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Literature Review

Advantages and Limitations of Nanomaterials in Restorative and Endodontic Treatments: A Literature Review

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ABSTRACT

Introduction: Nanotechnology has transformed dentistry by introducing nanomaterials with superior mechanical properties, improved aesthetics, and enhanced antibacterial effects, thereby improving treatment outcomes. These materials have been widely adopted in modern dental treatments. However, concerns remain regarding their potential toxicity, production costs, and long-term effects on human health and the environment. This review explores the benefits and challenges of nanomaterials in dentistry, particularly their applications in restorative and endodontic treatments. It examines potential risks to provide a balanced perspective on their clinical use.
Review: Nanomaterials enhance the strength and durability of dental restorations while reducing bacterial adhesion. In endodontics, nanomaterials enhance the antimicrobial activity and penetration of root canal sealers, thereby improving root canal disinfection and reducing the risk of reinfection. However, prolonged exposure to nanomaterials raises concerns about biocompatibility, oxidative stress, immune responses, and neurotoxicity. Current studies highlight the need for standardized safety protocols and long-term clinical trials.
Conclusion: Nanotechnology offers significant advancements in dentistry, improving treatment durability and patient outcomes. However, further research is required to assess long-term safety, optimize materials for clinical use, and develop regulatory guidelines. Ensuring the biocompatibility and environmental safety of nanomaterials is a priority for their widespread adoption.

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INTRODUCTION

Nanotechnology has revolutionized various fields of medicine, including dentistry, by introducing nanomaterials with particle sizes ranging from 1 to 100 nanometers. These materials exhibit unique chemical, physical, and biological properties that can enhance dental treatments and materials.[1] Nanomaterials offer improved mechanical strength, enhanced aesthetics, antibacterial properties, and improved biocompatibility. However, several studies have also reported potential limitations, including cytotoxicity, high production costs, and uncertain long-term biological effects.[2]

The purpose of this literature review is to further explore current research on the use of nanomaterials in dentistry, including the advantages and limitations of these materials. This review is based on an analysis of recent scientific publications related to nanomaterials in restorative and endodontic treatments, covering nanomaterials in restorative and endodontic treatment.

Nanomaterials used in restorative dentistry include nanocomposites and nanostructured titanium-based alloy materials. Nanocomposite materials characterized by filler-particle sizes ≤ 100 nm offer superior aesthetic and strength advantages over traditional composites.[3] They are used in restorative procedures to improve mechanical properties, increase abrasion resistance, and reduce polymerization shrinkage.[4,5]

Recent advances in nanotechnology have greatly impacted dentistry, resulting in innovative nanomaterials with improved properties and applications. Modern dental biomaterials are evolving from passive restorative materials into active systems capable of interacting with the oral environment. Researchers have developed smart material-based self-healing nanomaterials for dental caries restorations, utilizing microcapsules with healing agents to repair structural damage.[6]

Despite extensive research on dental nanomaterials, current studies predominantly emphasize their mechanical and antimicrobial benefits, with limited critical analysis of how differences between organic and inorganic nanoparticle components influence biological responses, particularly toxicity and biocompatibility. This gap highlights the need for a comprehensive review to better elucidate these relationships and guide safer clinical applications.

REVIEW

Nanomaterials in Restorative Dentistry

Resin-based nanomaterials typically consist of a Bis-GMA matrix combined with other monomers such as TEGDMA and UDMA. Common nanofillers include silica (SiO_2), zirconia (ZrO_2), hydroxyapatite (HA), and alumina (Al_2O_3), which contribute to improved mechanical and aesthetic properties.[7] Nanoparticle glass ionomer materials are composed of nanosized glass particles and polyacrylic acid. These nanofillers include calcium phosphate compounds that mimic the composition of natural tooth structures. They offer fluoride release for caries prevention and improved strength.[8] Calcium phosphate–based nanoparticles, including calcium silicate, calcium phosphate, and calcium sulfate formulations, are widely used due to their bioactive properties. They often incorporate hydroxyapatite and other calcium phosphate compounds as nanofillers. These bioactive materials promote bone regeneration and osseointegration, making them suitable for dental implants and bone grafts. Nanoparticle calcium phosphate-modified materials release calcium and phosphorus ions to remineralize tooth hard tissue.[9]

Bioactive glass nanoparticles can bond with bone and dental tissues. Common nanofillers include silica and other bioactive glass components that promote remineralization, have antibacterial properties, and are useful in restorative and preventive dentistry.[10]

Advantages of Nanomaterials in Dental Restoration

The suitability of nanomaterials for dental applications is primarily attributed to their exceptional mechanical performance, physicochemical stability, and superior biocompatibility, which collectively enhance their functional integration with the oral environment.[11] The advantages of nanomaterials in restorative treatments can be evaluated from several aspects, including enhanced mechanical properties, reduced polymerization shrinkage, physical properties, and antimicrobial properties.

