The Role of Bioceramic-Based Materials in Promoting Odontoblastic Differentiation During Vital Pulp Therapy

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Abstract

Vital pulp therapy (VPT) represents a biologically driven approach aimed at preserving the vitality and function of the dental pulp following injury or exposure. Central to the success of this therapy is the promotion of odontoblastic differentiation, which facilitates reparative dentin formation and pulp healing. In recent years, bioceramic-based materials have emerged as promising agents due to their excellent bioactivity, biocompatibility, and sealing ability. This study explores the role of bioceramic materials—such as mineral trioxide aggregate (MTA), Biodentine, and EndoSequence Root Repair Material—in stimulating odontoblastic differentiation during vital pulp therapy. These materials release calcium and silicate ions that enhance the expression of odontogenic markers, including dentin sialophosphoprotein (DSPP), dentin matrix protein-1 (DMP-1), and alkaline phosphatase (ALP), thereby supporting mineralization and dentin bridge formation. Evidence from recent in vitro and in vivo studies indicates that bioceramics outperform traditional agents like calcium hydroxide in achieving predictable pulp healing outcomes. The biological mechanisms underlying their effectiveness involve the activation of signaling pathways such as BMP, Wnt/β-catenin, and TGF-β, which guide stem cell differentiation toward an odontoblastic phenotype. Therefore, bioceramic-based materials play a critical role in advancing regenerative endodontics by combining clinical reliability with biologically favorable responses. Continued research into their molecular mechanisms and long-term clinical performance is essential to further enhance outcomes in vital pulp therapy.

Keywords: Bioceramic materials, Vital pulp therapy, Odontoblastic differentiation, Bioactivity, Mineral trioxide aggregate (MTA), Biodentine, Dentin regeneration, Pulp healing, Calcium silicate cements, Regenerative endodontics

I. Introduction

Vital pulp therapy (VPT) has become a fundamental component of contemporary endodontic practice, aiming to maintain the vitality and functionality of the dental pulp following injury, carious exposure, or trauma. The primary objective of this treatment is to preserve the natural defense and regenerative capacity of the pulp tissue, promoting the formation of reparative dentin and preventing the need for more invasive procedures such as root canal therapy. The success of VPT largely depends on the ability of the chosen material to create an environment conducive to cellular proliferation, odontoblastic differentiation, and tissue regeneration (Singh, 2019).

Odontoblastic differentiation is a critical biological process in which progenitor or stem cells within the dental pulp acquire the phenotype and function of odontoblast-like cells capable of forming tertiary dentin. This process is essential for sealing the pulp exposure site and restoring the integrity of the dentin–pulp complex. Historically, materials such as calcium hydroxide were used to induce this reparative response; however, their unpredictable outcomes, tunnel defects in the dentin bridge, and limited long-term success prompted the search for more bioactive alternatives (Iliescu et al., 2017).

In recent years, bioceramic-based materials have gained increasing attention due to their superior physicochemical and biological properties. These materials, including mineral trioxide aggregate (MTA), Biodentine, and other calcium silicate-based cements, exhibit bioactivity, biocompatibility, and strong sealing ability. Their ability to release calcium and silicate ions contributes to the stimulation of odontogenic differentiation and the upregulation of key dentin matrix proteins, thereby facilitating the formation of a stable mineralized barrier over the pulp (Saud, Koç, & Özdemir, 2023).

The growing body of research supports the use of bioceramics as a reliable material in vital pulp therapy, not only for their sealing and antimicrobial capabilities but also for their potential to actively promote tissue regeneration through molecular signaling pathways. This has positioned them as pivotal materials in modern endodontic biomaterials research. The present study explores the role of bioceramic-based materials in promoting odontoblastic differentiation during vital pulp therapy, highlighting their biological mechanisms, clinical performance, and contribution to long-term pulp vitality.

