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Mineral trioxide aggregate in paediatric dentistry

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Objective. The aim of this study was to present a review of the reported literature on: (i) the physical and chemical properties; and (ii) clinical applications of mineral trioxide aggregate (MTA) in the practice of paediatric dentistry.

Method. Electronic literature search of scientific papers from January 1993 to June 2008 was carried out on the MEDLINE, Embase, Entrez Pubmed, and Scopus databases using specific key words. The search yielded 448 papers, out of which 100 were identified as conforming to the applied criteria. These papers formed the basis of the review and the clinical scenarios presented which demonstrate the application of MTA in the practice of paediatric dentistry.

Conclusion. Paediatric dentists have successfully employed MTA in a variety of endodontic/restorative applications since the late 1990s. Clinical impressions have generally been favourable and support the findings of laboratory and animal-based investigations. Very few clinical studies have been reported so far in humans, and although these have been positive, the body of research is currently insufficient to enable a meaningful systematic review and meta-analysis.

Introduction

Mineral trioxide aggregate (MTA) was developed at the Loma Linda University, California, USA, as a root-end filling material in surgical endodontic treatment[1]. Over the years, further research on the material has resulted in MTA being applied in various clinical situations in addition to its use as a suitable root-end filling material. The diverse application of MTA in the practice of paediatric dentistry is evident in its use as an apical barrier in immature non-vital teeth and in the coronal fragment of fractured roots, as a pulpotomy medicament in primary and permanent teeth, a pulp-capping agent in young permanent teeth, and as a repair material for perforation and resorptive defects.

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Method

An electronic literature search of scientific papers from January 1993 to June 2008 was carried out using the MEDLINE, Embase, Entrez Pubmed, and Scopus databases. These databases were used to search for the key words Mineral Trioxide Aggregate, MTA, Gray MTA, Grey MTA, White MTA, GMTA, WMTA, and mineral AND trioxide AND aggregate. All papers on MTA, which reported studies carried out *in vitro*, *in vivo*, and *ex vivo* on tissues, animals, and humans were included for reviewing. Papers not published in the English language and case reports were excluded. Use of the search keywords produced a total of 448 results. Manual checking of the reference list and application of the inclusion and exclusion criteria produced 100 citations used in this review.

Review of MTA

The review is presented in two main sections. The first section reviews the literature which has contributed to our understanding of the

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physical and chemical properties of MTA. The second section reviews the clinical studies which have been reported in the search period with case reports depicting the applications of MTA in paediatric dentistry.

The various commercially available products employed in the studies which are reviewed in the first section of this paper include: (i) ProRoot MTA (Dentsply Tulsa Dental, Tulsa, OK, USA); (ii) White ProRoot MTA (Dentsply Tulsa Dental); (iii) MTA-Angelus (Solucoes Odontologicas, Londrina, Brazil); (iv) MTA-Angelus Blanco (Solucoes Odontologicas); and (v) MTA Bio (Solucoes Odontologicas).

Chemical and physical properties of MTA

Chemical composition and structure. Studies analysing the constituents of both grey and white ProRoot MTA have conclusively shown that both materials are similar to Portland cement, but with bismuth oxide added, presumably to make the materials radiopaque for dental use[2–4]. Portland cement itself is a mixture of dicalcium silicate, tricalcium silicate, tricalcium aluminate, gypsum, and tetracalcium aluminoferrite[5,6].

It was reported that the amount of gypsum in ProRoot MTA is approximately half the amount found in Portland cements. Gypsum is an important determinant of setting time and is added by cement manufacturers to retard the setting time of the cement clinker in Portland cement. Modifying the gypsum content in the MTA mix can result in significant reduction of setting time, thereby reducing the number of treatment visits[7]. Dammaschke *et al.* described the marked differences between Portland cement and ProRoot MTA, by comparing the same chemical and physical surface, and bulk material characteristics[6]. They reported that ProRoot MTA contains lower levels of potentially toxic heavy metals (e.g. manganese and strontium), chromophores (iron oxide), aluminium, and potassium. In contrast to Portland cements, ProRoot MTA contains about 17–18wt% (= 2%) bismuth. Portland cements are composed of particles with a wide range of sizes, whereas ProRoot MTA showed smaller and more uniform particle size[6].

Studies have compared the constituents of grey and white ProRoot MTA materials. There are contradictory reports with respect to the iron and magnesium oxide phases in the grey and white forms. Asgary *et al.* reported that white MTA contained significantly less amounts of oxides of iron, aluminium, and magnesium than grey MTA[8]. There have been other studies, which have reported the complete absence of iron oxide in white MTA when compared to grey MTA[9,10]. When comparing the ProRoot MTA forms to MTA-Angelus, Song *et al.* also reported that MTA-Angelus had a lower content of bismuth oxide than the ProRoot MTAs[10]. There are no studies to date comparing the relative radiopacity of MTA-Angelus with the ProRoot MTAs.