Dental composites can enhance their mechanical properties without compromising workability through the incorporation of 40–50% filler content by weight. They exhibit superior mechanical properties compared to traditional composites.[12] Dental composites with silica nanoparticles (SiO_2) demonstrate enhanced flexural strength and modulus. The nanoparticle distribution and size are crucial: smaller particles (20–50 nm) offer better mechanical properties due to higher surface area interaction with the resin matrix. Ensuring optimal mechanical performance of dental composites is essential. Materials must have high flexural strength, modulus strength, and compressive strength to withstand forces during mastication.[13] The addition of zirconia (ZrO_2) and glass fillers significantly increases the compressive strength of dental resins.[14] Fracture toughness is enhanced due to the nanoparticle impedance of crack propagation in the composites.[15] Nanoparticles in composite resin demonstrate superior wear resistance compared to conventional composites due to their uniform distribution, which enhances abrasion resistance.[16]

Nanoparticles in dental composites minimize shrinkage, reducing gaps between teeth and restorations and the risk of secondary caries. The nanoclays and nanofillers can reduce shrinkage and strengthen restorations.[17] Reduced shrinkage and improved bonding to tooth structures are properties of liquid crystalline epoxy nanocomposites suitable for esthetic dentistry.[18] Lightweight nanoparticle composites are easier to handle and apply in dental procedures.[19] Nanocomposites provide superior color stability and brightness, making them highly suitable for aesthetic dental restorations, while maintaining a smooth surface to prevent plaque accumulation and ensure patient comfort.[16] Nanoparticles can reduce the risk of infection by releasing ions that inhibit bacterial growth. In addition, they promote remineralization of dental hard tissues.[20,21] Some nanoparticles, like silver, copper, and zinc oxides, exhibit strong antibacterial properties that can be used in dental composites.[21,22] Nanoparticles can modify dental materials' surfaces, decreasing roughness and energy, which affect bacteria adhesion. For example, nanoclays in PMMA reduce surface energy and prevent Candida albicans adhesion.[23] Nanocomposites enhance mechanical properties, particularly hardness and wear resistance, which also helps prevent adhesion by maintaining a smoother surface.[24] Including antibacterial properties in nanocomposites is essential to prevent infections, though achieving this without affecting other material properties is challenging.[25]

Nanomaterials in Endodontic Treatment

Nanotechnology improves endodontic materials. It has shown promising results, enhancing diagnosis, treatment, and outcomes.[26,27] Nanoparticles like Silver Nanoparticles (AgNPs) and Multi-Walled Carbon Nanotubes (MWCNTs) encapsulating Chlorhexidine (CHX) have shown significant antimicrobial properties, which are crucial for eradicating bacteria within root canals.[28] Other nanomaterials facilitate the controlled release of therapeutic agents, promoting regeneration.[29] Integration with tissue engineering approaches offers greater versatility in designing scaffolds that promote cell growth, which is essential for regeneration and revascularization.[30,31] Nano-identification techniques have advanced, enabling better characterization, evaluation, and treatment planning for endodontic diseases.[30] Nanomaterials modify rotary nickel-titanium files to be wear- and fatigue-resistant.[28] New root canal sealers with nanomaterials improve bonding and combat resistant bacteria.[32] Nanomaterials are being explored in direct pulp-cappings and tissue repair for predictably good results.[33]

