The Paradigm Shift to Biomimetic Materials in Conservative Dentistry: A Comprehensive Review of Bioactive Innovations

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ABSTRACT
Dentistry and endodontics are witnessing an epochal shift in philosophy from the mechanically based paradigm to the biological paradigm. Traditionally, metals, eugenol compounds, and other materials have been used in fillings where the principle of mechanical retention had to lead to removing healthy tissue along with the unhealthy one. The risk of failure associated with these materials was linked to marginal leakage, shrinkage during curing, polymerization stress, and material fracture. Biomimetic dentistry uses adhesive technologies and bioactive materials with characteristics that mimic those of natural enamel and dentin. This review describes the evolution of biomimetic concepts and focuses on two topics: (1) development from macro-retention to microretention; and (2) recent applications in dentistry, involving composite resins reinforced with fibers, calcium silicate-based cements, and bioglasses. In addition, current trends and future perspectives related to self-healing composites and biomineralization by peptides will be discussed.

Keywords- Bioactive materials, microadhesion, MTA.

INTRODUCTION

The integration of biomimetic principles into restorative dentistry and endodontics represents a fundamental shift in clinical philosophy, moving away from traditional mechanical retention toward biologically oriented preservation. Traditionally, conventional techniques of endodontic and restorative treatment involved the use of materials such as gutta-percha, silver amalgam, and gold alloys, which were based on mechanically retaining the restoration, while requiring considerable amounts of healthy tissue to be sacrificed in the process. Traditional materials, however, suffer from numerous shortcomings, such as lack of chemical bonding and compatibility, solubility, and structural inability to adhere to dental tissue, all of which cause various issues. [1,2,3]

Biomimetic dentistry represents a philosophy centered on mimicking the natural structure, function, and biomechanics of teeth when restoring damaged or decayed dental tissue. The term derives from the Greek bios (life) and mimesis (imitation), and the approach has gained significant traction in conservative dentistry over the past two decades. [1,4]

Understanding what is important about the biomimetic revolution requires an inspection of the "old" (conventional) method of restoration in dentistry (for more than 100 years). This phase was defined by mechanical retention rather than biological adhesion and was defined by the principles of G.V. Black. [5,6]

The limitations of traditional restoration materials used in the past, such as silver amalgam and cast gold/metal alloy, demonstrates that valuable materials are available which have more than enough strength and durability to be used in modern chairside restorations. [3,7]

The following traditional materials illustrate these limitations:

1. Silver Amalgam (Dental Amalgam)

Because of its availability, affordability, and compressive strength, amalgam has always been the most widely used restorative material. [6,8]

Dental amalgam has no chemical or mechanical bond to the tooth; it achieves retention through mechanical interlocking. In order to ensure proper retention, the clinician works to create specific undercuts within the cavity preparation (the area of tooth prepared for the restoration); therefore, in order for an amalgam restoration to be retained against dislodgement due to occlusal forces, the clinician creates an undercut within the preparation to create an opening larger than its base. [8,9]

2. Zinc Oxide Eugenol (ZOE)

In addition to being a common base or liner for fillings, Zinc Oxide-Eugenol (ZOE) is also frequently used as a temporary filling material. One of the reasons for using ZOE is because of its ability to calm (sedate) the nerve endings in the tooth; this sedative effect on the nerves is primarily due to the eugenol that it contains. [10,11]

The following are limitations associated with its use:

- ZOE has very low strength to tolerate the forces of occlusion/chewing, so it is not a suitable material for a permanent filling. [10]
- ZOE has high solubility (dissolves readily) in fluids in the mouth, which may result in loss of the marginal seal and, ultimately, exposure of bacteria to the nerve. [10,11]
- The eugenol in ZOE negatively affects the ability of modern resin-based materials to polymerize, so ZOE cannot be used in most cases as a base for aesthetic restorations. [10,12]

3. Early Glass Ionomer Cements (GICs)

GICs were the first type of dental materials that provided for bioactivity by establishing a chemical bond with hydroxyapatite as well as releasing fluoride. [1,3]

Drawbacks:

- Brittleness: The early versions of this material had poor resistance to both fracturing and wearing out; hence, it was susceptible to "bulk fracture" in the case of large surfaces under load. [1,3]
- Moisture Sensitive: The early GICs were very moisture sensitive both at early and late stages of the cementation process. [1,3]

