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Review Article

Emerging Biomaterials in Restorative Dentistry: A Comprehensive Review

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ABSTRACT

The increasing demand for durable, aesthetically pleasing, and biocompatible dental restorations has driven the development of emerging biomaterials in restorative dentistry. Conventional restorative materials have limitations, including polymerization shrinkage, material degradation, inadequate wear resistance, and restricted fracture toughness, necessitating continuous material innovation. This review comprehensively discusses the properties, clinical applications, advantages, and limitations of emerging biomaterials, including bioactive glasses, resin-based composites, ceramic materials, metallic biomaterials, fiber-reinforced composites, self-healing materials, and graphene-based nanocomposites. Bioactive glasses promote enamel and dentin remineralization through beneficial ion release, while advanced resin-based composites offer improved aesthetics, adhesive properties, and mechanical performance. Ceramic materials, particularly lithium disilicate and zirconia, provide enhanced strength, durability, and aesthetic outcomes in restorative procedures. Titanium and its alloys demonstrate excellent biocompatibility, corrosion resistance, and osseointegration, supporting their widespread application in dental implants. Fiber-reinforced composites enhance fracture resistance and flexibility, making them suitable for various restorative applications. Furthermore, self-healing materials demonstrate potential for autonomously repairing minor cracks, thereby reducing restoration failure and maintenance requirements. Graphene and nanocomposites offer promising improvements in mechanical strength, wear resistance, and antimicrobial properties, potentially enhancing restoration longevity. Despite these advancements, several challenges remain, including high production costs, limited long-term clinical evidence, material degradation, and concerns regarding mechanical performance and biocompatibility. The integration of these innovative biomaterials represents a promising advancement in restorative dentistry by addressing the limitations of conventional materials and supporting improved functional and aesthetic outcomes. However, further clinical investigations are essential to establish their long-term effectiveness, safety, and suitability for routine clinical applications.

Keywords: Bioactive glasses, Fiber-reinforced composites, Graphene, Nanocomposites, Resin-based composites.

BACKGROUND

Restorative dentistry has evolved significantly over the past few decades, moving from traditional materials like amalgam and gold to more advanced and biocompatible materials [1]. The key aim of restorative dentistry is to restore the function, structure, and aesthetic appeal of the

damaged or missing teeth. One of the most significant advancements in this field has been the development of emerging biomaterials that promise to offer better mechanical properties, enhanced aesthetics, and improved compatibility with the natural tooth structure [2]. These materials have the potential to transform dental practice by offering solutions that not only restore but also mimic the natural properties of teeth in a more effective and durable manner [3].

Biomaterials used in restorative dentistry are tailored to interact with the oral environment, contribute to healing, and maintain oral health. The perfect biomaterial should exhibit some character qualities such as high mechanical strength, wear resistance, biocompatibility, good aesthetics, bonding strength to natural tooth structure [4]. With the increased demand for advanced materials that are more patient-friendly, different biomaterials are being tested to meet these requirements. Emerging biomaterials to achieve this goal include bioactive glass, resin-based composites, ceramic, and newer forms of metals, among others. Their functions lie in restoring tooth functions as well as promoting tissue health of adjacent organs to teeth, such as the gingiva and the bone [5]. Bioactive glasses and calcium phosphates have been shown to promote the remineralization of the enamel and dentin, thereby making restorations more enduring [6]. Additionally, the ion release stimulates the healing of surrounding tissues hence reducing secondary caries. Resin-based composites, mainly used for direct restorations, have improved in mechanical and aesthetic properties over the years [7]. They can be shaped easily to fit the tooth's status and can be made to blend perfectly with the tooth's appearance. Their major shortcoming is their high composite wear, which should be worked on if they are to be more vigorous [8].

Ceramic materials, such as lithium disilicate and zirconia, are among the popular materials for metal substitution in restorative dentistry, offering high strength, acceptable aesthetics, and biocompatible characteristics [9]. As a result, they are most suitable for employing in dental crowns, bridges, and veneers where aesthetics and resilience are of the essence. Despite this, researchers are still investigating the challenge in the materials' low fracture toughness and high manufacturing costs [10]. Finally, improvement in metals, especially titanium and its alloys, remains pivotal in restorative dentistry. Utilizing the metal in dental implants has proven useful due to its biocompatible properties, and researchers are still investigating ways to enhance the material, including lessening the corrosion susceptibility and enhancing osseointegration via surface treatment [11].

