

Assessment of the Pros and Cons of Bioactive Glass Composites in the Repair of Dental Hard Tissues

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Abstract:

Bioactive glass (BAG), a bioactive material with excellent biocompatibility, has been increasingly utilized in the field of dental restoration. Along with the changes in clinical demands and the upgrading of preparation processes, the common types of BAG currently include nanobioactive glass, mesoporous bioactive glass, and bioactive glass composites, which show significant differences in mechanical strength, binding stability, preparation cost and bioactivity. This article compares the differences in physical properties, preparation methods, and functional activities among various bioactive glasses. We highlight the superior mechanical strength, drug-loading capacity, broad-spectrum antibacterial efficacy, and pronounced tissue-regenerative capacity of each BAG variant across multiple dimensions. The results indicate that bioactive glass composites have obvious advantages in mechanical properties, degradation rate regulation, and remineralization promotion compared with other BAG materials. These findings aim to provide guidance for material selection in dental hard tissue remineralization and systematically summarize the functional similarities and differences among various BAGs, offering new ideas for the future development of bioactive glass composites with broader adaptability.

Keywords: Bioactive glass; dental hard tissue; remineralization; antibacterial; composites.

1. Introduction

The visible part of the tooth in the oral cavity is the crown, which is covered by enamel on the outermost surface. Composed primarily of minerals such as calcium and phosphorus, enamel is a highly mineralized

tissue in the human body. A longitudinal section of the tooth is composed of three layers of hard dental tissues, including enamel, dentin, and cementum, along with the innermost layer of soft tissue, namely the pulp. Various chemical factors (changes in food pH), biological factors (oral microbiota imbalance,

gastroesophageal reflux), and behavioral factors (poor oral hygiene, food residue after meals) can all lead to an imbalance in the acid-base environment of the oral cavity. Under the influence of an acidic environment, the hard dental tissues, which are in direct contact with acidic substances or their products, gradually undergo chronic and irreversible superficial loss, a process known as demineralization. With the onset of the lesion, the enamel surface softens. Subsequently, the hydroxyapatite in the outer layer is progressively dissolved by acid, leading to further softening and demineralization of the enamel surface till the enamel is completely lost and the underlying layer is affected.

Biomaterials are commonly used to repair and fill damaged or diseased teeth. Early repair methods mainly relied on materials such as amalgam and composite resin. However, these bioinert materials are unable to promote the self-repair of dental tissues. Since the invention of the first bioactive glass (BAG), BAG has been widely used to repair bone tissue defects, to enhance the repair of enamel and dentin due to its excellent biocompatibility, bioactivity, and biodegradability. There is a phosphoprotein in human saliva that can prevent calcium precipitation and promote the combination of phosphorus and calcium with enamel, a process known as „remineralization.“ The core characteristic of BAG is its ability to form a bone-like apatite layer rich in hydroxyapatite (HAP) on its surface. This layer can form strong chemical bonds with natural dental tissues. Moreover, when BAG encounters saliva in the oral cavity, it rapidly reacts and releases calcium (Ca) and phosphorus (P) ions. This reaction has been proven to significantly enhance the activity of odontoblasts and ameloblasts, stimulate the deposition of hydroxyapatite and thus achieve the „remineralization“ of dental tissues [1]. During the dissolution process, BAG increases the local pH and releases ions with antibacterial properties, effectively inhibiting the growth of pathogenic bacteria. Compared with traditional dental repair materials, bioactive glass has significant advantages in promoting remineralization and biocompatibility. However, with the increasing clinical application of BAG, its low mechanical strength and brittleness have gradually become its limits. Researchers have turned to the development of bioactive glass composites to compensate for these limits while retaining the biocompatibility and other advantages of BAG. Currently, a variety of bioactive glass composites have been developed. This paper compares and analyzes the advantages of various new materials to provide a resource for future research and clinical applications.