Setting/Hardening time. There are few published reports of experimental data relating to the comparative setting times of the different forms of MTA. The setting time of grey ProRoot MTA was reported by Torabinejad *et al.* as 2 h and 45 min (± 5 min)[1]. Islam *et al.* reported final setting times of 140 min (2 h and 20 min) for white MTA, and 175 min (2 h and 55 min) for grey MTA[11]. Although the manufacturers of MTA-Angelus claim that this material has a setting time of 10 min, there appears to be no independent evidence to confirm this.

Several studies have compared various modified forms of Portland cement and ProRoot MTA in an effort to identify a material with all the advantages of MTA and without its extended setting time. The presence of gypsum is reported to be the reason for the extended setting time of MTA. Therefore, studies[7] have reported modified forms of Portland cement without the gypsum and with added plasticizers, which reportedly do not affect the biocompatibility of MTA. In order to reduce the setting time, the effect of accelerators such as sodium phosphate dibasic (Na_2HPO_4) and calcium chloride ($CaCl_2$) are being investigated currently[12–15]. MTA Bio is one commercially available product which incorporates an accelerator of this sort, and is promoted as a rapid-setting material.

Compressive strength. Compressive strength is the capacity of a material to withstand axially directed pressure generating compressive stress as a result of compression force. Torabinejad

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et al. reported comparable mean compressive strength after 21 days for ProRoot Grey MTA, IRM, and Super EBA[1]. The compressive strength of amalgam was higher than these materials after the same time period. Root-end fillings and apical barrier materials do not bear direct pressure during function, hence, their compressive strength is not thought as important as those materials used to repair or restore defects in load-bearing sites. The compressive strength of ProRoot grey MTA increased with time in the above study. The authors suggest that this increase over a period of time required the presence of moisture. Islam *et al.* reported greater compressive strength for the grey form of ProRoot MTA in comparison to the white form at 3 days and 28 days in a similar *in vitro* study[11]. Their study also showed that the compressive strength of the grey form of MTA was greater than that of Portland cement.

Radiopacity. An ideal restorative material should be more radiopaque than its surrounding structures when placed *in situ*, in order to allow the quality of the restoration or apical seal to be assessed. Several studies have confirmed that MTA is less radiopaque than Super EBA, IRM, amalgam, and conventional gutta-percha, but in the same range as zinc oxide–eugenol-based root canal sealers[1,16,17].

Setting conditions. Studies have reported that an initial period of exposure to moisture or humidity is required for the MTA to achieve optimum flexural strength[18,19]. These authors recommend the placement of a moistened cotton pellet in the root canal for a period of time before placement of the permanent coronal seal when placing an apical barrier in immature teeth. Currently, there is insufficient literature regarding the implications of the setting conditions on the use of MTA as a pulp capping and pulpotomy medication. The role of moisture drawn in from the pulp or peri-radicular tissues is also unclear.

Solubility. The manufacturer recommends the use of 0.33 g of water with 1 g of ProRoot MTA to achieve an optimum mix of the material. Earlier studies showed no signs of solubility of ProRoot MTA in water when tested under modified International Organization for Standardization (ISO) and American Dental Association specifications[1]. Fridland and Rosado demonstrated that both solubility and porosity of the material show a significantly increasing trend that follows the amount of water used when preparing the mix under ISO specifications[20,21]. The set or hardened/cured material, on exposure to water, was shown to release calcium as hydroxide, and the authors reported that their finding could explain the basis of the cementogenesis-inducing property of MTA. These studies also suggest that the water-to-powder ratio recommended by the manufacturer (0.33) would be the ideal proportion. Santos *et al.* reported that calcium and hydroxyl ions may be released from MTA Angelus during storage in moist conditions for periods up to 360 h[22].

Marginal adaptation and sealing ability. An effective root-end filling material should ideally provide a hermetic apical seal, preventing the movement of tissue fluids into the root canal system and the egress of micro-organisms and their by-products from the root canal system[23]. Investigations have been carried out on extracted human teeth which were prepared and restored with the root-end filling materials whose marginal adaptation and sealing ability were investigated by various methods. Historically, investigators have evaluated quality of the apical seal by the degree of dye, radioisotope, or bacterial penetration; electrochemical means; scanning electron microscopy (SEM); or fluid filtration. Each technique has significant limitations that can result in errors[24–27]. As a result, the validity of such data is questionable.

The results of some studies demonstrate correlation with respect to marginal adaptation with SEM and apical seal dye penetration for different root-end fillings[28,29]. These studies compared amalgam, Super EBA, IRM, and MTA, and were the earliest investigations comparing MTA to other traditional root-end filling materials. There are, however, conflicting results in the literature relating to the correlation between marginal adaptation and sealing ability of different root-end filling materials[30,31].

