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Review

Bioactive Restorative Materials: The Intersection of Restoration and Regeneration

Mohammed Thamer Alshahrani[1*], Reem Abdulkareem Rubehan[2], Samer Masad AlJohani[3]

[1] *Department of Restorative Dentistry, Abha Specialized Dental Center, Abha, Saudi Arabia*
[2] *Department of Dentistry, National Guard Hospital, Jeddah, Saudi Arabia*
[3] *Department of Restorative Dentistry, King Khalid Hospital, Majmaah, Saudi Arabia*

Correspondence should be addressed to **Mohammed Thamer Alshahrani**, Department of Restorative Dentistry, Abha Specialized Dental Center, Abha, Saudi Arabia, Email: dr.mohdthamer@hotmail.com

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Abstract

Bioactive restorative materials (BRM) have led to a paradigm shift in the field of restorative dentistry. These hybrid materials function like traditional dental-restorative materials–metals and ceramics–while also acting as physiologically active substitutes. Their interaction with the oral environment facilitates remineralization, enhances bonding, and supports tissue regeneration. These release calcium, phosphate, or fluoride ions, which are crucial for remineralizing demineralized enamel and dentin, thereby prolonging the lifespan of restorations. BRM combines restoration and regeneration, providing mechanical support similar to conventional materials while also stimulating the healing of the tooth structures. These materials are valuable for direct and indirect restorations, root canal treatments, and pulp capping procedures due to their ability to encourage odontoblast activity and stimulate hydroxyapatite formation. Their benefits include improved biocompatibility, significant reduction in secondary caries, and better patient outcomes. However, limitations such as material degradation, low mechanical strength, and high costs, hinder widespread application. Ongoing efforts to improve the material composition and develop new formulations aim to overcome these barriers. Future advancements will focus on improving mechanical properties, bioactivity, and nanotechnology integration to achieve optimal clinical performance. Researchers are working to develop multifunctional restorative materials with antibacterial properties and controlled ion release, contributing to sustainable improvements in oral health. The next generation of BRM will be driven by innovations in biomaterials science, providing more effective and long-lasting solutions for restorative dentistry.

Keywords: *bioactive, restorative materials, restoration, regeneration, pulp, dental, oral, dentistry, dentin, tooth, tooth structure*

Introduction

Traditional dental composites and amalgams have been used in tooth restoration for decades. They can withstand functional challenges for long period but lack biological activity. These materials rebuild lost tooth structures without actively interacting with surrounding tissues. However, restorations may fail over time due to secondary caries, microscopic leakage, or material deterioration. While composites provide aesthetic benefits, their effectiveness depends on adhesive bonding to dentin, which can weaken over time due to hydrolysis and enzymatic degradation (1). These limitations highlight the need for restorative solutions that go beyond structural repair.

Dental caries are among the most common chronic diseases worldwide, affecting both children and adults. Carious lesions damage the mineralized tooth, potentially leading to extensive destruction and increased susceptibility to further damage (2). In addition, trauma and deep restorations can irritate the pulp, leading to pulpitis or necrosis, which may require root canal therapy. Current restorative treatments do not fully address these biological challenges. Ideally, restorations should not only replace lost tooth structure but also promote dentin remineralization, pulp healing, and long-term tooth preservation (3).

Bioactive restorative materials (BRM) represent an important breakthrough in dental materials science. Unlike traditional restorations, which serve as inert barriers, bioactive materials interact with adjacent tissues to promote healing and regeneration. In dentistry, bioactivity refers to a material's ability to elicit biological effects such as mineral deposition, cellular stimulation, or antimicrobial action (4). Ions such as calcium, phosphate, and fluoride released from these materials benefit by promoting remineralization and reducing recurrent decay. Some bioactive formulations create an alkaline environment that neutralizes acids produced by cariogenic bacteria, enhancing their protective capabilities.

Different categories of BRM offer distinct properties. Calcium silicate-based compounds, such as mineral trioxide aggregate (MTA) and Biodentine are known for promoting dentin bridge formation and pulp healing. These materials are commonly used in vital pulp therapy, and have been reported to be successful during several procedures, such as direct pulp capping and pulpotomy (5). Bioactive glass, initially developed for bone regeneration, has also been adapted for dental applications. Composed of silica, calcium, sodium and phosphate, bioactive glass releases ions that facilitate hydroxyapatite formation, mimicking the natural mineral phase of teeth and promoting regeneration (6).

Resin-based bioactive materials incorporate bioactive properties in Giomer technology and bioactive composites, balancing aesthetics, adhesion and ion-releasing capabilities (7). These materials restore functionality while promoting dental health. Calcium- and phosphate-releasing materials enhance enamel remineralization and protect against acids. Some materials create an alkaline environment that inhibits bacterial growth, reducing the incidence of recurrent caries (8). Others stimulate the hydroxyapatite formation, fusing with the native tooth structure and extending the lifespan of restorations.