Endodontic Sealers

Silver nanoparticles (AgNPs) are frequently incorporated due to their strong antimicrobial properties, which make them effective against a broad spectrum of bacteria and fungi that cause endodontic infections.[34,35] Multi-walled carbon nanotubes (MWCNTs) enhance the bonding performance of sealers to dentin and improve their effectiveness against antibiotic-resistant bacteria such as E. faecalis, S. aureus, and Candida albicans.[28] MWCNTs and titanium carbide (TC) improve the compressive strength of bioceramic sealers like BioRoot™ RCS.[36,37] MWCNTs, along with carbon and boron nitride, can also shorten the setting times of sealers.[37] Nanomaterials can improve the stability and durability of sealers. BioRoot™ RCS composites with TC and BN exhibit the lowest solubility and elution rates.[37] Incorporating nanomaterials can enhance the alkaline pH profile of sealers for a healing process and antibacterial properties. BioRoot™ RCS composites with TC show a higher alkaline pH.[37]

Nano-ZnO is antimicrobial and effective in dentinal tubules.[38] It has shown comparable penetration ability to AH26, particularly in the apical regions of the root. Silver, copper, and zinc have inherent antimicrobial properties that can combat bacterial infections. These nanoparticles disrupt bacterial cell walls and can inhibit biofilm formation, which prevents reinfection.[27,39,40] Nanoparticles can be modified with other compounds to enhance antibacterial efficacy. This makes them effective in disinfection and sealing the root canal system.[39] Silver vanadate is a new nanomaterial in endodontics for its antimicrobial properties. Used in commercial sealers, it improves antimicrobial activity and ion release, but is still toxic.[34] Nano calcium hydroxide, used in endodontic sealers to enhance sealing and prevent dye leakage, shows significant improvements over traditional sealers.[41] Nano bioactive glass promotes tissue regeneration and is used in endodontics for its effectiveness in sealing root canals.[41]

Root Canal Disinfection

Nanotechnology has promising applications for root canal disinfection, addressing limitations of traditional endodontic treatments. Studies show that zinc oxide and chitosan nanoparticles in root canal sealers can improve antibacterial properties without altering flow characteristics, preventing bacterial adherence, and reducing Enterococcus faecalis. Chitosan, graphene, and zinc oxide nanoparticles exhibit diverse antimicrobial mechanisms, including stopping DNA replication and ion release, making them effective against resistant bacterial strains.[39]

Silver nanoparticles possess powerful antibacterial properties and can disrupt bacterial cell walls, increase membrane permeability, and generate reactive oxygen species, which effectively eliminate bacterial biofilms.[42] They can penetrate deeper into the root canal system and dentinal tubules, enhancing the antibacterial properties of endodontic irrigants and sealers. They also increase dentin hardness and promote the antibacterial properties of intracanal medications. Chlorhexidine-loaded silver nanoparticles demonstrate comparable significant antibiofilm activity to traditional sodium hypochlorite solutions.[43]

Nanoparticles in irrigants have superior effectiveness against bacterial biofilms compared to conventional solutions.[43,44] Nanoparticles with antimicrobial agents can penetrate deeply into dentinal tubules, significantly reducing microbial load compared to conventional methods.[44,45] These nanoparticles can enhance the antibacterial activity on root canal surfaces and within tubules, effectively killing *Enterococcus faecalis* when combined with hydrogen peroxide.[46] Incorporating nanoparticles into obturating materials and sealers can enhance their bioactivity, improving the sealing of the root canal system and preventing reinfection. They can be functionalized to improve antimicrobial efficacy.

Some use of nanoparticles may enhance tissue regeneration and repair.[47,48] Scaffolds made from nanoparticles are being used to regenerate tissue, offering an alternative to root canal treatments.[48] These nanoparticles can be used to deliver antimicrobial agents to improve disinfection.[27,44,49] Those made of biocompatible materials are safe.[42,49] Magnetically driven nanobots are being developed to provide active and controlled disinfection.[45]

Disadvantages of Nanomaterials in Dental Restoration and Endodontic Treatment

Because of their unique properties, nanomaterials are increasingly used in conservative dentistry. However, prolonged exposure to nanomaterials can pose several potential health risks, primarily due to their unique properties at the nanoscale.

