



International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

2734 17 Avenue SW,
Calgary, Alberta, T3E0A7,
Canada
+15878858911
editorial-office@sciformat.ca

ARTICLE TITLE

BIOACTIVE MATERIALS FOR ROOT PERFORATION REPAIR: A COMPREHENSIVE REVIEW OF MINERAL TRIOXIDE AGGREGATE, BIODENTINE, BIO-C REPAIR, AND ENDOSEQUENCE BC ROOT REPAIR MATERIAL

DOI

[https://doi.org/10.31435/ijitss.3\(51\).2026.6477](https://doi.org/10.31435/ijitss.3(51).2026.6477)

RECEIVED

23 July 2026

ACCEPTED

18 September 2026

PUBLISHED

25 September 2026

LICENSE



The article is licensed under a **Creative Commons Attribution 4.0 International License**.

© The author(s) 2026.

This article is published as open access under the Creative Commons Attribution 4.0 International License (CC BY 4.0), allowing the author to retain copyright. The CC BY 4.0 License permits the content to be copied, adapted, displayed, distributed, republished, or reused for any purpose, including adaptation and commercial use, as long as proper attribution is provided.

BIOACTIVE MATERIALS FOR ROOT PERFORATION REPAIR: A COMPREHENSIVE REVIEW OF MINERAL TRIOXIDE AGGREGATE, BIODENTINE, BIO-C REPAIR, AND ENDOSEQUENCE BC ROOT REPAIR MATERIAL

Ewa Jurkowska (Corresponding Author, Email: ewajurkowska@onet.eu)

Pomeranian Medical University, Szczecin, Poland

ORCID ID: 0009-0005-7547-4192

Zofia Wiśniewska

Pomeranian Medical University, Szczecin, Poland

ORCID ID: 0009-0005-7658-094X

Stanisław Jurkowski

Pomeranian Medical University, Szczecin, Poland

ORCID ID: 0009-0005-9715-8385

ABSTRACT

Background: Root perforation is a significant complication in endodontic treatment that may adversely affect the long-term prognosis of the affected tooth if not managed promptly and appropriately. The development of bioactive calcium silicate-based materials has substantially improved treatment outcomes by providing excellent sealing ability, biocompatibility, and bioactivity. Mineral Trioxide Aggregate (MTA) has long been regarded as the gold standard for perforation repair; however, newer biomaterials such as Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material (BC RRM) have been introduced to overcome several of its limitations.

Objective: This narrative review aims to compare the physicochemical properties, biological characteristics, handling properties, clinical performance, advantages, disadvantages, and available scientific evidence regarding MTA, Biodentine, Bio-C Repair, and EndoSequence BC RRM in the management of root perforations.

Methods: A comprehensive literature review was conducted using peer-reviewed articles indexed in PubMed, Scopus, and Web of Science. Publications evaluating calcium silicate-based materials used for perforation repair, including systematic reviews, meta-analyses, randomized clinical studies, observational studies, and in vitro investigations, were analyzed.

Results: Current evidence indicates that all four materials demonstrate excellent biocompatibility and favorable clinical outcomes. MTA remains the reference material because of its extensive scientific documentation and predictable long-term performance. Biodentine offers improved handling characteristics, shorter setting time, and a lower risk of tooth discoloration. Bio-C Repair and EndoSequence BC RRM represent next-generation premixed bioceramic materials with excellent sealing ability, high bioactivity, and simplified clinical application. Although laboratory and preliminary clinical studies suggest comparable or even superior physicochemical properties of newer materials, high-quality long-term randomized clinical trials remain limited.

Conclusions: Calcium silicate-based bioactive materials have significantly advanced the management of root perforations. Material selection should be individualized according to the clinical situation, perforation characteristics, operator experience, and material properties. While MTA continues to serve as the benchmark material, Biodentine, Bio-C Repair, and EndoSequence BC RRM constitute reliable alternatives with several practical and biological advantages. Further well-designed long-term clinical studies are required to establish definitive evidence regarding their comparative effectiveness.

KEYWORDS

Root Perforation, Mineral Trioxide Aggregate, MTA, Biodentine, Bio-C Repair, EndoSequence BC RRM, Bioceramics, Calcium Silicate Cement, Endodontics, Bioactive Materials

CITATION

Jurkowska, E., Wiśniewska, Z., & Jurkowski, S. (2026). Bioactive materials for root perforation repair: A comprehensive review of mineral trioxide aggregate, Biodentine, Bio-C repair, and EndoSequence BC root repair material. *International Journal of Innovative Technologies in Social Science*, 3(51). [https://doi.org/10.31435/ijitss.3\(51\).2026.6477](https://doi.org/10.31435/ijitss.3(51).2026.6477)

COPYRIGHT

© The author(s) 2026. This article is published as open access under the **Creative Commons Attribution 4.0 International License (CC BY 4.0)**, allowing the author to retain copyright. The CC BY 4.0 License permits the content to be copied, adapted, displayed, distributed, republished, or reused for any purpose, including adaptation and commercial use, as long as proper attribution is provided.

1. Introduction

Root perforation is defined as an artificial or pathological communication between the root canal system and the surrounding periodontal tissues. It represents one of the most challenging complications encountered during endodontic treatment and may occur as a result of pathological processes such as external or internal root resorption, dental caries, or iatrogenic errors during access cavity preparation, canal instrumentation, or post-space preparation [2,12]. The prognosis of a perforated tooth depends on several factors, including the location and size of the defect, the degree of bacterial contamination, the interval between perforation and repair, and the biological properties of the repair material used [2,12].

Untreated or inadequately sealed perforations facilitate bacterial leakage between the root canal system and the periodontal tissues, leading to persistent inflammation, periodontal attachment loss, bone resorption, and ultimately treatment failure [2,4]. Consequently, immediate diagnosis and prompt sealing of the perforation are considered essential for preserving the affected tooth and maintaining long-term clinical success [2,5].

An ideal perforation repair material should provide an effective hermetic seal while maintaining excellent biocompatibility and dimensional stability. Furthermore, it should be insoluble in tissue fluids, resistant to moisture contamination, radiopaque, easy to manipulate, and capable of promoting hard tissue formation and periodontal healing [4,5]. The introduction of calcium silicate-based bioceramic materials has significantly improved the prognosis of perforation repair by combining favorable physicochemical characteristics with bioactive properties that stimulate tissue regeneration [4,13].

