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THE USE OF BIOCERAMICS IN ENDODONTICS: A LITERATURE REVIEW ON PROPERTIES, APPLICATIONS, AND CLINICAL OUTCOMES

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RESUMEN

Introducción: El manejo de dientes permanentes inmaduros con necrosis pulpar representa un desafío en endodoncia debido a la falta de cierre apical completo. La apexificación busca inducir la formación de una barrera apical, permitiendo una correcta obturación del conducto. Históricamente, el hidróxido de calcio se ha utilizado ampliamente, pero se han desarrollado materiales más novedosos como el MTA y les biocerámicas; **Objetivos:** El objetivo de este estudio es comparar la efectividad de las biocerámicas con el hidróxido de calcio en los procedimientos de apexificación para dientes permanentes inmaduros; **Metodología:** Se realizó una revisión bibliográfica utilizando la base de datos MEDLINE (PubMed). Se seleccionaron nueve artículos según criterios de inclusión específicos, que incluían ensayos clínicos, estudios comparativos y análisis retrospectivos centrados en la apexificación y los materiales utilizados; **Resultados:** Los estudios analizados muestran altas tasas de éxito clínico y radiográfico para os tres materiales. El MTA y las biocerámicas presentan resultados comparables, o incluso superiores, al hidróxido de calcio, con una formación más rápida de la barrera apical y un menor número de citas. Las biocerámicas modernas, como Biodentine o los cementos a base de silicato de calcio, también demuestran una buena capacidad de cicatrización periapical; **Conclusiones:** Las biocerámicas representan una alternativa prometedora a los materiales tradicionales para la apexificación. Mejoran la eficacia del tratamiento y reducen su duración. Sin embargo, se necesitan más estudios clínicos con seguimiento a largo plazo para conformar su superioridad.

PALABRAS CLAVE

Odontología; apexificación; biocerámicas; MTA; hidróxido de calcio.

ABSTRACT

Introduction: The management of immature permanent teeth with pulp necrosis presents a challenge in endodontics due to the lack of complete apical closure. Apexification aims to induce the formation of an apical barrier, enabling proper canal obturation. Historically, calcium hydroxide has been widely used, but newer materials such as MTA and bioceramics have been developed; **Objectives:** The objective of this study is to compare the effectiveness of bioceramics with that of MTA and calcium hydroxide in apexification procedures for immature permanent teeth; **Methods:** A literature review was conducted using the MEDLINE database (PubMed). Nine articles were selected according to specific inclusion criteria, including clinical trials, comparative studies and retrospective analyses focusing on apexification and the materials used; **Results:** The analyzed studies show high clinical and radiographic success rates for all three materials. MTA and bioceramics, such as Biodentine or calcium silicate-based cements, also demonstrate good periapical healing capacity; **Conclusions:** Bioceramics represent a promising alternative to traditional materials for apexification. They improve treatment efficacy while reducing treatment time. However, further clinical studies with long-term follow-up are needed to confirm their superiority.

KEYWORDS

Dentistry; apexification; bioceramics; MTA; calcium hydroxide.

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1. INTRODUCTION

1.1. Background of endodontics in immature teeth

1.1.1. Endodontics treatments

We define the endodontic treatment as procedure that aims to remove infection from the root canal system by disinfecting the internal tooth structure and remove the Pulp. The main goal is to preserve the natural tooth by sealing the canal space with materials (1).

Endodontics is a branch that is developing since approximately 200 B.C and spreading worldwide and concerns a huge number of people. After the first attempts at intraarticular treatment during antiquity involving a bronze wire in a tooth canal, modern endodontics appeared between the 17th and 19th centuries with the first documents describing pulp removal and canal filling by Pierre Fauchard in 1728 (2) . In the 20th century, Pulp therapy and the anatomy were formalized thanks to radiography and aseptic techniques (3) . Between 1980 and 2020 , an estimated 8,2% of all teeth worldwide and 55,7% of individuals have received root canal treatment (4).

Endodontics plays a crucial role in preserving permanent teeth, ensuring their long-term functional maintenance in the adult dentition. However, traumatic injuries are a major cause of pulpal pathologies, particularly in young patients. Indeed, there is a high correlation between dental trauma and need for endodontic treatment to ensure the survival and maturation of immature teeth (5).

1.1.2. Immature teeth

Immature teeth can be defined as permanent teeth that have recently erupted and whose root apex is incomplete. When a permanent tooth erupts, it can take up to 3 years for its apex to close completely(6). Between the ages of 8 and 10 , trauma to an immature tooth can be significant as it can interrupt root development(7) .During this period, the permanent tooth is immature because the layers of tissue that compose it, commonly called the Hertwig epithelium,

have not yet completed their formation. The teeth are then composed of thinner walls, an open apex with a diameter greater than that of the mesio-distal root canal, and wide root canals.

However, during cell proliferation of the process of root development, wall thickening and apex closure, if the tooth is exposed to trauma, the pulp is less protected from potential micro bacterial attacks and is thus exposed to possible necrosis. This trauma, which increases in teeth after the eruption of the permanent tooth, can then cause a change in the proliferation of cells involved in root development. Therefore, given the anatomy of immature teeth, endodontic treatment on a developing root is more complicated and lead to more risk of fractures after it (6). Root canal treatment on an immature tooth is difficult because the apex is open and divergent, complicating the root filling procedure (7).

1.1.3. Pathophysiology

Immature permanent teeth have a young and highly vascular pulp, but this tissue is also more vulnerable to external irritation. When the tooth is affected by trauma or deep caries, the pulp can easily become inflamed and later necrotic because of the increased dentin permeability and the wide-open apex that allows bacterial penetration. When the bacteria reach the pulp chamber, the inflammatory reaction reduces the local blood flow, leading to hypoxia and cell death inside the pulp(7,8). Once necrosis occurs, root development stops, this phenomenon prevents the dentinal walls from thickening the function of epithelial of Hertwing root sheath, which normally guides the formation and closure of the root apex.

These biological and structural changes reduce the long-term prognosis of immature teeth and explain why specific endodontic treatments are needed. Techniques such as apexification aim to create an artificial apical barrier, while apexogenesis aim to maintain the pulp vitality to support continued root maturation(7,9).Depending on the degree of root development, different treatments can be considered to ensure apical closure and tooth preservation. When the pulp is necrotic and the apex remains largely open, approaches such as apexification using biocompatible materials like Mineral trioxide aggregate (MTA) or Biodentine can create an artificial apical barrier, promoting canal obturation and periapical healing. In other cases, particularly when some vital pulp cells persist, more biological treatments such as regenerative

endodontic procedures may be preferred to stimulate further root development and dentin wall thickening.

These different therapeutic approaches all aim to adapt management to the regenerative potential of the immature tooth, taking into accounts its fragile structure and large apical opening(9).

1.2. Overview of traditional approaches for immature teeth management

1.2.1. Traditional material

Before the introduction of the modern bioceramics, endodontic treatments of immature teeth relied on the use of so-called “traditional” materials. Their primary role was to promote the formation of an artificial apical barrier and to ensure a watertight seal of the canal, despite the absence of natural constriction at the root tip.

For several decades, calcium hydroxide was the material of choice. It’s biocompatibility and ability to stimulate the formation of hard tissue made it an essential tool for apical closure. However, its use often involved lengthy treatments, requiring multiple material replacements, which increased the risk of tooth weakening over time.

The advent of Mineral Trioxide Aggregate commonly calls MTA in the 1990s marked a decisive advance in endodontics. Thanks to its superior physical and biological properties, this material significantly reduces treatment time while ensuring better apical sealing. Its bioactivity and ability to promote the regeneration of the periapical tissues contributed to its rapid adoption as an alternative to calcium hydroxide.

Thus, these two materials formed the basis of traditional endodontic approaches applied to immature teeth, before the rise of next generation bioceramics, which have further improved the predictability and speed of treatments (7–9).

1.2.1.1. Calcium hydroxide

Calcium hydroxide is a material used in dentistry as an intracanal medications, to induce apexification, as sealant and to repair resorptions or even perforations.

