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Literature review: Degradation characteristics of bioactive materials in oral environment

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Abstract

Bioactive materials have been recognized as one of revolutionary advancements in the dental field due to its outstanding ability, such as enabling faster wound healing and tissue regeneration as well as enhancing dental remineralization. This literature review investigates bioactive materials' principles, behavior, and applications in dentistry focus on their interactions in the oral environment. The primary variables that affect the degradation include physicochemical, mechanical, and biological interactions, with salivary composition, pH variations, and biofilm emergence are all crucial. Current research gaps, including long-term clinical research and proficient in vivo testing simulations, are recognized, in addition to alternatives for future attempts to improve material properties and patient satisfaction. This review emphasizes the significance of knowing degradation processes of bioactive materials for long-term beneficial applications related to dentistry.

Keywords: Bioactive materials; Dental restoration; Material degradation; Oral Environment; Bioceramics

1. Introduction

Bioactive materials have been researched and utilized in dental restoration because of their mechanism of actions that involves interacting with our living cells (1). This is because they are known to be designed in a way that enables them to promote beneficial physiological responses which would interact dynamically with their biological environments and inevitably improve the regeneration of tissues (2)(3). For example, one of bioactive materials, such as calcium phosphate cement are known to be able to release calcium and phosphate ions into their surroundings, thus when applied in our dental hard tissue, they would initiate the remineralization and regeneration of enamel and dentin due to the shift of calcium and phosphate concentration (4). Recent investigations show that they can improve the duration along with efficacy of restorations along with minimizing the harmful effects linked to typical inert materials (1)(2).

Regardless of their enticing properties, their degeneration in the oral environment is not frequently discussed. As we all know, oral environments in which these materials are placed are subjected to constant exposure to chemical and physical stimuli, along with the metabolism of various kinds of bacteria. Temperature, dental plaque, components of food and beverages oral hygiene conditions along with quantity, quality, as well as pH of saliva are all have a significant effect on bioactive material disintegration in the mouth (5). Understanding how bioactive materials degrade in the oral environment is critical for optimizing their uses. This review aims to explore the mechanisms, influencing factors, and clinical implications of bioactive material degradation in dental environments.

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2. Overview of Bioactive Materials in Dentistry

2.1. Definition and Properties

Bioactive materials are materials that are designed with the capacity to induce biological activity (6). In the field of dentistry, biomaterials can be defined as materials that have been constructed to positively interact with the living biological tissue for therapeutic or regenerative purposes (7). Bioactive materials are commonly used due to their mechanical enhancing characteristic that enables them to bond strongly with the natural tooth structure (8), their outstanding prospect have been proved remarkable with the invention of glass ionomer materials that possess fluoride releasing properties (7) Other notable materials such as bioactive glasses, glass ceramics, calcium phosphates, and calcium silicates are also studied and have shown some of the most effective regenerative components. They tend to be designed mimicking the natural physiological components––which in this case like human bone and teeth structure (9). For example, a recent study done have even developed an enamel inspired biomaterial that mimics the natural enamel components which are also have been proved to possess even superior characteristics like antibacterial adhesion and higher elastic modulus properties (10). In terms of their mechanism of action, generally, most of them undergo three types of pathways mentioned below:

2.1.1. Ion Release

Bioactive materials, such as bioactive glasses (BAGs), are well-known for their ability to give off calcium and phosphate ions to serve as an important function in remineralizing tooth enamel and dentin. In their mechanism, for example, the released of calcium ions from calcium hydroxide materials, would initiate precipitations of the phosphate ions within the saliva, this then enhances the formation and deposition of hydroxyapatite (7) In addition to that, through a regulated manner of ion release, these materials would then be able to sustain its longevity when applied for a long-term tooth restoration ((8).

2.1.2. Regenerative capabilities

Bioactive materials can be constructed in a form of organic scaffolds that are usually derived from collagen and hyaluronic acid (11). They exhibit biomimetic function for tooth and soft tissue regeneration to attain near normal teeth biological and aesthetic function (12). To give an example, hydroxyapatite (HA), aside from its properties in inducing remineralization in dentin matrix, is able to induce odontoblast differentiation through receptor inducing action when coupled with mature mesenchymal stem cells (13)(12). Additionally, bioactive ions and proteins encourage the regeneration of tissues, thereby helping in the regenerative mechanism.

2.1.3. Biocompatibility

Bioactive materials, particularly bioactive glass, have been demonstrated to possess excellent biocompatibility with the oral environment, resulting in minimum levels of negative side effects to their surrounding tissues (14)(15,16). However, numerous studies concentrate on immediate effects, particularly quick remineralization or initial biocompatibility, lacking long-term investigation of materials longevity, functionality, and safety in the oral environment. As an example, despite its great properties, bioactive glass is known to cause prosthesis failures in the implant treatment due to fibrous capsule forming side effect (17).

