RESEARCH PAPER

Nanotechnology in Orthodontics: Revolutionizing Interventions Through Tiny Particles

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ABSTRACT

Nanotechnology in orthodontics has paved the way for researchers who are stridently making progress on improving treatment quality and patient care through understanding of the specific nanoparticles (NPs) applications in orthodontics in elevating treatment efficiency and improve patient outcomes. This review examines the scope of work nanoparticles assist in enhancing current treatment's antibacterial properties, and nanoparticles role as carrier in delivering medicine to a specific part of the body. Additionally, nanoparticles in the field of orthodontics holds promise for the prospects of smart orthodontic gadgets that could streamline better medical technology in the future. This means clinical outcomes, treatment efficiency, and medication performance can all be improved using nanoparticles. A comprehensive evaluation of the benefits and challenges associated with nanoparticles utilization including problems such as toxicity, biocompatibility with the human body, and regulatory factors. The latest developments in the field of orthodontic therapy and the relationship between nanotechnology and its impact towards human is discussed through the use of case studies and current clinical trials. Proposals for future research related to orthodontic nanotechnology using a number of innovative ways, such as genetically tailored treatment regimens, that can be used as nanoparticle drug delivery to offer personalized and efficient drug doses. Overall, this review highlighted the tantalizing concept of nanoparticles in orthodontics, which could greatly change the face of orthodontic therapy and set better standards for patient care, as well as improve clinical outcomes.

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INTRODUCTION

A satellite domain of dentistry, orthodontics focuses on the mechanical rectification of malpositioned skeletal and dental features. The specialty of orthodontics also fosters facial beauty and oral wellbeing [1, 2]. Orthodontic treatment improves in obtaining well-aligned teeth and improves biting and chewing function in harmonious occlusion. The use of braces, aligners, and other mechanical devices is commonplace

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for patients who want to achieve a more visually appealing look. These are the conventional techniques used in orthodontics; although they work and are constantly improving and changing, they can also be invasive or outdated. This has prompted discussion in the orthopedic community on better ways to achieve these goals [3]. Nanotechnology, the manipulation of matter on a supramolecular scale, has sparked a paradigm shift in many scientific arenas. This is because miniscule nanoparticles (NPs) hold exotic properties, unlike their larger relatives, that give them unique and exciting applications in medicine, especially in drug delivery [4-6]. The orthodontic techniques and materials used nowadays have major limitations, justifying the entrance of nanoparticles into orthopedic medical operations [7- 9].

The wide-ranging reverberations nanotechnology could have on the medical field is reflected in orthopedics - a field where far greater treatment results can be achieved through the use of nanoparticles in material, without having to rely on more invasive methods. Additionally, the nanoparticles are thought to render adhesives stronger and make wiring more efficient. On the other hand, this review outlines concerns such as biocompatibility (with the human body), toxicity, and ethical issues, highlighting the importance of thorough testing and regulatory supervision that would enhance prospects of safe and efficient application of nanotechnology in this specialty. Observing, regulating, and treating the biological system of the human body at the molecular level using nanostructures and nanodevices was how Robert A. Freitas Jr. initially put the concept of nanomedicine forth in 1993 [10]. The use of manipulated devices [11] such as biosensors [12], The Oral Fluid Nanosensor Test (OFNASET) [13], nanorobots [14, 15] and drug delivery vehicles [16-20] at the nanoscale for medical problems including dental problems is another way of investigating nanomedicine [11]. Antimicrobial photodynamic therapy (aPDT) combines a light source with photosensitizing drugs, such as methylene blue, to eradicate cells. Nanoparticles enhance this process, offering improved drug delivery and targeted destruction of oral biofilms. Specifically, indocyanine green nanospheres, acting as photosensitizers, have been effective against *P. gingivalis* by strongly attaching to bacterial surfaces and localizing the antibacterial effect [21].

Nanotechnology plays a crucial role in enhancing gene therapy. Nanomaterials like colloidal silver and gold reduce gingival inflammation and improve toothpaste effectiveness by filling enamel voids, thus preventing biofilm formation [22]. Dental implant success is increased through nanotechnology by improving osseointegration with nanostructured surfaces that enhance osteoblast adhesion. Self-assembling implants and nanomembranes offer innovative approaches for dental implants and bone regeneration, showing improved outcomes in osseointegration and bone defect repair [23]. Nanobubble technology for subgingival irrigation and the use of nanoparticles with lasers in periodontal therapy represent advanced techniques for treating dental issues [24]. Additionally, nanotechnology-based host immunomodulation therapy offers promising results in periodontal regeneration and microbial control by modulating the host immune response [25]. Nanotechnology introduces nanocomposites for restorations that are durable, esthetically pleasing and have reduced shrinkage [26, 27]. Nanoceramics, combining organic and inorganic materials, offer improved polishability and resistance to wear. Nanofilled dental cement enhances restoration esthetics and strength while reducing porosity. Innovations extend to dental durability and cosmetics with materials like sapphire or diamond for enamel replacement, offering enhanced hardness and esthetics [28].