Mechanical and Chemical Stability

Nanoparticles tend to agglomerate, which can affect the consistency and performance of the materials.[50] This agglomeration can lead to a decline in the rheological properties of the materials, making them less effective in clinical applications. The chemical instability of nanomaterials can pose challenges, particularly in maintaining the desired properties over time.[50] Exposure to body fluids can lead to nanomaterials' degradation, dissolution, or corrosion, which can alter their structure and mechanical properties, potentially causing adverse effects.[51] Achieving optimal delivery of nanoparticles within the intricate anatomy of the root canal system is complex and requires further innovation.[52] Ensuring that nanoparticles reach and effectively treat all root canal areas is a significant challenge. The reduction of materials to the nanoscale significantly alters their physicochemical properties, increasing their reactivity and interaction at the molecular level. This heightened reactivity can lead to unpredictable interactions with biological tissues, necessitating careful consideration and monitoring.[39,53]

Cytotoxicity

Nanomaterials are designed to be biocompatible, supporting cell adhesion and proliferation, and ensuring that they do not cause adverse reactions when in contact with biological tissues.[14,54,55] However, the biocompatibility of nanomaterials is a major concern because they can be cytotoxic. For instance, nanoparticle-coated orthodontic brackets have shown reduced cellular differentiation compared to conventional brackets, indicating potential cytotoxicity.[56] Safety and performance can be evaluated using both in vitro and in vivo testing methods.[57] Graphene-based materials face challenges related to long-term stability and toxicity. While graphene offers excellent properties, concerns about its long-term stability in corrosive conditions and potential toxicity remain.[58]

Nanomaterials used in dental applications, including endodontics, can exhibit cytotoxic and genotoxic effects. Some nanomaterials may release ions or particles that cause toxicity or tissue problems. Nanomaterials can exhibit cytotoxic properties, which may affect the surrounding tissues during endodontic procedures. Nanoparticles exhibit unique properties, including increased reactivity and potential for molecular interactions. This raises concerns about their toxicity and adverse effects.[59,60] This cytotoxicity is a significant concern and requires detailed evaluation to ensure safe clinical use.[60,61]

Nanoparticles can have different effects and influence toxicity depending on their concentration, size, type, coating, and composition. For example, Ag Nanoparticles are toxic to zebrafish embryos at high concentrations and less toxic at low concentrations.[62] Smaller particles with larger surface areas tend to be more reactive and more harmful. The chemical composition and surface coatings of nanoparticles can affect how they interact with biological systems and how toxic they are.[63] Some studies show that hydroxyapatite nanoparticles are highly cytocompatible, while others show that they are less so.[64]

The environmental impact of nanoparticles, especially their long-term effects, is largely unknown. This includes their behavior in ecosystems and their bioaccumulation potential.[65] Although some studies have shown certain nanoparticles to be biocompatible, further research is still needed.[59] Regulatory bodies have expressed concerns regarding the safety of nanoparticles in oral care products.[64] Comprehensive studies are needed to assess chronic exposure risks and ensure that nanomaterials do not pose significant health hazards over time.[60,65]

Allergic Reactions

The release of metal ions from nanoparticle-coated dental materials can trigger allergic reactions in some patients.[66] Nanomaterials can interact with both the innate and adaptive immune systems, can cause immunosuppression, hypersensitivity, immunogenicity, and autoimmunity.[67,68] Inappropriate immune responses can lead to autoimmunity and host damage.[67] Prolonged exposure to nanomaterials can also affect macrophages. For instance, nanomaterials can alter the phagocytic activity of macrophages, either enhancing or impairing their ability to clear pathogens. This can lead to a complex landscape of immune responses.[69]

Inflammatory Responses.

Nanomaterials can cause inflammation depending on their characteristics and the presence of pre-existing conditions. Certain nanomaterials, such as metal and metal oxide nanoparticles, can induce inflammatory responses. This can complicate the healing process and potentially lead to adverse effects in the treated area.[70,71] Prolonged exposure to nanomaterials can lead to chronic inflammation, which may exacerbate existing conditions or contribute to new health issues.[52]

Oxidative Stress and DNA Damage.

Nanoparticle exposure can induce oxidative stress and DNA damage, which can lead to chronic diseases like cancer.[72] Some nanomaterials generate ROS, which can be used for sterilization but may also cause oxidative stress and damage to surrounding tissues.[73] The potential for nanomaterials to cause genetic mutations is another area of concern, although more studies are needed to confirm these effects. There is concerning evidence suggesting that some nanomaterials may have carcinogenic properties; therefore, further research is required to fully understand these risks.[74]

Respiratory and Systemic Risks

Inhalation of engineered nanoparticles during dental procedures can lead to respiratory issues. Nanoparticles can translocate within biological systems, potentially causing lung inflammation and other respiratory problems.[75] Inhalation of nanoparticles can lead to lung inflammation and fibrosis. Nanoparticles can accumulate in the lungs, contributing to chronic respiratory conditions.[72,76] There's a potential risk of carcinogenic effects from prolonged exposure to certain nanomaterials, though further research is needed.

