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The role of nanotechnology in restorative dentistry: A review of current applications

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***Abstract*---**Background: Restorative dentistry has evolved significantly from the use of traditional materials such as amalgam to more advanced options like dental composite resins. Nanotechnology, which involves manipulating materials at the atomic or molecular scale, has introduced a new dimension to dental materials, offering improvements in mechanical properties, aesthetics, and functionality. Aim: This review aims to explore the current applications of nanotechnology in restorative dentistry, focusing on how nanomaterials enhance dental treatments and restorations. Methods: A comprehensive review of recent studies and advancements in nanomaterials applied to dental composite resins, adhesives, cements, and whitening agents was conducted. Key areas of investigation included the impact of nanomaterials on mechanical strength, wear resistance, antibacterial properties, and aesthetic outcomes. Results: Nanomaterials such as nanoparticles of silica, zirconia, titanium dioxide, silver, and zinc oxide have been integrated into dental materials to improve their performance. Nanocomposites demonstrate enhanced mechanical strength and durability, while nano-enhanced adhesives offer better bonding and self-healing capabilities. Antibacterial properties have been significantly improved with silver and zinc oxide nanoparticles, which help in preventing secondary caries and oral infections. Nanomaterials have also advanced dental cements and whitening agents, offering better fluoride release, controlled whitening effects, and improved imaging techniques. Conclusion: The integration of nanotechnology into restorative dentistry represents a significant advancement, providing enhanced material properties, improved aesthetic results, and greater durability. Continued research and development in this field hold promise for further innovations and applications, potentially transforming dental treatment and care.

***Keywords*---**Nanotechnology, restorative dentistry, dental composites, nanomaterials, adhesives, antibacterial agents, dental cements, tooth whitening.

Introduction

Tooth restoration constitutes a fundamental aspect of dental care, focusing on reinstating the natural structure of teeth so that the restored teeth replicate the function and appearance of their original, unaffected counterparts. The foundational principles of cavity preparation were developed by the late Dr. G.V. Black. His guidelines were designed to assist practitioners in preparing cavities such that, once restored, the tooth functions optimally and remains securely within the cavity, mimicking the natural characteristics and functionality of the original tooth. Historically, cavities prepared according to Dr. Black's principles were predominantly filled with amalgam, an alloy composed of silver and mercury in a 3:7 ratio [1]. Amalgam, which was enhanced over time with additional filler particles, served as the primary restorative material for most of the history of endodontics. However, advancements in technology and understanding have led to its widespread replacement with dental composite resins, which offer superior versatility, aesthetic appeal, and increased strength. Dental composite resins are favored for their ability to move away from Dr. Black's traditional tooth preparation principles, embracing a more conservative approach that involves removing only the carious and affected structures. This technique often allows patients to retain more of their natural tooth structure compared to conventional methods.

These composite resins are typically made from dimethacrylate monomers (such as Bis-GMA, TEGMA, and UDMA) and multi-functional filler materials, which enhance the elastic modulus, increase strength and wear resistance, and reduce polymerization shrinkage of the restoration [1]. The fillers used can be categorized into macro fillers, micro fillers, micro-hybrid fillers, and nanofillers. Just as amalgam was refined with copper, composites have been advanced with various fillers, including nanofillers. This article seeks to review the enhancements brought about by modern nanomaterials in dental composite resins relative to other filler materials.

Nanomaterials:

Nano-materials are engineered to manipulate substances at the atomic or molecular scale. On this nanoscale, the chemical, biological, and physical properties of an atom differ significantly from those of its naturally occurring compound forms [1]. Human dental structures, such as enamel, consist of 96% hydroxyapatite, with particles ranging from 10 nm to 200 nm [2]. Intertubular dentin measures 2-5 nm in thickness and 60 nm in length, while the collagen fibrils linking enamel and dentin stretch from 20 to 75 nm in length [3]. These specific characteristics underscore the importance of researching nano-material applications in dentistry. This field, known as nano dentistry, aims to enhance the detection, treatment, and prevention of dental pathologies, such as secondary caries [4,5]. The rise of digital technologies and growing patient demands for aesthetic and functional solutions present challenges for engineered nano-materials [6].

