Biomimetic Restorative Materials: Recent Trends and Future Directions

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Abstract- Biomimetic restorative material is an approach that utilizes nature as a model for restoring damaged or decayed teeth. It focuses on preserving as much of the natural tooth structure as possible while mimicking the natural tooth strength, function and esthetics using adhesive bonding techniques, minimal invasive procedure and advanced materials. To review the clinical outcomes and evidence-based findings regarding biomimetic material properties and its use .The advances in biomimetic materials have seen a rapid rise in the last decade, with the introduction of several newer materials being launched into the dentistry. These materials aim at preserving tooth structure, restoring the overall health of the tooth and making treatment outcomes more predictable. Biomimetic restorative materials represent a paradigm shift in dental care, emphasizing the replication of natural tooth structures to achieve superior functional and aesthetic outcomes. This review delves into recent advancements in biomimetic materials, highlighting their clinical applications, challenges, and future prospects in restorative dentistry.

Keywords: Dentistry, operative, tooth remineralization, biomimetic materials, dental materials.

INTRODUCTION

Restorative dental materials are biocompatible substances used to repair or replace damaged tooth structure, restoring form, function and esthetics. It is categorized into amalgam, composite, GIC, ceramics and gold alloys, each offering distinct mechanical and esthetic properties. [1] The selection of material is detected by factors like strength, durability, biocompatibility, appearance, crucial for long term oral health. Advance materials offer fluoride release and superior bonding, enhancing tooth preservation.

Natural teeth exhibit intricate biomechanical properties due to their layered structure of enamel, dentin and pulp which effectively dissipate masticatory forces; however, traditional restorations often fail to replicate this, leading to stress concentration and retention failure , while biomimetic approaches aim to restore the tooth natural biomechanics for optimal function and durability. [2]

In essence, biomimetic restorative materials represent a shift in restorative dentistry towards a more conservative and biologically integrated approach. These materials are designed to mimic the natural structure, function and esthetics of a tooth. These advanced materials include contemporary resin based composite, GIC and bioceramics that exhibit key characteristics such as modulus of elasticity, strength comparable to dentin and enamel. Application of these materials aims to restore not only the form and function but also biomechanical integrity of tooth and facilitating minimal invasive procedures. By achieving a strong, durable and seamless bond with a remaining tooth structure, these materials significantly reduce polymerization shrinkage, stress, postoperative sensitivity and risk of micro-leakage, enhancing the longevity of the restoration. [3] The application of biomimetic restorative materials, as examined by various researchers including Singer L. et al. (2023), concludes that biomimetic concepts and protocols aim to preserve tooth structure and vitality, enhance the durability of restorative dental treatments, and eliminate the need for future retreatment cycles. [1]

The ultimate goal of modern restorative dentistry is to achieve minimally invasive procedures that restore the intricate biomechanical properties of natural teeth. By mimicking natural tooth structure and function, these advancements lead to durable, esthetics and biologically sound restoration that minimizes stress and enhances the longevity of the restoration while maintaining the overall health of the tooth. [2] Thus an attempt has been made through the current review where the history, current developments and challenges of biomimetic restorative materials were discussed along with clinical approaches.

HISTORY

In 1974, Webster's Dictionary first formally included the phrase "biomimetics." Even though the history of biomimetics dates back to the first century, it wasn't until the publication of Janine Benyus' groundbreaking book "Biomimicry: Innovation Inspired by Nature" in 1997 that it gained widespread recognition among academics and scholars.
In the 1950s, Otto Schmidt first used the term "biomimetics," which means "imitation of nature."[10]

In dentistry specifically:

1. Takao Fusayama’s work in the 1980s on adhesive dentistry laid crucial groundwork, focusing on bonding to tooth structure. His research challenge to traditional subjective methods of caries removal and advocate for more scientific, objective approaches.

2. Dr. David Alleman’s research starting in 1995 further contributed to understanding dentin bonding and developing protocols to reduce post operative sensitivity and improved restoration longevity. He integrated over 1400 research articles into his “Six Lessons Approach to Biomimetic Restorative Dentistry”.