Dating back to the 20th century, calcium hydroxide is composed of approximately 54,11% calcium ions (Ca2+) and approximately 45,89% hydroxide ions (OH-). It is defined as strong base with a very high pH of 12,6. It's mechanism of action involves the ionic dissociation of calcium ions and hydroxide ions. Calcium ions are known for their healing properties. The released calcium ions stimulate fibronectin synthesis (the expression of this gene is dose-dependently stimulated by calcium ions), which induces the differentiation of dental pulps cells, creating mineralized cells and dentin bridges. Calcium hydroxide stimulates the formation of mineralized tissue and can create morphological and immunohistochemical changes to alter metabolism and break down bacterial cells, thus fulfilling its primary function of being antibacterial due to its high ph. It is available in various forms such as powder, paste, cement and hydro soluble. Protein denaturation depends on the form used. The mineralized barrier created after healing with this material is composed of five different layers: calcium carbonate granulation, dystrophic calcification zone, dentin, proliferation zone and normal pulp zone (7,10).

Calcium hydroxide is widely used material in endodontics due to its numerous advantages. It is biocompatible, antibacterial and can induce the formation of an apical barrier. However, it requires frequent replenishment, and the treatments are lengthy, necessitating multiple sessions. Indeed, the formation of an apical barrier can take anywhere from 3 to 24 months. Furthermore, it can weaken the root dentin over the long term and increase the risk of fracture due to its hygroscopic and proteolytic action (7,11). In addition, high concentration of calcium hydroxide can be toxic, and its use is limited within the root canal.

Nevertheless, it remains a suitable material for intraoral dressing of teeth diagnosed with pulp necrosis or apical periodontitis(10).

1.2.1.2. Mineral trioxide aggregate

Mineral trioxide aggregate was created by Dr. Mahmoud Torabinejab in the 1990s, 70 years after the industrialization of Calcium hydroxide.

Commonly called MTA, this calcium silicate cement is chemically composed of tricalcium silicate, tricalcium aluminum, tricalcium oxide, and primarily silicate oxide. It consists of 75% Portland cement, 5% hydrated calcium sulfate (gypsum), and 20% bismuth oxide. This material is used in dentistry in many areas, such as apexification, repair of furcal and lateral root perforations, retrograde obturation, pulpotomy and pulp capping, regenerative endodontics, root end filling and apical obturation. This material provides good sealing and reduces peri radicular radiolucency(10,12).Upon contact with connective tissue, it induces the formation of calcium hydroxide, which releases calcium ions, promoting cell adhesion and proliferation. MTA modulates the production of cytokines responsible for stimulating the differentiation and migration of cells producing hard tissues, such as hydroxyapatite. It has bioactive, antibacterial properties notably due to its high pH of 12,5 after complete administration and is biocompatible. It can create apical seals, dentin bridges and hard tissues. However, the MTA administration time remains long, the cost is high, it presents risks of discoloration and solubility issues during administration can occur(7,10).

Several forms of MTA exist. Originally, MTA was gray (GMTA), which presented discoloration problems and was unusable in the external environment. Then MTA became a white material (WMTA). Both forms of MTA have similar physicochemical and bioactive properties; only the gray MTA is composed of more iron oxide and alumina.

MTA is constantly evolving material. The original form is ProRoot MTA. More recent commercial versions (MTA Angelus, MTA Plus , MTA Repair HP) have been developed to improve handling and reduce setting time, while maintaining the excellent biocompatibility and clinical efficacy of the material(13).The development of Mineral Trioxide Aggregate marked a decisive step in evolution of endodontic materials. However, despite its excellent biocompatibility and sealing properties, MTA still had some limitations, including a long setting time, delicate handling, and the risk of discoloration in aesthetic areas. These constraints led researchers to refine the

chemical composition of calcium silicate-based cements , giving rise to a new generation of materials known as bioceramics(14–16).

1.3. Introduction of bioceramics in endodontics

1.3.1. Definition and classification

Bioceramics now play a crucial role in modern endodontics. This term refers to a group of mineral-based material composed of silicates, phosphates alumina and metal oxides. Their common characteristic is their biocompatibility and their ability to interact positively with biological tissues (16).Bioceramics, differently from the purely inert materials used previously do not simply seal a space, they can actively participate in repair and regeneration process of tissues ,making them both functional and bioactive biomaterials.

Chemically, bioceramics are mainly based on calcium silicate cement such as the structure of MTA but with a formulation that has been refined to offer improved clinical performance (15).They include components such as tricalcium silicate, dicalcium silicate , calcium phosphate and sometimes some additives like zirconium or tantalum to improve stability and radiopacity (14).Bioceramics have been used in several medical disciplines since the 1960s like in bone and orthopedic surgery. In dentistry , their introduction was in the 2000s when they were adapted for specific endodontic applications such as : repair of root perforations, reconstruction of dentin walls, apical closure of immature teeth… (15).

Based on their interaction with living tissues, bioceramics can be grouped into 3 main categories:
-Bioinert bioceramics: these do not react chemically with surrounding tissues but exhibit excellent biocompatibility and stability. They are primary used as structural components, but their role remains limited in endodontics. For examples: alumina and zirconia.
-Bioactive bioceramics: these interact with biological tissues and induce the formation of hydroxyapatite layer and allowing for direct chemical bonding between the material and dentin or bone. For examples: Biodentine, BioAggregate and TotalFill.
-Biodegradable bioceramics: these are gradually resorbed in the body and replaced by newly formed tissues. They are more commonly use in bone surgery and some of their formulations are derived from tricalcium phosphate or bioactive glass (10).

In principle, bioceramics used in endodontics belong to the bioactive category because they provide not only watertight mechanical barrier but also biological stimulation that promotes regeneration. This bioactivity is based on the release of calcium and silicate ions which stimulate the mineralization and the adhesion process of cells (10).

The role of bioceramics is not limited to obturation of the root canal system. Their introduction has redefined the very concept of endodontic treatment, shifting from an exclusionary approach where the canal is sealed to isolate the tissues to a bio integration approach where the material actively participates in healing. These materials provide three-dimensional sealing against micro-infiltration, stimulation of osteoblastic and cementoblastic cells and neutralization of bacteria thanks to an alkaline pH.

Bioceramics have thus introduced regenerative endodontics, in which materials are no longer simply obturation agents but true biological inducers capable of initiating healing and repair processes (15).

1.3.2. Properties

Bioceramics possess a range of physicochemical and biological properties that explain their widespread use in modern endodontics. These characteristics allow them to perform both a mechanical function of hermetic sealing of the root canal and a biological function of stimulating tissue healing and mineral regeneration. Unlike traditional materials such as calcium hydroxide or conventional MTA, next-generation bioceramics combine stability, bioactivity and ease of clinical use (15,17).

The chemical basis of bioceramics is primary calcium silicate, supplemented by oxides such as calcium phosphate , zirconium oxide or tantalum oxide, which are used as radiopacity agents (14). During hydration, these components release Ca^{2+} and OH^- ions, forming hydroxyapatite on the surface of the material. These crystals are gradually deposited in the dentinal tubules and ensure stable chemical adhesion between the dentin and the materiel, thus preventing bacterial infiltration (15). This precipitation reaction is responsible for the direct chemical bond between the material and the dentin (10). Bioceramics have an initially alkaline pH (around 10,2), which

reaches 12,5 after complete setting (14). This pH, along with the release of hydroxyl ions, contributes to their antibacterial effect and their ability to neutralize bacterial toxins released into the root canal by creating an environment unfavorable to the growth of anaerobic bacteria responsible for endodontic infections (10).This effect is particularly effective against enterococcus faecalis strains, often implicated in endodontic treatment failures (17).