This article discusses the most recent biomaterials in restorative dentistry, outlining their properties, current applications, and possible enhancements. By investigating the current trends and ongoing investigations, the review paper presents successful materials available in the field that plant a promising future in enhancing patient outcomes and solving challenges facing the sector.

REVIEW

In recent years, there have been significant advancements in restorative dentistry, mainly achieved through the utilization of newly developed biomaterials that have better properties for restoring teeth. Such materials offer solutions not only to return the tooth functionality but also solve aesthetic problems and benefit the surrounding tissues' health. This section will give a summary of the primary emerging biomaterials of restorative dentistry: bioactive glasses, resin-based composites, ceramics, and metals. It will review their properties, clinical applications, and examples along with their potential benefits and drawbacks.

Bioactive glasses

One class of materials which has shown great potential for application in this sector is bioactive glasses. These materials, which can bond to both hard and soft tissues, are more notably bioactive, which means they can interact with living tissues to promote regeneration and healing. This characteristic has allowed such materials as 45S5 – a blend of silica, calcium oxide, and phosphate – to be applied in restorative procedures by promoting remineralization and the generation of bone and dentin [12].

1. Properties and applications:

Bioactive glasses can release beneficial ions, such as calcium, phosphate, and sodium, which aid in remineralizing enamel and dentin, making them effective in preventing tooth decay. These materials also promote the formation of a hydroxyapatite layer on the surface, enhancing the bond between the restoration and the tooth [13]. Bioactive glasses have been employed in restorative procedures such as cavity fillings, root-end fillings, and inlays. Additionally, they are used in the development of regenerative products like scaffolds for periodontal regeneration [14].

2. Advantages:

- Promote remineralization of damaged enamel and dentin.
- Biocompatible and capable of forming a strong bond to both hard and soft tissues.

- Encourage the regeneration of surrounding tissues, reducing the risk of secondary caries.

3. Limitations:

- Limited mechanical strength compared to other restorative materials.
- The high solubility of bioactive glasses in acidic environments can compromise their durability.

Resin-based composites

Resin-based composites are widely used in restorative dentistry due to their versatility, aesthetic properties, and ability to bond to natural tooth structure. These materials are composed of a resin matrix (usually bisphenol A glycidyl methacrylate or UDMA) and inorganic fillers that provide strength and wear resistance [15].

1. Properties and applications:

The popularity of resin-based composites is mainly attributed to their ability to mimic the color and translucency of natural teeth. They are commonly used for fillings in posterior and anterior teeth due to their superior aesthetic appeal. Recent innovations have improved the mechanical properties of these composites, allowing them to perform better in load-bearing areas. Additionally, advances in adhesive technology have enhanced the bonding strength between composites and tooth structure, improving the longevity of restorations [16].

2. Advantages:

- Excellent aesthetic properties that closely match the natural tooth color.
- Good adhesive properties for bonding to tooth structure.
- Minimal tooth preparation required for restorations.

3. Limitations:

- Prone to wear and degradation over time, especially under high masticatory forces.
- Polymerization shrinkage, which can lead to microleakage and secondary caries.
- Long-term durability and fracture toughness can still be a concern, particularly for large restorations.

Ceramic materials

Ceramic materials, such as lithium disilicate and zirconia, have gained significant attention in restorative dentistry due to their excellent mechanical properties and aesthetic qualities. These materials are highly biocompatible and provide superior strength and wear resistance, making them ideal for high-stress applications like crowns, bridges, and veneers [17].

1. Properties and applications

On the other hand, lithium disilicate is a highly aesthetic material, thus enabling superior translucency, thus suitable for large anterior restorations. Because of its excellent strength and bonding properties, this material has quickly grown in popularity. In addition, zirconia is material selected for posterior restorations due to its exceptional strength. Therefore, zirconia materials are suitable for full crowns, bridges, and implants due to their high level of durability. Furthermore, both materials are used in CAD/CAM systems to produce precise and durable restorations [18].

2. Advantages:

- Superior strength and fracture resistance, especially for zirconia.
- Excellent aesthetic properties for anterior restorations.
- Highly biocompatible and well-tolerated by the oral tissues.

3. Limitations:

- High brittleness of certain ceramic materials, particularly lithium disilicate, can lead to fractures under extreme stress.
- Complex and time-consuming fabrication process, especially for zirconia restorations.
- Difficulties with bonding to tooth structure without additional surface treatments.