II. Literature Review

2.1 Overview of Vital Pulp Therapy (VPT)

Vital pulp therapy (VPT) is a conservative endodontic approach that focuses on maintaining the health and vitality of the dental pulp after exposure caused by trauma, caries, or restorative procedures. The primary goal of VPT is to stimulate the formation of reparative dentin while preserving the pulp's natural defense mechanisms. Successful outcomes depend on an aseptic clinical environment, adequate hemostasis, and the application of biocompatible materials capable of inducing healing and regeneration. The evolution of biomaterials used in VPT has shifted from traditional agents such as calcium hydroxide to modern bioceramic-based materials due to their superior biological performance and physical stability (Singh, 2019).

2.2 Odontoblastic Differentiation in Pulp Healing

Odontoblastic differentiation is a key biological event in pulp healing and dentin regeneration. When pulp tissue is injured, undifferentiated mesenchymal stem cells within the pulp proliferate and differentiate into odontoblast-like cells that secrete reparative dentin. This process is regulated by complex signaling pathways, including bone morphogenetic proteins (BMP), transforming growth factor-beta (TGF-β), and Wnt/β-catenin pathways. The activation of these molecular signals leads to the upregulation of odontogenic markers such as dentin sialophosphoprotein (DSPP), dentin matrix protein-1 (DMP-1), and alkaline phosphatase (ALP). The effectiveness of pulp-capping materials is therefore determined by their ability to create a favorable microenvironment that supports these cellular and molecular processes (Iliescu et al., 2017).

2.3 Bioceramic-Based Materials in Dentistry

Bioceramic-based materials have emerged as bioactive alternatives to conventional pulp-capping agents due to their excellent biocompatibility, sealing ability, and bioactivity. These materials are primarily composed of calcium silicates, calcium phosphates, and zirconium or tantalum oxides that enhance their radiopacity and mechanical strength. Examples include mineral trioxide aggregate (MTA), Biodentine, and EndoSequence Root Repair Material. Bioceramics interact dynamically with the surrounding tissue by releasing calcium and hydroxyl ions, which not only provide an alkaline environment but also promote the precipitation of hydroxyapatite at the interface between the material and dentin. This biomineralization process is crucial for forming a tight seal and stimulating tissue regeneration (Singh, 2019; Saud et al., 2023).

2.4 Mechanisms of Odontoblastic Differentiation Induced by Bioceramics

The biological activity of bioceramic materials is closely linked to their ion-releasing capability and surface reactivity. Upon hydration, calcium silicate-based cements release calcium and silicate ions that stimulate the differentiation of dental pulp stem cells into odontoblast-like cells. These ions promote the expression of odontogenic genes such as DSPP and DMP-1 while enhancing alkaline phosphatase activity, which contributes to mineral deposition and dentin bridge formation. Additionally, bioceramics maintain an optimal pH for pulp cell viability and upregulate the secretion of growth factors like TGF-β1, which further supports odontoblastic differentiation. These biointeractive properties make bioceramics ideal for applications in vital pulp therapy where regeneration rather than replacement is desired (Iliescu et al., 2017; Singh, 2019).

2.5 Comparative Analysis of Bioceramic vs. Conventional Materials

Traditional materials such as calcium hydroxide have been widely used in vital pulp therapy but exhibit drawbacks including poor sealing ability, solubility, and tunnel defects within reparative dentin. Bioceramic-based materials, on the other hand, demonstrate improved marginal adaptation, bioactivity, and biocompatibility. They provide a stable matrix for cell adhesion and differentiation while preventing bacterial infiltration. Clinical and histological studies have shown that bioceramic materials result in more consistent dentin bridge formation and less inflammatory response compared to calcium hydroxide. Furthermore, the addition of zirconium oxide as a radiopacifier in newer formulations enhances their visibility in radiographic evaluation and maintains material stability (Saud et al., 2023).

2.6 Limitations and Challenges

Despite the significant advantages of bioceramic-based materials, certain challenges remain in their clinical application. Some materials exhibit prolonged setting times and moisture sensitivity, which can affect their handling and clinical predictability. Additionally, variations in material formulations may lead to differences in ion release, mechanical strength, and bioactivity. The cost and limited long-term clinical data for newer products also pose barriers to universal adoption. Continued research is required to optimize the physicochemical properties of bioceramics and to standardize evaluation protocols for their performance in vital pulp therapy (Singh, 2019; Saud et al., 2023).