Several investigators report that the fluid filtration method has the advantage of

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measuring the cumulative leakage of the entire tooth restoration interface and is therefore quantitative[32–34]. Bates *et al.* reported that MTA was superior to amalgam and comparable with Super EBA in preventing microleakage when used as a root-end filling by the fluid filtration method on extracted human teeth[34].

Almost a decade later, Shipper *et al.* compared MTA with amalgam as a root-end filling material with a high and low vacuum SEM study on extracted human teeth[35]. Results showed that MTA demonstrated better marginal adaptation to the root end cavity wall than amalgam. This group of workers purport their findings to be linked to the inherent nature of MTA, and suggested that the expansion of the material during the hydration setting reaction contributed to the superior adaptation to dentine. The authors concluded that this expansion may play a role in the increased incidence of cracks at the interface compared to the amalgam specimens.

Investigators have also compared MTA with amalgam, Super EBA, and IRM with *in vitro* studies using specific bacterial leakage tests. The micro-organisms used in such tests have included *Staphylococcus epidermidis* and *Serratia marcescens*[36,37]. These studies have been consistent in reporting MTA as showing no or less leakage in comparison to the other three materials, respectively.

The peri-radicular environment may have varying pH from a neutral pH of 7.4 to an acidic pH as low as 5.0. An acidic pH has been shown to inhibit the setting reactions, affect adhesion, and increase solubility of materials placed to effect a root-end seal[38–41]. Roy *et al.* compared the sealing ability of materials tested by recording the linear dye leakage with Pelikan Ink under a surgical microscope, and reported that an acidic environment does not hinder the sealing ability of MTA, amalgam, Geristore, Super-EBA, CPS, and MTA with CPC matrix[42].

The protein leakage and assay test is claimed to provide the advantage of eliminating the problems involved with radio-isotopes, dye, and bacteria during leakage identification. Valois and Costa studied the influence of the thickness of MTA on the sealing ability of root-end fillings *in vitro* by using a protein–dye complex with Coomassie Blue G dye. It was shown that 4-mm-thick MTA was significantly more effective than others (1, 2, 3 mm) in preventing apical leakage[43].

Calcium hydroxide intra-canal medication has been shown to affect the sealing ability of MTA[44]. The *in vitro* sealing efficiency of white and grey ProRoot MTA as apical barriers was investigated in simulated divergent apices using a dye tracer (basic fuchsine). A comparable apical seal with both forms of ProRoot MTA was reported. It was also shown that residual calcium hydroxide intra-canal medication could interfere with the adaptation of MTA to the root canal walls by being a mechanical obstacle, and also by chemically reacting with MTA, thus influencing its surface characteristics.

The use of the internal matrix concept to limit the flow of the MTA material (in the root-end and perforation situations) and improve its sealing ability has been investigated. Zou *et al.* reported an *in vitro* study to evaluate internal matrices as barriers to prevent the over-extension of MTA. They reported that calcium sulphate provided a successful barrier against over-extension of MTA, but significantly decreased its sealing ability, and Collaplug (collagen plug) did not prevent over-extension or improve its sealing ability[45].

The validity of 'leakage studies' has recently been brought into sharp focus by a decision of the *Journal of Endodontics* to place a moratorium on the acceptance of such studies until more is known of their relevance[46].

Effect of compaction/condensation on MTA. Condensation pressure or compaction is an uncontrolled variable when MTA is placed as an apical barrier in an immature tooth, surgical or non-surgical perforation repair, a pulp-capping material, or as a retrograde filling material in a root-end cavity. It is likely that the condensation pressure during the placement of MTA as an apical barrier will be much reduced to prevent the material from being forced into the periodontal ligament or pulp tissue in some of these situations. Nekoofar *et al.* reported no statistically significant effect of condensation pressure on the compressive strength of white ProRoot MTA, but there was a significant reduction in surface hardness[47].

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This group of workers also concluded that greater condensation pressures could limit the space for the ingress of water required to hydrate the material in order to achieve an adequate surface hardness.

Effect of MTA on the strength and hardness of root dentine. Studies using sheep and bovine teeth (*in vitro* and *in vivo*) have shown that teeth with an MTA apical barrier and MTA root filling showed higher fracture resistance in comparison to teeth that had calcium hydroxide placed as an intra-canal medicament[48–51]. It has been previously suggested that the conventional apexification technique involving the placement of calcium hydroxide in the root canal for a prolonged period of time may be responsible for an increased susceptibility of immature incisors to root fracture[52]. In 2002, Andreasen *et al.* reported that long-term calcium hydroxide dressings weaken the root structure possibly by neutralizing, denaturing, or dissolving the acidic components of dentine[53]. Because these components act as 'bonding agents' between the collagen network and the hydroxyapatite crystals, their destruction may render the tooth more prone to fracture. In light of this evidence, the placement of MTA as a one-step apical barrier after appropriate debridement of the root canal, may be a suitable alternative to traditional apexification or the induced apical barrier technique. As with any other material, inadequate debridement and canal preparation could lead to persistent symptoms even after the apical seal has been placed with MTA. Once the MTA placed as an apical seal has hardened, it becomes extremely difficult to remove, and persistent symptoms can result in the need for surgery or even tooth extraction.