They are characterized by low solubility, good dimensional stability and high mechanical strength once hardened. Their fine and homogeneous texture allows them to be used as premixed paste, which facilitates handling and insertions into the canal without material shrinkage (e.g., TotalFill or EndoSequence BC RRM) (15). Setting time varies depending on the formulation, traditional cements required more than 2 hours while modern versions such as Biodentine or EndoSequence BC Sealer harden in less than 30 minutes (16,17). This improvement has significantly reduced clinical time while ensuring complete hardening even in the presence of moisture, which is a major advantage in the root canal environment. These materials also exhibit good radiopacity thanks to metallic oxide particles such as bismuth or zirconium, which replace the compounds previously responsible for discoloration (14).

One of the most important characteristics of bioceramics is their bioactivity. This means they actively interact with surrounding tissues by releasing calcium and silicate ions, which stimulate pulp stem cells (PSCs), osteoblasts and cementoblasts. This cellular interaction triggers odontoblastic differentiation, responsible for the formation of a continuous mineralized barrier at the apex (10,15). Their biocompatibility is excellent: histological studies show an absence of chronic inflammation and the presence of organized repair tissues, often comparable to cementum or secondary dentin. This compatibility is due to their chemical neutrality of the material and the absence of toxic component release (16).

Another essential property is their three-dimensional sealing capacity. Once hardened, bioceramics become virtually impermeable, preventing the re-infiltration of microorganisms. Thanks to their slight expansion during setting, bioceramics perfectly fill canal irregularities and ensure a hermetic seal with the dentin walls (15). This expansion results from a hydration reaction that generates calcium silicate gel, increasing the density of material and strengthening the cohesion between its particles. Unlike zinc-based resins or cements, bioceramics chemically bond to dentin through the formation of a mineralized intermediate layer. This property explains

their excellent resistance to micro-infiltration and long-term clinical stability, particularly in apexification and root canal treatments (14).

1.3.3. Historical evolution

The history of bioceramics in endodontics is closely links to the evolution of bioactive calcium silicate-based materials, whose development was driven by the search for improved sealing, increased biocompatibility and a tissue regeneration capacity superior to that of traditional materials. The evolution of these biomaterials spans nearly a century, from the first uses of calcium hydroxide to the emergence of premixed bioceramics in the 21st century (15,16).

The real turning point came in 1990s with the development of Mineral trioxide Aggregate by Torabinejab. First marketed as ProRoot MTA in 1998, this material marked the birth of the first generation of endodontic bioceramics (14).The components of MTA are similar to Portland cement but with superior purity (16).However, despite these advantages, practitioners quickly observed practical limitations (15).These constraints motivated the search for new, higher-performing formulations, paving the way for the second generation of bioceramics.

The 2000s saw the emergence of the first materials designed to improve MTA while maintaining its bioactivity. Among them, several cements were developed with targeted chemical and physical modifications:

- Biodentine (2009): a tricalcium silicate-based cement formulated with calcium carbonate and zirconium oxide, replacing bismuth oxide to prevent discoloration. It offers a rapid setting time of 12 minutes and excellent workability (15).
- BioAggregate (Innovative Bioceramix, 2008): an aluminum-free material containing calcium phosphate and calcium silicate. It is distinguished by prolonged ion release and improved acid resistance.
- Endosequence BC Sealer and BC RRM (Brasseler, 2010): premixed bioceramics that harden with moisture and eliminate dosing errors. Their stable formulation and fine particle size allow for deep penetration into dentinal tubules (15,17).

These innovations have improved the physical, chemical and aesthetic properties of materials while maintaining their biological advantages. They have also introduced the concept of bioceramics that are easier to handle and insert into the canal.

Starting in 2015, advances in nanotechnology and materials science led to the development of a third generation of bioceramics. These products combine an optimized microstructure, increased reactivity to moisture and improved bio integration. Materials such as TotalFill BC, MTA Repair HP, Well Root ST and BioRoot RCS have been introduced to address specific indications: apexification, root canal obturation, perforation repair, and regenerative treatment (15,18). This formulations include additives such as zirconium oxide (a bismuth substitute), silica nanoparticles and sometimes hydrophilic agents that accelerate setting in the presence of biological fluid (13).These improvements have resulted in better dimensional stability, a reduced stetting time of less than 20 minutes and an optimal biocompatibility.

The goal for manufacturers is now to obtain bio-integrative bioceramics that is those capable of chemically bonding with tissue and actively participating in the regeneration process(15).

In just a few decades, bioceramics have gone from being an experimental material to an international clinical standard. Recent systematic reviews confirm clinical success rates exceeding 90% with improved radiographic stability and a significant reduction in treatment time compared to traditional methods (4,19). Bioceramics particularly premixed versions have also standardized clinical protocols, facilitating their global adoption. They are now considered third-generation bioactive materials boundary between mechanical sealing and biological regeneration (15,18).

1.3.4. Mechanism of action

Bioceramics differ from traditional endodontic materials in their ability to actively interact with the biological environment. Their mode of action relies on a series of physicochemical reactions and biological responses that together lead to the formation of mineralized barrier, cellular stimulation and tissue healing. These processes extend from the first hours following application to several weeks after material placement (10).

Upon contact with moisture or tissue fluids, bioceramics undergo a hydration reaction. The main components , including tricalcium silicate and dicalcium silicate react with water to form hydrated calcium silicate and calcium hydroxide (14). This reaction results in the release of

calcium and hydroxyl ions into the surrounding environment. The Ca2+ ions participate directly in tissue mineralization, while the OH- ions raise the local pH to approximately 12.5 creating a strongly alkaline environment (10).The continuous ionic release maintains a stable bioactive environment around the material for several weeks, thus promoting tissue healing.

One of the key mechanisms of bioactivity in bioceramics is the formation of a hydroxyapatite (HA) layer on their surface. Upon contact with tissue fluids containing phosphate ions , the calcium released by the material combines with the phosphate ions to form hydroxyapatite crystals (20). This hydroxyapatite layer acts as biological interface between the material and the dentin. This allows for cell attachment, particularly of fibroblast, osteoblasts and cementoblasts promoting the regeneration of supporting tissues. Finally, it chemically stabilizes the material's surface and prevents the progressive solubilization observed with older materials such as Ca (OH)2.

Another essential characteristic of the mechanism of action of bioceramics is their ability to physically interact with the dentin. During setting, the material penetrates slightly into the dentin tubules and deposits phosphate and calcium crystals, forming what is called a "mineralized tag" (15). This tag reinforces the anchorage of the material and improves apical sealing by creating a mineralized hybrid transition zone. This combined mechanical and chemical bond gives the dentin-material interface high resistance to micro infiltration and durable dimensional stability. Bioceramics therefore do not require adhesive or pre-etching because their self-adhesion relies entirely on their ability to generate a bioactive interface with the dentin.

Beyond the chemical reaction, bioceramics exert a direct biological influence on pulp and periapical cells. The released calcium ions activate intracellular signaling pathways, notably MAPK (mitogen-activated protein kinases) and CaMKII (calcium/calmodulin-dependent protein kinases), which stimulate odontoblastic differentiation (10). As they differentiate, the cell deposits a mineralized extracellular matrix comparable to dentin or cementum. According to Dong, Biodentine and EndoSequence BC induce increased expression of mineralization genes (DMP1, DSPP, ALP) confirming their active role in the repair process. In vitro studies have also shown increased expression of growth factors such as TGF-β1 and VEGF, essential for vascular neoformation and wound healing (10,20).

Bioceramics reduce local inflammation. Tissues in contact with the material exhibit a minimal initial inflammatory reaction, rapidly followed by a healing phase with the deposition of cement or secondary dentin (10). This biological behavior is explained by the absence of toxic components and the controlled release of ions that promote the neutralization of inflammatory mediators. Thus, bioceramics do not induce tissue necrosis or chronic irritation, making them perfectly biocompatible materials.

The ultimate role of bioceramics in the healing process is to promote the regeneration of the dentin-pulp complex to promote the regeneration of the dentin-pulp complex and periapical tissues. The released ions and the formation of hydroxyapatite create an environment conducive to revascularization, cementum reformation and regeneration of local bone. This regenerative potential explains their success in apexification and apexogenesis treatments, but also in more recent approaches to regenerative endodontics. Bioceramics therefore act as true biological catalysts, capable of inducing cellular and tissue responses similar to those observed in physiological healing processes (20).

