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Mineral Trioxide Aggregate in Endodontics: A Review

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ABSTRACT: Mineral trioxide aggregate (MTA) is a calcium silicate–based material widely used in endodontics due to its biocompatibility, bioactivity, and capacity to induce hard-tissue formation. Since its development in the 1990s, MTA has been regarded as one of the reference materials for a range of clinical indications, including vital pulp therapies, apexification, perforation repair, and apical surgery.

The physicochemical properties of MTA are associated with calcium hydroxide formation following hydration reactions, a high alkaline pH, and hydroxyapatite deposition. These characteristics contribute to the material's sealing ability and biological performance. In addition, MTA can promote mineralization and may exhibit antimicrobial effects.

Clinical evidence indicates that MTA is associated with favorable outcomes across a broad spectrum of endodontic applications. Although more favorable results have been reported compared with calcium hydroxide, similar clinical performance has been documented for Biodentine and other calcium silicate–based materials. Nevertheless, certain limitations such as a prolonged setting time and handling difficulties have contributed to the development of newer-generation bioceramic materials.

KEYWORDS: Mineral trioxide aggregate (MTA), Endodontic applications, Calcium silicate based materials.

INTRODUCTION:

Calcium silicate based materials have gained increasing importance in endodontics due to their biocompatibility, biological activity, and ability to promote hard-tissue formation. Among these materials, mineral trioxide aggregate (MTA) is widely used in vital pulp therapies and other endodontic procedures because of its high biocompatibility, favorable sealing ability, and structure that supports hard-tissue formation. Owing to these properties, MTA has long been considered one of the reference materials in clinical practice [1,2].

MTA was first developed in the early 1990s as a tricalcium silicate–based material and soon became one of the most widely used bioceramic materials in endodontics. MTA is used in a variety of endodontic procedures, including pulp capping, perforation repair, apexification, and apical surgery [3].

In recent years, newer-generation calcium silicate–based materials such as Biodentine and premixed bioceramic putties have been developed to reduce certain disadvantages of MTA and improve handling characteristics. However, current studies indicate that there are no marked differences in clinical success between these materials and MTA. Studies evaluating pulpotomy treatments in primary teeth have reported no significant differences in clinical and radiographic success between MTA and newer-generation bioceramic materials [4–6].

The aim of this review is to evaluate the composition, biological and physicochemical properties, and clinical applications of MTA in endodontics in light of the current literature, and to delineate its relationship with newer generation calcium silicate based bioceramic materials.

1. DEVELOPMENT OF MINERAL TRIOXIDE AGGREGATE

MTA was developed in the early 1990s as a tricalcium silicate–based material similar to Portland cement and was introduced in endodontics as a biocompatible root-end filling material [3,7]. To provide radiopacity, bismuth oxide was added, and the material was rapidly adopted in clinical practice. Its first commercial form, ProRoot MTA, was introduced in 1999, and subsequently a white MTA formulation was developed to reduce discoloration [8,9]. In the following years, modified formulations such as MTA Angelus were introduced with the aim of shortening the setting time and improving handling characteristics [7].

Over time, newer generation calcium silicate–based bioceramic materials have been developed to mitigate certain disadvantages of MTA, including its prolonged setting time, difficult manipulation, and potential for discoloration [10]. Currently, these materials aim to preserve similar biological properties while offering improved handling and shorter setting times.

2. PHYSICOCHEMICAL PROPERTIES OF MINERAL TRIOXIDE AGGREGATE

2.1. Composition and Hydration Chemistry

The physicochemical properties of MTA largely depend on its composition and hydration reactions. The main phases of MTA are tricalcium silicate (C_3S) and dicalcium silicate (C_2S), and the material typically contains bismuth oxide or, in some formulations, zirconium oxide to provide radiopacity [11].

Hydration of MTA results in the formation of calcium silicate hydrate (C–S–H) gel and calcium hydroxide ($Ca(OH)_2$) from the C_3S and C_2S phases. The released $Ca(OH)_2$ reacts with phosphate ions in tissue fluids to form amorphous calcium phosphate, which over time transforms into hydroxyapatite or carbonated hydroxyapatite at the dentin–material interface. This process contributes to the formation of a hydroxyapatite-like interfacial layer between MTA and dentin, playing an important role in the material's sealing ability and biological activity [12].