Antibacterial and antifungal activity. As micro-organisms are the main aetiological factors in pulpitis and periodontitis, their elimination during treatment is essential. It is likely that even after caries removal and root canal debridement, micro-organisms with the potential to promote disease may persist, or new organisms may enter by coronal leakage[54]. The healing of tissues damaged by pulp or peri-apical pathology depends on the absence of irritating agents originating from microbial metabolic products, or of chemical origin from the sealing materials. For such healing to occur, the materials placed in contact with healthy pulp (pulp capping, pulpotomy) and peri-apical tissues (apical barrier, root-end filling) should not damage the tissues and should ideally stimulate the deposition of hard tissue, therefore promoting biological sealing[55,56]. MTA materials fulfil this requirement adequately.

Several studies have been carried out to ascertain the antibacterial and antifungal properties of the MTA cements. Sipert *et al.* reported that MTA-Angelus did not inhibit the growth of *Escherichia coli* in an *in vitro* study[57]. In 2006, Al-Hazaimi *et al*. assessed the antibacterial effects of the grey and white MTA materials against *Enterococcus faecalis* and *Streptococcus sanguis in vitro*. They reported that lower concentrations of grey MTA were required than the white MTA to exert the same antibacterial effect against each of these micro-organisms[57]. Eldeniz *et al.* also obtained similar results[58]. *Enterococcus faecalis* is one of the organisms more likely to be found in cases of failed endodontic therapy than in primary infections, and it is likely that on this basis that all reported literature regarding antibacterial activity of root filling materials is pertaining to this organism.

Reactions with other dental materials. In an effort to offset the extended setting time of MTA, researchers have reported various alternatives to the placement of a moist cotton pellet over the setting MTA material. An *in vitro* study conducted by Nandini *et al.* reported that conventional glass ionomer cement can be layered over partially set MTA for a single-visit procedure and that the setting of MTA proceeds unhindered underneath the layer of glass ionomer[59]. In such a procedure, Ballal *et al.* reported their observations on a glass ionomer cement layered upon partially set MTA. The setting of both materials was unaffected, and the glass ionomer cement showed no signs of dehydration[60]. Tunc *et al*. evaluated the bond strength of a composite and a compomer to white MTA using different bonding systems[61]. They concluded that the total-etch one-bottle system mediated a stronger bond to white

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MTA than the self-etch one-step system. The conclusions from these studies bear relevance to the use of MTA as a pulp-capping and pulpotomy wound-dressing material.

Biocompatibility. The biocompatibility of MTA has been reported widely over the past decade by researchers involved in *ex vivo* cell culture studies and *in vivo* studies in animals and humans.

1) Subcutaneous and intra-osseous evaluation: Studies in the late 1990s reported bacterial and cell culture assays, respectively, to conclude that MTA was not mutagenic or cytotoxic[62,63]. There have been several studies since then, which have tested samples of MTA as subcutaneous and intra-osseous implants in rats[64–66], guinea pigs[67], and rabbits[68]. These studies reported minimal inflammatory responses in the soft tissue and bone, and confirmed MTA to be capable of inducing osteogenesis.

2) Animal studies: The biocompatibility of MTA has also been studied in vivo as root-end fillings in dogs[69–72] and monkeys[73,74]. These studies reported satisfactory periapical tissue responses and healing with MTA. Animal studies have also reported MTA as a favourable pulp-capping material following traumatic exposures in monkeys and dogs[75–77]. MTA has been evaluated *in vivo* in rats as a pulpotomy medicament in comparison to formocresol and ferric sulphate, and reported to perform ideally as a pulpotomy agent, causing dentine bridge formation and simultaneously maintaining normal pulpal histology[78].

Cost implications and storage. Important barriers to the widespread use of MTA in paediatric dentistry include its perceived cost, difficulties with storage, and the need for appropriate training.

The list prices of some commercial products are as follows:

1) ProRoot MTA (White) 5 Dose Pack (ProRoot MTA) – £210.00 (€269.93) (USD363.41)

2) ProRoot MTA (White) 2 Dose Pack (ProRoot MTA) – £91.00 (€116.97) (USD157.48)

3) MTA- Grey and White 1G Pack 7 Applications (MTA-Angelus) – £37.50 (€48.20) (USD64.89)

4) MTA-Grey 2G 14 Applications (MTA-Angelus) – £70.00 (€89.97) (USD 121.13)

(Figures courtesy of QED, Peterborough, Cambs, UK).