1.4. Applications of bioceramics in endodontics teeth

1.4.1. Use of bioceramics in immature teeth

1.4.1.1. Treatment of vital pulp: pulpotomy and apexogenesis

Apexogenesis in an immature tooth with a vital pulp is an endodontic procedure that maintains pulp vitality to allow the tooth to continue its root development altered and halted by the trauma the tooth has sustained. It involves performing a partial or complete pulpotomy, removing the coronal portion of the pulp while preserving the vitality of the root pulp. Its objective is to prevent pulp necrosis and maintain the functionality of the remaining portion of the tooth to allow for natural apexogenesis. Once the pulpotomy is performed, we apply the chosen biocompatible material to the pulp tissue to promote root maturation and strengthen the tooth walls (9,10,16).

Bioceramics are now considered the material of choice for pulpotomy and apexogenesis , thanks to their high bioactivity and biocompatibility (10,15,16). Biodentine and MTA stimulate the differentiation of the pulp cells into odontoblasts, leading to the formation of a continuous dentinoid barrier (19). These materials promote the secretion of mineralization proteins such as DMP-1, DSPP and ALP which are involved in physiological apexogenesis(10). The alkaline pH of bioceramics neutralizes bacteria and creates an environment conductive to permit pulp healing and development of the root (19). Several clinical studies report success rates of 90-95 % in apexogenesis performs with bioceramics. Thanks to their sealing properties and the formation of a hydroxyapatite layer at the material-dentin interface , they ensure progressive apical closure without inflammation (19,20). Bioceramics thus promote pulp revascularization and maintain the vitality of the immature tooth , allowing for continued root development and apex closure (9). Apexogenesis with bioceramics offers reduced treatment time and a low complication rate (21). Histological analyses demonstrate a continuous junction between pulp tissue and the material , indicating complete integration and tissue regeneration (10,15).

1.4.1.2. Treatment of non-vital pulp: apexification and revascularization

Revascularization, also known as endodontic regeneration, is an endodontic treatment aimed at enabling continued root development, dentin wall thickening and periapical healing of an immature tooth with a non-vital pulp. It is a biological process designed to restore the vitality of a necrotic immature permanent tooth by inducing new vital tissue in the root canal. First, the canal must be disinfected, then controlled apical bleeding must be stimulated to form a blood clot. This clot will serve as a natural scaffold for the migration of pulp stem cells and the formation of new pulp-dentin tissue. Bioceramics act as a coronal barrier to protect the blood clot and stimulate mineralization (10,15,22).

Apexification is an endodontic procedure used to induce the formation of an artificial apical barrier in a necrotic immature tooth allowing for the hermetic filling of the root canal. The goal of apexification is to create controlled apical closure to facilitate obturation while ensuring the healing of periapical tissues (8,18,21,23).

Historically , calcium hydroxide was used for apexification procedures but because it required several months of treatment its was replaced by bioceramics such as MTA , Biodentine or

TotalFill allowing for an immediate apical barrier and better biocompatibility (24). MTA remains the historical reference : it stimulates the formation of mineralized barrier but its long setting time and discoloration limited its initial use (14). Biodentine, thanks to its rapid setting time and strong ionic release offers equivalent or even superior results for periapical healing(19). Comparative studies show that premixed bioceramics (EndoSequence BC , TotalFill) induce faster bone healing and a radiographically denser apex (15). Bioceramics exhibit sustainable bioactivity: they continue to release calcium ions for up to 30 days after placement , stimulating apical mineralization (10).For revascularization procedures, bioceramics are used as coronal barrier over the blood clot, ensuring a seal and stimulating pulp stem cells (22). BioAggregate and MTA Angelus have demonstrated effective induction of secondary vital tissue , resulting in thicker root and closed apex formation (16). Radiographically , a progressive disappearance of periapical lesions and thickening of the dentin walls are observed starting at 6 to 12 months (8).

Thus, apexification using bioceramics is associated with a reduced risk of root fracture because the material reinforces the tooth wall trough micro-expansion (15). Clinical success rates are very high , averaging 90 to 96 % for apexifications using MTA or Biodentine (22).

1.4.2. Evaluation of clinical performance

Clinical and radiographic studies show that bioceramics have success rate exceeding 90% both for treatment of a vital permanent tooth to achieve apexogenesis and for treatment of a necrotic immature tooth to achieve apexification (19,23). Evaluations after 6 to 12 months reveal complete apical closure , disappearance of periapical radiolucent deposits and thickening of the root canal wall , indicating canal regeneration and closure (24). Some histological studies confirm the formation of continuous mineralized studies often comparable to dentin or cementum , without any evidence of inflammation or resorption (10). Bioceramics exhibit chemical adhesion to dentin thus preventing potential micro-infiltration unlike conventional cements (15,20). Their volumetric stability and low solubility ensure the long-term durability of seal (13). Follow-up studies of more than three years confirm high tooth survival with complete maintenance of function thanks to the use of bioceramics (15,25). Regarding the treatment of apexogenesis , it has been revealed that teeth treated with Biodentine show better root continuity and an absence of fracture (19). Furthermore , randomized studies comparing MTA ,

calcium hydroxide and modern bioceramics demonstrate that the latter offer faster healing and superior aesthetic restoration (23).

1.4.3. Comparison with conventional materials (advantages and limitations)

Bioceramics differ from traditional endodontic material in several ways that explain their rapid adoption in clinical practice. Their main advantage lies in the considerable reduction of treatment time, both for the dentist and the patient.

While apexification with calcium hydroxide often required several months and numerous visits, bioceramics now allow for the creation of an apical barrier in a single session, improving predictability and patient comfort (7,15). Biologically, these materials are highly bioactive : they release calcium and silicate ions capable of inducing and promoting tissue regeneration(10,20). Their remarkable biocompatibility and lack of toxicity make them safe materials for pulp and periapical tissues, a significant improvement over older materials (16). Physically, bioceramics offer superior sealing, with no volumetric shrinkage after setting ensuring three-dimensional canal closure and limiting the risk of micro-infiltration (13). Modern versions, such as Biodentine or TotalFill, also offer optimal radiopacity without causing tooth discoloration, a major aesthetic advantage compared to first-generation MTA (15). Their premixed formulation greatly simplifies handling and ensures homogeneous mixing, thus reducing the risk of operative errors(5). Furthermore, the high alkaline pH of these materials provides a long-lasting antibacterial effect, contributing to canal disinfection and biological stability of the treatment(10). Finally, the mechanical strength obtained after hardening the risk of fracture, an essential aspect for immature teeth (8).

Despite these numerous advantages, some limitations remain. The high cost of bioceramics, compared to calcium hydroxide or conventional MTA, can hinder their routine use, particularly in public facilities (25). Furthermore, the lack of standardized protocols sometimes makes it difficult to compare studies and generalize results (23). Some recent formulations still lack long-term clinical follow-up , and further research is needed to confirm their stability beyond five to ten years (15). Sensitivity to excessive humidity can also affect the setting and handling of some products, especially in challenging operating conditions (13). Finally, differences in formulation between manufactures (such as between EndoSequence and TotalFill) lead to variations in

behavior, highlighting the need for independent comparative studies to standardize clinical data.

In summary, bioceramics represent a major advancement over conventional materials, combining bioactivity, biocompatibility, and clinical efficacy. However, like any innovative material, they still require long-term scientific validation and standardization of practices to ensure optimal and reproducible use in modern endodontics.

2. OBJECTIVE

The objective of this study is to evaluate the effectiveness of bioceramic materials used in apexification compared to traditional materials such as calcium hydroxide and mineral trioxide aggregate (MTA) in immature permanent teeth with incomplete root formation.

PICO: Is the use of bioceramic materials (I) in the apexification treatment in immature permanent teeth with incomplete root formation (P) more successful (O) than using traditional methods (C) such as calcium hydroxide and mineral trioxide aggregate (MTA)?