2.2. Applications in Dentistry

As mentioned previously, bioactive materials serve an important role due to its numerous applications in the field of dentistry. In the restorative dentistry field, bioactive glass-based materials, could triggering specific bioactivity inside host tissues such as cell proliferation and differentiation. Furthermore, bioactive glasses emit calcium and phosphate ions, that not only facilitate tissue remineralization but also aid in the development of brand-new, healthy tissue (18). They improve mechanical strength and encourage hydroxyapatite production, which addresses concerns such as persistent cavities and increases restorative lifetime (8). Another example, such as glass ionomer cement have been studied to encourage tissue remineralization and regeneration in both enamel and dentin by inducing osseous tissue deposition. Thus, it gives rise to its quality in regenerating dental tissues hardness which have been applied in dental restoration and endodontic treatment procedure (16).

3. Degradation Mechanisms in the Oral Environment

Despite its outstanding capacity, bioactive materials that is often used in dental procedures often come in contact with the oral environment, causing them to degrade overtime in the oral cavity through various manners. Therefore, addressing these pathways is crucial for enhancing functionality and clinical outcomes.

3.1. Physicochemical Degradation

Physicochemical alterations following biodegradation including dissolution, ion leaching, and surface wear, all of which can impair mechanical qualities. For example, bioceramic scaffolds like hydroxyapatite (19) and calcium phosphate have controlled biodegradability due to their composition. Reduced calcium-to-phosphate ratios enhance degradation rates, but greater ratios improve stability (13,20). Similar to that, the porous nature and microstructure of bioactive ceramics shown to impact degradation rates and ion release, which affects their lifespan and bioactivity in vivo. In addition to that, materials such as metals, ceramics, polymers, and combinations of these are would react chemically or electrochemically with their surroundings tissue. This continuous interaction over a long period of time might result in undesired release of other chemical molecules into its environment. Lists of procedure that utilizes them, such as implants, prosthetics, enamel and dentine restorations (5).

3.2. Mechanical degradation

Mechanical stresses in the oral cavity have been observed to contribute to bioactive materials' wear and breakage. Daily example of this forces is chewing and bruxism. These repetitive stresses can produce surface microcracks, resulting in a gradual degradation in the material structures' stability. Bioactive materials that are shown to be affected by these circumstances is polymer-based materials such as polylactide (PLA) and polycaprolactone (PCL) which over the time exhibit a considerable drop in modulus of elasticity, rendering them increasingly sensitive to biofilm formation and further deterioration (19). Aside from that, increases in bioactive materials' porosity and number of crystal imperfections, as well as reductions in crystal and grain size, generally increase the rate or extent of biodegradation (13)

3.3. Biological Degradation

Biological variables, like the existence of oral bacteria, have an important role in the breakdown of bioactive materials, particularly those formed of polymers. Microorganisms, in this case Streptococcus mutans and Candida krusei can connect to substrates and generate biofilms, affecting material characteristics. Biofilms release enzymes and acids, which breakdown the polymer components into smaller pieces, which subsequently pass across microorganisms' cellular membranes towards the interior, increasing degradation and adversely impacting bioactivity (20,21). For example, the biofilm enzymatic activity is capable of hydrolyzing ester linkages in polymeric materials, resulting in the shortening of chain and lower mechanical durability (22).

Other than external factors degenerative mechanism done by bacteria, resorbable ceramics, one of bioceramics meterials, can degrade through different mechanism. These ceramics' degradation products are either immediately phagocytosed by host's Inflammatory cells, osteoclasts, or even mesenchymal cells could phagocytosed the degradation products directly or they undergo chemical disintegrated by cell due to pH changes following implantation procedure (23).

3.4. Implications of Degradation

Degradation has profound impact for bioactive materials in dentistry. Reason such as mechanical property loss are essential since decrease in its density, would alter its surface micro- and microporosities, along with materials' size and weight. This changes in a long term would gradually give rise to ill-fitting restoration, shifts of environmental pH, and, ultimately, a reduction in their regeneration capability and function(20). Furthermore, the materials' degradation product, like ions or polymer segments, might cause adverse reactions or harm to the adjacent tissues. Biofilm production on deteriorated surfaces is likely to result in secondary caries or recurring infections, especially when fungal biofilms enter some degraded materials (19)

4. Factors Influencing Degradation

There are multiple different factors that could have an impact in how bioactive materials degrade in the oral environment, impacting biomaterials abilities, durability, and even biocompatibility. Hence, recognizing these different factors which influence degradation of bioactive materials is critical.

4.1. Material-Specific Factors

4.1.1. Composition

Materials containing a greater bioactive glass concentration release ions far quicker but might compromise their structural integrity quicker. As an illustration, adding calcium silicate into resin-based composites would optimize bioactivity while increasing brittleness (15).