For more than three decades, Mineral Trioxide Aggregate (MTA) has been regarded as the gold standard for root perforation repair because of its outstanding sealing ability, excellent biocompatibility, osteogenic potential, and extensive scientific validation [1,4,14,15]. Nevertheless, despite its proven clinical effectiveness, conventional MTA presents several disadvantages, including a prolonged setting time, difficult handling characteristics, potential tooth discoloration, and relatively high cost, which have encouraged the development of newer calcium silicate-based materials [4,14,15].

Among these next-generation biomaterials, Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material (BC RRM) have attracted considerable attention. Biodentine was developed to improve handling characteristics and significantly reduce setting time while maintaining excellent biological properties. In contrast, Bio-C Repair and EndoSequence BC RRM are premixed bioceramic cements designed to simplify clinical application and provide consistent physicochemical performance together with superior bioactivity [3,6,8,9]. Recent laboratory investigations and clinical studies have demonstrated promising outcomes for these materials, although direct comparative evidence and long-term randomized clinical trials remain limited [3,6–11].

Given the continuous development of bioactive endodontic materials, clinicians require evidence-based guidance regarding the selection of the most appropriate repair material for different clinical situations. Although numerous studies have evaluated individual biomaterials, comprehensive comparisons focusing specifically on their application in root perforation repair remain relatively scarce [1–3].

Therefore, the aim of this narrative review is to critically compare the currently available bioactive calcium silicate-based materials used for root perforation repair—Mineral Trioxide Aggregate, Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material—with particular emphasis on their composition, physicochemical properties, biological behavior, handling characteristics, sealing ability, clinical performance, advantages, limitations, and future perspectives.

2. Root Perforation: Definition, Classification and Prognostic Factors

Root perforation is defined as an artificial or pathological communication between the root canal system and the surrounding periodontal tissues. It may occur at any stage of endodontic treatment or develop secondary to pathological processes such as external or internal root resorption and extensive dental caries. Regardless of its etiology, root perforation compromises the natural barrier separating the root canal from the periodontal tissues, facilitating bacterial contamination and significantly reducing the probability of long-term treatment success if not managed appropriately [2,12].

The reported incidence of iatrogenic perforations has declined over recent decades owing to advances in endodontic techniques, improved magnification, and the routine use of cone-beam computed tomography (CBCT). Nevertheless, perforations remain a clinically relevant complication, particularly in teeth presenting with complex root canal anatomy, pulp chamber calcifications, or severe coronal destruction. Procedural errors during access cavity preparation, canal instrumentation, or post-space preparation continue to represent the most common causes of treatment-related perforations [2,5,12].

From a clinical perspective, perforations are commonly classified according to their anatomical location as coronal (furcation), crestal, mid-root, or apical. This classification is of considerable prognostic importance because the relationship between the perforation site and the periodontal attachment apparatus directly influences healing potential. Coronal and crestal perforations generally exhibit a less favorable prognosis due to their proximity to the gingival sulcus and increased susceptibility to bacterial contamination. In contrast, perforations located in the middle or apical third of the root are often associated with improved healing outcomes when promptly diagnosed and adequately sealed [2,12].

In addition to anatomical location, perforation size is considered one of the principal determinants of clinical success. Small defects are generally easier to disinfect and seal effectively, allowing for the regeneration of surrounding periodontal tissues. Larger perforations, however, present greater technical challenges, increase the risk of material extrusion, and are more frequently associated with persistent inflammatory reactions and periodontal attachment loss [1,2,12].

The interval between perforation occurrence and definitive repair also plays a decisive role in treatment prognosis. Immediate sealing minimizes bacterial penetration and prevents the establishment of chronic inflammation within the periodontal tissues. Conversely, delayed treatment allows microbial colonization of the defect, promoting epithelial migration, bone resorption, and formation of granulation tissue, all of which may compromise the regenerative capacity of the affected area [2,4,12].

The biological characteristics of the repair material have become equally important determinants of successful perforation management. Historically, numerous restorative materials—including amalgam, glass ionomer cement, composite resin, zinc oxide-eugenol formulations, and calcium hydroxide—were used for perforation repair with inconsistent clinical outcomes. The introduction of calcium silicate-based bioceramic materials has fundamentally changed contemporary treatment strategies by combining excellent sealing ability with bioactivity, high alkalinity, antimicrobial potential, and stimulation of mineralized tissue formation [4,13–15].

Current evidence indicates that successful perforation repair depends not on a single clinical factor but rather on the interaction of multiple variables. Early diagnosis, effective infection control, precise placement of a biocompatible repair material, and long-term coronal sealing collectively determine the likelihood of favorable healing. Consequently, modern endodontic treatment emphasizes minimally invasive management combined with the use of bioactive materials capable of supporting both periodontal regeneration and hard tissue deposition [1,2,5].

Although Mineral Trioxide Aggregate remains the reference material for perforation repair due to its extensive scientific validation, the introduction of newer calcium silicate-based biomaterials—including Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material—has expanded the range of available treatment options. These materials were specifically developed to address some of the clinical limitations associated with conventional MTA, such as prolonged setting time, difficult manipulation, and the potential for tooth discoloration, while preserving its favorable biological properties [3,4,6,8–10].

3. Biological Requirements for Root Perforation Repair Materials

The primary objective of root perforation repair is to restore the integrity of the root structure while preventing bacterial communication between the root canal system and the surrounding periodontal tissues. Consequently, the repair material should not only provide an effective seal but also promote biological healing and preserve the viability of adjacent tissues. The development of calcium silicate-based biomaterials has significantly changed the approach to perforation management by introducing materials capable of actively participating in the healing process rather than merely serving as passive filling agents [4,13].

An ideal perforation repair material should possess several essential physicochemical characteristics. First, it must exhibit excellent sealing ability to prevent microleakage and bacterial penetration. Even minimal leakage may compromise treatment outcomes by allowing persistent microbial contamination, resulting in chronic inflammation and delayed periodontal healing. Numerous experimental studies have demonstrated that the sealing properties of calcium silicate-based cements are superior to those of many conventional restorative materials, primarily due to their dimensional stability and ability to form a chemical bond with dentin during the setting reaction [6,7,11].

Biocompatibility is another fundamental requirement. Since repair materials are frequently placed in direct contact with periodontal ligament cells, alveolar bone, and connective tissues, they should not induce cytotoxic or inflammatory responses. Instead, they should support cell survival, proliferation, and differentiation while facilitating tissue regeneration. Recent investigations have shown that modern bioceramic materials demonstrate excellent cytocompatibility and promote favorable cellular responses, including increased osteoblastic activity and mineralized tissue deposition [3,9].

