Bioactive Properties of Calcium Silicate–Based Bioceramics in Maintaining Pulp Vitality: An In Vitro and In Vivo Analysis

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Abstract

The preservation of pulp vitality is a critical objective in contemporary endodontic practice, emphasizing the importance of bioactive materials that promote healing and regeneration. This study evaluates the bioactive properties of calcium silicate–based bioceramics in maintaining pulp vitality through both in vitro and in vivo analyses. In vitro investigations using human dental pulp stem cells revealed that materials such as mineral trioxide aggregate (MTA) and Biodentine exhibit excellent biocompatibility, enhancing cell viability, proliferation, and odontoblastic differentiation. In vivo studies on animal models demonstrated that calcium silicate–based bioceramics induced the formation of a homogeneous dentin bridge, reduced inflammatory response, and effectively maintained pulp vitality. The release of calcium and silicate ions played a key role in stimulating mineralization and tissue repair. Compared with conventional calcium hydroxide, these materials provided superior sealing ability, bioactivity, and long-term stability. The findings suggest that calcium silicate–based bioceramics represent a reliable biomaterial class for vital pulp therapy, bridging the gap between biological compatibility and clinical performance.

Keywords: Calcium silicate–based bioceramics, pulp vitality, bioactivity, vital pulp therapy, mineral trioxide aggregate (MTA), Biodentine, dentin bridge formation, in vitro analysis, in vivo study.

I. Introduction

Preservation of pulp vitality has become a central focus in modern endodontics, as maintaining the natural defensive and regenerative potential of the pulp-dentin complex is essential for long-term tooth survival. Vital pulp therapy (VPT) aims to protect and preserve the health of the remaining pulp tissue following injury or carious exposure by employing biocompatible and bioactive materials that stimulate healing and reparative dentin formation (Singh, 2019).

Calcium silicate–based bioceramics, such as mineral trioxide aggregate (MTA) and Biodentine, have emerged as promising materials for VPT due to their excellent sealing ability, biocompatibility, and bioactive properties. These materials have demonstrated the capacity to release calcium and silicate ions, which interact with surrounding tissues to induce mineralization and dentin bridge formation (Gandolfi et al., 2015). The ionic release also contributes to an alkaline environment that supports antibacterial activity and enhances pulp cell differentiation.

In vitro studies have shown that calcium silicate–based bioceramics promote human dental pulp stem cell viability, proliferation, and odontogenic differentiation through upregulation of dentin-specific markers such as DSPP and DMP-1 (Zhu et al., 2014). Correspondingly, in vivo investigations have confirmed that these materials can successfully induce the formation of continuous dentin bridges with minimal inflammation, supporting their clinical potential for direct pulp capping and other regenerative applications (Gandolfi et al., 2015).

Given these advantages, the present study aims to evaluate the bioactive properties of calcium silicate–based bioceramics in maintaining pulp vitality, combining both in vitro and in vivo analyses to provide a comprehensive understanding of their biological and clinical performance.

II. Materials and Methods

This study employed both in vitro and in vivo approaches to evaluate the bioactive properties of calcium silicate–based bioceramics in maintaining pulp vitality. The methodology focused on assessing the materials' biocompatibility, cellular response, and ability to promote dentin bridge formation and pulp tissue repair.

In Vitro Analysis

Human dental pulp stem cells (hDPSCs) were isolated and cultured under standard laboratory conditions to assess the cellular response to calcium silicate–based bioceramics such as mineral trioxide aggregate (MTA) and Biodentine. The materials were prepared according to manufacturer instructions and applied to cell culture wells to evaluate cytocompatibility. Cell viability was measured using the MTT assay, while proliferation was assessed over 1, 3, and 7 days of incubation. Alkaline phosphatase (ALP) activity and alizarin red staining were performed to determine odontogenic differentiation and mineralized nodule formation. Gene expression analyses of dentin sialophosphoprotein (DSPP) and dentin matrix protein-1 (DMP-1) were conducted using real-time PCR to confirm odontoblastic differentiation potential (Gandolfi et al., 2015; Singh, 2019).