3. MATERIAL AND METHODS

3.1. Design

This work is a documentary review of the scientific literature on the use of bioceramics in endodontics, particularly on the treatment of immature teeth. It is a descriptive analysis of published data on properties, mechanism, clinical indications, performances and comparisons with conventional materials. This subject is carried out based on clinical studies, randomized controlled trials, systematic reviews, meta-analyses and synthesize articles. Here, the objective is to identify, compare and synthesize the published results concerning apexogenesis, apexification, revascularization and clinical use of bioceramics in permanent immature teeth.

3.2. Data sources

The searches were carried out in several biomedical databases such as: PubMed, Medline complete, web of science… The keywords used are bioceramics, calcium silicate-based materials, bioactive endodontic materials, immature teeth, open apex, apexogenesis, apexification, regenerative endodontics, treatment canals, MTA, biodentine, calcium hydroxide, bio aggregate, Endosequence BC, clinical outcomes, apical barrier, vital pulp therapy, pulp regeneration. To ensure a modern vision of the evolution of bioceramics, the study period covers the articles from 2005 to 2025.

3.3. Inclusion and Exclusion criteria

Research has focused on studies involving immature permanent teeth, the use of bioceramics in endodontics, apexogenesis, pulpotomy, apexification, revascularization, biological properties. The articles are largely in English. The types of studies accepted are clinical trials, in vitro and in vivo studies, cohort studies, meta-analyses and relevant narrative reviews. The items not accepted are articles that refer only to mature teeth or classic root treatment, as well as non-bioceramic materials.

3.4. Data extraction

The data were extracted manually, only the relevant data of each article was used. The data analyzed are the types of bioceramics (MTA, Biodentin, Endosequence BC, …), clinical indications (vital pulp therapy, specification, revascularization…), biological parameters (bioactivity, ionic release, pH…), clinical results (apical closure, disappearance of periapical lesion, root maturation…) and complications, limits, comparisons between calcium hydroxide and MTA.

3.5. Analysis

The data analysis was conducted descriptively, comparing the results of the studies selected according to their objectives, the materials evaluated and the clinical protocols used. The objective was to identify recurring trends regarding the effectiveness of bioceramics in the treatment of immature teeth, in carrying out statistical meta-analyses. Each article was interpreted considering its methodology and limitations, which provided a coherent overview of the benefits, clinical performance and limitations reported in the current literature

4. RESULTS

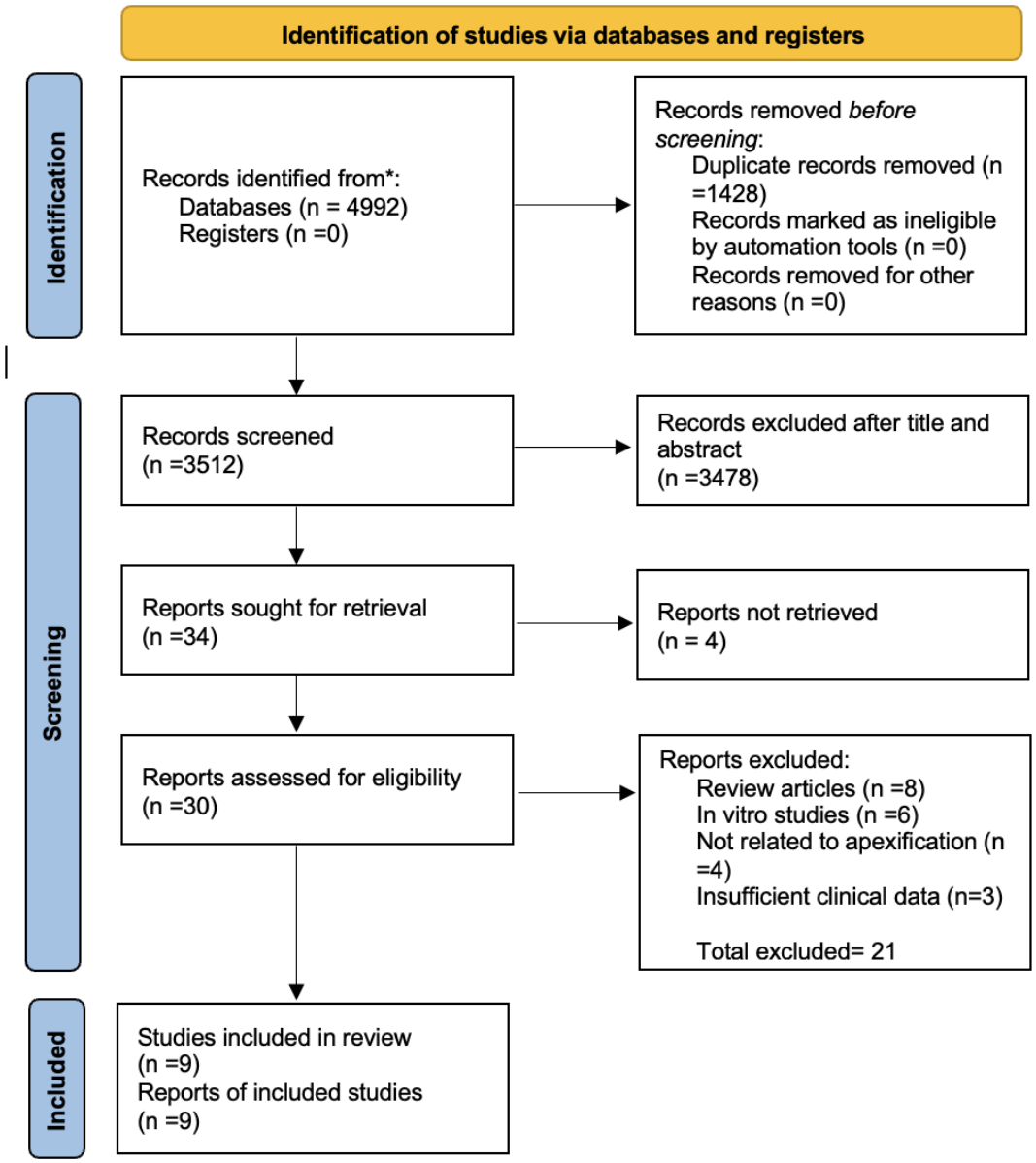


Figure 1. PRISMA Flowchart of the included reports in the study
Source : Page MJ, et al. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.

Table 1: Comparison of clinical outcomes of bioceramics, MTA and calcium hydroxide used for apexification in immature permanent teeth

Reference	Study design	Materials studied	Objective and methodology	Results
Avery & El Meligny,2006(26)	Prospective clinical comparative study	- Calcium hydroxide - MTA	- Compare MTA with Ca (OH)2 for apexification in necrotic immature teeth. - Study: 15 children with 2 necrotic permanent teeth requiring apexification - Evaluation at 3 ,6 and 12 months	- After 12 months, most treated teeth showed clinical and radiographic success. - Of the 15 teeth treated with calcium hydroxide, 2 teeth experienced persistent apical inflammation. - No complications were observed in the group treated with MTA, which demonstrated high efficacy in inducing apical closure. - MTA is a reliable alternative to Calcium hydroxide.
Flanagan, 2014 (7)	Narrative review	- Calcium hydroxide - MTA - Regenerative endodontic procedure	- Analysis and synthesis of published studies on the treatment of immature permanent teeth with open apices, including apexification techniques and regenerative procedures.	- Calcium hydroxide allows the formation of an apical barrier but requires a lengthy treatment and wan weaken the root. - MTA allows procedures represent a more recent approach that can promote continued root development; they are therefore used when the root length is too short to close with an apical MTA plug.
Shaik & al., 2021 (23)	Systematic review and	- Endo Sequence	- Determine whether Endo	- High success rate for all the three materials.