4. Cast Gold and Base-Metal Alloy Restorations

Gold inlays/onlays were once the benchmark when it comes to lasting restorations. But just like amalgams, these traditional cast restorations are non-adhesive. [2,7]

Drawbacks:

- Extensive Tooth Preparation: In order to accept a casting, the tooth is extensively prepared using "tapered" walls and a certain "path of insertion". This requires the stripping down of the tooth by removing its healthy functional cusps which would have otherwise been retained using adhesive dentistry. [2,5]
- Lack of Adhesion: These restorations use cements such as zinc phosphate that are soluble in nature and do not adhere to the tooth at all. Once the cement line is washed away, the restoration becomes susceptible to secondary decay. [2,7]

The Evolution Paradigm

1. From Macro-Retention to Micro-Adhesion

The core of the change between traditional and modern materials lays in different mechanisms of retaining restoration inside the tooth. [2,3]

- The Old Way (Mechanical): Traditionally, there was no bond between the tooth and restorative materials (e.g., amalgam or gold). Thus, dentists needed to create so-called undercuts and parallel walls (mechanical retention). Moreover, it often required removing healthy parts of the tooth (e.g., marginal ridges, pericervical dentin) to prevent falling out of the restoration. [5,8,9]

- The New Way (Biomimetic): The modern approach includes sophisticated adhesion technologies and micro-mechanical bonding. The tooth is now bound to the restorative material and, therefore, extension for prevention is not required anymore. [2,3]

2. Structural Integration: Mimicking the DEJ

An important development during the process of transformation was knowledge about the Dentino-Enamel Junction (DEJ). [13,14]

- Traditional Materials: Metallic fillings such as silver amalgam have a high modulus of elasticity (are highly rigid) and a different thermal expansion rate compared to the tooth. Under pressure from biting or when eating hot or cold foods, the metal moves separately from the tooth, serving as a wedge that will ultimately lead to the breaking of the tooth. [8,13]
- Materials of the Future: Biomimetic techniques use fibre-reinforced composite materials and hybrid resin materials. These materials simulate the modulus of elasticity of dentin. Using these materials in layers creates the "buffer zone" of the DEJ and enables the tooth and filling to move as one. [1,13,14]

3. From Simple Fillers to Bioactive Materials

The shift also involved a shift in the chemistry of the materials utilized, especially for endodontic and deep restoration applications. [1,15]

- Conventional Bases (e.g., ZOE): In the past, Zinc Oxide-Eugenol was mostly favored for its sedating effect. Nonetheless, the material was soluble, ineffective, and prevented the use of current resin bonding technology. While these materials offered a stopgap measure, there was no added benefit or strengthening of the teeth. [10,11,12]
- Current Bioceramics (e.g., MTA, Biodentine): Current materials are bioactive. Upon exposure to moisture or bodily fluids, these materials release ions of calcium and phosphate, resulting in the creation of hydroxyapatite. Not only does this result in a superior seal, but the process also activates body processes like creating a dentin bridge during pulpal capping. [15,16,17]

4. Polymerization Stress

With the shift to new resin-based materials from the previous metal options, a new issue was introduced: shrinkage. [1,3]

- Initial "New" Materials: The earliest generation of composite materials struggled with polymerization shrinkage problems, leading to post-surgical issues like leakage and sensitivity. [1,3]
- Contemporary Biomimetic Techniques: This transitional phase includes methods such as decoupling with time, incremental layering, and using stress-absorbing liners (e.g., Glass Ionomer Cement for the sandwich technique), which all help to maintain the integrity of the bond between the new material and tooth over time. [1,2,3]

Core Principles of Biomimetic Dentistry

The biomimetic approach rests on several foundational ideas: [2,7]

- Minimal intervention: Remove only what is necessary; preserve as much healthy tooth structure as possible. [1,2]
- Material-tissue compatibility: Select restorative materials whose mechanical properties (elasticity, thermal expansion, flexural strength) closely match enamel and dentin. [3,7]
- Stress distribution: Restore teeth in a way that allows forces to dissipate naturally, reducing the risk of cracks and fractures. [2,13]
- Sealed margins: Use adhesive techniques that create a bacterial-tight seal, protecting the pulp and preventing secondary caries. [1,2]

These principles reduce the need for more invasive treatments such as crowns or root canals down the line. [2,7]