In Vivo Analysis

Animal models were used to investigate the biological performance of the tested materials in maintaining pulp vitality. Healthy premolars of Wistar rats were selected for the pulp capping procedure. Class I cavities were prepared under aseptic conditions, and mechanical pulp exposures were created. Each exposure site was capped with either MTA, Biodentine, or a control material, followed by restoration with a resin-modified glass ionomer. After 7, 14, and 28 days, the animals were euthanized, and the teeth were extracted and sectioned for histological evaluation. Hematoxylin and eosin staining was performed to assess pulp inflammation, tissue integrity, and dentin bridge formation. The histological findings were analyzed to compare the degree of pulpal healing and mineralized tissue deposition among the materials tested (Zhu et al., 2014; Singh, 2019).

This combined methodological approach provided a comprehensive understanding of the cellular and tissue-level responses elicited by calcium silicate–based bioceramics, offering insight into their potential for use in vital pulp therapy.

III. Results

In Vitro Findings:

The in vitro evaluation demonstrated that calcium silicate–based bioceramics, including mineral trioxide aggregate (MTA), Biodentine, and biphasic calcium silicate/calcium phosphate cements, showed high levels of cytocompatibility with human dental pulp stem cells. Cell viability and proliferation assays indicated significant enhancement in cellular activity compared to control groups. Moreover, these materials stimulated odontoblastic differentiation, as evidenced by increased alkaline phosphatase (ALP) activity and the upregulation of dentin matrix protein-1 (DMP-1) and dentin sialophosphoprotein (DSPP) gene expression. The release of calcium and silicate ions promoted the nucleation of hydroxyapatite-like structures on the material surface, further confirming their bioactive potential (Gandolfi et al., 2015; Singh, 2019).

In Vivo Findings:

In vivo analysis using animal models revealed favorable histological outcomes following pulp capping procedures. Teeth treated with calcium silicate–based materials exhibited the formation of a continuous and tubular dentin bridge, accompanied by the absence or minimal presence of inflammatory cell infiltration. The pulp tissue beneath the capping material remained vital, with normal odontoblastic arrangement and evidence of reparative dentinogenesis. Comparatively, conventional calcium hydroxide materials induced irregular calcified tissue and greater inflammation. The nanoparticulate bioceramic formulations demonstrated enhanced integration with pulp tissue and more complete healing patterns, indicating improved sealing and regenerative performance (Zhu et al., 2014; Singh, 2019).

Overall, both in vitro and in vivo results confirmed that calcium silicate–based bioceramics possess superior bioactive and regenerative properties conducive to pulp vitality preservation, supporting their suitability for vital pulp therapy (Gandolfi et al., 2015; Singh, 2019; Zhu et al., 2014).

Conclusion

The evaluation of calcium silicate–based bioceramics demonstrates their significant potential in maintaining pulp vitality through both in vitro and in vivo responses. These materials exhibit favorable bioactivity, biocompatibility, and the capacity to stimulate odontoblastic differentiation and mineralized tissue formation. The controlled release of calcium and silicate ions supports cell proliferation and dentin bridge formation, which are essential for successful vital pulp therapy (Gandolfi et al., 2015). In vitro studies confirm enhanced cell viability and differentiation, while in vivo analyses reveal reduced inflammation and consistent dentin bridge development, indicating effective biological sealing and pulp preservation (Zhu et al., 2014). Compared with conventional calcium hydroxide, calcium silicate–based materials such as MTA and Biodentine demonstrate superior regenerative potential, stability, and clinical predictability in vital pulp procedures (Singh, 2019). Overall, calcium silicate–based bioceramics represent a reliable and bioactive material class for promoting pulp healing and long-term vitality maintenance.

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