	Meta-Analysis (PubMed, Scopus, Cochrane, Google Scholar, Wiley). A total of 410 studies were identified by their abstracts or title, but only 9 were included in the review	bioceramic root repair material (BC RRM) - MTA - Calcium hydroxide	sequence BCRRM, MTA or Ca (OH)2 offers better clinical and radiographic outcomes for apexification of immature permanent teeth.	- MTA: 90.9%, Ca $(OH)_2$: 81.8%. - MTA and bioceramics allows for faster apical barrier formation and require fewer appointments. - Ca (OH)2 may require 5 to 20 months of treatment -Limitations of MTA: risk of tooth discoloration - Authors conclude that MTA and bioceramics show results comparable to or superior to Ca (OH)2. But more long-term clinical studies are needed.
Yadav et al.,2020 (25)	Randomized controlled trial	- MTA - Biodentine - Calcium phosphate cement (CPC)	- Compare the clinical and radiographic efficacy of the 3 materials used for single-visit apexification of non-vital immature permanent teeth. - Study: 60 non-vital immature permanent teeth from patients aged 6 to 15 years divided in 3 groups - Evaluation: Clinical and radiographic follow-up was performed at 1, 3, 6, and 9 months.	- 100% clinical success rate for all three materials after 9 months - Disappearance of clinical signs (pain, swelling, tooth mobility, abscess) - Initial pain: 50% (MTA), 60% (Biodentine), 70% (CPC). No pain at 1, 3, 6 and 9 month follow ups. -Progressive reduction of periapical lesions in all the three groups. - At 3 months, Biodentine showed

				the best radiographic improvement - At 9 months CPC showed the best radiographic healing - Authors conclude that CPC can be an alternative to MTA and Biodentine with comparable clinical efficacy and favorable long-term radiographic results.
Tolibah & al.,2022 (27)	Randomized controlled clinical trial	- MTA - Biodentine	- Compare clinically and radiographically the apexification performed by MTA versus Biodentine (apical plug), with clinical (pain) and radiographic (API + calcified apical barrier) evaluation. - Study: 24 mandibular first molars with 30 impacted roots, 15 roots per group. - Evaluation: 1-postoperative pain: VAS, several time points (baseline, 1 day, 3 days, 1 week, 2 weeks); 2- periapical status: PAI (periapical index) on pre-operative and follow-up radiographs. 3-Apical calcified barrier (ACB): presence/absence at 12 months.	- Both materials showed satisfactory clinical and radiographic healing with the formation of a calcified apical barrier. - A significant difference in post-operative pain was observed only on the first day, with slightly higher pain levels for Biodentine (VAS 4.27 ± 1.53) than for MTA (3.20 ± 1.21). -At 6 and 12 months, patients were clinically asymptomatic in both groups - Authors conclude Biodentine provides results comparable to MTA and can be used as a reliable alternative for the apexification of immature teeth.

Barakat & Fathi,2020 (28)	In vivo clinical trial	- MTA - Bioceramic root canal sealer (Well-Root ST)	- Evaluate the effect of MTA and the bioceramics sealer for the management of immature permanent teeth with open apices. - Study: 60 non vital immature anterior teeth from 54 children between 7 to 10 years of age were studied. The number of teeth was divided equally in 2 groups - Evaluation: radiographic follow-up was then conducted immediately, and again at 3- and 6-months post-treatment.	- Clinical success rate (reduction of periapical radiolucency) was 93,3% for the bioceramic sealer versus 90% for MTA, with no statistical difference between the groups. - After 6 months, all the teeth showed a normal lamina dura on radiographs. - Clinically, 100% of cases showed soft tissue healing with no swelling, abscesses or ecchymosis. - The authors conclude that MTA and bioceramics provide satisfactory results for apexification of immature permanent teeth.
Donnell & Kandiah, 2024 (29)	Retrospective serie evaluation + cross-sectional analysis	- MTA - Biodentine - TotalFill Putty	- Evaluate the technical quality and clinical outcomes of orthograde endodontic treatment of immature permanent incisors in children by comparing 3 bioceramic materials used as apical plugs and to identify variables that may influence the results.	- The study compared the 3 materials to create an apexification. - The clinical and radiographic success rate at 12 months was 84% for MTA, 88% for Biodentine and 92% for TotalFill Putty. - Authors conclude that all three materials provide favorable results in the apexification of immature permanent teeth, but the modern bioceramics may offer

			- Study: 25 identified cases for each material - Evaluation: Radiographs were analyzed under standardized conditions with intra and inter-rater agreement	slightly superior results and fewer adverse effects than MTA
Damle & al., 2012 (30)	Randomized comparative clinical trial	- MTA A (ProRoot™, Dentsply, Tulsa Dental, USA) - Calcium hydroxide paste (Diapaste™)	- Evaluate and compare the efficacy of MTA and calcium hydroxide in inducing apical barrier formation in traumatized immature permanent anterior teeth. - Study: 22 immature, non-vital permanent incisors from children aged 8 to 13 years, divided into 2 groups: MTA (obturation with gutta-percha after 24 hours) and calcium hydroxide (obturation after radiographic confirmation of apical barrier formation). - Evaluation: assessments were performed at 3, 6 and 9 months with statistical analysis.	-Apical barrier formation at 9 months: 90.90% (MTA) vs. 81.81% ($Ca(OH)_2$). -Mean time to formation: 4.90 months (MTA) vs. 5.33 months ($Ca(OH)_2$). - At 3 months: 70% (MTA) vs. 30% ($Ca(OH)_2$) already had an apical barrier. - Similar clinical and radiographic success between the groups ($p = 0.9999$). - Decrease/ disappearance of periapical radiolucency in most patients after 6 months. - Failures were mainly due to material extrusion or root resorption. - MTA is an effective alternative to $Ca(OH)_2$ for immature permanent teeth because show comparable results for

				apexification and allows for faster apical barrier formation.
Ghaly & al.,2025 (31)	Prospective, randomized, controlled, double-blind clinical trial	- MTA+ (Cerkamed, Poland) - Well-Root PT (Vericom Co., Korea): "Premixed Bioceramic Putty"	- Compare the clinical and radiographic success of an apical plug of Well-Root PT versus MTA in the treatment of immature non-vital centra permanent maxillary incisors, with follow up and measurements of periapical healing and bone density. - Study: 83 incisors evaluated, 33 excluded, final sample= 50 incisors from 38 children (from 8 to 11 years olds) - Randomization of 2 groups composed by 25 teeth/group - Criteria: non vital teeth, restorable, immature root, radiographic sing of apical periodontitis + periapical radiolucency.	- Both groups showed clinical and radiographic improvement during follow up. - The reduction in periapical radiolucency and the increase in bone density was significantly greater with Well-Root PT than with MTA after 6 and 12 months ($p < 0.001$). - Authors conclude that both materials are effective but the Well-root PT bioceramic may offer more favorable radiographic healing than MTA.

5. DISCUSSION

5.1. Overview of the main findings

The studies included in this review show that apexification of immature permanent teeth can be achieved with various materials with high success rates. Historically, Calcium hydroxide has been widely used to induce apical barrier formation. However, some studies show that this treatment can be lengthy and require multiple visits. For example , Avery and El Meligny reported apical barrier formation in 90,9% of teeth treated with MTA versus 81,8% with Calcium hydroxide, with no significant difference in overall success between the two materials (26).

Several recent studies also indicate that modern bioceramics can be effective alternatives to MTA. High success rates have been observed with materials such as Biodentine, TotalFill and bioceramic sealers, with clinical and radiographic results comparable to those of MTA (25,29). Some studies have also shown significant radiographic improvement with modern bioceramics, particularly with Well-Root PT, which exhibited a more pronounced reduction in periapical radiolucency compared to MTA (31).

Overall, these results suggest that modern bioceramics now represent a reliable alternative to traditional materials for apexification of immature permanent teeth(7,23,30).