2. BAG Remineralization Mechanism and Application Forms

Dental hard tissue defects (such as dental caries and

enamel demineralization) are common clinical problems in dentistry, and BAG has become a hot research area due to its unique ability of remineralization. This section first elaborates on the core mechanism of BAG in regulation of enamel remineralization and then summarizes its main application forms under various clinical scenarios, thus laying the rationale for subsequent material classification and performance analysis. Enamel consists of 96% HAP, which is in a dynamic equilibrium of dissolution and deposition as well as demineralization and remineralization when it comes into contact with saliva and food in the oral cavity. As aforementioned, acid production from oral bacterial flora and consumption of acidic foods can lower the pH of the oral environment, leading to enamel demineralization and subsequent dental damage. In patients receiving BAG treatment, the enamel surface has a large number of nanospheres distributed in a sheet-like manner, covering the demineralized areas. This indicates that BAG has the ability to adsorb calcium and phosphate ions for deposition, thereby promoting enamel remineralization. The main components of bioactive glass include SiO_2 , CaO , P_2O_5 , etc. When exposed to saliva, BAG particles rapidly dissolve in saliva and release Ca^{2+} , PO_4^{3-} , and SiO_4^{4-} ions. The formed HAP can be deposited at the interface between the tooth and the glass, thus seamlessly „healing“ the damaged area [1]. Bioactive glass has a unique morphological structure that can enhance cell activity and the rate of biomineralization. With increasing studies look into the mineralization mechanism of bioactive glass, research on its application in the field of dental restoration has also gradually augmented.

Based on the core mechanism of remineralization, BAG can form diverse application forms through different processing techniques that adapt to different clinical scenarios such as dental restoration, implant surface modification, root canal treatment, etc. The core of its design is to maximize the interaction efficiency between materials and dental tissues. In terms of application forms, BAG can be shaped into coatings, particles, bone cements, and scaffolds according to the requirements of different clinical contexts. One of the traditional ways to exert the remineralization-promoting function of BAG is to cover the material on the surface of teeth or implants as surface coating technology. The coating application not only increases the contact area with the tissue but also ready to form chemical bonds between the molecules and the tissue after implantation, thereby achieving early stability after BAG attachment. More importantly, the presence of the BAG coating can effectively isolate the tissue from the environment and protect the tissue from corrosion. An alternative of dental application form is a particulate form of BAG, which can be used directly or mixed with a solute. When particulate BAG is added to toothpaste, it can distribute throughout the tooth surface with the friction of the tooth-

paste during tooth brushing. In the moist environment of the oral cavity, the particles are ready to react and release calcium as well as phosphate ions, which will deposit on the tooth surface together with the ions in saliva and form a layer of HAP similar to natural tooth material.

3. Classification of bioactive glass

With the diversification of material functional requirements for dental restoration, such as mechanical strength, drug delivery, and antibacterial activity, BAG materials have gradually evolved from single components to multifunctionality, generally including three core categories, i.e. micro-nano, mesoporous, and composite materials.

3.1 Micro-Nano Bioactive Glass

Micro-nano bioactive glass (MNBG) is biodegradable and will release ions during the degradation process. MNBG has been reported to induce specific biological responses, such as osteogenesis, angiogenesis, and antibacterial effects, when releasing active ions. MNBG is able to treat dental defects through increasing angiogenesis and reducing bacterial infections at the damaged site. In vitro cell assays have demonstrated that cells can upregulate the expression of sialin phosphoprotein, matrix protein 1, and osteocalcin in dental pulp cells to promote odontogenesis after uptake of MNBG through ATP-dependent endocytosis and micropinocytosis [2]. While retaining its remineralization ability, micro-nano bioactive glass can functionally regulate different cells in vivo based on the type of ion doping. This increasingly attracts research attention and it has become a bioactive material with broad application prospects. The core advantage of MNBG lies in its ability to retain BAG remineralization while it functionally modulate different cells in the body through ion doping. However, its limitations lie in its low mechanical strength and high brittleness, making it difficult to meet the long-term repair needs of weight-bearing areas in teeth. At present, MNBG is mainly used in non-load-bearing contexts such as early enamel demineralization and remineralization and regulation of pulp cell function in the dental field. Altogether, MNBG is a subject of bench-scale research with potential clinical translation.

3.2 Mesoporous BAG

After demonstration of the remineralization and repair capabilities of BAG, researchers switched to focus on other potential applications of BAG, especially in drug loading and release. The uneven pore structure of MNBG make it not suitable for controlled drug release. After mesoporous bioactive glass (MBG) was first synthesized in 2004, the use of MBG for drug delivery became a new direction. Compared with traditional BAG, MBG has a more or-

derly arrangement of porous structure with a larger pore volume, offering significant potential for applications in adsorbing metal ions as a drug carrier.

