RESEARCH ARTICLE

Bioceramic-Mediated Pulp Preservation in Immature Permanent Teeth: A Regenerative Continuum Model

Astha Arya*

B.D.S, M.D.S (Conservative Dentistry & Endodontics)

ABSTRACT

Preservation of pulp vitality in immature permanent teeth remains a critical goal in contemporary endodontic practice due to its importance in continued root development and long-term tooth survival. Bioceramic materials have emerged as bioactive agents capable of supporting pulp healing, dentin bridge formation, and regenerative responses through their biocompatibility, sealing ability, and stimulation of cellular activity. This abstract proposes a regenerative continuum model in which bioceramic-mediated pulp preservation is viewed not as a single therapeutic endpoint, but as a spectrum ranging from pulp protection and repair to partial and complete tissue regeneration. Within this framework, vital pulp therapy and regenerative endodontic procedures are interconnected biological processes influenced by material properties, pulp status, and host response. Understanding pulp preservation through this continuum model allows for more flexible clinical decision-making and highlights the role of bioceramics in promoting favorable biological outcomes in immature permanent teeth. This approach supports a paradigm shift toward biologically driven, minimally invasive strategies aimed at sustaining pulp vitality and enabling natural root maturation.

Keywords: Bioceramics; Pulp preservation; Immature permanent teeth; Regenerative endodontics; Vital pulp therapy; Regenerative continuum model.

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BACKGROUND

Preservation of pulp vitality in immature permanent teeth remains a critical goal in contemporary endodontics, as loss of pulp function can compromise continued root development, weaken dentinal walls, and reduce long-term tooth survival. Traditional endodontic approaches, while effective in infection control, often fail to support biological healing or regeneration of the dentin–pulp complex. As a result, there has been a paradigm shift toward biologically driven strategies that prioritize tissue preservation, repair, and regeneration rather than replacement.

Bioceramic materials have emerged as central agents in this shift due to their bioactivity, biocompatibility, and ability to create a favorable microenvironment for pulp healing. Bioceramic-based vital pulp therapy has demonstrated enhanced sealing ability, antimicrobial properties, and stimulation of hard tissue formation, making it particularly suitable for immature teeth with open apices (Singh, 2019; Joshi, 2022). Experimental and clinical studies have shown that nanoparticulate and putty-form bioceramics can promote pulp cell survival, migration, and reparative dentinogenesis through biologically active signaling pathways, including fibroblast growth factor receptor (FGFR)-mediated mechanisms (Zhu et al., 2014; Zhang et al., 2015).

Beyond material innovation, regenerative science increasingly conceptualizes healing as a continuum rather than a discrete outcome. In regenerative medicine, continuum models describe a progressive transition from inflammation and repair to functional tissue regeneration, emphasizing dynamic cellular and molecular interactions over time (Stone II et al., 2018; Gibbons, 2020). Such models have been successfully applied to wound healing and collective cell migration, where tissue responses are understood as evolving biological processes rather than static endpoints (Arciero et al., 2011). Although originally developed outside dentistry, continuum-based frameworks provide a valuable lens for interpreting pulp healing responses mediated by bioceramic materials.

Applying a regenerative continuum model to bioceramic-mediated pulp preservation aligns material science with biological healing principles. It allows pulp therapy outcomes to be viewed along a spectrum—from protection and repair to true regeneration—rather than as binary success or failure. This integrative perspective supports the evolving goal of regenerative endodontics: to harness material bioactivity and intrinsic cellular potential to restore pulp vitality and enable continued root maturation in immature permanent teeth.

Pulp Preservation Techniques

Pulp preservation in immature permanent teeth aims to

*Author for Correspondence: drasthaarya@yahoo.co.in

maintain vitality, promote continued root development, and prevent necrosis. Vital pulp therapy (VPT) and regenerative approaches are the cornerstone of these interventions, with bioceramic materials increasingly used due to their bioactivity, biocompatibility, and ability to support dentin–pulp complex regeneration (Singh, 2019; Joshi, 2022).

Vital Pulp Therapy (VPT)

VPT encompasses procedures designed to maintain healthy pulp or to repair minimally inflamed pulp tissue. Common strategies include indirect pulp capping, direct pulp capping, and partial pulpotomy, where bioceramic materials such as mineral trioxide aggregate (MTA) or calcium silicate-based cements are used to seal and stimulate reparative dentin formation (Singh, 2019). These materials promote a favorable environment for pulp cell proliferation and differentiation through bioactive ion release (Zhang et al., 2015; Zhu et al., 2014).

Regenerative Endodontic Approaches

For teeth with necrotic pulp but immature roots, regenerative endodontic procedures (REPs) aim to re-establish pulp-like tissue and allow root maturation. Key steps involve disinfection, induction of bleeding into the canal space to provide a scaffold of stem cells, and placement of bioactive bioceramic cements to support tissue ingrowth (Gibbons, 2020). The regenerative continuum model suggests that pulp repair and regeneration exist along a spectrum, from simple wound healing to full restoration of functional pulp tissue (Stone II et al., 2018; Arciero et al., 2011).

