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RESEARCH ARTICLE

Bioactive Ion Release Dynamics of Novel Bioceramic Pulp Capping Materials and Their Influence on Tertiary Dentin Architecture

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ABSTRACT

Bioceramic pulp capping materials have emerged as promising alternatives to conventional calcium-based agents due to their enhanced bioactivity and biocompatibility. This study investigates the bioactive ion release dynamics of novel bioceramic pulp capping materials and their influence on tertiary dentin architecture. Emphasis is placed on the controlled release of calcium, silicon, and phosphate ions and their role in modulating pulp cell behavior and mineralization processes. The interaction between ion release profiles and dentin–pulp complex responses is examined, highlighting mechanisms that promote odontoblastic differentiation and organized tertiary dentin formation. Findings suggest that sustained bioactive ion release contributes to improved dentinal bridge quality, structural integrity, and reduced inflammatory response. These outcomes underscore the potential of novel bioceramic materials to enhance pulp healing and long-term restorative success.

Keywords: Bioceramics; Pulp capping; Bioactive ion release; Tertiary dentin; Dentinal bridge; Pulp–dentin complex

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INTRODUCTION TO BIOCERAMIC PULP CAPPING MATERIALS

Preservation of pulp vitality is a central objective in contemporary restorative dentistry, particularly in the management of deep carious lesions and traumatic pulp exposures. Vital pulp therapy relies heavily on the selection of pulp capping materials capable of protecting the pulp tissue, stimulating repair, and promoting the formation of tertiary dentin. Traditional materials such as calcium hydroxide have demonstrated clinical success; however, their limitations—including poor sealing ability, material dissolution, and inconsistent dentin bridge formation—have driven the development of advanced bioactive alternatives (Singh, 2019; Iliescu et al., 2019).

Bioceramic pulp capping materials have emerged as a significant advancement due to their inherent bioactivity, biocompatibility, and capacity to release therapeutic ions. These materials are typically composed of calcium silicates, calcium phosphates, or bioactive glass systems that interact favorably with the dentin–pulp complex. Upon contact with physiological fluids, bioceramics release ions such as calcium, phosphate, strontium, and silicate, which play a critical role in mineralization processes, cellular signaling, and pulp tissue regeneration (Sanz et al., 2019; Pires et al., 2020).

Recent research has highlighted the role of nano-structured and ion-doped bioceramics in enhancing biological performance. Nanoparticulate formulations increase surface area and reactivity, thereby improving ion exchange and cellular interactions at the pulp interface (Porenczuk, 2018; Besinis et al., 2015). Experimental materials incorporating bioactive glasses or strontium-doped components have demonstrated promising results in stimulating odontogenic differentiation and reparative dentin formation both in vitro and in vivo (Mandakhbayar et al., 2019; Zhu et al., 2014; Mocquot et al., 2020).

Compared with conventional pulp capping agents, bioceramic materials exhibit superior sealing ability, chemical stability, and favorable interfacial bonding with dentin. These properties contribute to reduced microleakage,

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enhanced pulp cell viability, and more organized tertiary dentin architecture (Fayyad & ElBaz, 2018; Sanz et al., 2019). As a result, bioceramics are increasingly regarded as a paradigm shift in direct pulp capping and regenerative pulp therapies, offering biologically driven solutions aligned with minimally invasive dentistry principles (Iliescu et al., 2019).

Overall, bioceramic pulp capping materials represent a critical evolution in restorative and regenerative endodontics, with their bioactive ion release serving as a key mechanism underpinning pulp healing and dentin regeneration.

Ion Release Dynamics in Physiological Conditions

The bioactivity of novel bioceramic pulp capping materials is largely governed by their ability to release therapeutic ions when exposed to physiological conditions such as dentinal fluid, tissue fluids, or simulated body fluids. Upon contact with moisture, these materials undergo hydration and dissolution reactions that trigger the controlled release of biologically active ions, including calcium (Ca^{2+}), hydroxyl (OH^-), phosphate (PO_4^{3-}), silicate (SiO_4^{4-}), and, in some formulations, strontium (Sr^{2+}) or fluoride (F^-). This ion exchange at the material–pulp interface creates a dynamic microenvironment favorable for pulp healing and mineralized tissue formation (Singh, 2019; Sanz et al., 2019).