MBG can carry a variety of drugs through its mesopores, providing a multifunctional delivery platform for therapeutic agents such as antitumor, anti-inflammatory, and antibacterial drugs. Moreover, an increasing number of studies have found that MBG is also used for the delivery of protein-based drugs, such as bone morphogenetic proteins and growth factors. Given these findings, MBG has been applied in restorative dentistry and treatment of periodontal diseases. When self-adhesive resin is mixed with MBG, the material exhibits antibacterial effects against *Streptococcus* and *Porphyromonas gingivalis* while it retains its physical properties and remineralization ability [3]. A new material by combining calcium silicate cement with MBG can induce the regeneration of dental pulp stem cells and support cell proliferation while inhibiting the growth activity of *Enterococcus faecalis*. MBG developed based on MNBG has optimized the ability of adsorption and releasing, enabling functions such as antibacterial activity, promotion of cell proliferation, and tissue repair. However, there has been no significant improvement in other physicochemical properties.

3.3 Bioactive Glass Composites Materials

Single-component BAG (MNBG, MBG) has low mechanical strength and high brittleness and cannot match the mechanical properties of natural dental tissue and agree with the long-term clinical restoration needs. To overcome this limitation, researchers have developed bioactive glass composite materials by combining BAG with organic/inorganic materials, which significantly improve the abilities of biocompatibility, mechanical strength, biodegradability, and tissue repair compared to single BAG.

The initial type of composite material emerging was synthesized from bioactive glass and natural organic substances. Taking collagen (Col) as an example, Col as a key component of the extracellular matrix can stimulate the metabolic activity of osteoblasts and promote the osteogenesis and increase bone mineral density. After the synthesis of collagen-based composites with BAG, the interaction between collagen molecules and BAG particles is conducive to the formation of a more stable mesh structure. These features prevent Col from easy degradation and thus maintain the stability of the coating. Silk fibroin (SF), a natural fibrous protein with good hardness, biocompatibility, and degradability, can effectively compensate for the insufficient mechanical strength of BAG[4]. After BAG and SF are cross-linked and applied to cells, moreover, the high expression of alkaline phosphatase activity and Ca deposition within cells indicate that the composite material has a promoting effect on dental tissue repair. Chitosan (CS)/BAG composites promote mineral

deposition and can provide an effective clinical treatment approach for the remineralization of early enamel caries and desensitization of exposed dental tissues. The performance of the composite material after the combination of CS and BAG has been greatly improved, which promotes, to a large extent, its application in the fields of dentistry and wound healing.

Subsequently, composites synthesized from bioactive glass and biometals were developed as well. The combination of metal elements with BAG improves the performance defects of BAG itself and thereby enhance the comprehensive properties of the material. As an essential trace element in the human body, copper (Cu) participate in the composition and maintenance of protein functional conformations and is especially important for the regulation of immune functions. The incorporation of a certain concentration of Cu into BAG is conducive to tissue repair. Taking advantage of the mechanical and physical properties of Cu/BAG composite of nano-zinc phosphate bioactive glass and its biological effects on odontoblasts, the mechanical strength of Cu/BAG composites is remarkably increased and they can also promote the differentiation of odontoblasts [5]. Strontium (Sr) exists in 99% of the human body in the bones and has the dual effects of promoting osteogenesis and inhibiting osteoclasts. Compared with the osteogenic effects of BAG and Sr/BAG composites, Sr/BAG composites have the stronger mineralization promotion and collagen formation capabilities, faster degradation rates, and much higher bioactivity than BAG alone. When human dental pulp stem cells from deciduous teeth were cultured in BAG extracts containing different concentrations of Sr^{2+} , the cells in the BAG extracts containing Sr^{2+} had significantly higher alkaline phosphatase activity, mineralized nodule content, and upregulation of odontoblast differentiation-related genes. This suggests that Sr/BAG composites have a promoting effect on the differentiation of human dental pulp stem cells from deciduous teeth towards dentin. In summary, compared with MNBG or MBG, bioactive glass composites offer better toughness and plasticity and mechanical properties closer to those of natural dental tissues. Bioactive glass composites retain the advantages of MNBG and MBG, with key comprehensive material functions and broad application prospects.