Nanocomposites, a category of biomaterials featuring at least one phase within the nanometer range (5 nm to 100 nm), are employed to alter color and enhance the flexural strength of composite resin restorations [7]. The ongoing exploration of various nano-materials aims to improve products across multiple disciplines, including dentistry. In restorative dentistry, nano-materials are utilized to develop nanocomposites [8], glass ionomer cements, and endodontic sealers. Their primary role is to enhance strength, wear resistance, and microhardness of composites while minimizing polymerization shrinkage [9]. It is crucial to adhere to the optimal weight percentage of nanofillers, as exceeding this threshold does not yield further improvements in mechanical properties [6]. Nano-materials significantly contribute to improved mechanical properties, longevity, and bond strength between dentin and restoration [11]. Nano-materials are synthesized through two primary methods: the top-down approach, which involves reducing bulk material to nanoscale dimensions through various techniques, and the bottom-up approach, where individual atoms are assembled into nanostructures [11].

Nanomaterials and Dental Restoration:

The integration of various nano-materials into resin restorations has demonstrated the potential to enhance multiple facets of these restorations. Xiao et al. [12] developed a bioactive multifunctional composite (BMC) incorporating nanoparticles of nanoapatite (NACP), 2-methacryloyloxyethyl phosphorylcholine (MPC), dimethylaminohexadecyl methacrylate (DMAHDM), and silver nanoparticles (AgNP), and explored the impact of adding poly(amido amine) (PAMAM) to the BMC. This study, which focused on root caries, revealed that the BMC exhibited excellent root dentin remineralization properties. The composite was effective not only in remineralizing dentin but also in being protein-repellent and antibacterial. The results suggested that BMC combined with PAMAM is promising for various types of tooth cavity restorations, including Class I and Class II cavities [12].

Ghahremani et al. [13] assessed a color-modified heat-cure resin enhanced with titanium dioxide (TiO2) nanoparticles for tensile and impact strength. Their in vitro study involved incorporating TiO2 nanoparticles into a triplex hot heat-cure resin. The reinforced resin exhibited a significant increase in strength, specifically 7 MPa higher than the control group, with statistical significance ($p = 0.001$). The study concluded that adding 1% TiO2 by weight to the acrylic resin improved tensile and impact strength, although the study did not address any potential side effects on the resin's restorative capabilities [13].

In a comparative analysis, Meena et al. [14] investigated the performance of composite resins filled with marble powder versus those with nano alumina. Through dynamic mechanical analysis and thermogravimetric analysis, they found that marble dust-filled composites absorbed less water and had a lower diffusion coefficient. The thermal stability of nano-alumina composites was reduced by 20% compared to marble dust-filled composites. The results indicated that marble dust is a superior filler material, offering better physical and mechanical properties and being more cost-effective than nano alumina. However, further research is necessary to assess the long-term effects of marble dust-filled composites on tooth biology [14].

Wang et al. [15] explored the use of wrinkled mesoporous silica (WMS) with unimodal and bimodal fillers in resin matrices composed of Bis-GMA/TEGDMA. They found that bimodal WMS fillers, such as WMS-Si90 and WMS-Si190, allowed for a 60 wt% filler loading, exceeding the loading limits of unimodal WMS (35 wt%). The study demonstrated that resin composites with bimodal WMS fillers had superior mechanical properties compared to those with unimodal fillers [15].

Al-Mosawi [16] incorporated ZnO nanoparticles into composite resin and evaluated their antibacterial potential against various oral bacteria. The study, which tested different concentrations (5%, 7%, and 10%) on agar, identified S. mutans and Pseudomonas as the most susceptible bacterial isolates. The findings indicated that ZnO nanoparticles could effectively prevent secondary caries [16].