Calcium and hydroxyl ion release is particularly critical, as it leads to an alkaline pH that provides antibacterial effects and stimulates pulp cell differentiation. Elevated pH conditions promote the activation of alkaline phosphatase and other mineralization-related enzymes, enhancing the nucleation of calcium phosphate phases that resemble hydroxyapatite (Pires et al., 2020). Silicate ions further contribute by upregulating genes associated with odontoblastic differentiation and extracellular matrix formation, thereby supporting tertiary dentinogenesis (Porenczuk, 2018).

The kinetics of ion release are influenced by material composition, particle size, crystallinity, and porosity. Nanostructured bioceramics and bioactive glass–based systems exhibit a higher surface area, resulting in faster and more sustained ion release compared to conventional calcium hydroxide-based materials (Besinis et al., 2015; Zhu et al., 2014). Additionally, doped bioceramics, such as strontium-containing formulations, demonstrate enhanced bioactivity through synergistic ion release that improves cell proliferation and mineral deposition in the dentin–pulp complex (Mandakhbayar et al., 2019).

Importantly, ion release from bioceramic pulp capping materials is not a transient event but a prolonged process that supports continuous biological signaling. This sustained release profile distinguishes modern bioceramics from traditional materials and underpins their ability to induce a more organized and mechanically stable tertiary dentin structure (Iliescu et al., 2019; Mocquot et al., 2020).

Overall, the ion release dynamics of bioceramic pulp capping materials under physiological conditions play a central role in modulating the pulp healing response. Through sustained and multi-ionic release, these materials create a biologically instructive environment that supports pulp vitality and guides the formation of structurally organized tertiary dentin (Fayyad & ElBaz, 2018; Sanz et al., 2019).

Influence on Tertiary Dentin Formation and Architecture

Bioactive bioceramic pulp capping materials exert a significant influence on the quality, rate, and structural organization of tertiary dentin formed following pulp exposure. Their ability to release biologically relevant ions such as calcium, hydroxyl, phosphate, silicate, and trace elements (e.g., strontium) creates a microenvironment conducive to pulp healing and controlled hard tissue deposition. This bioactivity differentiates modern bioceramics from traditional pulp capping agents, which often induce irregular or poorly organized dentin bridges (Singh, 2019; Sanz et al., 2019).

Ion release from bioceramic materials stimulates odontoblast-like cell differentiation and promotes the secretion of extracellular matrix proteins essential for dentinogenesis. Calcium and silicate ions play a central role in activating signaling pathways associated with mineralization, including alkaline phosphatase activity and the expression of dentin sialophosphoprotein (DSPP), resulting in more continuous and tubular tertiary dentin (Pires et al., 2020; Zhu et al., 2014). Compared with reparative dentin formed under calcium hydroxide, bioceramic-induced tertiary dentin exhibits fewer tunnel defects, increased thickness, and improved sealing ability at the dentin–pulp interface (Iliescu et al., 2019).

Nanostructured and ion-doped bioceramics further refine tertiary dentin architecture by enhancing ion exchange kinetics and surface reactivity. Strontium-doped bioactive glass cements, for instance, have been shown to accelerate odontogenic differentiation while modulating inflammatory responses, leading to more homogeneous and mechanically stable dentin bridges (Mandakhbayar et al., 2019). Similarly, nanoparticulate bioceramic pastes promote the formation of dentin with well-aligned tubules

Table 1: Major Ions Released from Bioceramic Pulp Capping Materials and Their Biological Roles