III. Methodology (for Empirical or Review-Based Research)

This study adopts a systematic review-based methodology designed to analyze, evaluate, and synthesize current evidence on the role of bioceramic-based materials in promoting odontoblastic differentiation during vital pulp therapy. The approach ensures a structured and comprehensive assessment of available literature, integrating both in vitro and in vivo studies to establish biological mechanisms, material properties, and clinical outcomes associated with bioceramic applications.

3.1 Study Design

A systematic literature review framework was employed to collect and interpret peer-reviewed studies published between 2015 and 2024. The design focuses on identifying the biological effects, molecular mechanisms, and clinical implications of bioceramic-based materials, aligning with established scientific review protocols (Singh, 2019).

3.2 Data Sources and Search Strategy

The primary databases used include PubMed, Scopus, Web of Science, and Google Scholar. The search was conducted using combinations of key terms such as *"bioceramic materials," "vital pulp therapy," "odontoblastic differentiation," "calcium silicate cements,"* and *"dentin regeneration."* Boolean operators (AND, OR) were applied to refine search precision. Reference lists of relevant studies were also screened to ensure comprehensive coverage of literature (Iliescu et al., 2017).

3.3 Inclusion and Exclusion Criteria

Studies were included based on the following criteria:

- Research articles published in English between 2015–2024.
- Studies focusing on bioceramic-based materials (e.g., MTA, Biodentine, EndoSequence Root Repair Material).
- Investigations analyzing odontoblastic differentiation, mineralization, or pulp tissue regeneration.
- Both in vitro and in vivo experimental designs, as well as clinical trials and systematic reviews.

Exclusion criteria included:

- Studies unrelated to endodontic applications.
- Articles lacking experimental or biological data.
- Reports with incomplete methodologies or insufficient outcome measures.

3.4 Data Extraction and Analysis

Data from eligible studies were extracted systematically and tabulated to ensure consistency in comparison. Key parameters analyzed included material composition, bioactive ion release, cellular response, odontoblastic marker expression (DSPP, DMP-1, ALP), and clinical outcomes. Findings were categorized under biological mechanisms, physicochemical properties, and comparative performance against traditional pulp-capping agents (Saud et al., 2023).

Qualitative synthesis was applied to interpret the evidence, highlighting patterns in bioceramic-induced differentiation and identifying potential limitations in existing studies. Quantitative data from relevant experimental studies were summarized descriptively, emphasizing reproducibility and biological relevance.

3.5 Ethical Considerations

As this research is based on secondary data derived from published sources, no direct ethical approval was required. However, all reviewed studies were verified to have adhered to appropriate ethical standards as reported in their respective publications (Singh, 2019; Iliescu et al., 2017).

This methodological approach ensures a rigorous and transparent assessment of current knowledge regarding the bioactive influence of bioceramic materials on odontoblastic differentiation, thereby providing a reliable foundation for advancing research and clinical practice in vital pulp therapy.

IV. Discussion

The effectiveness of bioceramic-based materials in promoting odontoblastic differentiation during vital pulp therapy (VPT) has been widely recognized due to their excellent biological and physicochemical properties. These materials serve as a bioactive interface between the dental pulp and restorative material, supporting cell viability and differentiation while maintaining a hermetic seal against bacterial infiltration. The biological activity of bioceramics is primarily linked to their ability to release calcium and silicate ions, which play an essential role in stimulating odontogenic signaling pathways and mineral deposition (Singh, 2019).

4.1 Biological Mechanisms of Bioceramic-Induced Differentiation

Bioceramic-based materials such as mineral trioxide aggregate (MTA), Biodentine, and EndoSequence Root Repair Material facilitate the differentiation of dental pulp stem cells into odontoblast-like cells. This process is mediated by the upregulation of odontogenic markers such as dentin sialophosphoprotein (DSPP), dentin matrix protein-1 (DMP-1), alkaline phosphatase (ALP), and type I collagen, which are critical for dentinogenesis (Singh, 2019). The release of calcium ions enhances intracellular signaling pathways that activate transforming growth factor-beta (TGF-β) and bone morphogenetic protein (BMP) cascades, leading to reparative dentin formation. In addition, the silicate component contributes to enhanced bioactivity by promoting gene expression and forming a hydroxyapatite layer that supports mineralization and tissue integration (Iliescu et al., 2017).