Metallic biomaterials (Titanium and Alloys)

Titanium and its alloys have long been a mainstay in restorative dentistry, particularly for dental implants, due to their strength, biocompatibility, and corrosion resistance. These materials have been refined over time to enhance their properties for both aesthetic and functional purposes [19].

1. Properties and applications:

Osseointegration, is the capability of titanium to fuse with bone, and has led to its preferred use for dental implants. Currently, the osseointegration process is more readily achieved due to modern surface treatments (such as sandblasting and acid etching), which have increased the overall success of the implant. Apart from this, titanium alloys are also used in other restorative applications, such

as in the partial denture and crowns because of their better mechanical properties [20].

2. Advantages:

- Exceptional strength and corrosion resistance.
- Excellent biocompatibility and osseointegration properties, making it ideal for implants.
- Long-lasting and durable with proper care.

3. Limitations:

- Aesthetic limitations, as the metallic color of titanium can be noticeable in certain restorative applications.
- The complexity of implant placement and the need for precise surgical techniques.
- Limited ability to bond directly to tooth structure without the use of additional bonding agents.

Fiber-reinforced composites

Fiber-reinforced composites are a type of composites that introduce fibers – glass, carbon, or aramid – into the resin matrix to improve the material's mechanical characteristics. FRCs are used in restorative dentistry due to their high strength, elasticity, and toughness in comparison to classic resin-based composites [21].

1. Properties and applications:

Fiber-reinforced composites are employed for high strength and flexibility. This is due to the added potential of the fibers in combating external stress and strain. Most of the fiber-reinforced composites are often utilized with the crown, bridge, and denture, as well as fillings. These products are used when it comes to mechanical properties and flexibility [22]. Moreover, FRCs are found to have better wearability and lower the chances of fracture as opposed to the use of the normal composites. Moreover, with the strength, the employer ensures a more flexible type of material that can mould with various directions of the tooth movement. With this aspect, it finds more application in the posterior restoration. The development of fiber posts has also been studied for use in endodontic treatment. These are posts applied after a procedure of the root that receives a root canal treatment. [23].

2. Advantages:

- Enhanced strength and fracture resistance, especially under stress.
- Improved flexibility, reducing the risk of failure due to masticatory forces.
- More durable and wear-resistant than traditional composites.
- The ability to mold and shape the material for precise, customized restorations.
- Better adhesion to tooth structure and less risk of microleakage.

3. Limitations:

- Can be more challenging to handle and manipulate due to the complex layering process.
- Increased material cost compared to standard resin composites.
- Limited aesthetic properties compared to more translucent materials like ceramics.

Self-healing materials

Self-healing materials are an exciting area of research in restorative dentistry, as they can repair minor cracks and damage autonomously over time. These materials contain microcapsules or embedded healing agents that are activated when a crack or damage occurs, allowing the material to repair itself without external intervention. This concept mimics biological self-repair processes and offers the potential for restorations that require less maintenance and provide longer-lasting performance [24].

1. Properties and applications:

Self-healing materials are designed to respond to mechanical damage by releasing a healing agent when a crack forms. These materials have applications in restorative dentistry for fillings, crowns, and veneers, where they can reduce the likelihood of failure due to microcracks that develop over time. The release of the healing agent triggers the formation of new material that seals the crack, restoring the integrity and strength of the restoration [25].

These materials are especially valuable in restorative procedures involving high-stress areas, such as molars, where continuous wear and tear can lead to the development of cracks. The self-healing property could potentially reduce the need for frequent repairs or replacements, making dental restorations more durable and cost-effective in the long term [26].

2. Advantages:

- Autonomous repair of minor cracks and damage, improving the longevity of restorations.

- Reduced maintenance and fewer repairs required over time.
- Potential to extend the lifespan of dental restorations and fillings.
- Decreases the risk of secondary caries by maintaining the integrity of the restoration.

3. Limitations:

- Current self-healing materials are still in the experimental phase and are not yet widely available.
- Limited healing capabilities for larger cracks or fractures.
- The technology may add to the cost and complexity of the material's development.

Graphene and nanocomposites

Many functional materials have primarily been studied in the field of restorative dentistry. Graphene, characterized by a single layer of carbon atoms joined in a two-dimensional lattice, is one of them. Another is nanocomposites made up of nanoparticles combined with traditional materials like resins or ceramics. These materials can improve the performance of dental materials in several ways [27].