3. Early Concepts (Mid to Late 20th Century): The term "biomimetic restorative dentistry" became formalized in the early 2000s, notably through Pascal Magne's 2002 book, "Bonded Porcelain Restorations in the Anterior Dentition." Magne esmphasized that the "intact tooth is the guide to reconstruction."[4]

RECENT TRENDS IN BIOMIMETIC RESTORATIVE MATERIALS

1. **Development of Bioactive Composite:** The use of bioactive composites in restorative dentistry has changed the paradigm from inert restorative materials to ones that actively promote tissue regeneration and reduce secondary caries by interacting dynamically with the oral environment. By encouraging the remineralization of dematerialized tooth structures and triggering the de novo formation of hydroxyapatite, these sophisticated composites are designed to release therapeutic ions like calcium, phosphate, and fluoride, improving the marginal seal integrity and strengthening the tooth restoration interface.[7] Key bioactive components like bioactive glasses (BAGs) and amorphous calcium phosphate(ACP) facilitate this biomineralization, while the incorporation of antimicrobial agents like quaternary ammonium dimethacrylates and silver nanoparticles provide intrinsic bacterial inhibition. Even though research is still being done to improve the mechanical qualities and long-term clinical efficacy of

restorations, this complex bioactivity not only prolongs their lifespan by lowering microleakage and secondary decay but also promotes pulp vitality and general oral health.

2. **Use of Nanotechnology:** Nanotechnology fundamentally transforms biomimetic restorative dentistry by enabling the precise manipulation of materials at the nanoscale to emulate the natural tooth's intricate structure and function. The incorporation of nanofillers, such as nano-hydroxyapatite and amorphous calcium phosphate, into composite resins significantly enhances mechanical properties, while also reducing polymerization shrinkage. This nanostructured approach allows for superior aesthetics and its distribution can be optimized to mimic the natural translucency and light-scattering properties of enamel. Furthermore, these materials exhibit bioactive and therapeutic functionalities. Nanoparticles actively release calcium and phosphate ions to promote the remineralization of demineralized dentin, preventing secondary caries. The small particle size also facilitates improved penetration of bonding agents into dentinal tubules, creating a stronger, more stable hybrid layer.[6] Additionally, the integration of antimicrobial nanoparticles imbues these materials with effectively inhibiting biofilm formation and reducing the risk of secondary caries, ultimately contributing to the longevity and clinical success of the restoration.
3. **Integration of Digital Dentistry:** The integration of digital dentistry is fundamentally transforming the application of biomimetic restorative materials, creating a synergistic workflow that prioritizes precision, conservation, and efficiency. This convergence is driven by technologies such as intraoral scanners, computer-aided design and manufacturing and 3D printing. The process begins with digital data acquisition, where intraoral scanners capture a highly accurate, three-dimensional impression of the patient's teeth. This digital model is then transferred to CAD software, where the clinician meticulously designs the restoration as it allows for the precise replication of the tooth's natural form. Once the design is finalized, it is sent to CAM miling machine where physical restoration is fabricated from a block of high-quality, pre-cured biomimetic materials.

   Ultimately, the integration of digital dentistry with biomimetic restorative materials creates a streamlined, predictable, and highly conservative treatment approach. It allows for the fabrication of restorations that are precisely designed to mimic the natural biomechanics, aesthetics, and function of the tooth, all while preserving as much healthy tooth structure as possible.

   4. **Advancement in adhesive technologies:** They are introductory to biomimetic restorative dentistry, enabling the precise replication of tooth structure and function. The evolution from early etching techniques to sophisticated universal adhesives, often incorporating 10-MDP for enhanced chemical bonding, has significantly improved bond strength and simplified clinical protocols. Crucially, the integration of nanoparticle technology enhances adhesive penetration and mechanical properties, while bioactive components like micro- and nano-hydroxyapatite and bioactive glasses actively promote remineralization and inhibit secondary caries. These material innovations, coupled with optimized bonding protocols such as Immediate Dentin Sealing and selective enamel etching, collectively facilitate minimally invasive, durable, and aesthetically superior restorations that preserve tooth vitality and mimic natural biomechanics.[1]

CLINICAL APPROACHES

With the aim of preserving as much healthy tooth as possible, preserving pulp vitality, and extending the restoration's lifespan, biomimetic dentistry is a restorative approach that directs the choice of materials and techniques to create restorations that behave like natural tooth structure. The clinical method is distinguished by a series of procedures intended to minimize stress on the tooth structure and optimize the binding between the restorative material and the tooth. [1]

Key Principles of the Clinical Approach:

1. **Minimally Invasive Dentistry:** Maintaining healthy tooth structure is the main objective. This entails avoiding "extension for prevention" theories that remove healthy tooth structure and just extracting the problematic tissue, in order to aid the affected dentin and preserve the layer of reparable dentin.
2. **Protocols for Bond-Maximization:** It is essential that the restorative material and tooth form a solid, long-lasting relationship and advanced adhesive techniques are used to achieve this extensive bond. Moreover t he DEJ, the natural contact between dentin and enamel that is also essential for biomechanical integrity.
3. **Stress-Reducing Protocols**: In semi direct or indirect techniques, the restorative material is placed in thin incremental layer which helps to lessen the tension brought by polymerization shrinkage. Stress reduced by maintaining the maximum possible bond strength which is the ultimate goal of biomimetic restorative technique.[11]