In prosthodontics, nanotechnology has led to the development of improved impression materials with better flow and precision, and nanofilled composite denture teeth with superior esthetics and durability. CAD/CAM blocks based on nanotechnology provide exceptional esthetics results [29]. Endodontics benefits from nanoparticle-based disinfection for more effective root canal treatments and nanosealers that enhance the seal of root canal obturations [30]. Dental nanorobots or “dentifrobots” offer innovative approaches to oral hygiene and halitosis prevention by patrolling and cleaning teeth surfaces [31].

NANOPARTICLES IN ORTHODONTICS: SCOPE AND APPLICATIONS

The use of nanoparticles in orthodontics represents a paradigm shift, with the goal of improving the orthodontic materials’ and therapies’ therapeutic capacities, longevity, and

Table 1. Overview of Nanoparticles in Orthodontics: Types, Applications, and Antibacterial Properties

Material	Type	Use in Orthodontics	Properties
Gold (Au)	Noble Metal	Antimicrobial coatings, fillings	Broad-spectrum bactericidal properties [33].
Copper (Cu)	Noble Metal	Antimicrobial brackets, wires	Effective against a wide range of bacteria [34]
Platinum (Pt)	Noble Metal	Nanocoatings for implants and devices	Enhances biocompatibility and resistance to corrosion [35]
Silver (Ag)	Noble Metal	Antimicrobial coatings, fillings	Strong antibacterial and antifungal effects [36]
Magnesium Oxide (MgO)	Metal Oxide	Bone regeneration materials	Supports osteoblast activity [38]
Iron Oxide (FeO)	Metal Oxide	MRI contrast agents for imaging	Facilitates tracking of orthodontic progress [38]
Zinc Oxide (ZnO)	Metal Oxide	Cavity liners, cements	Antimicrobial, promotes dental repair [36]
Titanium Dioxide (TiO2)	Metal Oxide	Photocatalytic antibacterial coatings	Activated by light to kill bacteria [36]
Silicon Dioxide (SiO2)	Metal Oxide	Composite fillers, adhesives	Improves mechanical strength and wear resistance [36]
Zirconium Dioxide (ZrO2)	Metal Oxide	Brackets, implants	High strength and aesthetic appeal [37]
Nanodiamonds	Unconventional	Drug delivery systems	High surface area for medication attachment [36]
Quantum Dots	Unconventional	Imaging, tracking devices	Fluorescent properties for easy visualization [38]
Nanoshells	Unconventional	Therapeutic agents delivery	Can be tailored for targeted therapy [38]

efficacy. Researchers and clinicians in the field of orthodontics are striving to solve long-standing problems and open up new treatment options using a range of nanomaterials by integrating nanoparticles into different parts of orthodontic systems. Creating antimicrobial coatings for orthodontics adhesives and brackets using nanoparticles is a top priority. Problems like demineralization and cavities near orthodontic appliances might arise from the abundance of certain bacteria in the complicated environment of the oral cavity [32, 38]. The use of such nanoparticles not only aims to enhance oral health outcomes during orthodontic treatment but also reduces the overall treatment time by preventing secondary conditions that could delay progress. Table 1 shows various nanoparticles used in orthodontics.

Orthodontic appliances with their intricate surface designs and prolonged presence in the mouth, are prone to plaque and biofilm accumulation, complicating oral hygiene efforts [39]. These conditions foster microbial growth, elevating the risk of periodontal diseases and causing demineralized spots on enamel, known as white spot lesions. Addressing biofilm adhesion effectively can mitigate these orthodontic treatment-related issues. Research highlights the role of NPs in this context by disrupting bacterial metabolism and communication, thereby impairing their growth capabilities, or reducing biofilm adhesion, as evidenced by smoother surfaces on nanosilver-coated brackets and anti-adhesive effects against specific bacteria and fungi in studies [40].