4. Comparison and Selection of Preparation Methods for BAG

4.1 Traditional Preparation Methods

Hench et al. Initially used the melt-quenching method to prepare the first bioactive glass. However, this method requires high temperatures and sophisticated equipment, and

it is difficult to precisely control the content of each component in the final product. Afterwards, a new technology for preparing bioactive glass at room temperature (the sol-gel method) was developed. The sol-gel method involves mixing compounds containing Ca, P, Si, etc., under acidic or basic catalysis to form a glass solution. This solution is then subjected to aging and other post-treatments to form a glassy gel. Finally, the unreacted organics in the gel are removed by drying to obtain bioactive glass. Compared with the traditional melt-quenching method, bioactive glass prepared by the sol-gel method has particle sizes of micro- and nano-scale and a larger specific surface area. The melt-quenching and sol-gel methods are relatively early methods for manufacturing BAG, mainly used for the preparation of BAG or MNBG. These methods are technologically mature and have lower production costs.

4.2 New Preparation Methods

Template synthesis is a method for preparing bioactive materials based on sol-gel technology, using template self-assembly techniques. Typically, large molecules with special structures or surfactants with specific shapes are used as morphological templates or structural directors, or multiple structural substances are assembled layer by layer. After subsequent treatments such as elution or thermal evaporation, nanostructured bioactive glass materials with specific structures and properties are synthesized.

Highly ordered mesoporous bioactive glass has been synthesized using nonionic surfactant block copolymers as structural directors through an evaporation-induced self-assembly process. The combination of the sol-gel method and template synthesis is currently the main method for generating MBG. However, due to the high cost of template agents, the complexity of the process, the strict control of parameters, and the high energy consumption of calcination, template synthesis is mainly used at the laboratory scale and has not been widely utilized.

The synthesis of bioactive glass composites depends on the composite material combined with BAG. Common techniques include thermally induced phase separation, solution blending-filtration, and 3D printing. Currently, the phase separation method is commonly used. This method involves inducing phase separation in a polymer-diluent mixture by changing the temperature to form a high-temperature homogeneous solution. Cooling the solution triggers phase separation to form a regular composite. Using this method, Cu/BAG composite nano-zinc phosphate cement with a certain concentration of Cu incorporated into BAG is produced. This composite has high mechanical strength and can promote the differentiation of odontoblasts [6].

The thermally induced phase separation method has low cost and moderate technical barriers, with great application potential. It can be seen that the preparation method

of bioactive glass composites is superior to the sol-gel method of BAG in terms of product characteristics and is more universal than the template synthesis method of MBG in terms of technological maturity and cost control.

5. Innovation and Performance Advantages of Bioactive Glass Composites

As an upgraded direction of BAG materials, bioactive glass composite materials have achieved breakthrough improvements in mechanical properties, interface bonding, biological functionalization, and degradation regulation through the synergistic effect of the composite system, while retaining the core function of traditional BAG remineralization. They are significantly superior to MNBG and MBG. This section mainly focuses on the analysis of their core innovative characteristics.

5.1 Mechanical Performance Optimization

Compared with MNBG and MBG, bioactive glass composites have significant advantages in mechanical properties, multifunctionality as well as bonding and degradation rates. For example, the addition of fluoride to BAG combines the dual advantages of BAG's activity and fluoride ions to enhance the acid resistance of enamel. This can form fluorapatite that not only promotes mineralization but also strengthens the material's acid resistance [7]. The incorporation of strontium into BAG leverages the dual effects of strontium ions in promoting dentin formation and regulating the oral microecology (such as the abundance of *Streptococcus mutans*), achieving a synergy between repair and antibacterial properties. The addition of microcrystalline cellulose (MCC) and its derivatives to BAG results in mMCC-PDMS-BAG biocomposites that exhibit significantly enhanced apatite formation and tensile strength in vitro. The introduction of carbon fiber-reinforced polyetheretherketone (CF/PEEK) composites into BAGs to create ternary composites has significantly increased the levels of Ca and Cl in the material as well as the Vickers hardness of the material surface. The increased Ca ions in the material are more conducive to the formation of hydroxyapatite, surface cell adhesion, and cell proliferation.