ProRoot products are supplied in single-dose sachets, whereas Angelus products are supplied in double-sealed glass vials.

The composition of MTA is not unlike that of the cement used in the building industry to make concrete. Such a material should be kept dry during storage because moist air leads to the phenomenon of air setting, which reduces the strength of the mix. The presentation of ProRoot products as a 1 g sachet for single use, would result in considerable wastage of material, and the transfer of this material to a sealed container such as an Eppendorf tube (Eppendorf UK Ltd, Cambridge, UK) would extend the life of the material and allow more than one treatment to be completed from a single 'dose'.

The Angelus vials of material are marketed with guidance that 1 g may allow up to seven treatments, depending of course on the volume of material to be used.

Clinical applications of MTA in paediatric dentistry

There is a paucity of *in vivo* human studies on the performance of MTA in its various clinical applications. This section will review these studies. Table 1 outlines the evidence available from human clinical studies for the use of MTA in its various clinical applications.

Pulp treatment in permanent teeth

(i) Pulp capping: There have been few studies to date on MTA as a pulp-capping agent in human permanent molars. Four prospective human clinical studies have compared MTA and calcium hydroxide as pulp-capping medicaments in third permanent molars following the *mechanical exposure* of healthy pulps[79–82]. Aeinehchi *et al.* reported a 0.28-mm-thick dentine bridge in teeth pulp capped with grey MTA at 2 months, and 0.43 thickness at 6 months in contrast to a 0.15-mm-thick dentine bridge noted with calcium hydroxide at 6 months[79]. This study also reported tissue inflammation and adjacent pulp tissue necrosis

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Table 1. Evidence from human clinical studies for the clinical applications of mineral trioxide aggregate (MTA).

Clinical application	Studies	Evidence
Pulp capping – permanent teeth	Prospective studies comparing MTA to calcium hydroxide ($Ca[OH]_2$)	*Studies in teeth capped after mechanical pulp exposures* (Validation by histopathology)
	– Aeinehchi *et al.* 2003[79]	Thicker dentinal bridge, less pulpal inflammation with MTA
	– Iwamoto *et al.* 2006[80]	No significant difference between MTA and $Ca(OH)_2$
	– Nair *et al.* 2008[81]	Thicker dentinal bridge, less inflammation with MTA
	– Accorinte Mde L *et al.* 2008[82]	Initial healing is better with MTA; subsequent healing similar in MTA and $Ca(OH)_2$
	MTA – observational study	*Study in teeth capped after carious pulpal exposures*
		Clinical success outcomes
	– Bogen *et al.* 2008[83]	97.6% of the sample showed favourable outcomes; all immature teeth showed subsequent complete root formation
Pulpotomy – permanent teeth	MTA – observational study	*Studies in teeth with pulpal exposures due to caries/fractures*
		Clinical success outcomes
	– Barrieshi-Nusair and Qudeimat 2006[84]	
	– Witherspoon *et al.* 2006[85]	< 75% of the sample in both studies showed favourable outcomes
	Prospective studies comparing MTA to formocresol	
	– El-Meligy and Avery 2006[86]	Similar clinical and radiographic outcomes
Pulpotomy – primary teeth	Prospective studies comparing MTA to formocresol	*Studies in teeth with carious pulpal exposures*
		Clinical success outcomes
	– Eidelman *et al.* 2001[87]	Grey: > 90% over 6–30 months
	– Agamy *et al.* 2004[88]	Grey: 100% over 1 year. White: 84.2% over 1 year
	– Holan *et al.* 2005[89]	Grey: 97% over 4–72 months
	– Farsi *et al.* 2005[90]	Grey: 100% over 2 years
	– Aeinehchi *et a*l. 2007[91]	Grey: 100% over 6 months
	– Noorollahian, 2008[92]	White: 100% over 2 years
	Prospective longitudinal studies	
	– Maroto *et al.* 2005[93]	Grey: 100% over 6 months
	– Maroto *et al.* 2007[94]	White: 100% over 42 months
	Prospective study comparing MTA to $Ca(OH)_2$	Grey: 95 % over 1 year
	– Percinoto *et al.* 2006[95]	
	Prospective study comparing MTA to FC and $Ca(OH)_2$	Grey: 100% over 2 years
	– Moretti *et al.* 2008[96]	
Pulp Capping – Primary teeth	Prospective study comparing MTA to calcium hydroxide ($Ca[OH]_2$)	Study in teeth with pulpal exposures due to caries
	– Tuna and Olmez 2007[97]	Clinical and radiographic outcomes were comparable for MTA and $Ca(OH)_2$. Histological validation recommended.
Apical barrier –permanent teeth		Studies in non-vital immature teeth
	– Simon *et al.*, 2008[98]	Radiographic success outcome
	– Saris *et al.* 2008[99]	81 % over 1 year
		76.5 % over 1 year
Root fractures – permanent teeth	Case reports only available at the time of this review	–