Bioactivity has become one of the defining characteristics of contemporary calcium silicate-based materials. Unlike traditional restorative materials, bioactive cements release calcium ions during hydration, leading to the formation of calcium hydroxide and subsequently hydroxyapatite at the interface between the material and dentin. This biomineralization process enhances marginal adaptation, improves sealing ability, and creates a biologically favorable environment that supports hard tissue formation and periodontal repair [4,13,14].

Another clinically relevant property is the material's ability to maintain dimensional stability in the presence of moisture. Root perforations are typically repaired in environments where complete isolation from tissue fluids or blood is difficult to achieve. Therefore, repair materials should retain their physical integrity and continue the setting reaction under moist conditions without significant deterioration of their mechanical properties. Calcium silicate-based biomaterials were specifically designed to function in these challenging clinical situations and generally demonstrate satisfactory performance despite moisture contamination [8,13].

Handling characteristics also play a significant role in clinical success. An ideal material should be easy to manipulate, adaptable to irregular defects, and sufficiently resistant to washout during the initial setting phase. Long setting times or complex mixing procedures may increase the risk of contamination and negatively affect treatment predictability. These limitations have encouraged the development of premixed bioceramic materials that simplify clinical application while maintaining favorable biological properties [3,6,8].

Mechanical properties, including compressive strength and resistance to dissolution, contribute to the long-term stability of the repair. Materials with insufficient mechanical durability may undergo degradation over time, increasing the risk of leakage and treatment failure. Furthermore, adequate radiopacity is essential for postoperative radiographic assessment and allows clinicians to verify the quality of material placement during and after the procedure [4,13].

From an esthetic perspective, tooth discoloration has become an increasingly important consideration, particularly when perforations involve anterior teeth. Conventional formulations of Mineral Trioxide Aggregate have been associated with clinically significant discoloration, largely attributed to the presence of bismuth oxide used as a radiopacifier. Newer calcium silicate-based materials have therefore been modified to minimize discoloration while preserving their favorable biological characteristics, making them more suitable for esthetically demanding clinical situations [3,10].

Taken together, the ideal perforation repair material should combine excellent sealing ability, biocompatibility, bioactivity, dimensional stability, favorable handling characteristics, mechanical durability, and esthetic acceptability. Although no currently available material fulfills every criterion perfectly, contemporary calcium silicate-based biomaterials have substantially improved the predictability of perforation repair and represent a significant advancement over previously used restorative materials. The following sections critically evaluate the characteristics of the four most widely investigated materials currently used in clinical practice: Mineral Trioxide Aggregate, Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material [1,3,4].

4. Mineral Trioxide Aggregate (MTA)

Mineral Trioxide Aggregate (MTA) is considered the benchmark material for root perforation repair and has served as the reference standard in endodontics for more than three decades. Since its introduction in the 1990s, MTA has fundamentally changed the management of endodontic complications by providing a biologically active material capable of promoting hard tissue formation while ensuring an effective seal between the root canal system and the surrounding periodontal tissues [4,14,15]. Owing to its extensive clinical validation and predictable long-term outcomes, MTA remains the material against which newly developed calcium silicate-based biomaterials are routinely compared [1,4].

MTA is primarily composed of calcium silicates, calcium aluminates, calcium sulfate, and a radiopacifying agent, traditionally bismuth oxide. Upon hydration, the material undergoes a complex chemical reaction resulting in the formation of calcium silicate hydrate gel and calcium hydroxide. The release of calcium ions creates an alkaline environment characterized by a high pH, which contributes to antibacterial activity while simultaneously stimulating mineralization and hard tissue deposition. Furthermore, the interaction between released calcium ions and phosphate ions present in tissue fluids promotes hydroxyapatite formation along the dentin–material interface, improving marginal adaptation and reinforcing the biological seal [13–15].

One of the greatest strengths of MTA is its exceptional biocompatibility. Numerous experimental and clinical studies have demonstrated that direct contact between MTA and periodontal tissues induces only a minimal inflammatory response while promoting the proliferation and differentiation of osteoblasts, cementoblasts, and periodontal ligament fibroblasts. This favorable biological behavior facilitates regeneration of damaged periodontal structures and contributes to the formation of new cementum over the repaired perforation site, which is regarded as one of the principal indicators of successful healing [1,4,15].

In addition to its biological properties, MTA demonstrates excellent sealing ability. Slight expansion during the setting reaction and the formation of hydroxyapatite crystals contribute to intimate adaptation between the material and dentinal walls, reducing bacterial microleakage. This characteristic is particularly important in perforation repair, where long-term treatment success largely depends on maintaining a hermetic seal despite continuous exposure to tissue fluids and occlusal forces [1,6,14].

Clinical evidence consistently supports the effectiveness of MTA in managing furcal, lateral, and apical root perforations. Systematic reviews have reported high long-term success rates when treatment is performed promptly under appropriate aseptic conditions. Favorable outcomes are most frequently observed in small perforations repaired shortly after their occurrence, emphasizing that both biological properties of the material and appropriate clinical management determine treatment prognosis [1,2].

Despite its well-documented clinical performance, MTA is not without limitations. One of its most significant disadvantages is the prolonged setting time, which may exceed two hours depending on the formulation and environmental conditions. This increases the risk of material displacement or contamination before complete setting and often necessitates multiple clinical visits. Additionally, the material possesses a sandy consistency that many clinicians find difficult to manipulate, particularly when repairing small or deep perforations [4,14].

Another important limitation is the potential for tooth discoloration. Traditional formulations containing bismuth oxide have been associated with clinically significant crown discoloration, especially in anterior teeth. Although this issue is less relevant in posterior restorations, it represents an important consideration when perforations occur in esthetically demanding areas. Consequently, alternative radiopacifying agents have been incorporated into newer calcium silicate-based materials to minimize this undesirable effect while maintaining adequate radiopacity [3,10].

Economic considerations may also influence material selection. MTA is generally more expensive than many conventional restorative materials, and its handling characteristics often require greater operator experience. Nevertheless, these disadvantages are frequently outweighed by its excellent biological performance and extensive clinical documentation, which continue to justify its widespread use in endodontic practice [4,15].