Key Biomimetic Materials

Calcium Silicates and Aluminates

Mineral Trioxide Aggregate (MTA) and its new-age derivatives (such as Biodentine) are highly hydrophilic cement materials made up of calcium silicates. In contact with phosphate-containing bodily fluids or saliva, these compounds form crystals of calcium hydroxide and precipitate an enamel-like coating of hydroxyapatite. The high pH environment provides inherent antibacterial properties and aids the successful formation of dentin bridges over the vital pulp tissue. [15,16,17,18]

Bioactive Glass (BAG)

BAG materials contain micro- and nano-crystals of amorphous calcium phosphate (ACP) or customized silica lattices. Following their reaction with moisture, BAG material forms a reservoir of locally available calcium, sodium, and phosphorus ions, which undergo a quick ion exchange and precipitate mineral crystals, leading to the physical occlusion of open dentinal tubules, preventing further fluid movement and hypersensitivity while facilitating intrafibrillar remineralization at the adhesive interface. [19,20]

Fiber-Reinforced Composites (FRCs)

Fiber-reinforced composites (FRCs) are a new type of material that has potential applications in restorative dentistry. These biomimetic materials are designed to overcome one of the main limitations of traditional particulate-filler composites: the inherent brittleness of these materials and their tendency to fracture under heavy loads on the dentition. [21,22]

STRUCTURAL COMPOSITION AND MECHANISM:

By incorporating high-performing fibres into a resin matrix, FRCs have been developed to duplicate the natural qualities of the dentino-enamel junction (DEJ) and collagen network within dentin. Specifically, FRCs combine two phases: a polymer matrix (the continuous phase) and reinforcing fibres (the dispersed phase). FRCs are made with both: the fibres can be made from E-glass or polyethylene, and they are treated with silane to create a strong chemical bond to the resin matrix. The resin matrix is most commonly comprised of dimethacrylate-based resins (Bis-GMA or TEGDMA). [21,22]

CLINICAL APPLICATIONS:

1. Fiber-reinforced composites are becoming the "gold standard" for core post restorations of endodontically treated teeth, as they provide a robust core capable of supporting an onlay or crown without the risk of vertical fracture. [21,23]
2. In the case of large class II cavities with lost marginal ridges, an SFRC base can help to strengthen the "peripheral rim" of the tooth left from the loss of the marginal ridges. [22]
3. Fiber-reinforced composites are used extensively in the construction of endocrowns for reinforcing the internal portion of the large volume of restorative material used in the fabrication of the pulp chamber. [21,22]

Resin Modified Glass Ionomer Cements (RMGIC) — Sandwich Technique

RESIN MODIFIED GLASS IONOMER CEMENTS (RMGIC) are utilized in biomimetic protocols using the so-called Sandwich Technique. This technique involves placing RGIs as a buffer between the tooth and a rigid composite material. [1,3]

- Elasticity: Dentin is more elastic than enamel. Therefore, by placing RGIs between the tooth and the composite, they provide a buffer to absorb stress transmitted from the composite to the tooth. This mimicking of the elasticity of dentin reduces the "C-factor" stress that occurs due to the top layer of composite material shrinking during the light-curing process. [1,3,13]

Smart and Regenerative Innovations

One newer direction in innovation departs from the idea of mimicking completely. Such material reacts to stress either inside the restoration itself or mineral degradation outside of it: [24,25]

Self-Healing Composite Materials:

Microcapsules filled with a certain liquid monomer are pre-integrated in the composite material. These microcapsules are made of polyurea-formaldehyde and silica coatings. Microcracking due to the pressure inside the tooth causes cracks and makes the coating break. Monomers diffuse out and come into contact with catalysts. Then, they polymerize and bridge the crack before it becomes clinically significant. Thus, the composite repair occurs before any issues can become noticeable. [24,25]

Biomineralization by Peptides:

While the previous strategy aimed to fill in any void, this approach aims to regenerate the lost mineral. Self-assembling peptides, including Polyvinyl Phosphonic Acid, can be used as a scaffold to direct deposition of minerals precisely where they are needed, namely the areas previously occupied by minerals. This means that there will be no substitute but instead, there will be actual reconstruction of the natural structure. [26,27,28]

Conclusion

The shift toward biomimetic materials represents the maturation of dentistry into a biological science. By utilizing hydraulic calcium silicates for endodontic repair and bioactive adhesives for conservative restoration, clinicians can provide treatments that are more durable, aesthetic, and respectful of the natural tooth's physiology. While challenges such as cost and handling persist, the integration of nanotechnology and regenerative protocols promises a future where the distinction between "natural" and "restored" tooth structure becomes increasingly invisible. [1,2,3,7]

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