EDITORIAL

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Nanotechnology in dentistry.

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Recent years have seen a rapid advancement in medicine and treatment with the inclusion of technology in the field. Among others, nanotechnology has been proposed as a significant booster of dental development, enabling the creation of new solutions in numerous branches. In consideration of both the growing patient expectations and the complexity of oral disorders, the era of nanodentistry—the use of nanotechnology in dentistry—will most likely revolutionize current treatment concepts. With the advent of such < 100 nm particles, the development of new materials having structures different from those of the past has been achieved [1]. Nanoparticles incorporated in dental materials possess a high surface-volume ratio and an increased surface activity and are thus in direct contact with biological systems [2]. These properties enable the development of novel nanomaterials with enhanced performance, including biocompatibility, durability, antibacterial efficiency, and the ability to promote tissue regeneration. In dentistry, the applications of nanotechnology are so widespread that they are applied from directly restorative techniques (using nanocomposites and nano-ionomer cement) to implantology (using nanostructured coatings for faster osseointegration) [3]. The most challenging aspect of the endodontic field has always been the removal of resistant microorganisms (e.g., *Enterococcus faecalis*). Studies on nanoparticles have yielded promising results, which could lead to more effective disinfectants as alternatives to currently popular ones [1]. Periodontology also benefits from nanotechnology through the use of nanostructured scaffolds and targeted drug delivery systems, which can enhance tissue repair with high precision [4, 5].

Dental aesthetic expectations among patients have now been raised dramatically, particularly concerning tooth shade, in line with today's standard of beauty, which includes the orofacial beauty line, with white teeth as a standard [2]. Enamel damage has been reported in conventional tooth whitening procedures, but nanoceramics and whitening agents containing nanoagents appear to be free from this limitation. The development of nanosensors and molecular markers using quantum dots is considered a promising direction for the early diagnostics of inflammation and malignancies in the oral cavity in the future. Dentistry is currently in the throes of its discovery phase concerning nanotechnology. While the potential benefits identified provide a promising basis for the future, concerns about possible cytotoxicity, expense, and lack of regulatory control need to be carefully considered and suitably managed.

Nevertheless, progress in basic research and interdisciplinary cooperation among medical, materials engineering, and bioinformatics, together with new regulations, can provide opportunities for the development of dental nanotechnology and its responsible use. Tooth caries is the second most common disease globally, and it has been declared the most common non-communicable disease affecting the aesthetics and function of individuals by the World Health Organization (WHO). Nanotechnology has had a significant impact on the area of dental restorations. Nanocomposites, which incorporate routine restorative materials with SiO2, hydroxyapatite (HA), and zirconium-based nanoparticles, exhibit better aesthetics, bioactivity, and mechanical properties [1]. Translucent nanocomposites, similar to natural enamel, are the material of choice for aesthetic restorations, especially in the anterior tooth decay treatment [6, 7].

Furthermore, the very small particle size is beneficial for gloss and its lifetime, as reported by Kaviya et al. [5]. Nanotechnology also improves the antibacterial properties of materials used in restorative dentistry. For instance, incorporating silver nanoparticles (AgNPs) or zinc oxide nanoparticles (ZnONPs) into composites and adhesives has demonstrated significant inhibition of *Streptococcus mutans* and *Lactobacillus* species, which are responsible for secondary caries and restoration failure [8].

In restorative dentistry, nanocomposites demonstrate higher compressive and tensile strength than conventional composites, reduced polymerization shrinkage, improved polishability, and enhanced marginal adaptation. Moreover, nanofillers provide a smoother surface finish, which reduces plaque accumulation and staining over time.

Esthetic dentistry has also benefited substantially from nanotechnology. Nano-based ceramics exhibit enhanced polish retention, light reflection similar to natural enamel, and superior wear resistance. These properties make them ideal for anterior restorations, veneers, and aesthetic corrections. Furthermore, tooth-whitening products now include nano-hydroxyapatite to help remineralize the enamel surface post-whitening, reducing sensitivity and enhancing luster. Some whitening agents also incorporate nano-zinc or nano-calcium particles to buffer acidic components and protect the enamel matrix [9].

Nano-toothpastes, rich in bioavailable calcium, phosphates, and antibacterial agents, are increasingly used as adjuncts to clinical cosmetic procedures to maintain whitening results and oral hygiene.

Another important application is found in endodontics, where complete decontamination of the root canal system remains a major clinical challenge. Traditional irrigants such as sodium hypochlorite and chlorhexidine are often not fully effective against resistant biofilms. Nanoparticles like chitosan, titanium dioxide (TiO_2), and graphene oxide are being explored for their superior antibacterial activity, ability to penetrate dentinal tubules, and capacity to disrupt biofilms at the molecular level [10].

Furthermore, nanoparticles can serve as drug-delivery vehicles, allowing for the localized and sustained release of antimicrobials or regenerative agents within the root canal system, thereby enhancing healing and reducing the risk of reinfection [4].

The direct structural and functional connection between the bone and the implant surface has been optimized by the introduction of nanotechnology in implantology. Nano-modifications (e.g., coated with HA nanoparticles, nano-spraying, or natopography) made to the implant surface may improve osteoblastic adhesion and shorten bone healing time [6]. Biocidal nanoparticles, either silver or copper, serve for the prevention of peri-implantitis by suppressing bacterial adhesion without toxic impacts on cell viability [1, 11, 10]. Novel strategies also involve loading the implant surface with growth factors or anti-inflammatory agents using nanoporous carriers, enabling controlled release and local immunomodulation.