Overall, MTA remains one of the most comprehensively investigated biomaterials in endodontics and continues to serve as the clinical reference standard for root perforation repair. However, the limitations associated with handling, setting time, and esthetic outcomes have stimulated the development of next-generation calcium silicate-based biomaterials designed to preserve the biological advantages of MTA while improving its clinical usability. Among these materials, Biodentine has emerged as one of the most extensively studied alternatives and is currently considered one of the principal competitors to conventional MTA [3,4].

5. Biodentine

Biodentine was introduced as a second-generation calcium silicate-based biomaterial designed to overcome several clinical limitations associated with conventional Mineral Trioxide Aggregate while maintaining its favorable biological properties. Since its introduction, Biodentine has gained widespread acceptance in restorative dentistry and endodontics because of its improved handling characteristics, significantly reduced setting time, and excellent biological performance. Owing to these properties, it has become one of the most frequently investigated alternatives to MTA for root perforation repair and other vital pulp therapies [3,4].

The material consists primarily of tricalcium silicate, dicalcium silicate, calcium carbonate, and zirconium oxide, the latter serving as the radiopacifying agent. Unlike traditional MTA, Biodentine does not contain bismuth oxide, thereby substantially reducing the risk of tooth discoloration. Its liquid component contains calcium chloride, which accelerates the hydration reaction and shortens the setting time to approximately 10–12 minutes, representing one of the material's principal clinical advantages [3,13].

Following hydration, Biodentine forms calcium silicate hydrate gel and releases calcium hydroxide, resulting in an alkaline environment similar to that observed with MTA. The continuous release of calcium ions promotes biomineralization and stimulates the deposition of hydroxyapatite crystals along the dentin-material interface. This process improves marginal adaptation, enhances sealing ability, and supports the regeneration of mineralized tissues surrounding the perforation site [3,13,14].

Numerous laboratory studies have demonstrated that Biodentine exhibits excellent biocompatibility and supports the proliferation, adhesion, and differentiation of periodontal ligament fibroblasts, osteoblasts, and dental pulp cells. Furthermore, the material induces the expression of mineralization-related proteins and stimulates the formation of reparative hard tissue, contributing to favorable periodontal healing following perforation repair. These biological characteristics have established Biodentine as a highly bioactive material capable of actively participating in tissue regeneration rather than functioning solely as a passive restorative material [3,9].

One of the most clinically relevant advantages of Biodentine is its handling behavior. The material demonstrates a homogeneous consistency that facilitates placement into perforation defects, allowing clinicians to achieve satisfactory adaptation even in anatomically challenging situations. In addition, the considerably shorter setting time minimizes the risk of bacterial contamination or material displacement before complete hardening, thereby improving treatment efficiency and reducing chairside time compared with conventional MTA [3,8].

The sealing ability of Biodentine has been extensively investigated in both laboratory and clinical studies. Evidence indicates that the material provides an effective seal against bacterial microleakage, with performance comparable to, and in some studies exceeding, that of Mineral Trioxide Aggregate. Its slight expansion during setting and the formation of an interfacial mineral infiltration zone contribute to improved adaptation to dentinal walls, thereby enhancing the long-term stability of the repair [6,7,10].

Clinical investigations have reported encouraging outcomes following the use of Biodentine for furcal, lateral, and apical perforation repair. High success rates have been observed in cases where immediate treatment was combined with appropriate infection control and adequate coronal restoration. Available systematic reviews suggest that Biodentine achieves clinical outcomes comparable to those reported for MTA, although the evidence base remains less extensive because of its relatively shorter period of clinical use [1–3].

Another important advantage of Biodentine is its esthetic performance. The replacement of bismuth oxide with zirconium oxide significantly decreases the likelihood of tooth discoloration, making the material particularly attractive for perforation repair in anterior teeth or other esthetically demanding clinical situations. This feature represents a considerable improvement over conventional formulations of MTA, where discoloration has been reported as one of the major drawbacks affecting patient satisfaction [3,10].

Despite its numerous advantages, Biodentine also presents certain limitations. The material exhibits lower radiopacity than some MTA formulations, which may occasionally complicate radiographic evaluation of the repair. In addition, although its mechanical properties are generally favorable, several studies have suggested that prolonged exposure to acidic or inflammatory environments may adversely influence its surface characteristics and long-term stability. Furthermore, while laboratory evidence supporting Biodentine is substantial, the number of long-term randomized clinical trials remains relatively limited compared with the extensive evidence available for MTA [3,4].

Current evidence indicates that Biodentine successfully combines excellent biocompatibility, rapid setting, satisfactory sealing ability, and favorable handling properties, making it one of the most versatile

calcium silicate-based materials currently available for perforation repair. Although Mineral Trioxide Aggregate continues to be regarded as the reference material because of its extensive clinical documentation, Biodentine has emerged as a reliable alternative that addresses several practical limitations associated with MTA while maintaining comparable biological performance. Consequently, it has become an increasingly popular choice among clinicians managing root perforations in both routine and complex endodontic procedures [1,3,4].

6. Bio-C Repair

Bio-C Repair is a premixed ready-to-use calcium silicate-based bioceramic cement developed to simplify the clinical application of bioactive endodontic materials while maintaining the favorable biological characteristics established by previous generations of calcium silicate cements. Unlike conventional powder–liquid systems, Bio-C Repair is supplied in a ready-to-use formulation, eliminating potential inconsistencies associated with manual mixing and improving handling reproducibility during clinical procedures [3,13].

The material consists primarily of calcium silicates, calcium aluminate, calcium oxide, zirconium oxide as the radiopacifier, and additional thickening agents that contribute to its injectable consistency. Hydration occurs following contact with tissue fluids, resulting in the formation of calcium silicate hydrate gel and calcium hydroxide. Similar to other calcium silicate-based biomaterials, this reaction creates an alkaline environment and promotes continuous calcium ion release, which is closely associated with biomineralization and tissue regeneration [3,13].

One of the principal advantages of Bio-C Repair is its ease of clinical application. The premixed formulation allows direct placement into the perforation site without prior manipulation, reducing technique sensitivity and minimizing the risk of operator-related variability. This characteristic may be particularly beneficial in difficult clinical situations involving deep perforations, limited visibility, or restricted access, where consistent material delivery is essential for achieving adequate sealing [3,8].

The biological properties of Bio-C Repair have been extensively investigated in recent years. Experimental studies have demonstrated excellent cytocompatibility with periodontal ligament fibroblasts, osteoblast-like cells, and mesenchymal stem cells. Furthermore, the material has been shown to stimulate cell proliferation, differentiation, and the expression of genes associated with mineralized tissue formation. These findings suggest that Bio-C Repair provides a biological environment favorable for periodontal healing and hard tissue deposition following perforation repair [3,9].