Nanoparticles can enter the bloodstream and distribute to various organs, raising concerns about systemic toxicity and long-term health effects.[75,77] Evidence suggests that nanoparticles can cause thrombosis in diseased animals, indicating a potential risk for humans with pre-existing conditions.

Neurotoxicity

Nanomaterials used in dental applications, including endodontic treatments, may cross the blood-brain barrier and accumulate in the central nervous system (CNS).[78] Titanium dioxide (TiO_2) nanoparticles have been shown to induce neuroinflammation and neurotoxicity.[79] Rats exposed to TiO_2 nanoparticles had increased levels of interleukin-6 (IL-6) and glial fibrillary acidic protein (GFAP)-markers of inflammation and brain damage. Similar effects may occur with dental nanomaterials. Exposure to nanosized particles, including those from air pollution, can contribute to neuroinflammation and neurodegenerative diseases.[80] Studies have shown that dental technicians and dentists can develop airway obstructions and hypersensitivity reactions due to exposure to nanoscale particles.[81] Studies have shown that nanoparticles can exhibit neurotoxic effects under both in vivo and in vitro conditions. Understanding these effects is crucial for developing safety assessment systems for dental nanomaterials.[82]

Risk Management Strategies

Using appropriate personal protective equipment (PPE) can help reduce occupational exposure to nanomaterials. Implementing engineering controls, such as proper ventilation and containment systems, can minimize the release of nanoparticles into the environment. Developing and adhering to regulatory guidelines for the safe handling and disposal of nanomaterials is crucial to protect both dental professionals and patients.[52 83] There is a need for standardized protocols to ensure consistent clinical outcomes. Variability in study designs and microbial strains used in research makes it difficult to draw definitive conclusions about the efficacy of nanomaterials.

Despite the benefits, there are ongoing discussions about the safety of nanomaterials in direct contact with tissues. The unique physicochemical properties of nanomaterials, which contribute to their effectiveness, also raise concerns about their potential reactivity and long-term safety.[84] Long-term safety data are scarce regarding the use of nanomaterials in endodontics. Potential risks such as chronic toxicity, long-term inflammatory responses, and other adverse effects need a comprehensive study to ensure safe application.[52,85] Understanding these risks is essential for the safe and effective use of nanomaterials in endodontic treatments. Further research and development of safety protocols are necessary to mitigate these potential hazards. In conclusion, while nanomaterials offer significant benefits in endodontic treatment, their potential health risks must be carefully managed through rigorous safety protocols, ongoing research, and adherence to regulatory standards.

DISCUSSION

Nanotechnology has introduced revolutionary advancements in dentistry, offering substantial improvements in restorative and endodontic treatments. The integration of nanomaterials has led to superior mechanical properties, enhanced aesthetics, improved antibacterial activity, and increased biocompatibility. Resin-based nanomaterials, nanoparticle-modified glass ionomers, and calcium phosphate-based materials illustrate how nanoscale innovations contribute to more durable and bioactive dental restorations. Similarly, the application of nanotechnology in endodontics has improved root canal disinfection, sealing, and regenerative procedures, utilizing materials like silver nanoparticles (AgNPs), multi-walled carbon nanotubes (MWCNTs), and nano-bioactive glasses.

The enhanced mechanical performance observed in nanocomposites, particularly their flexural strength, compressive strength, and reduced polymerization shrinkage, supports their clinical viability. Nanoparticles, through their small size and high surface area, enable better interaction with resin matrices, leading to improved material performance. Additionally, the antimicrobial properties of nanomaterials, particularly silver, zinc oxide, and copper-based nanoparticles, represent a significant advancement in infection control, crucial for both restorative and endodontic success.