Visualization techniques have shown that NPs attach to bacterial cell membranes, creating irreversible damage and allowing NPs to enter cells. Different NPs cause various effects for example, ZnO NPs disrupt cell shape, while Ag NPs damage the membrane. This interaction increases membrane permeability and leads to cell death [41]. NPs also generate Reactive Oxygen Species (ROS) like superoxide and hydroxyl radicals, causing oxidative stress that damages and kills bacterial cells. Ag NPs, through electron spin resonance analysis, have been confirmed to produce radicals that damage the membrane. Additionally, positively charged metal ions from NPs disrupt bacterial membranes by binding to them, leading to cell death, with Ag NPs particularly affecting membrane permeability and function. Nanoparticles introduce ROS and metal ions to bacteria, increasing oxidized proteins and causing cell death. ROS target crucial enzymes, disrupting bacterial structure and function [42, 43]. Antioxidants play a vital role in controlling many human diseases [44] including oral microbes, especially the oral parasites [45, 46].

The surface modification of wires and braces with nanoparticles can reduce friction, improve wear resistance, and provide antibacterial effects, further optimizing the treatment process [47, 48]. Orthodontic treatments traditionally plagued by friction-related issues may benefit from wires coated with fullerene-like tungsten disulfide nanoparticles, which have been shown to reduce friction significantly [49]. On the other hand, orthodontic nanorobots could revolutionize treatment by quickly adjusting teeth without discomfort, a stark contrast to the lengthy processes of current methods. Emerging nanorobots might soon manipulate periodontal tissues directly, enabling swift and effortless reorientation and alignment of teeth in a much shorter time frame, from minutes to hours. In a similar vein, orthodontic devices known as Temporary Anchorage Devices (TADs), when coated with a titanium nanotubular layer, exhibit improved biocompatibility. This coating aids in the earlier fusion of the device with the bone, serving as a crucial connection point between the TAD and the newly formed bone. [50]. The integration of nanoparticles into orthodontics is a vivid illustration of how nanotechnology is reshaping the landscape of dental treatment. By leveraging the unique properties of nanoparticles, orthodontic materials and systems are being re-engineered to offer enhanced performance, improved therapeutic outcomes, and a more favorable treatment experience for patients. As research in this area continues to advance, it is anticipated that the scope and applications of nanoparticles in orthodontics will further expand, heralding a new era of precision, efficiency, and effectiveness in orthodontic care. Table 2 illustrates the nanoparticle applications in orthodontic materials and devices with their corresponding effects.

CHALLENGES AND CONSIDERATIONS

Although the use of nanoparticles in orthodontics opens up new avenues of research, there are a number of obstacles and issues to be resolved before its full potential can be realized. These difficulties include issues with biocompatibility and toxicity, ethical and legal considerations, technical and production barriers, and more. All of these factors add to the difficulty of applying nanotechnology in clinical practice. For nanoparticles to be used in orthodontics in a way that is ethical, safe, and productive, several factors must be taken into account. The ability of a material to coexist with a living tissue or system without posing a risk of toxicity, injury, physiological reactivity, or immune rejection is known as biocompatibility. Dental biomaterials can be categorized as biotolerant, bioinert, or bioactive based on biocompatibility—the tissue's response to the utilized biomaterial as highlighted in Table 1. Dentistry uses a wide range of materials, including filling materials (like composites, amalgam, polymeric monomers, and cement) [88], restorative materials, intracanal medications, prosthetic materials, various implant types (like pure titanium, titanium alloys, and zirconium), liners, irrigants, and mouthwash (like antiseptic and anti-plaque rinse).

Dental materials should be chemically stable and inert for the oral cavity because they are typically utilized to replace damaged or faulty dental tissues. However, all material degrades or dissolves to some extent. Then, local or systemic reactions are likely when a material's dissolved components are hazardous. Consequently, it is imperative to guarantee the biocompatibility of dental materials because of their prolonged use and durability in the oral cavity, as well as their interaction or exposure with dental personnel. Since a zinc chelator prevented the toxicity, amalgam produces neurotoxicity in cortical cell culture by releasing zinc. Nanoparticles have also been shown to be antibacterial agents, the consequences they may have on cells, however, are still unknown. Dental nanoparticles may be hazardous to the production, research, and development staff by inhalation or using dental instruments that may absorb through the mouth mucosa and reach the circulation or lymph fluid causing an allergic reaction or after ingesting, they could possibly enter the body through the digestive tract. Therefore, before being used in a clinic, dental materials must undergo a number of toxicity and biocompatibility tests and individual clinical testing is the best approach for evaluating biocompatibility.

FUTURE PERSPECTIVES

Nanotechnology has a fascinating future ahead of it, with limitless potential to transform

Table 2. Overview of Nanoparticle Applications in Orthodontic Materials and Devices.