4.1.2. Additives and coatings

Study have found that when chlorhexidine (CHX) is added to resin-based polymers, it would form bioactive systems which the biodegradation of its mechanical properties along with change in surface and color appearance ((24). his indicate that adding layers or coatings of other bioactive materials into the oral environment may increase or decrease bioactive material resilience. For example, fluoride ions found in oral care products can affect the physical properties of dental implants. High levels of fluoride in prophylactic medication can harm the barrier film on titanium (Ti) implants, causing corrosion. Toothpaste and gels containing up to 1% NaF or Na_2FPO_4 are typical sources of fluoride exposure, which may affect implant lifetime (24)

4.2. Oral Environmental Factors

Oral biological degradation refers to changes in the chemical, physical, and mechanical qualities of devices caused by environmental circumstances that can eventually impair the way they function. Its operations are typically triggered by factors such as salivary contents (e.g., water, enzymes), mechanical force (e.g., chewing), physical force (e.g., temperature variations), and chemical (e.g., pH variations) fluctuations caused by daily eating, drinking, and breathing (24). According to Dawid et al., temperature, pH, and microbial variety are the primary degrading factors in the oral cavity.

4.2.1. Oral pH

Variations in oral pH have substantial effects on material breakdown. Acidic environments, either by bacterial activity or diet, hasten the degradation of materials such as calcium phosphate and bioactive glass. Smaller pH values promote the breakdown of chemical residue from bioactive materials(25). Consequently, smaller pH means higher corrosion potential of dental metals and alloys, fortunately the degree varies according on their composition, so future improvement should be done in considerations of this behavior (5)

4.2.2. Temperature Variations

Elevated oral temperatures, especially those caused by inflammation or extended contact to hot liquids, accelerate polymer degradation (19).

4.2.3. Saliva Concentration

Resin-based materials are susceptible to degradation when exposed to saliva and microbial enzymes, which would cleave its ester bonds, resulting in the dispersion of monomer, thus, reducing their durability (26). Bioceramics and other bioactive materials may cause inflammatory reactions when mixed with biological fluids, resulting in alteration and degradation of its surface (23). Water concentration in saliva is also able to influence bioactive materials, specifically polymer, by increasing their water absorption. The gradual increase of water absorption could disintegrate polymer bonds into smaller components, resulting in polymer erosion and a steady loss of mechanical strength (27)

4.2.4. Oral Hygiene Factors

Biofilm deposition on surfaces of a semi-open mouth environment were shown to reduce bioactive polymeric materials' strength which then would cause an even higher degree of bacterial infections. This is important because an inadequate oral hygiene would promote biofilm growth and cause in acidic environment generation (lower pH) which have been previously mentioned as one of the factor that negatively influence bioactive material's properties, thus, the combination of both factors would the accelerate the material breakdown even more in the oral environment (19).

5. Current Research Gaps and Future Directions

5.1. Current Research Gaps

- Long-term Clinical Studies: While numerous in vitro studies give useful information, long-term clinical data are scarce on bioactive material performance, especially within the dynamic settings of the oral environment.
- The Impact of Emerging Oral Care Products: The impact of additional material components, for example like fluoride-free and antibacterial agents, on bioactive material degradation has yet to be investigated.
- Degradation Pathways in Complex Environments: The interaction of mechanical, biological, and chemical degradation pathways requires more exploration, especially in multi-material systems.

5.2. Future Directions

- Advanced Testing Models: Designing in vivo models that better reflect the intricate oral environment conditions, particularly salivary flow, presence of biofilm and its dynamics, as well as pH variations.
- In Vivo vs. In Vitro Correlations: Closing the discrepancy between controlled laboratory results and clinical outcomes.
- Innovative Material Design: Developing hybrid and nanocomposite bioactive materials that strike a balance between bioactivity, mechanical strength, and degradation resistance.
- Customized Treatments: Investigating patient-specific characteristics such as dental hygiene, food, and overall health to help guide the construction and application of bioactive materials.
- Sustainability and Biocompatibility: Investigating biodegradable materials that have low long-term environmental and biological implications while remaining effective.

6. Conclusion

This literature focuses on parameters that determine bioactive degradation in the oral environment. Bioactive materials have enormous promise for improving dental repair by supporting physiological healing and increasing the lifespan of restorations. However, how they operate in the oral environment is intrinsically linked to degradation behavior, which is determined by a complex interaction of material qualities, oral conditions, and clinical variabilities. Understanding these pathways and resolving present research gaps allow us to enhance bioactive materials for greater practical application, subsequently enhancing patient outcomes and developing the scientific field of restorative dentistry. Understanding the mechanisms of degradation is critical for increasing the long-term performance as well as reducing the adverse effects of these materials in the oral environments, which in turn can improves the patient outcomes and oral health.

Compliance with ethical standards

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Disclosure of conflict of interest

The author declares no conflict of interest associated with this study.

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