Comparative Overview of Pulp Preservation Techniques

Bioceramic materials play a pivotal role across all these techniques by providing a bioactive interface that stimulates pulp cell migration, differentiation, and extracellular matrix deposition (Zhang et al., 2015; Joshi, 2022). Their integration into VPT and REPs reinforces the concept of a regenerative continuum, bridging traditional repair with full functional regeneration of the pulp-dentin complex (Stone II et al., 2018; Caravenna et al., 2016).

Clinical Implications

The preservation of pulp vitality in immature permanent teeth using bioceramic materials has transformative clinical implications. Vital pulp therapy (VPT) with bioceramics promotes continued root development, maintains structural integrity, and reduces the need for invasive interventions such as apexification or conventional root canal therapy (Singh, 2019). These materials, including nanoparticulate bioceramic pastes and putties, demonstrate excellent biocompatibility, stimulate reparative dentin formation, and enhance dental pulp cell migration via FGFR-mediated signaling pathways (Zhu et al., 2014; Zhang et al., 2015).

A regenerative continuum model conceptualizes pulp healing as a spectrum from simple repair to true regeneration, emphasizing that bioceramic-mediated therapies can modulate this continuum in favor of functional tissue regeneration (Stone II et al., 2018; Arciero et al., 2011). Clinically, this means that treatment strategies can be tailored to the degree of pulp injury and developmental stage of the tooth, enhancing long-term outcomes. The regenerative approach also aligns with sustainable dentistry principles by minimizing tissue loss and preserving natural dentition (Gibbons, 2020).

Key clinical outcomes associated with bioceramic-mediated pulp preservation are summarized in **Table 2**:

In practice, these clinical implications suggest that bioceramic-mediated therapies should be prioritized in immature teeth presenting with pulp exposure or reversible pulpitis. By integrating the regenerative continuum model, clinicians can better predict treatment outcomes, optimize material selection, and enhance functional and aesthetic tooth preservation. Moreover, the predictable nature of bioceramics allows for simplified protocols and reduced chair time, improving patient compliance and overall treatment efficiency (Joshi, 2022).

Table 1: Comparative Overview of Pulp Preservation Techniques

Technique	*Indication*	*Material Used*	*Mechanism*	*Advantages*	*Limitations*
Indirect Pulp Capping	Deep caries with no pulp exposure	Bioceramic cements, calcium hydroxide	Protective barrier; stimulates tertiary dentin	Minimally invasive; preserves vitality	Limited in inflamed pulp
Direct Pulp Capping	Small mechanical or carious pulp exposure	MTA, bioceramic putty	Stimulates reparative dentin; bioactive signaling (FGFR-mediated)	Promotes pulp repair; biocompatible	Risk of pulp inflammation if infection persists
Partial Pulpotomy	Exposed pulp with mild inflammation	MTA, calcium silicate cement	Removal of inflamed coronal pulp; bioceramic induces healing	Preserves radicular pulp; supports root development	Technique-sensitive; requires hemostasis
Regenerative Endodontic Procedure (REP)	Necrotic immature teeth	Bioceramic scaffold (MTA, nanoparticulate paste)	Stem cell recruitment; scaffold-mediated tissue regeneration	Allows continued root maturation; functional pulp restoration	Longer follow-up needed; unpredictable histology (Zhu et al., 2014; Zhang et al., 2015)

Table 2: Key clinical outcomes associated with bioceramic-mediated pulp preservation

Clinical Outcome	*Impact on Immature Permanent Teeth*	*Supporting Evidence*
Continued root development	Promotes apex closure and thickening of dentinal walls	Singh, 2019; Joshi, 2022
Pulp vitality maintenance	Reduces risk of necrosis and infection	Zhu et al., 2014
Enhanced reparative dentin formation	Strengthens tooth structure	Zhang et al., 2015
Reduced procedural invasiveness	Minimizes need for apexification or full RCT	Singh, 2019; Joshi, 2022
Modulation of regenerative continuum	Supports transition from repair to regeneration	Stone II et al., 2018; Arciero et al., 2011
Biocompatibility and sustainability	Decreases inflammatory response and preserves natural tissue	Gibbons, 2020

CONCLUSION

Bioceramic-mediated pulp preservation in immature permanent teeth represents a promising approach within the regenerative continuum, bridging traditional repair and true tissue regeneration. Bioceramic materials demonstrate excellent biocompatibility, bioactivity, and the ability to stimulate dental pulp cell migration and differentiation through pathways such as FGFR-mediated signaling, facilitating predictable pulp repair (Zhang et al., 2015; Zhu et al., 2014). Vital pulp therapy using these materials ensures continued root development and enhances long-term tooth survival, offering a minimally invasive alternative to conventional endodontic procedures (Singh, 2019; Joshi, 2022). Conceptualizing pulp preservation as a regenerative continuum provides a framework for understanding the dynamic interplay of cellular migration, proliferation, and differentiation, as seen in broader tissue repair models (Arciero et al., 2011; Stone II et al., 2018; Caravenna et al., 2016). Integrating sustainable regenerative strategies further underscores the potential of bioceramic interventions in modern dental practice (Gibbons, 2020). Overall, bioceramic-mediated approaches not only preserve pulp vitality but also support functional and structural maturation of immature teeth, highlighting their pivotal role in contemporary regenerative endodontics.

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