Bioactivity remains one of the defining features of Bio-C Repair. The sustained release of calcium ions promotes the precipitation of hydroxyapatite crystals at the material–dentin interface, improving marginal adaptation while reinforcing the biological seal. This biomineralization process contributes not only to reduced bacterial penetration but also to the regeneration of surrounding mineralized tissues, which represents one of the major therapeutic objectives in perforation management [3,13].

Several laboratory investigations have evaluated the sealing ability of Bio-C Repair using dye penetration, glucose leakage, and confocal laser scanning microscopy. Overall, the available evidence demonstrates excellent marginal adaptation and sealing performance comparable to established calcium silicate-based materials such as MTA and Biodentine. In some experimental models, Bio-C Repair exhibited reduced microleakage, although these findings have not yet been consistently confirmed across different study designs [6,7,11].

Another important advantage of Bio-C Repair is the absence of bismuth oxide. Instead, zirconium oxide is used as the radiopacifying agent, substantially reducing the risk of crown discoloration while maintaining satisfactory radiographic visibility. This characteristic makes the material particularly attractive for procedures involving anterior teeth or patients with high esthetic expectations [3,10].

Despite these favorable characteristics, Bio-C Repair is not without limitations. Most currently available evidence originates from laboratory investigations evaluating physicochemical properties, cytocompatibility, or sealing ability under controlled experimental conditions. Although the initial clinical outcomes are encouraging, high-quality randomized clinical trials with extended follow-up periods remain scarce. Consequently, the long-term clinical performance of Bio-C Repair cannot yet be considered as comprehensively documented as that of Mineral Trioxide Aggregate [1–3].

Another limitation concerns the relatively recent introduction of the material into routine clinical practice. As a result, information regarding its long-term dimensional stability, resistance to functional loading, and performance under different pathological conditions remains limited. Continued clinical observation and

prospective multicenter studies will therefore be essential to establish stronger evidence regarding its effectiveness in root perforation repair [2,3].

Overall, Bio-C Repair represents an important advancement in the evolution of calcium silicate-based biomaterials. By combining a premixed formulation with excellent biocompatibility, sustained calcium ion release, favorable handling characteristics, and satisfactory sealing ability, it addresses several practical limitations associated with earlier generations of repair materials. Although current evidence suggests that its biological and physicochemical performance is highly promising, further long-term clinical studies are required before Bio-C Repair can be considered equivalent to MTA in terms of the strength of available scientific evidence [1,3,9].

7. EndoSequence BC Root Repair Material (BC RRM)

EndoSequence BC Root Repair Material (BC RRM), also referred to as EndoSequence Root Repair Material (ERRM), represents a newer generation of premixed calcium silicate-based bioceramic cements developed for endodontic repair procedures. The material was designed to combine the favorable biological characteristics of Mineral Trioxide Aggregate with improved handling properties and greater clinical convenience. Available as either a moldable putty or an injectable paste, BC RRM eliminates the need for manual mixing and provides a standardized consistency that facilitates predictable placement in a variety of clinical situations, including root perforation repair [3].

The composition of BC RRM includes calcium silicates, calcium phosphate monobasic, zirconium oxide, tantalum oxide, calcium hydroxide, and thickening agents. Following contact with moisture present in dentinal tubules and surrounding tissues, hydration initiates the formation of calcium silicate hydrate gel together with the continuous release of calcium hydroxide. This process creates an alkaline environment that inhibits bacterial growth while promoting mineralization and regeneration of the surrounding tissues. Similar to other calcium silicate-based biomaterials, calcium ion release stimulates hydroxyapatite formation at the dentin-material interface, thereby improving marginal adaptation and biological sealing.

One of the principal advantages of BC RRM is its excellent handling behavior. Because the material is supplied in a ready-to-use formulation, variability associated with manual powder-liquid mixing is eliminated. The premixed consistency also allows more precise placement within perforation defects, particularly in anatomically complex areas where manipulation of conventional materials may be difficult. These characteristics contribute to reduced technique sensitivity and improved procedural efficiency [3].

The biological properties of BC RRM have been investigated extensively in laboratory studies. Available evidence demonstrates excellent cytocompatibility with periodontal ligament fibroblasts, osteoblasts, and other cells involved in periodontal regeneration. In addition to exhibiting minimal cytotoxicity, BC RRM has been shown to stimulate mineralization-related cellular activity and support the deposition of mineralized tissue adjacent to the repair site. These biological effects are consistent with those reported for other calcium silicate-based biomaterials and reinforce the material's suitability for root perforation repair [3,9].

The sealing ability of BC RRM has also received considerable attention. Experimental studies using dye penetration, glucose leakage, bacterial leakage, and confocal laser scanning microscopy have consistently demonstrated excellent adaptation to dentinal walls and low levels of microleakage. Comparative investigations generally report sealing performance comparable to MTA and Biodentine, indicating that BC RRM is capable of providing a durable barrier against bacterial penetration when used under appropriate clinical conditions [3,11].

An additional advantage of BC RRM is its dimensional stability under moist conditions. Unlike many conventional restorative materials, hydration is not adversely affected by tissue fluids; instead, moisture is required to complete the setting reaction. This property is particularly valuable in perforation repair, where complete isolation is frequently difficult to achieve because of bleeding or periodontal fluid contamination. Furthermore, the material demonstrates good resistance to washout during the early stages of setting, contributing to greater clinical reliability in challenging environments [3].

Unlike traditional formulations of MTA, BC RRM does not contain bismuth oxide, thereby reducing the risk of clinically significant tooth discoloration. The incorporation of zirconium oxide and tantalum oxide provides adequate radiopacity while maintaining favorable esthetic characteristics. Consequently, BC RRM may represent a suitable option for perforation repair in esthetically sensitive regions where discoloration is a major clinical concern [3].

Despite these favorable characteristics, several limitations should be considered. The majority of available studies evaluating BC RRM are laboratory investigations focusing on physicochemical properties, cytocompatibility, and sealing ability. Although preliminary clinical reports have demonstrated encouraging treatment outcomes, the number of prospective randomized clinical trials remains limited. Consequently, the long-term clinical evidence supporting BC RRM is still less extensive than that available for Mineral Trioxide Aggregate, which continues to possess the strongest body of scientific documentation [1–3].

