

Popular Article

The Marvel of Nanoparticles: Tiny Particles, Big Impact

Manvi Sharma, Rakesh Kumar*, Mehul Sharma,
R. K. Asrani

Department of Veterinary Pathology, DGCN College of Veterinary and Animal Sciences, CSK Himachal Pradesh
Agricultural University, Palampur, Himachal Pradesh, India.

**Corresponding author: Rakesh Kumar, Email: rkvetpath@gmail.com*

Introduction

In the domain of scientific innovation, little advancement has captured the imagination and promise of future possibilities like nanoparticles. These tiny particles, which usually have a diameter of 1-100 nanometers, are revolutionizing various industries, including medicine and electronics. Nanoparticles are having a massive influence despite their minuscule size, emphasizing that sometimes; the smallest things can bring about the most significant changes.

What Are Nanoparticles?

Nanoparticles are materials that exist at the nanoscale, typically ranging in size from 1 to 100 nanometers, where one nanometer is equivalent to one billionth of a meter. For context, the diameter of a single human hair is approximately 80,000 nanometers. This nanoscale dimension endows nanoparticles with distinctive physical and chemical properties, distinguishing them from larger particles. Key characteristics of nanoparticles include a significantly increased surface area to volume ratio, enhanced chemical reactivity, improved solubility, the capacity to traverse

biological membranes, and unique optical properties.

The concept of nanoparticles is not entirely new, as natural processes have been generating them for millennia through phenomena such as volcanic ash, ocean spray, and wildfire smoke. However, the deliberate synthesis and manipulation of nanoparticles is a comparatively recent advancement, gaining significant momentum during the latter part of the 20th century.

In the 1950s and 1960s, researchers started to appreciate the potential of nanoparticles. The advent of electron microscopy, which enabled scientists to observe and analyze nanoparticles in detail, marked a significant milestone. By the 1980s, progress in nanotechnology gained momentum, resulting in the advanced methods we now employ to create and manipulate nanoparticles.

Applications in Medicine

One of the most promising applications for nanoparticles is in the field of medicine. Due to their diminutive size, nanoparticles can engage with biological systems at the molecular level, presenting unparalleled opportunities for both diagnosis and treatment.

Drug Delivery

Targeted Drug Delivery: Nanoparticles provide an advanced method for targeted drug delivery, overcoming the limitations of traditional therapies that often result in systemic toxicity and limited effectiveness. The distinctive characteristics of nanoparticles, such as their small size and large surface area, enable them to be designed for precise delivery of drugs to specific cells or tissues. This targeted strategy is especially advantageous in cancer treatment. For example, liposomes, which are vesicles composed of lipid bilayers, can encapsulate chemotherapy drugs. By modifying the surface of these liposomes with targeting ligands, such as antibodies or peptides, they can specifically bind to receptors that are overexpressed on cancer cells. This ensures precise delivery of the drug to the intended site, minimizing harm to healthy tissues and reducing side effects.

Controlled Release: Nanoparticles can be engineered to release their therapeutic payload in a controlled manner, facilitating sustained drug release over time. Polymeric nanoparticles, crafted from biodegradable polymers such as PLGA (poly(lactic-co-glycolic acid)), are frequently utilized. The polymer's degradation rate can be adjusted to regulate the release kinetics of the encapsulated drug, ensuring a consistent and prolonged therapeutic effect. This method is especially beneficial for managing chronic conditions requiring stable drug levels over extended periods.

Overcoming Biological Barriers: Nanoparticles can be tailored to traverse biological barriers, such as the blood-brain barrier (BBB). The BBB acts as a selective

barrier that protects the brain while restricting the passage of numerous therapeutic agents. Nanoparticles can be engineered to cross this barrier by utilizing mechanisms like receptor-mediated transcytosis. For instance, nanoparticles coated with transferrin-a protein that transports iron across the BBB can bind to transferrin receptors on the endothelial cells of the BBB, facilitating their transport into the brain.