One of the most important physicochemical characteristics of MTA is its high alkalinity. After setting, the material creates an alkaline environment with a pH of approximately 10–12, which is associated with $Ca(OH)_2$ release [13,14]. In addition, MTA has been reported to release high levels of calcium ions (Ca^{2+}), while smaller amounts of ions such as silicon, aluminum, and magnesium may also be released. This ion release promotes hydroxyapatite formation and contributes to the material's biological activity [15].

The setting time of conventional MTA formulations is relatively long; however, it can be shortened through the use of additives and different mixing methods [16,17].

2.2. Factors Affecting Physicochemical Properties

The physicochemical properties of MTA can be influenced by several factors, including phase composition, additives, and mixing methods. For example, the C_3S/C_2S ratio is an important parameter that determines hydration kinetics. A higher C_3S content has been associated with faster hydration, a shorter setting time, and a higher pH, whereas a higher C_2S ratio has been linked to slower setting, lower solubility, and improved workability [18].

Radiopacifying agents may also affect the properties of the material. Formulations containing bismuth oxide have been reported to prolong the setting time and reduce microhardness [19].

Mixing methods can likewise influence the physical properties of MTA. Mechanical and particularly ultrasonic mixing has been reported to improve characteristics such as microhardness, flowability, solubility profile, and porosity compared with manual mixing, although it does not appear to cause significant changes in pH or Ca^{2+} release [20].

Certain additives incorporated into MTA formulations can also modify physicochemical properties. Low concentrations of $CaCl_2$ or Na_2HPO_4 may shorten the setting time and improve physical characteristics, whereas the use of high amounts of $CaCl_2$ has been reported to reduce material strength and cell viability [21]. In addition, propylene glycol has been reported to increase flowability, potentially shorten the setting time, and have minimal effects on pH or Ca^{2+} release at low concentrations [14]. Nanoparticle modification and reduction in particle size may increase surface area, contributing to a shorter setting time, increased microhardness, and reduced porosity [16].

3. BIOLOGICAL PROPERTIES OF MTA

3.1. Biocompatibility and Cytotoxicity

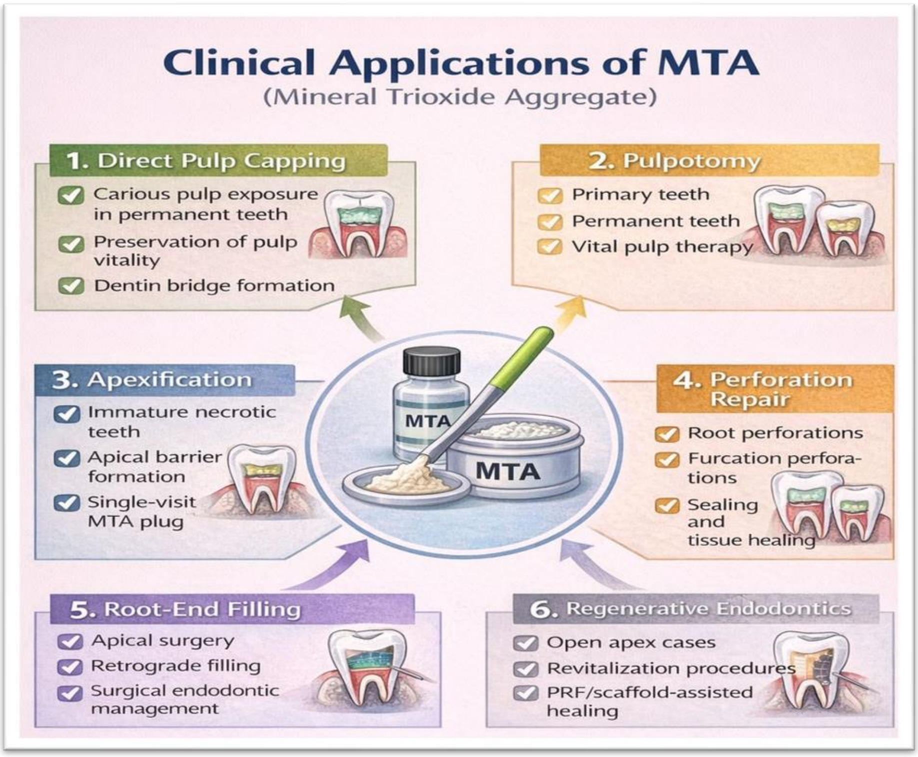
The biocompatibility of MTA has been extensively evaluated in both in vitro and in vivo studies. Experimental studies conducted under laboratory conditions and in animal models have demonstrated low cytotoxicity and high cell viability rates in fibroblasts, dental pulp cells, macrophages, and osteoblasts [22,23]. Moreover, these evaluations have shown that MTA is generally biologically compatible with pulpal and periapical tissues and can be used for pulp capping, pulpotomy, apexification, perforation repair, and as a root-end filling material [9,24,25].