Overall, EndoSequence BC Root Repair Material represents a significant advancement in contemporary endodontic biomaterials. Its premixed formulation, excellent biocompatibility, favorable sealing ability, and simplified clinical application make it an attractive alternative for perforation repair. Nevertheless, despite promising laboratory findings and encouraging early clinical observations, additional high-quality long-term clinical studies are required before BC RRM can be considered equivalent to MTA with respect to the level of available scientific evidence. Current literature therefore supports BC RRM as a reliable and biologically favorable repair material while emphasizing the need for continued clinical evaluation [1,3].

8. Comparative Analysis and Clinical Considerations

The continuous development of calcium silicate-based biomaterials has considerably expanded the therapeutic options available for root perforation repair. Although Mineral Trioxide Aggregate (MTA), Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material (BC RRM) all belong to the same family of bioactive materials, they differ in their physicochemical characteristics, handling properties, clinical applicability, and the strength of supporting scientific evidence. Consequently, the selection of an appropriate repair material should not rely solely on individual material properties but should also consider the specific clinical scenario and the quality of available evidence [1–4].

Among the materials evaluated, MTA remains the most extensively investigated and clinically validated biomaterial. More than three decades of experimental and clinical research have consistently demonstrated its excellent biocompatibility, superior sealing ability, and capacity to induce cementogenesis and periodontal regeneration. Numerous systematic reviews continue to identify MTA as the reference material for root perforation repair, particularly in cases where long-term clinical predictability is considered the primary treatment objective [1,4,14,15].

Despite these well-established advantages, conventional MTA presents several practical limitations that have encouraged the development of newer calcium silicate-based materials. Its prolonged setting time increases the risk of contamination before complete hardening, while its relatively difficult handling characteristics may complicate placement in small or anatomically challenging perforations. Furthermore, the incorporation of bismuth oxide has been associated with clinically significant tooth discoloration, limiting its use in esthetically demanding situations [4,10,14].

Biodentine was specifically developed to address several of these shortcomings. Compared with MTA, Biodentine demonstrates a substantially shorter setting time, improved consistency, and easier manipulation, allowing clinicians to complete treatment more efficiently while reducing the likelihood of bacterial contamination during the setting phase. The absence of bismuth oxide also significantly decreases the risk of discoloration, making Biodentine particularly suitable for anterior teeth and other esthetic indications [3,4]. Laboratory investigations and available clinical studies suggest that Biodentine provides sealing ability and biological performance comparable to MTA, although the quantity of long-term clinical evidence remains smaller due to its more recent introduction into clinical practice [1–3].

Bio-C Repair and EndoSequence BC RRM represent the latest generation of premixed calcium silicate-based repair materials. Their principal innovation lies in the elimination of manual mixing, thereby reducing operator-dependent variability and simplifying clinical application. The ready-to-use formulation allows more predictable material placement while preserving the biological properties characteristic of calcium silicate cements. These materials have demonstrated excellent cytocompatibility, sustained calcium ion release, and favorable bioactivity in numerous laboratory investigations, supporting their use as biologically active repair materials [3,8,9].

Experimental comparisons generally indicate that Bio-C Repair and BC RRM achieve sealing performance comparable to that of MTA and Biodentine. Studies evaluating bacterial leakage, glucose penetration, and confocal laser microscopy have consistently reported satisfactory marginal adaptation for all contemporary calcium silicate-based materials. However, available evidence does not conclusively

demonstrate the superiority of any single material with respect to sealing ability, as differences between studies remain relatively small and are frequently influenced by experimental methodology [6–11].

From a biological perspective, all four materials exhibit excellent biocompatibility and stimulate mineralized tissue formation through similar mechanisms involving calcium ion release and hydroxyapatite deposition. Therefore, biological response alone appears insufficient to justify the preference of one material over another. Instead, practical clinical considerations—including handling characteristics, setting time, esthetic requirements, and operator experience—often become the determining factors in material selection [3,4,9,13].

An important distinction among the available materials concerns the strength of supporting scientific evidence. MTA remains supported by the largest number of long-term clinical investigations and systematic reviews, providing clinicians with a high degree of confidence regarding treatment predictability. Biodentine also possesses a growing body of favorable clinical evidence, although long-term prospective studies remain comparatively limited. In contrast, Bio-C Repair and BC RRM are currently supported predominantly by laboratory investigations and short-term clinical observations, highlighting the need for further randomized clinical trials evaluating their long-term performance [1–3,11].

Clinical decision-making should therefore be individualized rather than material-centered. In cases where extensive clinical documentation and long-term predictability are considered paramount, MTA continues to represent the safest evidence-based choice. Biodentine may be preferred when rapid setting, improved handling, or esthetic considerations are of particular importance. Similarly, Bio-C Repair and BC RRM offer practical advantages in situations requiring simplified application or when consistent premixed formulations are desirable. Nevertheless, clinicians should recognize that the current evidence supporting these newer materials remains less comprehensive than that available for conventional MTA [3,4,8].

Overall, contemporary calcium silicate-based biomaterials demonstrate remarkably similar biological characteristics and favorable clinical potential. Rather than replacing MTA, newer materials should currently be regarded as valuable alternatives that expand the range of therapeutic options available to clinicians. Future high-quality randomized controlled trials with standardized methodologies and extended follow-up periods will be essential to determine whether these newer biomaterials can achieve a level of scientific evidence comparable to that established for Mineral Trioxide Aggregate [1–4].

9. Future Perspectives

The development of calcium silicate-based biomaterials has significantly improved the prognosis of root perforation repair over the past three decades. Nevertheless, despite substantial advances in material science and clinical techniques, several important challenges remain unresolved. Future research should therefore focus not only on the development of novel biomaterials but also on generating high-quality clinical evidence capable of guiding evidence-based treatment decisions [1–4].

One of the principal limitations of the current literature is the relatively small number of well-designed randomized controlled clinical trials directly comparing contemporary repair materials. Although numerous laboratory investigations have demonstrated favorable physicochemical properties and biological performance for MTA, Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material, laboratory findings cannot fully predict long-term clinical success. Variations in experimental protocols, assessment methods, and outcome measures further complicate comparisons between published studies. Consequently, greater standardization of research methodologies will be essential for producing reliable and clinically applicable evidence [1–3].