with calcium hydroxide at 6 months, and no pulp tissue inflammation adjacent to MTA with a near-regular odontoblastic layer for the same duration. These results were not significant due to the small sample size. A similar study by Iwamoto *et al.* compared white MTA with calcium hydroxide at 30 days and 136 days post-treatment[80]. At these evaluation periods, no significant difference was found between the groups with regard to the clinical presentation and the histological status. Initial results indicate that both grey and white MTA may perform as well as calcium hydroxide in non-carious mechanical pulp exposures in permanent teeth with normal pulp tissue. In contrast, Nair *et al.* reported that MTA resulted in less pulpal inflammation and more predictable hard tissue barrier formation in permanent

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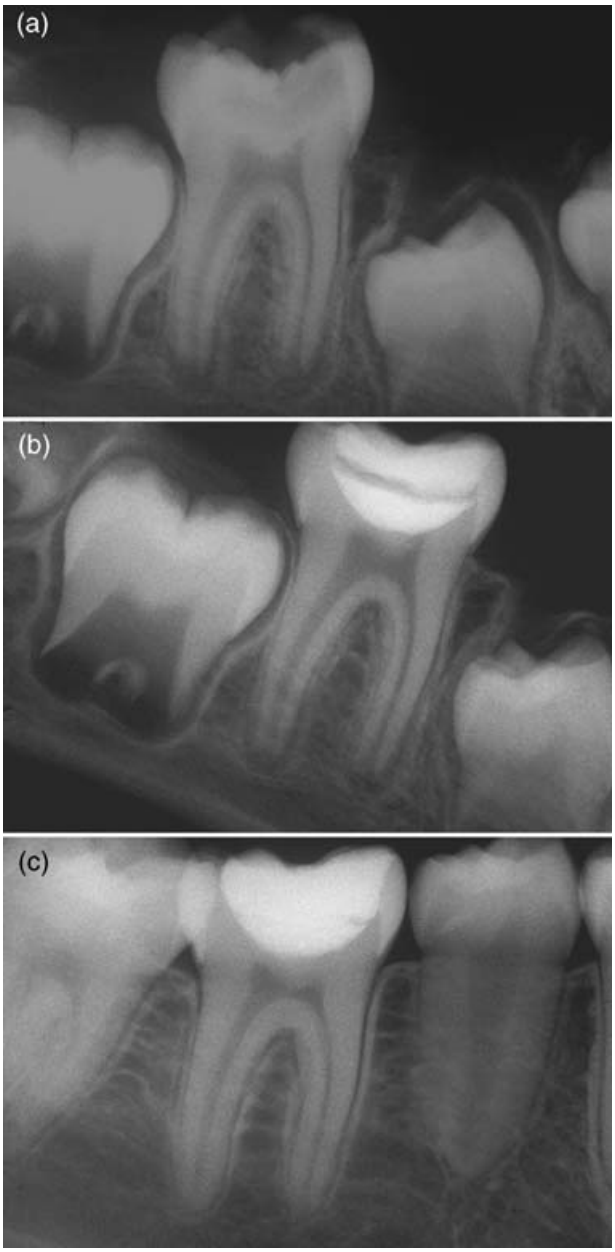

Fig. 1. (a) Radiographic image prior to treatment in a mandibular molar with deep caries and immature apices in a 9-year-old patient (Bogen G, Kim JS, Bakland LK. Direct pulp capping with mineral trioxide aggregate. An observational study. *J Am Dent Assoc* 2008; **139**(3): 313. Copyright ©2008 American Dental Association. All rights reserved. Reprinted by permission.). (b) Radiographic image of the tooth with mineral trioxide aggregate as a pulp-capping agent. (Bogen G, Kim JS, Bakland LK. Direct pulp capping with mineral trioxide aggregate. An observational study. *J Am Dent Assoc* 2008; **139**(3): 313. Copyright ©2008 American Dental Association. All rights reserved. Reprinted by permission.). (c) Radiographic image of the tooth at 5.5-year recall showing a permanent restoration and evidence of complete root formation. The tooth exhibited a normal response to cold testing. (Bogen G, Kim JS, Bakland LK. Direct pulp capping with mineral trioxide aggregate. An observational study. *J Am Dent Assoc* 2008; **139**(3): 313. Copyright ©2008 American Dental Association. All rights reserved. Reprinted by permission.).

teeth in comparison to hard-setting calcium hydroxide[81]. Accorinte Mde *et al.* also reported their support of the safety of MTA for pulp capping in human teeth[82]. Their study reported that MTA seemed to heal the pulp tissue at a faster rate than calcium hydroxide cement, although after 60 days both materials reached similar and excellent results for pulp capping in human teeth.