CLINICAL APPLICATIONS

Biomimetic materials and techniques are used in a wide range of clinical applications, including:

1. **Restorative Dentistry:** Because of its foundation, minimally invasive restorations can be used to repair damaged teeth or carious lesions with little to no disturbance of the healthy tooth structure.[8] These materials replicate real teeth in terms of design, color, and translucency and repairing the early-stage carious lesions is being facilitated by such kind of materials. In order to effectively absorb and distribute functional stresses, biomechanical restoration uses materials that closely match the layers of dentin and enamel. Casein phosphopeptide-amorphus calcium phosphate (CPP-ACP) or bioinspired peptides are found in materials that help remineralize damaged enamel and dentin. . [1]
2. Endodontics: MTA and cements based on calcium silicate are among the materials used in both direct and indirect pulp capping. To promote healing and protect pulp, they promote the formation of a dentin bridge. These processes support the growth of roots or aid in the development of an apical barrier in immature teeth.[9]

CHALLENGES

Although there are many benefits of using biomimetic restorative materials in dentistry, there are drawbacks as well. These difficulties are frequently caused by the materials themselves, the necessary technique, and the larger dental practice.

Material-Related Challenges: The sophisticated hierarchical structure of a normal tooth, with its separate layers of enamel and dentin, each with unique qualities, is difficult to replicate. However, research is still being done to achieve a flawless, seamless integration of all features. Successful operations depend on elements such as controlling moisture, using bonding agents correctly, and precisely layering materials. Compared to more conventional options, biomimetic restoration may be more costly due to the research and development of these cutting-edge materials as well as the specific tools and equipment needed for their use. Incomplete cure in other situations, particularly in deep cavities, may jeopardize the restoration's integrity. [5]

Clinical and Procedural Challenges: Stress-reducing layering techniques and rapid dentin sealing are two examples of biomimetic procedures that frequently require more time to complete than traditional methods. The use of caries detector dyes might occasionally result in the excessive removal of healthy dentin, which is contrary to the fundamental idea of minimal intervention. Applying biomimetic approaches calls for a high degree of expertise. Not all dentists have received the advanced protocols training, and inadequate instructions can have negative consequences. Although pulp capping and controlling an inflamed or damaged pulp are ideal uses for biomimetic MTA, the process can still be complicated, and there is a chance that post-operative sensitivity or the necessity for a root canal will arise. [5]

FUTURE OUTLOOK

In spite of fewer impediments, biomimetic dentistry is still developing quickly. The goal of ongoing research is to create materials that are more cost-effective, long-lasting, and less technique-sensitive. In order to get a long-lasting, functional, and aesthetically beautiful result, the ultimate goal should be the development of the restorative materials or processes that will serve as an extension of the natural tooth.[1]

DISCUSSION

Various authors have discussed the use and properties of biomimetic restorative materials which marks a fundamental shift in dental care. According to Singer et al. (2023)[1], the main objective of this idea is to maintain the vitality and structure of the teeth in order to increase the longevity of restorations and reduce the need for retreatments in the future. A major theme in the literature is this view, which stresses the replication of natural tooth structures to produce better functional and cosmetic results. This revolution is being driven by recent developments in the field. According to Zafar et al. (2020)[6], the creation of bioactive composites signifies a paradigm shift away from inert materials and toward ones that actively support tissue regeneration. This strategy is further improved by nanotechnology since the mechanical and cosmetic qualities are improved by the addition of nanofillers such nano-hydroxyapatite. Because these materials are made to resemble the tooth's natural structure, function, and appearance, Magne and Belser's et al. (2022)[2] study emphasizes the value of a conservative and biologically integrated approach.

Even with all the advantages, there are still difficulties. It is challenging to replicate the intricate hierarchical structure of a genuine tooth, as said by Sharma et al. (2023)[5] in their literature. These processes can be more expensive since they take longer working time and call for specialized equipment and a high level of technical knowledge. Even there is a chance that deep cavities won't cure completely, which could jeopardize the quality of the restoration. However, research is still being done to create more affordable, long-lasting, and technique-insensitive materials, so the future of biomimetic dentistry seems bright.

CONCLUSION

Biomimetic restorative materials and techniques are fundamentally transforming dentistry by providing a biologically viable, conservative, and aesthetically enhanced alternative to conventional approaches. Continuous advancements in material science, including bioactive composites, nanotechnology, and sophisticated adhesives, complement this concept, which is centered on maintaining tooth structure and mimicking natural biomechanics. As a result of these developments growing integration with digital dentistry workflows, treatment techniques are becoming more efficient, predictable, and conservative. At the end creating restorative materials that truly function as an extension of the natural tooth in order to create durable, aesthetically pleasing and physiologically sound restorations should be the ultimate goal.

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