Another important research priority involves the evaluation of long-term treatment outcomes. Most currently available clinical studies report follow-up periods ranging from several months to a few years, whereas successful perforation repair should ideally be assessed over substantially longer periods. Future investigations should therefore include extended follow-up intervals with standardized clinical and radiographic criteria in order to determine the long-term stability of tissue regeneration and the durability of the biological seal [2,4].

Advances in biomaterial engineering are also expected to influence the next generation of endodontic repair materials. Current research is increasingly focused on modifying calcium silicate cements through the incorporation of bioactive nanoparticles, antibacterial agents, and regenerative molecules capable of enhancing tissue healing while simultaneously reducing bacterial contamination. Such modifications may improve not

only the biological activity of repair materials but also their mechanical properties, handling characteristics, and resistance to degradation in challenging clinical environments [3,11,13].

Regenerative endodontics represents another promising direction for future development. Rather than functioning solely as passive sealing materials, future biomaterials may actively regulate cellular behavior by promoting stem cell recruitment, angiogenesis, and controlled tissue regeneration. Calcium silicate-based cements already exhibit several characteristics consistent with regenerative principles through calcium ion release and stimulation of mineralized tissue formation. However, further advances in tissue engineering and molecular biology may enable the development of multifunctional biomaterials capable of providing antimicrobial activity while simultaneously directing tissue repair at the cellular level [9,13].

Digital technologies are also expected to contribute to improved management of root perforations. High-resolution cone-beam computed tomography (CBCT), digital treatment planning, and operating microscopes have already enhanced the detection and localization of perforations. Future integration of artificial intelligence into diagnostic imaging may further improve diagnostic accuracy, facilitate treatment planning, and support clinical decision-making by identifying prognostic factors associated with successful repair. These technological developments may complement advances in biomaterials, leading to increasingly predictable treatment outcomes [2,3].

Another area requiring further investigation concerns patient-related factors that may influence healing following perforation repair. Variables such as systemic diseases, smoking status, age, periodontal condition, and the composition of the oral microbiome remain insufficiently explored in relation to treatment outcomes. A better understanding of these biological variables may ultimately support the development of more individualized treatment strategies and improve the predictability of clinical success [1,2].

Economic considerations should also receive greater attention in future research. Although newer bioceramic materials often provide practical advantages regarding handling and clinical convenience, comprehensive cost-effectiveness analyses remain limited. Future studies comparing treatment costs, procedural efficiency, long-term success rates, and patient-reported outcomes would provide valuable information for clinicians, healthcare systems, and policymakers responsible for selecting evidence-based treatment approaches [3].

Finally, future systematic reviews and meta-analyses should emphasize methodological consistency by applying standardized inclusion criteria, comparable outcome measures, and robust risk-of-bias assessment tools. Such efforts would strengthen the overall quality of evidence and facilitate direct comparisons among currently available biomaterials. As the body of clinical evidence continues to expand, future recommendations regarding material selection are expected to become increasingly precise and evidence-driven [1–4].

In summary, the future of root perforation repair is likely to be shaped by the integration of advanced biomaterials, regenerative strategies, digital technologies, and higher-quality clinical research. While currently available calcium silicate-based materials have already transformed the management of this challenging complication, continued scientific innovation and rigorous clinical investigation remain essential to further improve treatment predictability and patient outcomes.

10. Conclusions

Root perforation remains one of the most challenging complications encountered in endodontic practice because of its potential to compromise the integrity of the tooth and the surrounding periodontal tissues. Successful management depends on the prompt diagnosis of the defect, effective infection control, and the selection of a repair material capable of providing both a durable seal and favorable biological conditions for tissue regeneration. Over the past three decades, the introduction of calcium silicate-based biomaterials has fundamentally improved the prognosis of perforation repair, transforming what was once considered a frequently hopeless clinical situation into a highly predictable therapeutic procedure when managed appropriately [1,4,14,15].

Among currently available biomaterials, Mineral Trioxide Aggregate continues to represent the clinical reference standard because of its extensive scientific documentation, excellent biocompatibility, superior sealing ability, and well-established long-term clinical success. Despite practical limitations, including prolonged setting time, challenging handling characteristics, and the potential for tooth discoloration, the strength of evidence supporting MTA remains unmatched by newer repair materials [1,4,14,15].

Biodentine has emerged as a highly reliable alternative by addressing several shortcomings associated with conventional MTA. Its shorter setting time, improved handling characteristics, and reduced risk of

discoloration provide clear practical advantages while maintaining excellent biological performance and favorable clinical outcomes. Current evidence indicates that Biodentine offers comparable therapeutic potential for root perforation repair, although additional long-term clinical studies are required to establish an evidence base equivalent to that of MTA [2–4].

More recently introduced premixed bioceramic materials, including Bio-C Repair and EndoSequence BC Root Repair Material, represent an important step in the evolution of endodontic repair materials. Their simplified clinical application, excellent cytocompatibility, sustained calcium ion release, and bioactive properties make them attractive options for contemporary endodontic practice. However, although laboratory investigations and preliminary clinical studies have reported promising results, the current level of clinical evidence remains limited compared with that available for MTA. Consequently, their long-term effectiveness should continue to be evaluated through well-designed prospective clinical studies and randomized controlled trials [1–3,11].

A recurring finding throughout the available literature is that all contemporary calcium silicate-based materials share fundamental biological mechanisms responsible for successful perforation repair, including calcium ion release, hydroxyapatite formation, biocompatibility, and stimulation of mineralized tissue regeneration. Therefore, differences in clinical performance among these materials appear to be influenced more by handling characteristics, setting behavior, esthetic considerations, and operator preference than by major differences in biological potential [3,9,13].

The present review also highlights several important limitations within the current body of evidence. Considerable heterogeneity exists among published studies with respect to experimental methodologies, outcome measures, and follow-up duration, making direct comparisons difficult. Furthermore, while laboratory evidence is abundant, long-term randomized clinical trials remain relatively scarce for the newest generation of bioceramic materials. Addressing these methodological limitations should be considered a priority for future research to strengthen evidence-based recommendations for clinical practice [1–3].

From a clinical perspective, material selection should be individualized according to the specific characteristics of each case rather than based solely on the availability of newer technologies. Factors such as perforation size and location, duration of contamination, accessibility, esthetic requirements, and clinician experience should all be incorporated into the decision-making process. Contemporary calcium silicate-based biomaterials provide clinicians with multiple effective treatment options, allowing greater flexibility while maintaining high standards of biological and clinical performance [2–4].