Released Ion	*Primary Source in Bioceramics*	*Biological Function in Physiological Conditions*	*Influence on Dentin–Pulp Complex*
Calcium (Ca^{2+})	Calcium silicates, bioactive glass	Stimulates odontoblast differentiation; promotes mineral nucleation	Enhances tertiary dentin thickness and continuity
Hydroxyl (OH^{-})	Hydration of calcium silicates	Increases local pH; antibacterial effect	Protects pulp tissue and favors reparative dentin formation
Phosphate (PO_4^{3-})	Bioactive glass, calcium phosphates	Combines with calcium to form apatite	Supports biomimetic dentin mineralization
Silicate (SiO_4^{4-})	Calcium silicate cements, bioactive glass	Activates mineralization-related genes	Improves dentin matrix organization
Strontium (Sr^{2+})	Doped bioactive glass cements	Enhances cell proliferation and mineral deposition	Improves quality and stability of tertiary dentin

resembling primary dentin rather than tubular calcified barriers (Zhu et al., 2014; Porenczuk, 2018).

The architectural characteristics of tertiary dentin formed under bioceramic materials are also influenced by their interfacial behavior with dentin. The formation of a mineral infiltration zone and apatite-like layers enhances micromechanical bonding and provides a scaffold for guided dentin deposition (Pires et al., 2020; Mocquot et al., 2020). This results in a more functional dentin–pulp complex capable of long-term pulp vitality preservation.

Overall, the influence of bioceramic ion release on tertiary dentin formation is characterized by improved structural continuity, biomimetic tubularity, and enhanced biological sealing. These features support a paradigm shift toward regenerative-oriented pulp capping strategies rather than mere reparative responses (Fayyad & ElBaz, 2018; Besinis et al., 2015).

Comparative Performance with Conventional Materials

Bioceramic pulp capping materials demonstrate clear performance advantages over conventional materials such as calcium hydroxide and resin-modified glass ionomer cements, particularly in terms of bioactivity, ion release stability, and quality of tertiary dentin formation. Conventional calcium hydroxide has long been considered the gold standard due to its antibacterial properties and ability to stimulate reparative dentin; however, it exhibits significant drawbacks, including poor sealing ability, material solubility, tunnel defects in dentin bridges, and limited long-term stability (Singh, 2019; Sanz et al., 2019).

In contrast, novel bioceramic materials—such as calcium silicate–based cements, nanoparticulate bioceramics, and ion-doped bioactive glasses—release biologically relevant ions (Ca^{2+}, Si^{4+}, Sr^{2+}, PO_4^{3-}) in a sustained manner. This controlled ion release enhances odontoblast-like cell differentiation, promotes mineralized matrix deposition, and results in thicker, more homogeneous tertiary dentin with fewer structural defects (Zhu et al., 2014; Mandakhbayar et al., 2019). The alkaline pH generated by bioceramics is more stable over time compared to calcium hydroxide, reducing pulp inflammation while maintaining antimicrobial activity (Sanz et al., 2019).

Resin-based materials, although mechanically strong and aesthetically favorable, are generally bioinert and may release unpolymerized monomers that adversely affect pulp cell viability. Ion-releasing bioceramic materials show superior interfacial behavior with dentin, including biomineralization at the material–tissue interface and formation of hydroxyapatite-like layers, which are not observed with conventional resins (Pires et al., 2020; Mocquot et al., 2020).

Nano-engineered bioceramic formulations further enhance performance by increasing surface area, accelerating ion exchange, and improving cellular interactions. Studies comparing nano-bioceramics with their conventional counterparts report improved pulp healing, higher-quality dentin bridges, and reduced inflammatory response (Fayyad & ElBaz, 2018; Porenczuk, 2018). These findings support a paradigm shift toward bioactive, ion-releasing systems in vital pulp therapy (Iliescu et al., 2019).

