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Recent Updates About Clinical Applications of Nanotechnology in Dentistry: A Review.

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Abstract

In contemporary dentistry, nanotechnology has paved the way for new materials and technologies that have improved diagnosis, prevention and treatment. Its clinical applications are varied among several dental specialties such as restorative dentistry, implantology, periodontology, orthodontics and endodontics. Use of nanoengineered materials in restorations and implants enhance the mechanical properties, biocompatibility and antibacterial activity; nanoscaling of implant surfaces supports better bone apposition for osseointegration thus offering long term stability. In addition, nanomaterials have been incorporated into biomimetic oral care formulations, biosensors for the early detection of disease and nanoparticle-medicated drug delivery systems.

The review reflects about the increasing involvement of nanotechnology in clinical dentistry and outlines its promise for revolutionizing oral health in personalized, minimally invasive, and patient-centric care. It highlights cutting-edge technologies and methods developed using nanotechnology for improving the material properties, performance, biocompatibility, and clinical success of various dental products and devices.

Keywords: Nanotechnology, Restorative Dentistry, Implantology, Periodontology

Introduction

Technological advancements have continuously shaped clinical practice within healthcare to be more targeted, effective, and patient-centric over time. Of these technologies, nanotechnology – the creation, manipulation or use of materials on the scale of approximately 1 to 100 nanometres has been disruptive and transformative in multiple areas which includes dentistry (Dipalma et al., 2024). It is known that particles and materials at the nanoscale have unique physicochemical properties, including larger surface area, altered reactivity, augmented bioactivity among others, which make them differ from their bulk (Sreenivasalu et al., 2022). These unique properties make nanomaterials especially appropriate for application in dentistry, where formulations that are biocompatible, durable, antimicrobial and minimally invasive are increasingly required.

Concerning dentistry, the term “nanodentistry” describes the implementation of nanomaterials and nano-enabled devices in preventive treatment as well restorative, prosthetic including endodontic and periodontal treatments, implantology (Jin Taek Jeong & Won Hee Park, 2013; Rasouli et al., 2018). Traditional materials in dentistry—resin composites, metallic implants, adhesives or sealants—and they have provided the patient well for a long time but may not satisfy all patients' needs, leaving shortcomings such as secondary caries, non-acceptable abrasion resistance (Seghi and Sorensen, 1995), poor osseointegration/biofilm formation/patient with quick breakdown of the solution (Padovani et al., 2015). Nanotechnology presents an opportunity to overcome these challenges by enhancing material properties (e.g., mechanical strength, adhesion and antimicrobial activity, etc.), improving surface interactions (e.g., implant-tissue interfaces), as well as reversing the delivery mechanisms for new systems that could potentially administer drugs more effectively or act as regenerative scaffolds (AlKahtani 2018).

One of the early and well-studied applications in this field is restoration materials, with addition of NPs into composites or adhesives to enhance the filler-matrix interface, decrease the polymerisation shrinkage and provide antibacterial effect (Chaudhary et al. 2024). In the field of implantology, also, nanoscale morphological changes in titaniumand zirconia have been found to have a positive impact on osseointegration time, as well as healing and bacterial colonisation rates leading to long-term implant success (Rasouli et al., 2018). In addition to material advances, diagnostic and preventive nano-medicine are also developing: examples such as nanoparticle biosensors and remineralising or biofilm inhibiting enamel-based formulations demonstrate that nanotechnology represents not only better materials but fundamentally new treatment modalities (Khatami et al., 2020).

Due to this exciting transformation, nano-enabled dental products are not yet in use for clinical practice. Although various laboratory trials invariably highlight that nanomaterials outperform classical material counterparts, the clinical superiority is not globally established in systematic reviews and concerns on biocompatibility, long-term safety, regulatory approval, and cost are still significant impediments (Cuevas-González et al., 2021). Understanding the reasons which make nano structures behave differently—what specific principle that is responsible for their heightened performance—is important in order to enable clinicians and researchers to properly assess new products, and incorporate these into practice (Sreenivasalu et 2022). For instance, although nanoparticles provide a high surface-to volume ratio with more active sites for bonding or antibacterial effect they are also highly reactive leading to potential cytotoxic effects in oral tissues that are constantly exposed to saliva, biofilm and mechanical forces (Padovani et al., 2015).