Bogen *et al.* have reported an observational study where MTA was placed over *carious exposures* in permanent teeth with reversible pulpitis, over a 9-year period[83]. They followed 49 teeth over this period and reported favourable outcomes of 97.6% of the sample based on radiographic appearance, subjective symptoms, and cold testing. All teeth in younger patients (15/15) that initially had open immature apices showed complete root formation (apexogenesis) (Fig. 1).

(ii) Pulpotomy: At the time of this review, three studies had been reported on the outcome of MTA as a wound dressing following pulpotomy in permanent teeth[84–86]. Two of these were observational studies reporting a small sample of 28 and 23 teeth, respectively[84,85]. Barrieshi-Nusair and Qudeimat evaluated the success of grey MTA for partial pulpotomy in 28 cariously exposed young permanent first molars[84]. This was an observational study over a period of 12–26 months with an average of 17.5 months. The authors reported that 79% of the teeth tested positive to sensibility testing with no clinical or radiographic failures. Seven of the teeth which had immature apices at the beginning of treatment showed continued root maturation. A similar outcome was also reported by Witherspoon *et al.* in permanent molars with clinical signs of irreversible pulpal disease[85]. El-Meligy and Avery reported a study comparing MTA and calcium hydroxide as pulpotomy agents in young permanent teeth[86]. This was a split-mouth study, in which 15 pairs of young permanent molar teeth in the same number of children were followed-up for a period of 12 months.

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The authors reported similar clincial and radiographic success for MTA and calcium hydroxide as pulpotomy agents in immature permanent teeth, and concluded that MTA was a suitable alternative to calcium hydroxide.

Pulp treatment in primary teeth. (i) Pulpotomy: Several studies have evaluated MTA as a wound dressing following pulpotomy in primary teeth. Six of these studies have compared formocresol to the two forms of MTA (grey and white), and reported MTA to be an acceptable alternative to formocresol as a wound dressing in the pulpotomy of primary teeth[87–92].

Maroto *et al.* have reported longitudinal and observational clinical studies on grey and white MTA[93,94]. Both studies reported favourably on the clinical outcomes with these materials as a pulpotomy medicament in primary teeth. Percinoto *et al.* have compared MTA to calcium hydroxide as a pulpotomy dressing, and reported both materials to be equally effective in primary teeth[95]. MTA has also been compared to formocresol and calcium hydroxide as a pulpotomy dressing in primary molars by Moretti *et al.* with satisfactory clinical and radiographic outcomes[96].

The clinical outcome measures are similar in all the mentioned studies, but there is variation in the definition of radiographic 'success', making comparisons difficult. The radiographic outcome has been perceived to be successful in all of the mentioned studies if there have been no pathological signs of peri-apical and furcal radiolucencies, and there has been variable or no sign of reparative dentine bridge formation at the time of the reported recall. Sign of internal resorption has been recorded as a negative radiographic outcome in most of the studies. Root canal calcification of the primary molars has been observed and recorded, but not perceived as a negative radiographic outcome in the study reported by Maroto *et al.*[93,94]

(ii) Pulp capping: A single study was identified on the outcome of MTA pulp capping in primary teeth[97]. Tuna and Olmez reported that MTA was as successful as calcium hydroxide in direct pulp capping, and recommended further histological validation to support their findings.

Root-end filling in immature permanent teeth. Two prospective, observational studies have investigated MTA as an apical barrier in non-vital immature permanent incisors[98,99]. Simon *et al.* reported a range of follow-up periods from 6 to 36 months for 57 teeth, 14 of which were in patients under the age of 16, in which an apical plug of MTA was placed as a barrier. This group of workers reported a decrease in the size of the pre-existing peri-apical lesion in 81% of their cases[98]. A similar study by Saris *et al.* reported similar results in 17 non-vital permanent immature incisors[99]. The one-step placement of an MTA apical barrier was viewed as a promising alternative to traditional, multiple-visit apexification with calcium hydroxide. The advantages of a one-step MTA procedure were cited as reduced treatment time, reduced risk of calcium hydroxide-induced changes to dentine, and consequently reduced fracture risk, and the early placement of a sealing and possibly reinforcing coronal/intra-radicular restoration.

Figure 2 shows the radiographic appearance of an MTA apical barrier in the non-vital immature maxillary incisors of a 13 years old.

Apical seal in the non-vital coronal portion of permanent teeth following root fracture. Root canal treatment of the coronal fragment with calcium hydroxide followed by filling with gutta-percha is the traditional treatment of choice for non-vital root-fractured teeth[100].

As in the case of open root apices, the use of calcium hydroxide has been promoted to induce hard-tissue barrier formation at the fracture site. The hard tissue barrier is then able to serve as a matrix for the condensation of gutta-percha and sealer. In this situation, MTA has the potential to offer all of the advantages noted for one-step root-end filling.