5.2. Clinical outcomes, applications and properties of bioceramics

5.2.1. Clinical outcomes of apexification materials

The clinical results report in an analyzed studies show that the various materials used for apexification generally lead to the resolution of signs and symptoms associated with pulp infection. Several studies observed the disappearance of pain, swelling and signs of infection after treatment. In several clinical studies, these parameters were assessed during regular follow-up visits. For example, the study by Yadav & al. analyzed the clinical evolution of teeth treated with 3 different materials, specifically evaluation pain, tooth mobility and signs of infection during follow up. The authors observed a progressive disappearance of symptoms in all three-group studied with 100% clinical success rate for MTA, Biodentine and Calcium

phosphate Cement (CPC), thus confirming the overall effectiveness of these materials for apexification. The authors reported that CPC showed slightly better radiographic healing after nine months compared to MTA and Biodentine (25). However, this result should be interpreted with caution, as the follow-up period remains relatively short and the number of clinical studies evaluating CPC in the apexification of immature teeth is limited. Therefore, further clinical trials with longer term follow-up are needed to confirm these observations.

The results of some studies also allow for direct comparison of the performance of different materials. In the study by Barakat and Fathi, the authors compared a bioceramic sealer with MTA, evaluating clinical and radiographic healing during follow up. The results obtained suggest that these two materials have similar performance. They observed high clinical success with a bioceramic sealer (93,3%) compared to MTA (90%) with no statistically significant difference between the two groups (28). Radiographic results also confirm these observations, with a progressive reduction of periapical lesions in most of the studies analyzed. Similarly, the retrospective analysis conducted by Donnell and Kandiah compared three different bioceramic materials in the treatment of immature permanent incisors, evaluating long-term clinical and radiographic outcomes (29). The results of this study suggest that some recent bioceramics may offer comparable or even slightly superior, clinical performance to MTA, with calcium hydroxide remains effective but often requires longer treatment (23).

5.2.2. Properties of bioceramic materials and their influence on treatment outcomes

The results observed in the analyzed studies can be partly explained by the biological and physicochemical properties of the materials used. Modern bioceramics exhibit high biocompatibility and the ability to interact with surrounding tissues, promoting the formation of mineralized tissue and the healing of periapical tissues. These properties are particularly important in the treatment of immature teeth, where tissue regeneration plays a crucial role in the healing process.

Some studies have also evaluated the radiographic effects associated with these biological properties. For example, the clinical study by Ghaly & al. compared a premixed bioceramic material with MTA by measuring the reduction of periapical lesions and the evolution of bone

density during follow-up (31). The results of this study suggest that bioceramics can promote progressive bone healing around the apex, which could be related to their bioactive properties.

Other comparative studies, such as those by Tolibah & al. and Donnell and Kandiah, have also shown that materials such as Biodentine or bioceramic putties can achieve radiographic results comparable to those of MTA suggesting that their biological properties also contribute to their clinical effectiveness (25,29).

5.2.3. Applications of bioceramics in apexification procedures

The use of bioceramics in the endodontics of immature teeth has grown in recent years due to their biological properties and clinical advantages. Traditionally, apexification was performed with calcium hydroxide, a technique that often required several months of treatment and numerous clinical visits. Some studies indicate that apical barrier formation with calcium hydroxide can take between 5 and 20 months, which can significantly prolong treatment time (23). The introduction of MTA has reduced treatment time by allowing the creation of an artificial apical plug in one or two appointments. Modern bioceramics, such as Biodentine, TotalFill and Well-Root PT have subsequently been developed to improve the clinical handling and biological properties of these materials. The results of the studies analyzed show that these materials can be used effectively for apexification, with success rates comparable to those of MTA (27,29).

5.3. Limitations

5.3.1. Limitations of traditional materials

Despite the favorable results observed in the analyzed studies, some traditional materials have limitations. Calcium hydroxide while effective in inducing apical barrier formation generally requires a longer treatment time, which can increase the number of clinical visits and prolong patient care.

MTA was introduced to mitigate these limitations, but some studies have reported drawbacks associated with its use. For example, the study by Donnell and Kandiah mentions the possibility

of coronal discoloration after MTA use in some clinical cases (29). These limitations have led to the development of new bioceramic materials aimed at improving the clinical performance and biological properties of materials used in endodontics.

5.3.2. Limitations of the present review

This review also has some limitations. First, the number of clinical studies directly comparing different materials remains relatively limited. The methodologies used in the analyzed studies also vary, which can make direct comparisons more difficult. For example, some studies are based on controlled clinical trials, while others use retrospective analyses or observational studies.

Furthermore, sample sizes and follow-up periods differ between studies which can influence the interpretation of the results. Finally, some of the bioceramic materials studied are relatively new, meaning that date regarding their long-term effectiveness is still limited.

5.4. Future perspectives

Given these limitations, further research is needed to better understand the role of modern bioceramics in the endodontic treatment of immature permanent teeth. Randomized clinical trials with larger samples and longer follow-up periods would allow for a more precise comparison of the performance of different materials.

Future studies could further explore the influence of the biological properties of bioceramics on periapical tissue healing and apical barrier formation. This research could contribute to improving treatment protocols and optimizing the management of immature teeth in endodontics.

6. CONCLUSIONS

The results of this literature review show that several materials can be used successfully for the apexification of immature permanent teeth. Historically, calcium hydroxide has been widely used to induce the formation of an apical barrier. However, the analyzed studies show that this material often requires a longer treatment time and multiple clinical visits. The introduction of Mineral Trioxide Aggregate (MTA) has improved some limitations of traditional treatment by allowing the creation of an apical plug and reducing treatment time.

The results of the included studies indicates that modern bioceramic materials, such as Biodentine, TotalFill or Well-Root PT, provide comparable and sometimes even superior clinical and radiographic results to thus of MTA and Calcium hydroxide in the apexification of immature permanent teeth. These materials also offer several advantages, including good biocompatibility, high bioactivity and simpler clinical handling making them promising alternatives to traditional materials for treating immature permanent teeth.

However, the number of available clinical studies remains limited, particularly for some recent bioceramics and further clinical trials with long-term follow-up are needed to confirm their efficacy and optimize their use in clinical practice. In conclusion, modern bioceramics represent a promising alternative to traditional materials for apexification, offering favorable clinical outcomes and the potential to improve treatment protocols in endodontics.

7. SUSTAINABILITY

In endodontic treatments, the concept of durability relies heavily on treatment time and resource usage. Apexification with calcium hydroxide generally requires several sessions over sessions over a long period, increasing material consumption and the number of consultations (23,26).

Conversely, MTA and bioceramics often allow treatment to be completed in one or two sessions, thus reducing clinical time and the resources required. This approach can improve the organization of care and patient comfort (27,29,30).

However, these materials can be more expensive and require specific handling.

Thus, bioceramics appear to be an interesting option from a clinical and organizational perspective but their overall environmental impact remains poorly documented. Further studies are therefore needed to be assess their long-term sustainability (23,31).

8. REFERENCES

1. American Association of Endodontists. Treatment Standards: Non-surgical Endodontics—Uncomplicated Mature Permanent Teeth [Internet]. 2018 [citado 7 de noviembre de 2025]. p. 1-26. Report No. Disponible en: https://www.aae.org/specialty/wp-content/uploads/sites/2/2018/04/TreatmentStandards_Whitepaper.pdf

2. American Association of Endodontists. Endodontic History [web page]. American Association of Endodontists [Internet]. 2024 [citado 7 de noviembre de 2025]. Disponible en: https://www.aae.org/specialty/endodontic-history/

3. Ingle, John I.; Bakland, Leif K. endodontics. 6th ed. BC Decker Inc.; 2008.

4. León-López, M.; López-Fuentes, C.; Martínez-Hernández, A.; Jiménez-Gayosso, S.I.; Cervantes-García, J.C. Prevalence of root canal treatment worldwide: A systematic review and meta-analysis. 36016509. 2022;55(11):1225-38. doi:10.1111/iej.13864

5. Murray PE. Review of guidance for the selection of regenerative endodontics, apexogenesis, apexification, pulpotomy, and other endodontic treatments for immature permanent teeth. Int Endod J. 2023;56 Suppl 2:188-188-99. Located at: MEDLINE Complete; 35929348. doi:10.1111/iej.13809

6. Nagy, M. M.; Tawfik, H. E.; Hashem, A. A.; Abu-Seida, A. M. Interventions for managing immature permanent teeth with necrotic pulps and open apices. 2019;(8):CD013527. doi:10.1002/14651858.CD013527