After all, due to its wide applications and the complicatedly of clinical use, it is important to conceptualize likewise as the core of principles(including designing nanomaterials, acting mechanisms and their properties) and practical use (daily dental specialty uses). This twofold surveillance enables stakeholders such as researchers, material scientists, clinicians, dental educators and industry partners to methodically evaluate the scientific foundations and practical implications for nanodentistry. Therefore, this review article provides a unified overview of the concepts and clinical relevance of nanotechnology in dental sciences with special emphasis on how nano-scaled works have revolutionized dental materials, implants, diagnosis and therapeutics. By combining the evidence in all peer--_reviewed articles published since 2015, we will deliver a comprehensive overview of current evidence describing studies that bridge laboratory innovation and regular clinical practice.

Principles of Nanotechnology

Nanotechnology has evolved from the bench to chairside in dentistry so quickly, bringing about real clinical benefits in restoratives, implantology, antimicrobial therapies, diagnostics and site-specific drug delivery. In the past five years, the literature has transitioned from proof-of-concept implementations to translational projects that evaluate nano-enabled therapies in clinically relevant models and (in some instances) early-stage human studies. This section reviews key clinical advances and the data supporting them.

Function In dentistry, restorative is one of the most mature applications for nanomaterials. The introduction of nanoscale fillers and modification of the surfaces of nanoparticles incorporated into resin composites and glass-ionomer matrices has enhanced their mechanical properties, polishability, and durability while also providing controlled antibacterial activity (Chokkattu et al., 2023). Current nanofillers are more efficient in the enhancement of filler-matrix interfacial bonding and the decrease in polymerization shrinkage, leading to better marginal integrity in laboratory and some in-vivo investigations. Hybrid compositions containing bioactive glass or calcium-phosphate nanoparticles also have as their goal doing more than filling a cavity but exerting secondary remineralization at the restoration-tooth interface (Dipalma et al., 2024). While evidence from long-term randomized clinical trials is still sparse, reviews in the form of systematic and narrative state that nanocomposites indeed show some potential improvement over conventional materials, especially for high stress posterior restorations (Chokkattu et al., 2023; Dipalma et al., 2024).

Nanoscale surface modification has revolutionised implantology. Nanotopographies (EE, titania nanotubes, nanopores) modulate the immune peri-implant response and the Nano particle coated too enhance early osseointegration and inhibits bacterial adhesion; which are crucial to implant success (Alamoudi, 2024; Soe et al., 2024). Recent literature specifically addresses composite coatings tailored for simultaneous osteo-inductive cues and antibacterial reservoir (drug-eluting nanotube arrays or ion-doped nanoceramic layers) allowing for dual strategy of accelerated bone integration along with peri-implant infection prophylaxis (Marasli et al., 2024; Soe et al., 2024). preclinical animal work and short-term clinical studies have shown faster bone-to-implant contact healing times with decreased early peri-implant inflammation for select nanoengineered surfaces; however, large long-term clinical trials are still required to prove sustained benefit over time and evaluate the safety of longterm corrosion or ion release.

Antimicrobial nanozymes (and catalytic nanoparticles) are an emerging clinical direction. Nanozymes can destroy biofilms and produce controlled local ROS, which is expected to improve either root canal disinfection or decontamination of periodontal pocket (Chokkattu et al., 2023). These nanozyme approaches are attractive as they bypass classical antimicrobial resistance mechanisms and could be incorporated into a irrigants, varnishes or topical gels. The early lab and ex-vivo data are exciting, clinical translation is advancing via pilot trials and device development pipelines; however, regulatory approval and biocompatibility challenges persist.