Currently, there have been no human or animal studies reported on the use of MTA as an apical barrier for the coronal fragment of the root-fractured tooth. There are, however, case reports explaining the technique with follow-up of up to 2 years.

Figure 3 illustrates the radiographic appearance of MTA placed as an apical seal in a coronal fragment of a fractured maxillary right central incisor in an 11 years old.

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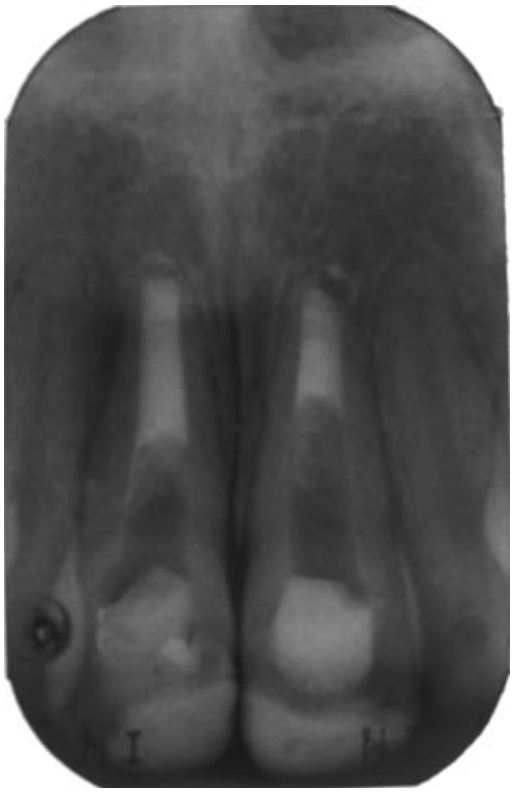

Fig. 2. Radiographic image of mineral trioxide aggregate placed as an apical barrier in a non-vital immature maxillary incisors in a 13 years old.

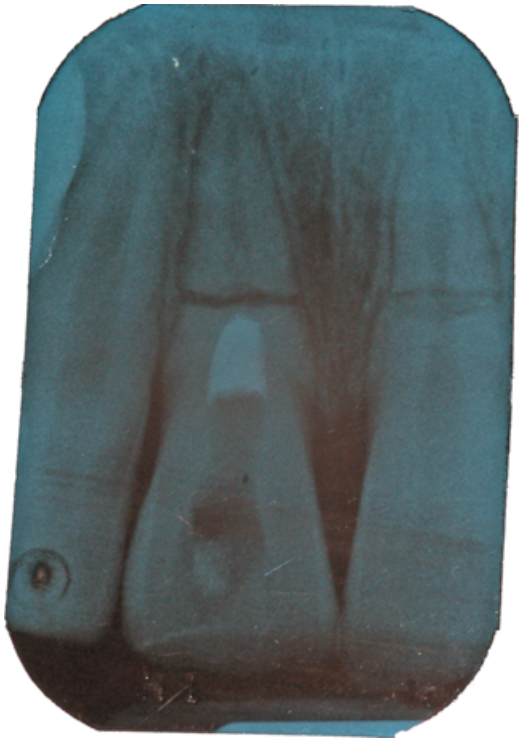

Fig. 3. Radiographic image of mineral trioxide aggregate placed as an apical seal in a coronal fragment of a maxillary right central incisor in an 11 years old.

Conclusion

The paucity of human clinical studies on MTA is likely to change within the next decade. Considering that the material has been in routine clinical use for a little more than a decade, all aspects of its profile as a dental material are currently being investigated. Studies designed to conform with CONSORT guidelines in terms of power, blinding, control groups, and recall times have the potential to validate the clinical impressions of MTA as a useful and versatile material in the armamentarium of the paediatric dentist.

What this paper adds

- This paper provides a synopsis of the key chemical and physical properties of MTA, many of which are of direct clinical relevance.
- This paper reviews the available evidence on the effectiveness of MTA in a range of clinical applications. It also highlights weaknesses in the literature and points to the need for further studies.

Why this paper is important to paediatric dentists

- All paediatric dentists should be familiar with the fundamental properties of the materials they use on patients. This paper provides readers with helpful information on a relatively new restorative material which comes into direct contact with soft connective tissues (pulp and peri-apical tissues).
- Paediatric dentists may be hesitant to adopt a relatively new material into their clinical regimes, lacking confidence in the available evidence or having concerns about its cost and handling characteristics. This paper provides illustrated evidence on the success which can accompany the use of MTA in a range of settings including: (i) primary teeth, as a pulpotomy medicament; (ii) young permanent teeth, as a pulp-capping agent; (iii) immature traumatized permanent teeth, as an apical barrier; (iv) traumatized permanent teeth with root fractures, as an apical barrier of the coronal root fragment; and (v) permanent teeth, as a repair material for perforation and resorptive defects.

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