Research has demonstrated that BRM improves restoration stability and reduces the need for retreatment, ultimately benefiting patient outcomes and tooth longevity. By promoting healing, fighting bacterial infections and strengthening bonds, bioactive materials represent a shift in restorative dentistry, moving toward healing rather than merely filling cavities. These advancements have the potential to improve oral health and help preserve our natural teeth longer (9).

Methodology

A comprehensive literature search in the PubMed, Web of Science, ScienceDirect, and Cochrane databases on March 11, 2025. The search utilized medical topic headings (MeSH) and relevant keywords such as 'bioactive' AND 'restorative materials' OR 'restoration' OR 'regeneration' AND 'pulp' AND 'dental' OR 'oral' OR 'dentistry' OR 'dentin' OR 'tooth' OR 'tooth structure' and a

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combination of all available related terms. Peer-reviewed articles involving human subjects and available in the English language were included. Using the reference lists of the previously mentioned studies as a starting point, a manual search for publications was conducted through Google Scholar to avoid missing any potential studies. There were no limitations on date, publication type, or participant age.

Discussion

Amalgam and composite resins have long been used for tooth restoration. However, these materials exhibit several drawbacks. Amalgam, while strong, raises concerns due to its mercury content. Composite resins, though aesthetically preferable, suffer from shrinkage during curing, loss of adhesion in deep cavities, and susceptibility to secondary caries (10). Fluoride-releasing glass ionomer cements (GICs) offers some benefits but have weaker mechanical properties than composites.

There is a growing clinic-dental need is for materials that not only restore but also promote the biological repair of tooth tissues (11). BRM fulfill this role by interacting with the oral environment to stimulate dentin remineralization and pulp healing. Unlike passive restorative materials, bioactive materials release therapeutic ions that promote hydroxyapatite formation, enhance biological sealing, and extend the longevity of restorations. This significantly reduces the risk of secondary caries by virtue of resistance conferred to microbial colonization (12). Bioactive materials represent a paradigm shift in restorative dentistry that connects the gap between restoration and regeneration.

Mechanism of bioactivity

Bioactive materials function through regulated ion release and interaction with aqueous environments, such as saliva or dentinal fluid. These types of interactions typically lead to the release of calcium and phosphate ions, that work synergistically with fluoride to enhance dentinal remineralization, strengthen adjacent soft tissues, and bond with the tooth structure (13).

One of the major operative mechanisms through which these materials restore tooth integrity is through hydroxyapatite formation. When calcium and phosphate ions can also form an oversaturated solution, hydroxyapatite precipitates, strengthening dentin, extending restoration longevity, and sealing of the hybrid layer. This process reinforces dentin, extending the lifespan of restorations while sealing the interface between the restoration and the tooth structure (14). Some other compounds, such as calcium silicate cements, promote secondary dentin formation, thus creating an added barrier over the pulp. Another important feature of bioactive materials is their antimicrobial activity. Many bioactive materials elevate local pH, inhibiting acidogenic bacteria responsible for secondary caries. Fluoride-releasing compounds further impede bacterial metabolism and prevent enamel demineralization. BRM inhibits biofilm formation, thus reducing recurrent decay and post-restorative complications (15).

Types of bioactive restorative materials

BRM can be classified into several categories based on their composition and functional properties. Bioactive glass-based materials (BAG) are silicate-based materials that release calcium and phosphate ions upon dissolution in oral fluids. This process leads to the formation of a hydroxyapatite-like coating that binds to tooth and bone tissues (16). NovaMin is a well-known bioactive glass formulation that has been incorporated into dentifrices and restorative materials. In addition to its remineralizing properties, it promotes dentin desensitization by forming a calcium-phosphate coating over exposed dentin tubules (17). In restorative dentistry, bioactive glass fillers have been incorporated into composites to enhance remineralization while maintaining mechanical properties similar to those of traditional resin materials (18).

Calcium silicate cements, including MTA and Biodentine, are widely used in endodontic and restorative applications. These materials release calcium ions and have demonstrated strong biocompatibility. MTA has long been considered the gold standard for pulp capping, perforation

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repair, and apexogenesis due to its superior biological sealing properties. However, it has notable drawbacks, such as prolonged setting time and difficulties in manipulation. Biodentine was developed as an alternative to MTA to overcome these challenges, offering a shorter setting time, improved handling, and excellent biocompatibility. It is commonly used for deep carious lesions, indirect and direct pulp capping, and apexogenesis (19).

Resin-based composites traditionally lack biological activity. However, newly modified bioactive composites incorporate specialized fillers that allow for the controlled release of calcium and fluoride ions, enhancing remineralization with maintaining adequate mechanical properties. One of the challenges in the development of bioactive resin composites is balancing strength, esthetics, and the ionic release. Increasing the filler content may improve mechanical strength, but this must be achieved without compromising ionic release. Research continues to refine these formulations to enhance (20,21).