Ai et al. [17] aimed to develop a functional one-dimensional nanofibrous filler for composite resins that would enhance reinforcement and exhibit excellent antibacterial activity. Hydroxyapatite (HA) nanowires were synthesized using calcium oleate as a precursor and coated with polydopamine (PDA), followed by treatment with Ag nanoparticles. These HA-PDA-Ag nanowires were mixed with Bis-GMA [50/50 w/w] and subjected to thermo-curing. The resulting composite demonstrated strong adherence to the resin matrix, effective reinforcement, high bactericidal activity, and no cytotoxicity, making it an ideal nanofiller [17].

Paiva et al. [18] developed polyacid formulations by photo-reducing silver nanoparticles in a polyacrylate solution of standard glass ionomer cement (GIC) in a single step. They evaluated the antibacterial activity and mechanical properties of the AgNP-enhanced GIC compared to conventional GIC. The modified GIC exhibited excellent antibacterial activity, attributed to the oxidative dissolution of silver ions from the cement matrix. This study concluded that silver nanoparticle-enhanced GIC could effectively prevent caries and inhibit biofilm formation [18].

Stewart [19] focused on creating a restoration with inherent antibacterial properties to prevent secondary caries. He incorporated octenidine dihydrochloride (OCT) into drug-eluting mesoporous silica nanoparticles (DMSNs), fabricated using a bottom-up synthesis method. OCT is noted for its high biocompatibility [19], and no microbial resistance has been reported to date [20]. The silica nanoparticles were used to develop a dental resin adhesive with localized, long-term drug release, minimizing systemic exposure. The study demonstrated that such restorations could effectively contribute to long-term prevention of secondary caries [21].

Yue et al. [22] developed a self-healing adhesive with antimicrobial and remineralizing properties, incorporating microcapsules containing DMAHDM and nanoparticles of NACP. The microcapsules were created with polyurea-formaldehyde (PUF) shells, including 10% DMAHDM and 20% NACP. The fracture toughness, Kic, and crack-healing efficiency were evaluated using the single-edge V-notched beam method. The new adhesive resin achieved autonomous crack healing, antimicrobial effects, and remineralization due to the calcium phosphate nanoparticles. It significantly reduced the colony-forming units of microcosm biofilms compared to conventional controls. The innovative combination of self-healing microcapsules, DMAHDM, and NACP presents a promising approach for various dental adhesives, cements, sealants, and composites [22].

Cao et al. [23] developed a resin filled with nano-silver (Ag), utilizing AgBr/BHPVP nanocomposites to avoid negative effects on flexural strength and modulus. The resin exhibited a substantial increase in Vicker's hardness and a sustained release of Ag+ ions without interference from anaerobic conditions. The resin was effective against anaerobic cariogenic bacteria, particularly S. mutans, through continuous Ag+ ion release. The study established that the optimal concentration of AgBr/BHPVP in Bis-GMA/TEGDMA is 1.0 wt% [23].

ZnO nanoparticles have shown a superior antibacterial effect compared to AgNPs against S. mutans [24-26]. Additionally, nanodiamonds have demonstrated potential, with 1 wt% quaternized copolymer functionalized nanodiamond-reinforced resin composites inhibiting biofilm formation without damaging tooth structure [27]. Nano-materials also integrate well with glass ionomer cement

(GIC), which inherently releases fluoride ions to prevent secondary caries [18]. Copper-doped GIC has been found to offer enhanced antibacterial properties and reduced collagen degradation. Renné et al. [28] showed that adding nanohydroxyapatite powder to GIC improved its fluoride ion-releasing capability, and another study confirmed that hydroxyapatite nanoparticles enhance the mechanical and antibacterial properties of GIC [29].

Xie et al. [30] developed an adhesive with three key properties: calcium phosphate ion recharging, protein repellence, and antibacterial function. By combining MPC and DMAHDM, they created an NACP-rechargeable adhesive with strong protein-repellent and antibacterial capabilities to combat biofilms and caries. The bioactive adhesive effectively protected tooth structures and reduced biofilm formation and caries progression [30].