Another exciting area is the development of magnetically responsive nanostructured coatings on implants that can be stimulated externally to control cellular activity or therapeutic delivery.

In periodontology and tissue regeneration, nanotechnology has revolutionized the concept of guided tissue regeneration (GTR) by developing biodegradable nanofiber membranes, scaffolds, and hydrogels loaded with regenerative agents. These materials mimic the natural extracellular matrix, enhancing cell adhesion, proliferation, and differentiation of periodontal ligament cells and osteoblasts [1, 6].

Nanofiber-based membranes made from polycaprolactone (PCL), chitosan, and collagen, combined with bioactive glass or nano-hydroxyapatite, have shown promising results in in vitro and in vivo studies. Some of these membranes are also functionalized with antibacterial agents, growth factors (e.g., BMPs, VEGF), or stem cells to accelerate healing and improve outcomes.

Similarly, nanoparticle drug delivery systems are increasingly used in periodontal pockets to deliver antibiotics or anti-inflammatory drugs directly to the site of infection, minimizing systemic exposure [12].

In the realm of diagnostics and molecular imaging, nanosensors, quantum dots, and gold nanoparticles are being developed for the early detection of oral diseases, including oral squamous cell carcinoma and chronic periodontitis. These tools are capable of detecting biomarkers in saliva or gingival crevicular fluid, enabling non-invasive, real-time diagnostics [13].

For example, salivary nanosensors can identify the presence of MMPs, cytokines, or tumor markers at extremely low concentrations, providing earlier and more accurate diagnoses compared to conventional methods. Quantum dots can bind to specific proteins or cancer cells and fluoresce under light, helping surgeons visualize tumor margins precisely during resections [13].

These tools are integrated into lab-on-a-chip systems and connected devices, enabling point-of-care diagnostic applications even in general dental practice.

Nanodentistry has brought significant advances in terms of treatment precision, therapeutic efficiency, and long-term results. However, these technologies also involve a series of ethical, clinical, and technical challenges that must be carefully managed.

Limitations and issues of concern

1. Toxicity – some nanoparticles (such as silver, TiO_2) may provoke oxidative stress, inflammation, or cytotoxicity at high concentrations or long-term exposure [14, 3, 9, 5, 15].
2. High cost – Traditional materials are cheaper, so nanotechnology materials may not be available, particularly in public health systems [9, 16, 17].
3. Specialist knowledge - The successful use of nanomaterials is not without a learning curve, as specific protocols and dedicated devices are not present in every office [9, 18, 17].
4. Instability and degradation - Some nanoparticles may be prone to aggregation or oxidation in a biological milieu, which may reduce their bioavailability or activity [3, 9].
5. Inadequate regulation and ethical considerations – the integration of nanodentistry raises potential questions regarding how the long-term safety of this material would be monitored, the confidentiality of molecular data, and how, in the event of complications, manufacturers would bear liability for its end users [9, 19].

While the change in dentistry after nanotechnology is undeniable, this must happen with caution, only after strict scientific and clinical research and according to the regulation standards and also after difficult, continuous education of the staff that actually uses these "tools". A manner in which to balance innovation with safety will need to be struck for these technologies to be incorporated into routine dental practice.

The first scientific steps in dental nanotechnology have been made, but its implementation in clinical practice is still under development. The future of nanodentistry is based on a combination of innovation in materials, regenerative therapies, artificial intelligence and molecular biotechnologies.

The development of "smart" materials that will be able to release antimicrobial or remineralizing substances depending on chemical changes in the salivary environment is one of the most important future directions. Personalized nano-regeneration, which combines bioactive nano-scaffolds with autologous stem cells and growth factors released in a controlled manner, is another future development trend. Such technology could enable the regeneration of alveolar bone, periodontium, or even dental pulp, paving the way for minimally invasive and fully regenerative dental treatments [14, 13].

Studies on multifunctional implants coated with nanostructures are under development, aiming to facilitate faster osteointegration, prevent infection, and stimulate the regeneration of peri-implant soft tissues. Other studies are moving towards the development of implant systems that have the ability to release drugs or bioactive proteins locally, adapted to the patient's biological profile [6].

Rapid, real-time diagnosis of pathological changes in the oral cavity will be possible by introducing nanointegrated salivary biosensors coupled to portable devices connected to mobile applications [4, 20, 21, 22].

Advances in medical nanorobotics are opening up fascinating perspectives in dentistry as well. Dental nanorobots are expected to emerge – entities programmed to circulate through oral or pulp fluids, with the ability to remove bacterial colonies and intervene in affected dental structures [4, 5, 23]. Although this direction is still in the experimental stage, interdisciplinary research is promising.

The progress of nanotechnology in dentistry cannot be achieved without close collaboration between researchers, whether they are doctors, engineers, practitioners, or the authorities responsible for regulating these technologies.

In conclusion, although it may seem like a futuristic concept, nanodentistry, driven by current advances and the scientific results provided, is a reality that will play a significant role in the future of dentistry, bringing personalized treatments to the forefront for each patient.

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