
<td>1. Grey MTA 2. Grey MTA + calcium sulfate 3. Amalgam 4. Amalgam + calcium sulfate</td>
<td>Grey MTA alone</td>
<td>Use of CaSO₄ as matrix causes inflammatory reaction; Immediate repair is also necessary with MTA</td>
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<td>90 days</td>
<td>Contaminated perforations with MTA (with and without calcium hydroxide-based paste); Non-contaminated perforations with MTA</td>
<td>MTA in non-contaminated perforations MTA is significantly better in non-contaminated perforations/ temporary filling with Ca(OH)₂-based paste did not result in any significant difference</td>
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<tr>
<td>6 months to 5 years</td>
<td>MTA</td>
<td>MTA</td>
<td>100% success rate</td>
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<tr>
<td>3 months</td>
<td>1 MTA 2. Calcium enriched mixture (CEM) cement</td>
<td>No statistically significant differences in outcomes between the two materials</td>
<td>90% success rate</td>
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<td>1 to 10 years</td>
<td>MTA</td>
<td>MTA</td>
<td>73.3% success rate Preoperative lesion at the perforation site and direct contact between the perforation and the oral cavity were identified as prognostic factors for healing</td>
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<td>1 to 8 years</td>
<td>MTA</td>
<td>MTA</td>
<td>Good sealing quality independent of perforation location / 86% healing rate</td>
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References


