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Chapter 5

Nanoparticles: Recent developments, current status and future perspectives

Surabhi Halder [1], Rajesh Kumar S. [2]

[1] *Department of Prosthodontics crown and Bridge, Priyadarshini Dental College and Hospital, Chennai, Tamil Nadu, India*
[2] *Nanobiomedicine lab, Centre for global health and Research, Saveetha Institute of Medical and Technical Siences, Chennai, India*

surabhihalder7@gmail.com

1 Introduction

Nanotechnology serves as a crucial link between the biological and physical sciences by leveraging nanostructures and nanophases in diverse scientific disciplines (Liu et al., 2009), especially in fields such as nanomedicine and nano-based drug delivery systems where these particles play a pivotal role. Substances considered as nanomaterials usually have sizes from 1 to 100 nm and are instrumental in critical aspects of nanomedicine including biosensors, microfluidics, drug delivery mechanisms, microarray tests, and tissue engineering. At the nanoscale, therapeutic agents are employed to develop nanomedicines. The realm of biomedicine, encompassing nanobiotechnology, drug delivery, biosensors, and tissue engineering, has progressed significantly through the adoption of nanoparticles. Because nanoparticles are crafted at the atomic or molecular level, they are typically small, spherical entities that traverse the human body more readily than larger counterparts. The initial wave of nanoparticle-based treatments included lipid-based configurations such as liposomes and micelles, which have gained FDA approval. These vehicles are capable of housing inorganic nanoparticles like gold or magnetic ones. This capability has spurred the increased application of inorganic nanoparticles, especially in the domains of drug delivery, imaging, and therapeutic interventions. Cells absorb nanostructures at a much higher rate than larger particles, usually between 1 to 10 µm, thus they can specifically target afflicted cells, enhancing the effectiveness of treatments while minimizing or eliminating side effects.

2 Current status: Fundamentals of Designing

Research on nanodrug design has been comprehensive and is recognized as a leading technology in nanoparticle utilization, owing to its significant potential advantages (Ahmed et al., 2021; Britto et al., 2021; Kumar et al., 2022; Li, 2023). These advantages encompass the capability to enhance critical features such as solubility, release behaviors of drugs, diffusivity, bioavailability, and immunogenicity. Consequently, these enhancements may lead to better drug delivery approaches, diminished toxicity, reduced adverse effects, improved biodistribution, and extended duration of drug action.

In recent developments, there has been a growing trend of integrating nanoparticles with natural substances to address toxicity issues. The eco-friendly approach in developing drug-carrying nanoparticles is highly endorsed because it minimizes the incorporation of toxic materials in the synthesis process. Therefore, the use of eco-friendly nanoparticles in drug delivery systems can decrease the undesirable effects linked with pharmaceuticals. Moreover, modifying the size, shape, hydrophobicity, and surface attributes of nanostructures can further enhance the biological effectiveness of these materials.

Nanotechnology delivery systems

Researchers have explored the administration of paclitaxel encapsulated in human albumin-based nanoparticles (albumin Nfis) through intra-arterial infusion as a preliminary chemotherapy option before definitive treatment of advanced tongue cancer. Paclitaxel, a lipophilic medication, requires surfactants to be solubilized in organic liquids. Moreover, this drug is known to trigger severe allergic reactions when given intravenously. Albumin Nfis appear to be effective carriers, capable of encapsulating significant amounts of the drug due to the numerous drug-binding sites on albumin molecules. Damascelli and colleagues have found that delivering paclitaxel via albumin nanoparticles through intra-arterial routes is both repeatable and efficacious.

Nanotechnology presents a myriad of benefits for the treatment of chronic human diseases by facilitating precise and targeted drug delivery (Al-Shargabi et al., 2022; Li et al., 2022; McLean & Yarovsky, 2024; Mohanta et al., 2023). Nonetheless, the limited knowledge of the potential toxicity of nanostructures poses a substantial hurdle, underscoring the need for continued research to improve their effectiveness and safety. Therefore, meticulous development of these nanoparticles is crucial to overcome the difficulties associated with their application. Table 1 shows nanoparticles-recent developments, current status and future perspectives.

Table 1 Nanoparticles-recent developments, current status and future perspectives.