Despite these advantages, the application of nanomaterials is accompanied by important limitations and safety concerns. Nanoparticles' high reactivity and surface energy, while beneficial for therapeutic purposes, also present challenges, such as mechanical instability due to agglomeration and chemical degradation under physiological conditions. These changes may compromise the long-term effectiveness of dental materials. Cytotoxicity remains a major concern, with studies indicating that some nanomaterials can affect cell proliferation, induce oxidative stress, or even cause DNA damage. The biological effects of nanoparticles vary significantly depending on their size, concentration, chemical composition, and surface modifications. For instance, while hydroxyapatite nanoparticles are generally biocompatible, other materials like silver nanoparticles have demonstrated dose-dependent cytotoxic effects. Additionally, the environmental and systemic impacts of nanoparticle exposure, including potential respiratory, neurotoxic, and immunological consequences, require further exploration. Allergic and inflammatory responses triggered by metal ion release or nanoparticle-induced immune modulation represent another significant risk, particularly in patients with pre-existing sensitivities. Moreover, the potential for nanoparticles to induce chronic inflammation and neurodegenerative changes necessitates caution, especially given the increasing prevalence of nanoparticle-containing products in dental practice.

A critical aspect that warrants further clarification is the fundamental distinction between organic and inorganic components in dental nanomaterials, as this directly governs their antimicrobial efficacy and biological safety. Most contemporary restorative and endodontic nanomaterials are not purely organic or inorganic, but rather hybrid nanocomposites consisting of a polymeric organic matrix (e.g., Bis-GMA, TEGDMA, UDMA) reinforced with inorganic nanofillers such as silica, zirconia, hydroxyapatite, calcium phosphate, and metal-based nanoparticles (e.g., silver, zinc oxide). This compositional duality is central to their functional behavior. Inorganic nanoparticles, particularly metal and metal oxide-based systems, are primarily responsible for antimicrobial activity through mechanisms including ion release, reactive oxygen species (ROS) generation, and disruption of microbial cell membranes. However, these same mechanisms are closely associated with increased cytotoxicity, oxidative stress, and potential long-term systemic effects. In contrast, the organic matrix generally contributes to structural integrity and handling properties, and is relatively more biocompatible, although it may still present cytotoxic risks related to residual monomers and degradation by-products. Therefore, the current trend in material development emphasizes the optimization of organic–inorganic interactions to achieve a balance between antimicrobial performance and biocompatibility. This highlights the necessity for more standardized evaluations that explicitly differentiate the biological effects of organic versus inorganic nanoparticle components, particularly in relation to dose, particle size, and surface modification, which remain critical determinants of clinical safety and efficacy.

Risk management strategies must be prioritized to ensure the safe implementation of nanomaterials in clinical settings. These include the use of personal protective equipment (PPE), engineering controls, strict regulatory oversight, and the establishment of standardized testing protocols. Long-term clinical studies are essential to assess the chronic effects and environmental behavior of nanomaterials to ensure that their benefits outweigh the risks.

In summary, while nanotechnology holds great promise for improving dental treatments, the unique properties that grant nanomaterials their therapeutic potential also pose significant biological and environmental challenges. A balanced approach, emphasizing innovation alongside comprehensive safety evaluations, is crucial for the sustainable advancement of nanotechnology in dentistry.

CONCLUSION

Nanotechnology has significantly advanced the field of dentistry, particularly in restorative and endodontic treatments. The integration of nanomaterials has resulted in dental materials with enhanced mechanical strength, superior aesthetics, improved antibacterial properties, and greater biocompatibility. Innovations such as resin-based nanocomposites, nanoparticle glass ionomers, and nano-bioactive glasses have contributed to better clinical outcomes in dental restoration, while nanoparticle-modified sealers and irrigants have improved disinfection and regeneration in endodontics.

However, despite these promising advantages, concerns regarding the cytotoxicity, mechanical instability, immunological reactions, inflammatory responses, and potential long-term environmental and systemic health risks associated with nanomaterials cannot be overlooked. The heightened reactivity and unique behavior of nanoparticles at the molecular level demand thorough evaluation and monitoring. Moreover, the lack of extensive long-term clinical data necessitates cautious application of nanomaterials in dental practice.

Thus, while nanotechnology holds transformative potential for modern dentistry, its clinical adoption must be balanced with careful consideration of potential risks, standardized safety protocols, and continuous research efforts to ensure both patient safety and environmental sustainability.

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