Applications:

The integration of nanomaterials into dental treatment and restoration represents a significant advancement in the field of dentistry, enabling improved performance, enhanced aesthetic outcomes, and greater durability of dental materials. Nanomaterials, characterized by their dimensions in the nanometer range (1-100 nm), exhibit unique chemical, physical, and biological properties that differ from their bulk counterparts. This article explores the various applications of nanomaterials in dental treatment and restoration, highlighting their impact on materials science, adhesive technology, caries prevention, and more (31).

1. Nanocomposites for Dental Restorations

Nanocomposites are a major application of nanomaterials in dentistry. These materials combine traditional dental resins with nanoparticles to enhance their properties. The inclusion of nanoparticles such as silica, zirconia, and titanium dioxide improves the mechanical strength, wear resistance, and optical properties of dental composites.

- **Mechanical Strength and Durability**: Nanoparticles like silica and zirconia increase the hardness and flexural strength of dental composites. For instance, silica nanoparticles contribute to better dispersion and bonding within the resin matrix, leading to improved structural integrity and resistance to fracture. This enhancement in mechanical properties makes nanocomposites suitable for high-stress applications like posterior restorations.
- **Aesthetic Improvements**: Nanocomposites can be engineered to match the natural tooth color more closely. The small size of nanoparticles allows for a more refined and homogeneous distribution of filler particles, which helps in achieving better polishability and translucency. This results in restorations that blend seamlessly with the surrounding tooth structure, offering superior aesthetic results compared to traditional composites.

2. Nano-Enhanced Adhesives

Adhesive technologies have also benefited from the incorporation of nanomaterials. Nanoparticles are used to modify the adhesive properties, improving the bond strength between dental materials and tooth substrates.

- **Improved Bond Strength**: Nanoparticles like hydroxyapatite and silica are added to dental adhesives to enhance their bonding capabilities. Hydroxyapatite nanoparticles, in particular, can mimic the natural tooth structure and facilitate better integration with the tooth enamel and dentin. This leads to more durable and long-lasting dental restorations.
- **Self-Healing Adhesives**: Recent innovations have led to the development of self-healing adhesives incorporating nanomaterials. For example, self-healing microcapsules containing nanoparticles of calcium phosphate or other remineralizing agents can repair minor cracks in dental restorations. This functionality not only prolongs the life of the restoration but also helps in maintaining its structural integrity.

3. Antibacterial and Anticariogenic Properties

Nanomaterials are increasingly used for their antibacterial and anticariogenic properties, which are critical for preventing secondary caries and managing oral infections.

- **Antibacterial Agents**: Silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO) are commonly used for their antimicrobial properties. These nanoparticles can be incorporated into dental resins, cements, and coatings to provide continuous antibacterial activity. AgNPs, in particular, release silver ions that inhibit the growth of bacteria such as Streptococcus mutans, a primary pathogen associated with dental caries.
- **Caries Prevention**: Nano-sized hydroxyapatite particles can be used to remineralize early carious lesions. These particles penetrate the tooth enamel and dentin, promoting the natural remineralization process and reversing demineralization. This application is especially useful in managing non-cavitated carious lesions and enhancing the longevity of restorative treatments.

4. Nano-Enhanced Dental Cements

Dental cements are essential for various restorative procedures, including crown and bridge placements. Nanomaterials enhance the properties of these cements, making them more effective and durable.

- **Glass Ionomer Cements (GICs)**: Incorporation of nanohydroxyapatite or nanosilica into GICs improves their mechanical strength, fluoride release, and antibacterial properties. These enhancements result in cements that provide better adhesion, resistance to wear, and caries prevention.
- **Resin Ionomer Cements**: Nanoparticles in resin ionomer cements help in achieving improved mechanical properties and enhanced fluoride release. The addition of nanoparticles can also reduce the susceptibility of the cement to degradation and wear over time, making it a more reliable material for long-term restorations.