Diagnostics and point-of-care testing likely have realized the most rapid clinical translation with the help of nanomaterial-based biosensors. Nowadays, saliva-based electrochemical and/or capacitive sensors using nanostructured electrodes (graphene, gold or platinum nanoparticles) can reach very low levels of detection for viral, bacterial and host biomarkers and are interesting for fast chair-side screening (Moreira et al., 2022). Among these are examples from the last few years focused on laser-induced graphene platforms functionalized with metal nanoparticles (Panhuis and Strunk, 2016) and ACE2- based biorecognition layers for SARS-CoV-2 detection in saliva that serve as a proof of concept to demonstrate feasibility of nano-enabled biosensing for oral testing (Moreira et al., 2022). In addition to infectious disease, nanoparticle-enhanced assays are being designed for salivary markers of periodontal inflammation and caries risk, while oral cancer assessment may soon allow minimally invasive monitoring in community or primary-care environments.

Other clinical frontiers include targeted drug delivery and regenerative medicine. Drug carriers (liposomes, polymeric nanoparticles, mesoporous silica) offer the possibility of providing prolonged release at an oral lesion or implant site of antimicrobials, anti-inflammatories or growth factors with decreased systemic exposure and enhanced local efficacy. Similarly, nanofibrous scaffolds and hydroxyapatite nanoparticles are being developed in conjunction with grafts and membranes to stimulate bone formation within extraction sockets and around implants (Dipalma et al., 2024; Soe et al., 2024). Early human pilot studies and case series report superior bone fill and rapid soft tissue healing with nano-enabled scaffolds which merits future controlled evaluation.

However, although clear advances have been made, clinical utility continues to be limited by a number of universal factors: the heterogeneity of employed materials and methods, incomplete long-term safety data (especially relevant for continued presence of nanoparticles in body fluids or tissues) as well as ion release and potential cytotoxicity), regulatory lacunae and cost/affordability concerns comprising cost due to shortages within the supply chain (Alamoudi et al. As a result, a balanced viewpoint is emerging – that nanodentistry offers tremendous technological potential to improve restorative, implant and diagnostic outcomes however widespread clinical testing, standardized assays and robust post-market surveillance are necessary before many of the nano-enabled products can be considered as being standard of care.

Clinical Applications

One of those tools, nanotechnology-itswarddentistry-hasgreatly shapedmodern dentistry by providingnanoscale materials and devices to facilitate diagnosis, prevention and treatment of oral diseases. Based on multiple vast physiochemical properties of NP such as high surface area to volume ratio, improved mechanical strength and superior biocompatibility, novel dental materials, drug delivery systems and diagnostic tools have been developed. Particularly in restorative dentistry, endodontics, implantology, periodontology, orthodontics as well as prosthodontics and oral diagnostics, the new dimensions on offer with nanomaterials have consequences as they not only mean better healing success but also satisfied patients (Chokkattu et al., 2023; Alamoudi, 2024).

1. Restorative and Preventive Dentistry

The improvement of restorative materials is one of the first and most successful applications of nanotechnology in clinical dentistry. Nanocomposites with incorporation of nanometer size particles like silica, zirconia or hydroxyapatite have better mechanical properties, greater wear resistance and high esthetics in comparison with conventional composites. More particle loading at nanoscale and lesser polymerization shrinkage during cure minimize marginal leakage in various test specimens and that would tend to improve the longevity of restorations (Dipalma et al., 2024). Furthermore, these nanofillers also enhance the polishability and translucency of the restoration for realistic aesthetics.

As preventive dentistry, nano-Hydroxyapatite (nHAp) has received extensive acceptance towards its use in bioefficient remineralizing agent of toothpaste and mouth rinses. It may go through micro-defects of enamel and dentin layers to create a protective apatite layer that reinforces the tooth and reduces hypersensitivity (Kheur et al. Clinical studies indicate that nHAp toothpastes are equal or superior to the fluoride-based and control formulations in enhancing enamel remineralization and decreasing caries susceptibility. In addition, nanomaterials like silver and zinc nanoparticles were formulated in to the sealants and varnishes due to their antibacterial action against S. mutans as well as Lactobacillus species (Chokkattu et al., 2023).

2. Implantology and Periodontal Therapy

Nanotechnology has made massive contributions to the enhancement of success rates in dental implants. Nanotextured implant surfaces have improved osseointegration and reduced bacterial adhesion. Osteoblast cell adhesion, extracellular matrix-generation and bone healing of implants are accelerated by titanium dioxide nanotubes, nanoporous coatings and nanostructured calcium phosphate layers (Soe et al., 2024). Silver, zinc and copper nanoparticles also have antibacterial capabilities and they can reduce the probability of having peri-implantitis.