Sr. No.	Nanoparticle Type	Recent Developments	Current Applications	Challenges	Future Perspectives
1	Metallic	Advancements in synthesis methods for improved stability and functionalization.	Electronics, catalysis, medical imaging, and biosensors.	Toxicity, environmental impact, and cost of large-scale production.	Eco-friendly, biocompatible metallic nanoparticles for medical and industrial use.
2	Ceramic	New fabrication techniques to enhance biocompatibility and mechanical properties.	Biomedical implants, drug delivery systems, and coatings.	Scalability and reproducibility of properties.	Advanced coatings for implants and tissue regeneration applications.
3	Carbon-based	Progress in controlling the shape and size of carbon nanotubes and graphene for better performance.	Energy storage (batteries, supercapacitors), sensors, and electronics.	Long-term stability, functional integration, and environmental disposal.	Flexible electronics, advanced supercapacitors, and regenerative medicine.
4	Polymeric	Improved drug encapsulation and release mechanisms.	Drug delivery, tissue engineering, and therapeutic agents.	Immune rejection and achieving precise targeting.	Smart delivery systems responsive to stimuli (pH, temperature, magnetic fields).
5	Liposomes	Enhanced targeting and payload capacity for cancer therapy.	Cancer therapy, vaccine delivery, and gene therapy.	Stability of liposomes, controlled release rates, and high production costs.	Personalized medicine and multi-drug delivery in single liposome systems.

6	Quantum Dots	Development of non-toxic quantum dots for biomedical imaging.	Biomedical imaging, photovoltaic devices, and LEDs.	Toxicity of conventional quantum dots (heavy metals).	Widespread use in bio-imaging and advanced display technologies with safer materials.
7	Magnetic	Improved synthesis of superparamagnetic nanoparticles for medical and industrial applications.	Magnetic resonance imaging (MRI), drug delivery, and separation technologies.	High cost of production and safety concerns for human use.	Multi-functional magnetic nanoparticles for combined imaging and therapy.
8	Plasmonic	Enhanced plasmonic properties for improved sensing and therapeutic uses.	Biosensors, cancer therapy, and enhanced imaging systems.	Stability under various conditions and high production costs.	Nanoscale plasmonic devices for real-time diagnostics and photothermal therapy.
9	Silica-based	New strategies for controlled porosity and functionalization for drug delivery.	Drug delivery, diagnostics, and catalysis.	Limited biodegradability and scalability challenges.	Development of biodegradable and functionalized silica nanoparticles.
10	Gold	Innovations in gold nanoparticle-based diagnostics and therapy (e.g., photothermal therapy).	Cancer diagnostics, therapy, and biosensing.	Cost of gold and toxicity at high concentrations.	Wider applications in diagnostics and personalized medicine.
11	Zinc Oxide	Advancements in UV-blocking and	Sunscreens, coatings, and	Nanotoxicity concerns and	Eco-friendly, biodegradable

		antimicrobial properties.	antibacterial products.	environmental persistence.	zinc oxide for consumer products and biomedicine.
12	Hybrid	Combination of organic and inorganic materials for multi-functional properties.	Drug delivery, diagnostics, and energy storage.	Complex synthesis processes and achieving compatibility between materials.	Next-generation hybrid nanoparticles for energy, environment, and healthcare sectors.

3 Future Perspectives: New Approaches and Challenges

Nanocarrier systems are becoming a viable solution to overcome some obstacles that have hampered effective targeting of diverse cancer cell types (Rabaan et al., 2022; Rahman et al., 2024; Rajoriya et al., 2021; Skripka et al., 2021). These systems exhibit several beneficial properties, including enhanced efficacy in combating oral cancers, which conventional chemotherapy fails to achieve. Consequently, the U.S. Food and Drug Administration (FDA) has approved a recent clinical trial for a nanoparticle-based therapy aimed at treating solid tumors in humans. In 2003, Yang et al. explored the use of cucurbitacin BE polylactic acid nanoparticles (CuBE-fiLA-Nfis) for targeted delivery to cervical lymph nodes via submucosal injection in perioral cancer, evaluating their therapeutic effectiveness. Their findings indicated that drug levels in the cervical lymph nodes were significantly elevated post-injection with CuBE-fiLA-Nfis compared to the control group, while drug concentrations in the bloodstream were notably reduced, underscoring the treatment's efficacy. These developments suggest that nanotechnology-driven drug delivery systems could soon provide oncologists and their patients with improved therapeutic results and lower treatment costs.

Although the application of nanotechnology in oral cancer remains under-studied, its potential to transform dental healthcare is immense (Smith et al., 2021; Verma et al., 2024; Virmani et al., 2023; Wang et al., 2022a; Wang et al., 2022b). It promises innovative approaches for cancer detection and the customization of treatment regimes tailored to the individual characteristics of patients. Nevertheless, further research is required to convert nanotechnology from concept to clinic, fine-tune dosages, and perfect the release mechanisms needed to treat various cancers with specific molecular and cellular profiles.

Conclusion

Nano drug delivery systems are progressively offering the pharmaceutical industry innovative solutions for drug formulation, as well as opportunities for expanding existing drug lines by enhancing therapeutic effectiveness or providing alternative administration routes. As nanotechnology continues to gain research funding, the variety of colloidal structures available for these applications will be more thoroughly understood, and more efficient and dependable manufacturing techniques will be developed.

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