5. Nano-structured Materials for Tooth Whitening

Tooth whitening products have also benefited from the advancements in nanotechnology. Nanomaterials are used to enhance the effectiveness and safety of whitening agents.

- **Whitening Agents**: Nano-sized abrasives and whitening agents can provide a more effective and less abrasive polishing action compared to traditional materials. These nanoparticles can better penetrate the enamel and dentin, improving the overall whitening effect while minimizing damage to the tooth surface.

- **Controlled Release Systems**: Nanocarriers are used to deliver whitening agents more effectively. These carriers can provide controlled release of the active ingredients, ensuring a more consistent and sustained whitening effect while reducing potential side effects.

6. Diagnostics and Imaging

Nanomaterials play a role in advancing diagnostic and imaging techniques in dentistry. They enhance the sensitivity and specificity of various diagnostic tools.

- **Nano-Imaging Agents**: Nanoparticles such as quantum dots and superparamagnetic nanoparticles are used as imaging agents in dental radiography and magnetic resonance imaging (MRI). These agents improve the contrast and resolution of images, aiding in the early detection of dental diseases and abnormalities.
- **Diagnostic Sensors**: Nanomaterials are used in developing diagnostic sensors that can detect biomarkers associated with oral diseases. These sensors offer rapid and accurate detection, which is crucial for early diagnosis and treatment planning.

7. Innovative Prosthetic Materials

The field of prosthodontics has also seen innovations through the use of nanomaterials, leading to the development of advanced prosthetic materials with enhanced properties.

- **Nano-ceramics**: Nano-ceramic materials are used in the fabrication of dental crowns and bridges. These materials offer superior strength, wear resistance, and aesthetic quality compared to traditional ceramic prosthetics.
- **Nano-composite Resins**: In prosthetics, nano-composite resins provide improved mechanical properties and durability, making them suitable for the fabrication of long-lasting dental prostheses.

Conclusion

The integration of nanotechnology into restorative dentistry has heralded a new era of innovation, significantly enhancing the performance and functionality of dental materials. Nanomaterials, defined by their dimensions in the nanometer range, exhibit unique properties that differ markedly from those of bulk materials. These properties are leveraged to improve various aspects of dental treatment and restoration. Nanocomposites, which combine traditional resins with nanoparticles like silica, zirconia, and titanium dioxide, have demonstrated substantial improvements in mechanical strength and wear resistance. The inclusion of these nanoparticles enhances the structural integrity and durability of dental restorations, making them more suitable for high-stress applications. Moreover, nanocomposites offer superior aesthetic outcomes, as their refined particle size enables better polishability and translucency, resulting in restorations that blend seamlessly with natural teeth. Nano-enhanced adhesives have revolutionized bonding techniques, offering improved bond strength and the development of self-healing adhesives. The addition of nanoparticles such as hydroxyapatite has facilitated better integration with tooth structures, while self-healing microcapsules containing nanoparticles can repair minor cracks, prolonging the life of dental restorations. The antibacterial and anticariogenic properties of nanomaterials, including silver and zinc oxide nanoparticles, have proven effective in preventing secondary caries and managing oral infections. Nanoparticles can be incorporated into resins and cements to provide continuous antibacterial activity, addressing the critical issue of infection control in dental restorations. Advancements in dental cements have also been achieved with nanotechnology. Nanohydroxyapatite and nanosilica have improved the mechanical properties and fluoride release of glass ionomer and resin ionomer cements, enhancing their performance and longevity. Nanotechnology has also impacted tooth whitening products and diagnostic tools. Nano-sized abrasives and controlled release systems have enhanced the effectiveness and safety of whitening agents, while nano-imaging agents have improved the resolution and contrast of dental imaging, facilitating early disease detection. In summary, the application of nanotechnology in restorative dentistry represents a transformative advancement, offering enhanced material properties, better aesthetic results, and greater durability. As research progresses, the continued exploration of nanomaterials promises further innovations, potentially revolutionizing dental treatment and care.

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