3.2. Bioactivity and Mineralization

One of the most important biological properties of MTA is its bioactivity. During hydration, the material releases calcium ions (Ca^{2+}), which react with phosphate ions in tissue fluids to form hydroxyapatite-like precipitates. This process contributes to the formation of an adhesive interfacial layer between dentin and the material, thereby supporting both sealing ability and dentinogenic and osteogenic activity [26]. In addition, the strongly alkaline environment created by MTA (approximately pH 12) supports biological processes that promote hard-tissue formation [25].

In recent years, the biological properties of modified MTA formulations have also been investigated. Modified MTA containing calcium fluoride, bioactive glass, polyvinyl alcohol, and various polymers have been reported to preserve biocompatibility while enhancing the mineralization potential of pulp cells or stem cells [27,28].

4. CLINICAL APPLICATIONS OF MTA



4.1. Direct Pulp Capping

Direct pulp capping with MTA in permanent teeth with carious pulp exposure has been associated with high rates of pulp vitality preservation, particularly when compared with calcium hydroxide. Moreover, MTA has been reported to exhibit clinical performance comparable to that of newer-generation calcium silicate–based materials such as Biodentine [29,30]. Studies comparing MTA with other materials have shown that, especially relative to calcium hydroxide, MTA achieves higher success rates and is associated with more regular dentin bridge formation and lower levels of inflammation [31–33]. When compared with Biodentine, no significant difference in clinical success has been reported between the two materials, and both have demonstrated similar success rates in the range of 85–96% [34]. Comparisons with other alternative materials (CEM, PRF, propolis, TheraCal) have also indicated similar short-term success rates; however, long-term clinical data for these materials remain limited [35–37].

Among the factors affecting the success of direct pulp capping, the provision of an early and well-sealed coronal restoration is particularly important. It has been reported that delays in restoration placement may increase the risk of failure [29]. Success rates have been reported to be high across all age groups, although a slight decrease may be observed in older individuals. Nevertheless, accurate diagnosis (reversible pulpitis), effective hemostasis, adequate isolation, and good coronal sealing are considered the key determinants of treatment success [38,39].

4.2. Pulpotomy

MTA is a bioceramic material widely used in pulpotomy treatment in both permanent and primary teeth and is associated with high success rates. In permanent teeth, pulpotomy performed with MTA has been reported to yield overall success rates of approximately 86.7% to 92% at follow-up periods of one year or longer. Compared with calcium hydroxide, MTA has been shown to provide superior clinical outcomes, while exhibiting similar success rates to other bioceramic materials such as Biodentine and calciumenriched mixture (CEM) [40,41].

MTA pulpotomy has also been reported to be effective in more advanced clinical conditions, including irreversible pulpitis and periapical radiolucency. Achieving success rates above 80% even in such cases suggests that these clinical findings may not constitute absolute contraindications for pulpotomy [42]. In long term follow up studies extending up to three years, success rates of approximately 92.7% have been reported, along with hard-tissue barrier formation and periapical healing [43].

In primary teeth, MTA has likewise been reported to provide generally higher clinical and radiographic success rates than materials such as ferric sulfate, formocresol, and 3Mixtatin. However, it is emphasized that the level of evidence is low due to methodological limitations of the available studies, and that better designed studies are needed [44,45]. In addition, different modifications of MTA have been reported to demonstrate similar clinical performance. For example, MTA mixed with sodium hypochlorite gel has been reported to show success rates comparable to those of conventional MTA in primary molars [46].

4.3. Apexification

MTA is a bioceramic material widely used for apexification in immature teeth with necrotic pulp to achieve apical closure. The apical plug technique using MTA offers important advantages over conventional calcium hydroxide treatment, particularly by enabling outcomes to be achieved in a shorter period. This approach, which can be completed in a single visit, has been reported to provide a healing success rate of approximately 81% and to yield predictable clinical results [47].