Orthodontic Appliances	Nanoparticles Used	Effect
Orthodontic brackets	Silver and Titanium oxide [51- 53], Diamond-Like Carbon Nanoparticles [54], Nitrogen-Doped Nanoparticles [55-57], Zinc Oxide [58], Copper (II) Oxide Nanoparticles [59]	Friction/antibacterial/ Surface characterization
Orthodontic archwires	Titanium Dioxide [60, 61], Silicon Dioxide [61], Silver [62], Zinc Oxide [63, 64], Silica Nanoparticles [61].	Surface Roughness/ Tribological Properties/ Frictional resistance
Removable orthodontic appliances and retainers	Silver [65, 66], Silica Nanoparticles (Silicon Dioxide Nanoparticles) [67], Chitosan [68], Curcumin [69], Nisin-poly (l-lactic acid) (Nisin-PLLA) [70].	Antibacterial/ mechanical
Clear aligners	4,6-Diamino-2-pyrimidinethiol-modified Au NPs [71, 72], Zinc Oxide [73].	Antibacterial/ mechanical
Orthodontic adhesives	Silver and Hydroxyapatite [74], TiO_2 [75], Curcumin [76], doped zinc oxide, Fluoride- Containing Bioactive Glass [77], Spherical Srbioactive glass (Sr-BGNPs) and Silica (SiO_2-NPs [78], CaF_2 NPs [80], Graphene oxide NPs [79].	Enamel demineralization prevention /Antibacterial/ mechanical/ Physical/ Cytotoxic
Orthodontic elastomeric ligatures	Silver nanoparticles [81]	Antibacterial
Mini-implants	Titanium oxide nanotube [82], silver nanoparticles [83].	Osseointegration/ Antibacterial
Orthodontic tooth movement	Graphene oxide NPs [79].	Acceleration of tooth movement

healthcare. Further, much research is being done in the field of nano dentistry, but practical applications will always present difficulties. Future research should focus on enhancing current technology to facilitate simpler manufacture and application. Tooth-colored shape-memory polymers that move teeth in an aesthetically pleasing way are a promising development in the field of orthodontics. It has been suggested that pure nanoscale sapphire and diamonds be used in place of outer enamel layers for esthetic purposes in order to provide durability high strength and fracture resistance. One of the most promising applications of nano dentistry could be the administration of drugs via nanoparticulate systems for the treatment of oral cancer. Nanoshells are composed of a silica core and a metallic outer layer. It is possible to construct beads that absorb infrared light by adjusting the layer thickness. This produces a high temperature that can destroy cancer cells. The focus going forward should be on enhancing the benefits of nanotechnology while lowering its related toxicity.

Integrating artificial intelligence (AI) in the development of nanotechnology is paving the way for innovative breakthroughs [84]. AI algorithms enable precise design and optimization of nanoparticles, improving their functionality and biocompatibility.

The creation of stimuli-responsive nanoparticles, which may change their activity in response to alterations in the oral environment, is one of the most promising application fields. For instance, patient comfort during treatment might be greatly enhanced through the release of nanoparticles that release analgesic or anti-inflammatory drugs in reaction to the mechanical stress associated with the moving of teeth. Parallel to this, the synthesis of nanoparticles that actively facilitate the remineralization of the enamel surrounding orthodontic brackets may aid in preventing caries and demineralization which are common problems during orthodontic treatment. Contemporary orthodontic appliances incorporate nanosensors that monitor the forces applied in tooth movement and assess the condition of surrounding oral tissues. These sensors provide orthodontists with real-time data, enabling them to implement immediate modifications to treatment protocols based on current information, which is expected to improve treatment outcomes.

CONCLUSION

The prospective integration of nanotechnology into orthodontics represents a potential paradigm shift in this dental subspecialty, offering innovative solutions to persistent challenges. Investigations into various nanoparticles, including silver, zinc oxide, graphene oxide, and modified gold nanoclusters, have shown promise in enhancing the safety and efficacy of orthodontic treatments. These advancements introduce novel antimicrobial strategies to mitigate risks associated with bacterial colonization and biofilm formation. Additionally, by reducing friction and improving durability, they contribute to enhancing the mechanical properties of orthodontic appliances. Research into orthodontic nanorobots and biocompatible coatings, such as titanium nanotubular layers on temporary anchorage devices, suggests a future where orthodontic procedures could become more efficient, less invasive, and better tolerated by patients. It is evident that nanotechnology holds significant potential to revolutionize orthodontic care, although researchers are proceeding cautiously with the clinical integration of nanomaterials in modern orthodontic practice.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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