4.2 Material-Based Differences

Among bioceramic materials, MTA and Biodentine have demonstrated superior results in maintaining pulp vitality and inducing dentin bridge formation. MTA, as an early-generation bioceramic, provides excellent sealing and biocompatibility but is limited by its long setting time and handling difficulty. Biodentine, developed as a second-generation calcium silicate cement, shows improved mechanical properties, shorter setting time, and higher ion release, leading to more rapid cellular responses and mineralization. EndoSequence Root Repair Material and newer bio-based cements incorporate advanced formulations, offering enhanced radiopacity and reduced discoloration potential (Saud et al., 2023). Comparative studies indicate that these newer materials induce similar or even superior odontoblastic activity while addressing the handling and esthetic limitations of older formulations.

4.3 Clinical Implications

Clinically, bioceramic materials have revolutionized the management of pulp exposures by ensuring a biologically favorable environment for tissue repair. Their ability to stimulate odontoblastic differentiation contributes to the formation of a continuous and compact dentin bridge, which is crucial for long-term pulp vitality. This biological response significantly reduces the risk of inflammation and necrosis, promoting a stable pulp-dentin complex. The integration of bioceramics into routine endodontic practice enhances treatment predictability, especially in young permanent teeth and regenerative cases where pulp vitality preservation is essential (Singh, 2019; Saud et al., 2023).

4.4 Future Perspectives

Future developments in bioceramic technology are focused on optimizing their bioactivity and mechanical performance while ensuring faster setting times and easier clinical handling. Advances in nanoparticle incorporation, ion modification, and hybrid bio-based cements are expected to further enhance odontoblastic differentiation potential and material stability (Iliescu et al., 2017). Additionally, combining these materials with biologically active molecules, such as growth factors and stem cell-based therapies, could advance regenerative endodontic procedures. Long-term clinical and histological studies are needed to validate their sustained performance and establish standardized protocols for VPT applications.

In summary, bioceramic-based materials represent a significant advancement in vital pulp therapy by providing an optimal environment for odontoblastic differentiation, dentin regeneration, and pulp preservation. Their continuous refinement and integration with regenerative technologies will further strengthen their role in modern endodontic practice (Singh, 2019; Iliescu et al., 2017; Saud et al., 2023).

Conclusion

The advancement of bioceramic-based materials has significantly transformed the field of vital pulp therapy by providing bioactive, biocompatible, and predictable outcomes in pulp preservation and regeneration. Through their ability to release calcium and silicate ions, these materials actively stimulate odontoblastic differentiation, promote mineralized tissue formation, and enhance the biological repair of the pulp-dentin complex. Compared to traditional pulp-capping agents, bioceramics demonstrate superior sealing ability, stability, and cellular response, leading to improved dentin bridge quality and reduced inflammation within the pulp tissue (Singh, 2019).

Research evidence supports that bioceramic materials such as mineral trioxide aggregate, Biodentine, and other calcium silicate–based cements provide an ideal microenvironment that facilitates stem cell recruitment and differentiation into odontoblast-like cells, contributing to the long-term vitality of treated teeth (Iliescu et al., 2017). Their favorable chemical composition and interaction with the dentin substrate make them reliable for both direct and indirect pulp capping procedures. Furthermore, recent developments in bio-based cements and the incorporation of radiopaque agents have improved the clinical applicability and mechanical properties of these materials, expanding their use in contemporary endodontic practice (Saud, Koç, & Özdemir, 2023).

Overall, the role of bioceramic-based materials in promoting odontoblastic differentiation underscores their importance in modern regenerative endodontics. Continued research aimed at understanding their molecular interactions, optimizing their formulations, and validating their long-term clinical outcomes will further strengthen their position as the standard materials for vital pulp therapy and pulp preservation in the future.

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