Overall, the comparative evidence indicates that novel bioceramic pulp capping materials outperform conventional alternatives by combining favorable mechanical properties

Table 2: Major Comparative Table: Bioceramic vs Conventional Pulp Capping Materials

Bioceramic Material Type	*Key Released Ions*	*Biological Effect on Pulp Cells*	*Characteristics of Tertiary Dentin*	*Key References*
Calcium silicate-based cements	Ca^{2+}, OH^{-}, SiO_4^{4-}	Odontoblast-like cell differentiation; increased ALP activity	Thick, continuous dentin bridge with reduced tunnel defects	Singh (2019); Sanz et al. (2019)
Nanoparticulate bioceramic pastes	Ca^{2+}, PO_4^{3-}, SiO_4^{4-}	Enhanced cell adhesion and mineralization	Tubular, well-organized tertiary dentin resembling primary dentin	Zhu et al. (2014); Porenczuk (2018)
Strontium-doped bioactive glass cements	Sr^{2+}, Ca^{2+}, PO_4^{3-}	Accelerated odontogenic differentiation; anti-inflammatory modulation	Homogeneous, mechanically stable dentin bridge	Mandakhbayar et al. (2019)
Experimental bioactive glasses	Ca^{2+}, Na^{+}, SiO_4^{4-}	Improved pulp cell viability and matrix production	Dense reparative dentin with improved interfacial adaptation	Mocquot et al. (2020)
Nano-bioactive pulp capping materials	Multiple ions (nano-scale release)	Controlled ion signaling and reduced cytotoxicity	Biomimetic dentin architecture with enhanced sealing	Fayyad & ElBaz (2018); Besinis et al. (2015)

Table 3: Influence of Bioactive Bioceramic Materials on Tertiary Dentin Formation and Architecture

Property / Outcome	*Calcium Hydroxide (Conventional)*	*Resin-Based Materials*	*Novel Bioceramic Materials*
Bioactivity	Moderate	Low / Bioinert	High
Ion Release	Rapid, uncontrolled Ca^{2+}	Minimal	Sustained Ca^{2+}, Si^{4+}, Sr^{2+}, PO_4^{3-}
Sealing Ability	Poor	Good	Excellent
Dentin Bridge Quality	Thin, porous, tunnel defects	Limited formation	Thick, homogeneous, organized
Pulp Cell Viability	Moderate	Potential cytotoxicity	High
Inflammatory Response	Mild to moderate	Variable	Minimal
Long-Term Stability	Low	High	High
Interfacial Biomineralization	Absent	Absent	Present

with biologically driven regeneration. Their ability to modulate ion release dynamics directly influences the architecture and quality of tertiary dentin, positioning them as superior materials for contemporary vital pulp therapy (Singh, 2019; Pires et al., 2020; Sanz et al., 2019).

CONCLUSION

Novel bioceramic pulp capping materials demonstrate a clear advancement in vital pulp therapy through their ability to release bioactive ions that actively regulate the healing microenvironment of the dentin–pulp complex. The sustained release of calcium, phosphate, silicate, and therapeutic ions such as strontium plays a critical role in promoting pulp cell viability, differentiation, and mineralization, thereby supporting the formation of structurally organized tertiary dentin (Singh, 2019; Sanz et al., 2019).

Evidence from in vitro and in vivo investigations indicates that ion release dynamics are closely linked to favorable biological responses, including enhanced odontoblastic activity, controlled inflammatory reactions, and improved dentin bridge quality compared with conventional pulp capping agents (Zhu et al., 2014; Fayyad & ElBaz, 2018). The incorporation of nano-scale features further optimizes ion exchange, surface reactivity, and cellular interactions, contributing to more biomimetic dentin architecture (Porenczuk, 2018; Besinis et al., 2015). Contemporary ion-releasing restorative materials and bioactive glasses highlight the importance of material–tissue interfacial properties in achieving predictable pulp healing outcomes (Pires et al., 2020; Mocquot et al., 2020). Overall, the bioactive ion release behavior of bioceramic pulp capping materials represents a paradigm shift from passive protection toward biologically driven regeneration, reinforcing their potential to improve long-term clinical success in dentin–pulp complex therapy (Iliescu et al., 2019; Mandakhbayar et al., 2019).

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