5.2 Combining Interface Optimization

Pure BAG suffers from insufficient surface properties, leading to poor bonding, brittleness, and poor wear resistance. To overcome these defects, researchers first considered adding composite resins to BAG in order to create bioactive glass composites. Traditional acid etching exposes the demineralized dentin collagen network. If the adhesive does not fully penetrate, it can lead to leakage at the material-tooth interface, ultimately causing resto-

ration failure. By mixing composite resin with BAG, the Ca^{2+} ions released by BAG in an acidic environment can promote mineral deposition within and on the surface of collagen fibers. This enhances the stability of the collagen network, reduces hydrolytic degradation, and seals the bonding interface, improving its long-term durability. Natural products can also be used as adhesives. The combination of propolis and BAG can enhance BAG's maximum bonding strength in caries, protecting the dentin. Transmission electron microscopy shows good interaction between the adhesive and dentin, with the increased bonding strength being maintained for over six months [8]. The greatest advantage of composites is that they address the limitations of BAG application, effectively ensuring the stability of the materials' therapeutic effects in dental tissue repair, which is unparalleled by other materials.

5.3 Antibacterial and Biological Functionalization

The addition of different chemical elements with antibacterial properties, such as silver, zinc, or copper, can significantly enhance the antibacterial ability of BAG, thus reducing bacterial infection. Comparing the antibacterial effects of BAG, Cu-BAG exhibits a longer ion release cycle, making it more suitable as a material for long-term antibacterial protection. The introduction of these metal elements significantly enhances the antibacterial capabilities of the glass material, expanding its prospects for clinical application. Through bioactive glass composites or MBG, it is also possible to achieve intelligent release of antibacterial drugs in terms of rapidly releasing high concentrations of drugs in the early stages of infection and then maintaining a long-term bacteriostatic concentration, thereby achieving long-term control of oral lesion inflammation [9]. The success of root canal treatment depends on thorough debridement and tight sealing. The application of bioactive glass composites in root canal sealers and pastes is currently a hot area for the biofunctional design of their antibacterial properties. These composites not only have good biocompatibility and osteogenic activity, which is beneficial for the healing of periapical tissues, but also continuously release alkaline products and specific ions (such as Zn^{2+} , Ag^+) that can effectively inhibit residual bacteria in the root canal (such as *Enterococcus faecalis*) and prevent reinfection [10]. Compared with MBG, the advantage of bioactive glass composites relies on their controllable degradation, which is more suitable for different patients' treatment cycles.

Bioactive glass composites can form a stable calcified barrier in the dental pulp and modulate the microenvironment within the pulp chamber through ion release, thereby promoting the differentiation of dental pulp stem cells and the formation of reparative dentin. For example, a ternary complex constructed with hydrogel and Cu ions can

simultaneously enhance the protection of dentin collagen fibers and inhibit microbial activity. This dual functionality highlights its great potential in dental tissue repair and root canal therapy. In future, new types of bioactive ceramics with rapid mineralization and high strength characteristics could be developed through composite technology to meet the needs of dentistry.

Overall, bioactive glass composites, as multifunctional bioactive materials with inherent capacity to interact with biological tissues, have broad application prospects and await further development. However, the existing studies needs in vitro models with sufficient clinical evidence and long-term clinical data. Therefore, further in vivo investigations and clinical trials are urgently needed to validate their translational application value. With the progress of biomedicine and materials science, more materials with multifunctionality and bioactivity will be developed, playing an increasingly pivotal role in dentistry, orthopedics, dermatology, and other fields.

6. Conclusion

This article compares the differences in physical properties, preparation methods, and functional activity between bioactive glass composite materials and conventional bioactive glass, in order to determine whether bioactive glass materials have superior therapeutic effects in repairing dental hard tissues. The main advantages of the application of bioactive glass composite materials in the remineralization of dental hard tissues are divided into four aspects. Firstly, in enamel remineralization, bioactive glass composite materials have superior therapeutic effects compared to most biologically inert materials. Secondly, compared with MNBG or mesoporous bioactive glass, bioactive glass composite materials have better toughness and plasticity, and their mechanical properties are closer to natural tooth tissue. Thirdly, the degradation rate of pure BAG is fixed and cannot well match the individual tooth tissue remineralization rate of different patients with dental tissue lesions. In contrast, bioactive glass composite materials synthesized from polymers with different degradation rates can be precisely designed to synchronize the overall degradation time of the composite material with

the tissue regeneration rate. Finally, the functionality of pure bioactive glass is relatively limited. Overall, composite materials can easily integrate multiple functions, such as drug loading, antibacterial activity, altering local pH environment, and regulating cellular biological activity.

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