GICs are another category of bioactive materials, recognized for their ability to release fluoride and chemically bond to enamel and dentin. This sustained release of fluoride promotes continued remineralization of surrounding dental tissues and provides protection against recurrent caries (22).

Lastly, resin-modified glass ionomers (RMGICs) are an advancement over conventional GICs due to the incorporation of resin, which contributes to increased strength and corrosion resistance. They maintain fluoride release while offering esthetic properties, in addition to improved longevity. RMGICs are also widely used in pediatric dentistry as well as in less invasive dentistry due to their enhanced durability and therapeutic benefits (23).

Clinical applications

BRM are currently widely used for restorative treatments in high-caries-risk individuals. Such materials promote dentin remineralization, thereby reducing the incidence of secondary caries. Bioactive composites and GICs are often used in Class I, II, and V restorations due to their prolonged therapeutic benefits through ion release. However, in load-bearing applications, the primary challenge remains mechanical strength. While bioactive materials exhibit regenerative properties, they have not yet fully replaced traditional resin-based materials. The mechanical performance of bioactive materials used in posterior tooth restorations is continuously being improved through ongoing research (24).

Bioactive agents are indispensable in pulp therapy and root canal closure. Among these bioactive materials, MTA and Biodentine are the most routinely utilized for direct pulp capping, apexogenesis, and the repair of root perforations. Their primary function in endodontics is to induce dentin formation and establish an effective biological seal. Due to their unique properties, they facilitate the healing process, thereby improving the success rate of endodontic treatments. This makes them an integral part of modern root canal therapy and pulp management (25).

Bioactive glass has broad applications in bone grafts and in the healing of periodontal defects through stimulation of bone formation and osseointegration. These materials are also considered an important factor when it comes to guided tissue regeneration, acting as supportive matrices that promote the growth of new tissue. Additionally, bioactive materials help combat bacterial colonization during the healing period. With their specialized properties, bioactive materials facilitate natural tissue regeneration, contributing to gum health by promoting tissue repair and accelerated healing, thereby achieving long-term stability in periodontal treatment (26).

Advantages and limitations of BRM

BRM boast many advantages. They penetrate the tooth structure to repair decayed dentin, extending the longevity of the restoration. Besides protection against secondary caries through release of ions and antibacterial activity, these materials also facilitate pulp repair due to their high biocompatibility and anti-inflammatory properties, thus improving treatment success. Taken together, all these aspects

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contribute to better success rates of restorations, promoting long-term dental health. Therefore, bioactive materials play a crucial role in modern restorative dentistry by ensuring durability, and encouraging natural healing (27).

Despite their benefits, BRM have certain limitations. Some, such as MTA, present challenges in manipulation and require lengthy curing times. Additionally, advanced bioactive materials tend to be more expensive than conventional alternatives, which may limit their accessibility. Further clinical validation is necessary, as long-term clinical trials are required to establish efficacy across various applications. Nonetheless, research continues to support their overall effectiveness (28, 29).

Future direction of BRM

The future directions for BRM will be predominantly guided by advances in nanotechnology, smart materials, and hybrid composites. Nanotechnology boosts bioactivity with nano-sized fillers and a more controlled ion release. Nano-hydroxyapatite is being studied for its potential advantages related to remineralization and bonding properties (30). Another promising advance involves the use of smart materials capable of controlled ion release. These materials are capable of detecting pH changes and releasing ions when really necessary, thereby optimizing the therapeutic results while retaining the material's integrity. Hybrid materials aim to integrate bioactivity and superior mechanical properties, providing durability while supporting remineralization. By incorporating bioactive components into high-strength composites, research aims to develop materials able to withstand occlusal stresses while actively contributing to tooth restoration (31).

Conclusion

BRM have transformed contemporary dentistry by combining the properties of restoration and bioactivity, distinguishing them to be different from conventional materials. They stimulate remineralization, reinforce bonds, and enhance tissue regeneration, contributing to greater durability, reduced secondary caries, and improved long-term outcomes. However, BRM clinical impact extends beyond mechanical restoration, as their bioactivity enables the healing of restored teeth, leading to better oral tissue health–an important factor in patient satisfaction. Ongoing innovations are necessary to optimize BRM formulations, particularly in enhancing antimicrobial performance and longevity. Further research should focus on developing next-generation materials that maximize both the functional and regenerative potential of restorative dentistry, ultimately improving clinical outcomes.

Disclosures

Author contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Ethics statement

Not applicable.

Consent for publications

Not applicable.

Data availability

All data is provided within the manuscript.

Conflict of interest

The authors declare no competing interest.

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