Nanomaterials are also used for regenerative periodontal treatment. Bioactive nanoparticles-loaded nanofibrous scaffolds made from polymeric polymers (e.g., polycaprolactone, collagen) serve as a template for the regeneration of new bone and connective tissues. Such scaffolds may be doped with growth factors as, e.g., plateletderived growth factor (PDGF) or bone morphogenetic proteins (BMPs), in order to promote periodontal regeneration (Dipalma et al. Enhanced clinical attachment level and bone fill in intrabony defects when nanocomposite membranes or gels are used in guided tissue regeneration also have been demonstrated.

3. Endodontics and Antimicrobial Applications

Nanotechnology has improved root canal disinfection and obturation in endodontics. Silver, chitosan and zinc oxide nanoparticles have been added to irrigants and sealers for their strong anti-microbial effect and ability to disrupt the biofilm. Such nanomaterials can enter the dentinal tubules and eradicate stubborn microorganisms, for example Enterococcus faecalis much better than traditional irrigants (Sharma et al., 2022). Nanoparticle incorporated sealers show better adhesion and lower microleakage leading to higher long-term endodontic therapy success.

Antimicrobial nanocoating and nanozymes: catalytic nanoparticles with enzyme-like activity are being explored as novel strategy for oral infection control. Nanozymes: Local ROS are created in proximity from immune cells by nanocatalysts, eradicating bacterial biofilm without harming the tissue (Chokkattu et al., 2023). They are being investigated in the management of caries, periodontitis and peri-implant infections.

4. Orthodontics and Prosthodontics

Nanotechnology has also affected orthodontic materials through the use of nanostructured coatings applied to brackets that have led to reduced friction against archwires with improvement in treatment efficiency and comfort. Nano-titanium and diamond-like carbon against corrosion and mechanical behavior of orthodontic appliances (Soe et al., 2024). Furthermore, nanocomposite adhesives exhibit higher bond strength and antibacterial effect that help in reduction of WSLs during orthodontic therapy.

In prosthodontics, nanostructures are able to improve physical and mechanical properties of the acrylic resins employed in constructions of dentures. The addition of either silver or zirconia nanoparticles imporve the impact strength, hardness and microbial resistance of the denture base (Alamoudi, 2024). Additionally, nano-coatings ceramics display an enhanced translucency and wear resistance making it aesthetic and durable for crowns and bridges.

5. Nanotechnology in Diagnostics and Drug Delivery

There is a significant progress in early detection of oral diseases with nano-enabled biosensors and diagnostic systems. Saliva-based biosensors for the detection of biomarkers of oral cancer, caries risk and systemic diseases (e.g. diabetes) have been developed using nanotructured electrodes and quantum dots (Moreira et al., 2022). These sensors will provide immediate, non-invasive and highly accurate tools for diagnostics to be used in personalized dentistry.

Nanocarriers like liposomes, dendrimers and polymeric nanoparticles have been used in DDS to achieve targeted delivery of drugs at selected areas of oral cavity with controlled release. For instance, nanoformulations of chlorhexidine and curcumin have been employed to obtain the prolonged release of antimicrobials from periodontal pockets, thus promoting effective therapeutic action with reduced systemic contact (Kheur et al., 2020). In the same token, incorporating analgesics or growth factors into nanocarriers also leads to the faster healing of wounds after oral surgery9–11.

Conclusion

In general, the field of nanotechnology has opened up new horizons for the development of modern clinical dentistry materials and methods aimed at increasing accuracy in diagnostic procedures and treatment efficiency as well as patient-based outcomes. While many of the applications have been shown to be safe and effective, concerns regarding standardisation, cost, as well as long-term biocompatibility exist. Clinical studies, regulatory streamline and bringing nano-based systems to digital and regenerative dentistry platforms should be key areas of focus for the future. With the ongoing development of nanotechnology, there will be more customized and effective use for oral health in the near future.

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