Imaging and Diagnostics

Enhanced Imaging Contrast: Nanoparticles are extensively employed to enhance contrast in various imaging modalities, facilitating early disease detection. Gold nanoparticles, for instance, are utilized in imaging and diagnostic applications due to their robust optical properties. They serve as excellent contrast agents for techniques such as X-ray, MRI, and computed tomography (CT) scans because their high atomic number results in strong X-ray attenuation. When administered into the body, these nanoparticles accumulate in specific tissues, thereby enhancing contrast and improving the resolution of CT images, yielding clearer and more detailed visuals.

Molecular Imaging: Nanoparticles can be functionalized with specific molecules that bind to disease-associated biomarkers, facilitating molecular imaging. For example, superparamagnetic iron oxide nanoparticles (SPIONs) can be coated with antibodies that target cancer cell antigens. When employed in magnetic resonance imaging (MRI), these targeted SPIONs enhance the contrast of tumors, enabling early detection and precise localization of cancerous tissues.

Multimodal Imaging: Nanoparticles can be engineered to facilitate multimodal imaging, integrating various imaging techniques to deliver comprehensive diagnostic information. Quantum dots, which are semiconductor nanoparticles, possess unique optical properties such as size-tunable fluorescence. By incorporating additional imaging functionalities, such as magnetic properties for MRI or radiolabels for positron emission tomography (PET), quantum dots enable multimodal imaging. This strategy allows clinicians to acquire detailed anatomical, functional, and molecular information within a single imaging session.

Therapeutic Applications

Hyperthermia Treatment: Nanoparticles can be utilized in hyperthermia treatment to selectively heat and eradicate cancer cells. Magnetic nanoparticles, such as iron oxide nanoparticles, can be directed to the tumor site using an external magnetic field. Once localized, the application of an alternating magnetic field induces the nanoparticles to generate heat via Néel and Brownian relaxation mechanisms. This localized heating can cause cell death in the tumor without harming the surrounding healthy tissue. Hyperthermia treatment is often combined with other therapies, such as radiation or chemotherapy, to enhance their efficacy.

Photothermal Therapy: Gold nanoparticles can be employed in photothermal therapy, a technique that uses light to generate heat for therapeutic purposes. When exposed to near-infrared (NIR) light, gold nanoparticles absorb the light and convert it into heat through the surface plasmon

resonance effect. This localized heating can effectively destroy cancer cells or bacteria. Gold nano shells and nanorods are particularly well-suited for this application due to their tunable optical properties, which enable efficient absorption of NIR light.

Gene Therapy: Nanoparticles are also being investigated for gene therapy, where they can deliver genetic material to cells to correct or modulate gene expression. Lipid-based nanoparticles, such as lipid nanoparticles (LNPs), have been employed to deliver messenger RNA (mRNA) vaccines, including the COVID-19 vaccines developed by Pfizer-BioNTech and Moderna. These LNPs protect the mRNA from degradation and facilitate its uptake by cells, enabling the production of the target protein antigen to elicit an immune response.

Environmental Impact: Nanoparticles are also being investigated for gene therapy, where they can deliver genetic material to cells to correct or modulate gene expression. Lipid-based nanoparticles, such as lipid nanoparticles (LNPs), have been employed to deliver messenger RNA (mRNA) vaccines, including the COVID-19 vaccines developed by Pfizer-BioNTech and Moderna. These LNPs protect the mRNA from degradation and facilitate its uptake by cells, enabling the production of the target protein antigen to elicit an immune response.

Conclusions

Despite their small size, nanoparticles represent a formidable tool in modern medicine, providing innovative solutions for drug delivery, diagnostic

imaging, and therapeutic applications. Their capacity for precise engineering and functionalization paves the way for personalized medicine, allowing treatments to be tailored to the specific needs of individual patients. As research in nanotechnology progresses, the potential for nanoparticles to revolutionize healthcare becomes increasingly clear, promising more effective and less invasive options for diagnosing and treating a wide array of diseases.