1. Properties and applications

Graphene exhibits outstanding mechanical properties as well as electrical and mechanical strength. When incorporated in the composite gel, the resultant material becomes stronger, more durable, and elastic. This implies that the graphene composite materials can be used for a variety of applications, particularly in areas where they overperform the other materials. For instance, the addition of the graphene nanoparticles to resin enhances the mechanical strength [28]. This paper concludes that the resultant material does not wear out and break down easily with time over the added equivalent date. The nanocomposites with nanoparticles such as silica and zirconia exhibit physical and chemical properties superior to the traditionally available composite. Some of the physical properties include mechanical strength and hardness, fracture toughness, and wear resistance. It is found that nanocomposites have superior physical properties compared to the conventional composite. Besides, the high physical strength in the long run sustains the restoration material longer than the traditional one. In some instances, the nanocomposites bonding properties are more rigid, and they reduce the polymerization shrinkage to avoid failures around the restoration [29].

Graphene's antimicrobial properties

Therefore, given the observable killing of bacteria or at least inhibition of their growth in the presence of graphene or graphene oxide, the two are ideal for application in making surfaces antimicrobial. Specific to this study, being used in the manufacture of dental restorations may contribute to preventing bacterial growth on the surface. Restorative dentistry protocols may benefit from such compositions, considering bacteria proliferation in the mouth resulting in decay and infections. Hence, including graphene kills the bacteria ensuring no secondary infections occur and playing a role in enhancing health [20].

1. Advantages:

- Exceptional mechanical strength and wear resistance.
- Improved aesthetic properties due to enhanced translucency.
- Antimicrobial properties that help prevent infection and bacterial growth.
- Better bonding to tooth structure and reduced risk of microleakage.
- Potential for more durable, long-lasting restorations.

2. Limitations:

- High cost of production and processing.
- Long-term clinical studies are required to fully understand the biocompatibility and potential risks.
- Challenges in integrating nanoparticles uniformly within the composite matrix.

DISCUSSION

The integration of emerging biomaterials in restorative dentistry has significantly advanced the field, offering a broader range of solutions to address the evolving demands of dental care. As restorative dentistry focuses on improving both functional and aesthetic outcomes, the development of materials that more closely mimic natural tooth structure, enhance mechanical properties, and provide longer-lasting performance is crucial [32].

On the other hand, the limitations of common dental materials have inspired research into diverse alternatives. Bioactive glasses, resin-based composites, ceramics, fiber-reinforced composites, self-healing materials, and graphene-based nanocomposites are some examples of materials that hold promise in overcoming the known limits to existing materials. For example,

bioactive glasses help in remineralizing enamel and dentin [33].

Bioactive glasses used in fillings and teeth cavities, and on the root end, have also been shown to prevent further enamel damage. The major limitation of this material is its relatively lower mechanical properties. Here, a key challenge arises: striking a delicate balance between bioactivity and mechanical performance [34].

Even though bioactive materials can be readily used to enhance dental health, increasing their strength is critical to ensure that mastication and oral conditions do not weaken them. Resin-based composites are modified versions of the traditional composites. Even though they have become widely used lately, they suffer the drawbacks related to polymerization, wear resistance, and longevity [35].

Dental ceramics also refer to brittle materials that require cautious handling due to their brittle properties. The ceramics are used to treat crown and bridge restorations. Since ceramic has high mechanical properties, it can even be used to treat posterior teeth [36].

CONCLUSION

The progress of emergent biomaterials including FRCP, self-healing material and graphene-based nanocomposite has penetrated the fabric of restorative dentistry. These materials offer immense improvements in mechanical properties, erosion resistance and esthetically satisfying solutions for some old problems encountered during dental restorations. Fiber-reinforced composites are designed to improve the strength and flexibility of the materials for load-bearing purposes, while self-healing materials can deliver longer-lasting restorations with less maintenance. Graphene and nanocomposites provide not only improved mechanical properties but also antimicrobial effects, which contribute to the general performance and longevity of dental restorations. Although promising, more studies such as clinical trials are needed to address the limitations and allow them to reach their full potential in dentistry.

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AUTHOR CONTRIBUTIONS

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ABBREVIATIONS

a) **CAD/CAM:** Computer-Aided Design/Computer-Aided Manufacturing
b) **FRCs:** Fiber-Reinforced Composites
c) **UDMA:** Urethane Dimethacrylate
d) **FRCP:** Fiber-Reinforced Composite Polymer

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