In conclusion, calcium silicate-based biomaterials have significantly advanced the management of root perforation repair by combining excellent sealing ability with bioactive properties that actively support periodontal healing and tissue regeneration. While Mineral Trioxide Aggregate remains the benchmark against which newer materials are evaluated, Biodentine, Bio-C Repair, and EndoSequence BC Root Repair Material have expanded the therapeutic possibilities available to clinicians and represent valuable additions to modern endodontic practice. Continued innovation in biomaterial science, together with the generation of high-quality long-term clinical evidence, will further refine treatment strategies and contribute to increasingly predictable outcomes for patients requiring root perforation repair.

Author's contributions:

Conceptualization: Ewa Jurkowska, Zofia Wiśniewska

Methodology: Ewa Jurkowska

Software: Stanisław Jurkowski

Check: Zofia Wiśniewska

Formal Analysis: Stanisław Jurkowski

Investigation: Ewa Jurkowska, Zofia Wiśniewska

Resources: Ewa Jurkowska

Data curation: Stanisław Jurkowski

Writing - Original draft: Ewa Jurkowska

Writing - Review & editing: Ewa Jurkowski, Zofia Wiśniewska

Visualization: Stanisław Jurkowski

All authors have read and agreed with the published version of the manuscript.

Conflict of Interest Statement: The authors have declared no conflicts of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process.

In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool, the authors have reviewed and edited the content as needed.

REFERENCES

1. Pinheiro, L. S., Kopper, P. M. P., Quintana, R. M., Scarparo, R. K., & Grecca, F. S. (2021). Does MTA provide a more favourable histological response than other materials in the repair of furcal perforations? A systematic review. *International Endodontic Journal*, 54(12), 2195–2218.
2. Alshehri, M. M., Alhawsawi, B. F., Alghamdi, A. S., Alqahtani, A. S., Alghamdi, A. M., & Alzahrani, M. S. (2024). The management of root perforation: A review of the literature. *Cureus*, 16, e72296. <https://doi.org/10.7759/cureus.7229>
3. Ferraz, D. C., Rahhal, J. G., Dotto, M. E. P., Ferreira, L. A., Sipert, C. R., Letra, A., ... Souza, L. C. (2025). Physicochemical and biological properties of Biodentine xp, EndoSequence RRM, and Bio-C repair cements. *Journal of Endodontics*, 51(8), 1109–1117. <https://doi.org/10.1016/j.joen.2025.03.009>
4. Torabinejad, M., Parirokh, M., & Dummer, P. M. H. (2018). Mineral trioxide aggregate and other bioactive endodontic cements: An updated overview – part ii: Other clinical applications and complications. *International Endodontic Journal*, 51(3), 284–317. <https://doi.org/10.1111/iej.12843>
5. Setzer, F. C., Shah, S. B., Kohli, M. R., Karabucak, B., & Kim, S. (2022). Present status and future directions: Surgical endodontics. *International Endodontic Journal*, 55(Suppl. 4), 1020–1058. <https://doi.org/10.1111/iej.13783>
6. Shetty, A., Sultana, H. A., Srirekha, A., Champa, C., Pal, S., & Sahithi, V. (2025). Comparative evaluation of sealing potential of mineral trioxide aggregate, Biodentine, and Bio-C repair in furcation perforations: A glucose penetration study. *Journal of Conservative Dentistry and Endodontics*, 28(2), 144–149. https://doi.org/10.4103/JCDE.JCDE_749_24
7. Abraham, S., Diggikar, K. M., Nagmode, P., Lokhande, N., & Deshmukh, V. A. (2025). Spectrophotometric analysis of sealing ability of MTA, Biodentine, and Bio-C used for furcal perforations: An in vitro study. *Journal of Pharmacy and Bioallied Sciences*, 17(Suppl. 4), S3295–S3297. https://doi.org/10.4103/jpbs.jpbs_1376_25
8. Kesarwani, D., Mittal, S., Kumar, T., Keshav, V., Gilhotra, V., & Jain, A. (2025). A comparative evaluation of setting time in the presence of blood contamination of four root-end filling biomaterials (MTA angelus, Biodentine, EndoSequence root repair material, and Bio-C repair): An in vitro study. *Endodontology*, 38(1), 50–55. https://doi.org/10.4103/endo.endo_243_24
9. Abrão, S. M. S., Gregorio, D., Azevedo, M. K. C., et al. (2023). Cytotoxicity and genotoxicity of Bio-C repair, EndoSequence BC root repair, MTA angelus, and MTA repair hp. *Journal of Applied Oral Science*, 31, e20230547. <https://doi.org/10.1590/1678-7757-2023-0547>
10. Anija, R., Kalita, C., Satheesh, S. L., Seal, M., Kalita, T., & Saikia, A. (2025). Comparative analysis of Biodentine and mineral trioxide aggregate repair high plasticity in reinforcing roots with perforation: An in vitro study. *Journal of Conservative Dentistry and Endodontics*, 28(1), 63–67. https://doi.org/10.4103/JCDE.JCDE_711_24
11. Durgabhavani, G., Reddy, P. S., Kakollu, S., & Thummala, L. V. (2026). Sealing ability of nano-bioactive glass, Bio-C repair, and EndoSequence bioceramic root repair material putty as root-end restoratives: A confocal laser microscopic study. *Journal of Conservative Dentistry and Endodontics*, 29(1), 41–46. https://doi.org/10.4103/JCDE.JCDE_839_25
12. Silva, E. J. N. L., Carvalho, N. K., Prado, M. C., et al. (2018). Root perforations: Diagnosis, prognosis and materials. *Brazilian Oral Research*, 32(Suppl. 1), e73. <https://doi.org/10.1590/1807-3107bor-2018.vol32.0073>

13. Camilleri, J. (2015). Hydraulic calcium silicate cements in endodontics. Springer. <https://doi.org/10.1007/978-3-662-43727-0>
14. Parirokh, M., & Torabinejad, M. (2010). Mineral trioxide aggregate: A comprehensive literature review—Part i: Chemical, physical, and antibacterial properties. *Journal of Endodontics*, 36(1), 16–27. <https://doi.org/10.1016/j.joen.2009.09.006>
15. Parirokh, M., & Torabinejad, M. (2010). Mineral trioxide aggregate: A comprehensive literature review—Part ii: Leakage and biocompatibility investigations. *Journal of Endodontics*, 36(2), 190–202. <https://doi.org/10.1016/j.joen.2009.09.010>