7. Flanagan TA. What can cause the pulps of immature, permanent teeth with open apices to become necrotic and what treatment options are available for these teeth. Aust Endod J J Aust Soc Endodontology Inc. 2014;40(3):95-95-100. Located at: MEDLINE Complete; 25470507. doi:10.1111/aej.12087

8. Gill I, Mittal S, Kumar T, Keshav V. Open Apex and its Management: Review Article. J Pharm Bioallied Sci. 2024;16:S31-S31-4. Located at: Scopus®; edselc.2-52.0-85187129210. doi:10.4103/jpbs.jpbs_615_23

9. Management of permanent teeth with necrotic pulps and open apices according to the stage of root development. Vol. 9. 2017;9(4):230-6. doi:10.1038/ijos.2017.35

10. Estrela, Carlos, Olavo A.; Alencar, Amarílis H. G. de; Estrela, Cintia R. A.; Silva, Rogério S., Guedes. Mechanism of Action of Bioactive Endodontic Materials. Vol. 18. 2023;18:125-37. doi:10.22037/iej.v18i3.40276

11. Boufdil H, Mtalsi M, El Arabi S, Bousfiha B. Apexification with Calcium Hydroxide vs. Revascularization. López-López J, editor. Case Rep Dent. enero de 2020;2020(1):9861609. doi:10.1155/2020/9861609

12. Gerard LM, Gaur S. Application of Biodentine for Apexification of Immature Teeth of Children: A Scoping Review. Int J Clin Pediatr Dent. 2025;18(5):573-573-9. Located at: Dentistry & Oral Sciences Source; 187102766. doi:10.5005/jp-journals-10005-3128

13. Camilleri J, Montesin FE, Brady K, Sweeney R, Curtis RV, Ford TRP. The constitution of mineral trioxide aggregate. Dent Mater. 2005;21(4):297-297-303. Located at: Dentistry & Oral Sciences Source; 16737290. doi:10.1016/j.dental.2004.05.010

14. Parirokh, Massoud, Torabinejad, Mahmoud. Mineral trioxide aggregate and other bioactive endodontic cements: an updated overview – Part I: Chemical composition, physical and mechanical properties. Vol. 18. 2023;18:1-14. doi:10.22037/iej.v18i1.34706

15. Dong X, Xu X. Bioceramics in Endodontics: Updates and Future Perspectives. Bioengineering. 13 de marzo de 2023;10(3):354. doi:10.3390/bioengineering10030354

16. Raghavendra SS, Jadhav GR, Gathani KM, Kotadia P. Bioceramics in endodontics - a review. J Istanb Univ Fac Dent. 2017;51(3 Suppl 1):S128-S128-37. Located at: MEDLINE Complete; 29354316. doi:10.17096/jiufd.63659

17. Walsh RM, He J, Schweitzer J, Opperman LA, Woodmansey KF. Bioactive endodontic materials for everyday use: a review. Gen Dent. 2018;66(3):48-48-51. Located at: MEDLINE Complete; 29714700

18. PocketDentistry Review. Bioceramics as an Apical Plug – From MTA to Next Generation Materials [Internet]. 2024. Disponible en: https://pocketdentistry.com/bioceramics-as-an-apical-plug/

19. Paranna S, Gogawale R, Patil A, Huddar S, Patro K, Kanetkar J. Clinical and Radiographic Evaluation of Biodentine for Apexogenesis in Young Permanent Mandibular Molars: A Systematic Review and Meta-Analysis. Cureus. 2025;17(7):e88240-e88240. Located at: MEDLINE Complete; 40827160. doi:10.7759/cureus.88240

20. Gandolfi M.G, Prati C. Calcium silicate bioactive cements: Biological perspectives and clinical applications. Vol. 31. 2015;31:351-70. doi:10.1016/j.dental.2015.01.004

21. Chauhan R, Chauhan S, Bhasin P, Sood A, Kumar H, Gupta A, et al. Precision at the apex: Apexification under magnification: A case report. World J Methodol. 2025;15(4):104655-104655. Located at: MEDLINE Complete; 40900852. doi:10.5662/wjm.v15.i4.104655

22. Abu Zeid ST, Alamoudi RA, Alothmani OS, Mokeem Saleh AA, Siddiqui AY. A Prospective Study of Long-Term Regenerative Endodontics Outcomes of Necrotic Immature Permanent Teeth: An 8-Year Follow-Up. Healthc Basel Switz. 2021;9(12). Located at: MEDLINE Complete; 34946396. doi:10.3390/healthcare9121670

23. Izaz Shaik, Bhargavi Dasari, Rashmi Kolichala, Mina Doos, Fida Qadri, Jenefer Loveline Arokiyasamy, et al. Comparison of the success rate of mineral trioxide aggregate, endosequence bioceramic root repair material, and calcium hydroxide for apexification of immature permanent teeth: Systematic review and meta-analysis. J Pharm Bioallied Sci. 2021;13(5):43-43-7. Located at: Directory of Open Access Journals; edsdoj.2f6dcf1f62f42658118e93fd422de5b. doi:10.4103/jpbs.JPBS_810_20

24. Wikström A, Brundin M, Mohmud A, Anderson M, Tsilingaridis G. Outcomes of apexification in immature traumatised necrotic teeth and risk factors for premature tooth loss: A 20-year longitudinal study. Dent Traumatol. 2024;40(6):658-658-71. Located at: Academic Search Ultimate; 180851011. doi:10.1111/edt.12973

25. Yadav A, Khanna R, Chak RK. Comparative evaluation of mineral trioxide aggregate, biodentine, and calcium phosphate cement in single visit apexification procedure for nonvital immature permanent teeth: A randomized controlled trial. Int J Clin Pediatr Dent. 2020;13:S1-S1-13. Located at: Scopus®; edselc.2-52.0-85108002866. doi:10.5005/jp-journals-10005-1830

26. El Meligy OAS, Avery DR. Comparison of apexification with mineral trioxide aggregate and calcium hydroxide. Pediatr Dent. 2006;28(3):248-248-53. Located at: Scopus®; edselc.2-52.0-33746501536

27. Yasser Alsayed Tolibah, Chaza Kouchaji, Thuraya Lazkani, Ibrahim Ali Ahmad, Ziad D. Baghdadi. Comparison of MTA versus Biodentine in Apexification Procedure for Nonvital Immature First Permanent Molars: A Randomized Clinical Trial. Children. 2022;9(3):410-410-410. Located at: Directory of Open Access Journals; edsdoj.2a1a2cad7804dae9742675b01331aef. doi:10.3390/children9030410

28. Ibrahim Farouk Barakat, Adel Fathi Hussien. Clinical and Radiographical Evaluation of Bioceramic Root Canal Sealer and MTA in Apexification of Immature Permanent Teeth. Egypt Dent J. 2020;66:2057-63. doi:10.21608/edj.2020.41085.1241

29. Donnell CC, Kandiah P. Comparing the technical quality and clinical outcomes of root canal treatment on immature permanent incisors in children: a retrospective evaluation of three bioceramic plug materials. Eur Arch Paediatr Dent Springer Sci Bus Media BV. 2024;25(6):821-821-35. Located at: Supplemental Index; 180990150. doi:10.1007/s40368-024-00941-3

30. S G Damle, Hiteshwar Bhattal, Dhanashree Damle, Abhishek Dhindsa, Ashish Loomba, Sumit Singla. Clinical and radiographic assessment of mineral trioxide aggregate and calcium hydroxide as apexification agents in traumatized young permanent anterior teeth: A comparative study. Dent Res J. 2016;13(3):284-284-91. Located at: Directory of Open Access Journals; edsdoj.581b1ff74acf4d1fb7007ea977d5a49b. doi:10.4103/1735-3327.182191

31. ghaly MS, Abozena NI, Kabbash IA, El-Desouky SS. clinical and radiographic evaluation of premixed bioceramic putty as an apical plug in nonvital immature anterior permanent teeth. Sci Rep. 2025;15. doi:10.1038/s41598-025-11407-x