The success of MTA in apexification is associated with its biocompatibility, favorable sealing ability, and dimensional stability. Nevertheless, certain disadvantages, such as a prolonged setting time and handling difficulties, may limit its clinical use [48].

Following apexification, the structural integrity of immature teeth is an important clinical concern. Because MTA apexification does not promote continued root development, the tooth's resistance to fracture may remain limited. Therefore, restorative reinforcement using fiber posts and appropriate core materials has been recommended, and these approaches have been reported to provide higher fracture resistance than conventional gutta-percha fillings [49].

In comparisons with alternative treatment modalities, regenerative endodontic approaches have been shown to be more advantageous than MTA apexification in terms of promoting root development. However, both methods have been reported to be effective in achieving periapical healing in immature necrotic teeth [50].

4.4. Perforation Repair

MTA is widely preferred for the repair of root and furcation perforations due to its biocompatibility, superior sealing ability, and supportive effects on tissue healing. Clinical studies have shown that perforation repairs performed with MTA result in high success rates, with healing achieved in approximately 80–86% of cases over follow-up periods ranging from 1 to 9 years. During this period, regression of lesions and re-establishment of normal tissue architecture have been reported [51,52].

Compared with traditional materials, MTA has been shown to offer advantages in perforation repair. Relative to materials such as amalgam and IRM, MTA has been reported to promote better cementum formation, exhibit lower microleakage, and induce a reduced inflammatory response [53,54].

In recent years, the performance of certain biomimetic materials in perforation repair has also been evaluated. Premixed bioceramic materials and calcium enriched mixtures have been reported in some studies particularly in primary molars to demonstrate higher clinical success rates than MTA [55]. In vitro studies have suggested that Biodentine may be superior to MTA in terms of sealing ability; however, MTA has been shown to perform similarly or better than materials such as TheraCal LC and modified MTA variants [56].

4.5. Root-end filling material

Retrograde fillings performed with MTA have been associated with high success rates in apical surgery. Depending on follow up duration and methodological differences, studies have generally reported success rates ranging from approximately 80% to over 90%. Long-term data have indicated success rates of 81.5% at around 10 years of follow up and 76–83% at 5 years [57,58]. In addition, MTA has been reported to provide superior healing outcomes compared with traditional retrograde filling materials such as SuperEBA [59].

Surgical techniques used in apical surgery also significantly influence success rates. In particular, modern approaches employing magnification systems and microsurgical instruments are associated with higher success rates and lower failure rates than conventional techniques [60].

In studies comparing MTA with other calcium silicate–based materials, no significant differences in clinical success have been reported between MTA and EndoSequence root repair material (RRM) or other bioceramic filling materials, although some studies have indicated a slight advantage in favor of MTA [61].

4.6. Regenerative Endodontics

MTA is a bioceramic material widely used in regenerative endodontics due to its high biocompatibility, bioactivity, and capacity to induce hard tissue formation. Particularly in immature teeth with necrotic pulp and open apices, it plays an important role in regenerative processes by providing effective apical sealing. The release of calcium ions from MTA interacts with phosphate ions in tissue fluids, supporting hydroxyapatite formation and creating a favorable biological environment for pulp revitalization and dentin bridge formation. In addition, through its reported pro-revascularization effects, MTA supports tissue healing and regeneration [62,63].

In regenerative endodontic procedures, MTA is commonly used in combination with biological scaffolds such as platelet-rich fibrin (PRF), and this combination has been reported to support the healing process and apical development, particularly in immature permanent teeth [48,64].

CONCLUSION

MTA has long been used as a reliable material in endodontics due to its biocompatibility, bioactivity, and capacity to support hardtissue formation. Its physicochemical properties and biological effects have contributed to its association with successful outcomes across a broad range of clinical indications.

From a clinical perspective, MTA appears to provide effective and predictable results in multiple areas, including vital pulp therapies, apexification, perforation repair, and apical surgery. Nevertheless, certain limitations—such as a prolonged setting time, handling difficulties, and potential discoloration may partially affect its clinical use.

In conclusion, MTA remains one of the reference materials in endodontics and continues to occupy an important place in contemporary practice due to its clinical efficacy and reliability. However, there is a need for long-term, well-designed clinical studies to support the existing evidence with stronger data.

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