WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Nanoparticle-Based Drug Delivery Systems: A Review of Current Status and Future Directions

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ABSTRACT:

Drug delivery systems based on nanoparticles have become a viable strategy for raising the effectiveness and lowering the toxicity of different medicinal medicines. This assessment seeks to give a thorough summary of the present state and potential future paths of methods for medication delivery based on nanoparticles. We go over the different kinds of nanoparticles, such as metal, polymeric, and liposome nanoparticles, as well as how they are used in medication delivery. We also look at the current state of drug delivery systems based on nanoparticles, including their pharmacokinetics, biodistribution, and toxicity. We also discuss the challenges and limitations of developing nanoparticle-based medication delivery systems and provide recommendations for future research directions. Our review highlights the potential of nanoparticle-based drug delivery technologies to revolutionize medicine and improve human health.

Keywords: pharmacokinetics, biodistribution, targeted therapy, nanomedicine, nanoparticles, and toxicity.

INTRODUCTION:

Nanotechnology is the use of this knowledge to develop or alter new goods, while nanoscience is the study of the special characteristics of materials with a size between 1 and 100 nm. The production of nanomaterials is made possible by the capacity to modify structures at the atomic level. Nearly every industry and sphere of society has been significantly impacted by nanotechnologies because they provide

I. better constructed ii) cleaner and safer
II. more durable and
III. intelligent products for daily use, communications, healthcare, agriculture, and other sectors.

The special optical, electrical, and/or magnetic characteristics of nanomaterials at the nanoscale can be advantageous for a variety of applications, including electronics and health.

The high surface area to volume ratio of nanomaterials makes them special. Nanomaterials are subject to the laws of quantum mechanics rather than the traditional physics and chemistry principles, in contrast to normal large-scale manufactured objects and systems. Nanotechnology is the engineering of functional systems and valuable products at the atomic or molecular level.

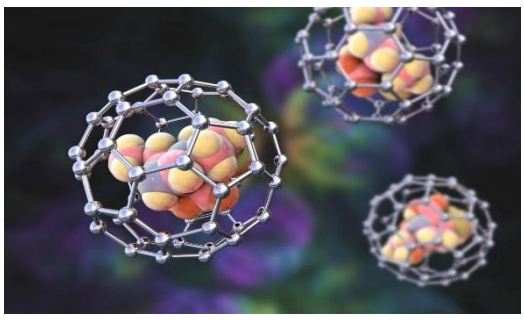

Figure 1: Structure of Nanoparticles

MECHANISM OF ACTION OF NANO-PARTICLE BASED DRUG DELIVERY:

The way in which nanomedicine delivery systems work:

Nanoparticles offer advantageous qualities that can be utilised to enhance drug delivery when they are made to evade the body's defence processes. In an effort to improve the effectiveness, safety, and tolerability of integrated medications, several nanoparticle formulations have been shared in the drug development process. Formulations based on nanoparticles have demonstrated enhanced pharmacokinetic and pharmacodynamic qualities, regulated release, and high solubility. When developing efficient nanoparticle delivery systems that work via a range of processes, particle size, surface charge, and shape are crucial factors.

1.Particle size:

The most important characteristics of nanomaterials are their particle size and size distribution, which determine their chemical and physical characteristics. These nanomaterials' hydrodynamic size and size distribution dictate their in vivo distribution, biological destiny, toxicity, and targeting ability for drug delivery systems. They can regulate the loading, release, and stability of medications. Because of their small size and excellent mobility, which allow for better cellular uptake and make them suitable for a wider range of intracellular and cellular targets, nanomaterials are said to be superior to microscale particles.

2.Loading Drugs:

The technique of adding a drug to or into nanoparticles is known as medication loading. A high drug-loading capacity that inhibits agglomeration is excellent for a drug delivery system utilizing nanoparticles. A large drug loading capacity can cut down on the quantity of doses required or how much management is needed. Dispersibility is necessary for the drugs to be administered efficiently. Drug solubility in the nanoparticles, the dispersion medium, the size and composition of the nanomaterials, the drug molecular weight (MW) and solubility, the drug-nanomaterials interaction, and/or the presence of surface functional groups (such as carboxyl, amine, ester, etc.) on the drugs or the nanomaterials are some of the factors that affect the efficacy of entrapment and drug loading.

3.Surface Charge:

Surface charge is commonly expressed and measured using the zeta potential of nanomaterials, which is the electrical potential of particles influenced by their composition and the medium in which they are dispersed. A zeta potential of ± 30 mV has been demonstrated to be stable in suspension and to inhibit particle aggregation [30]. The surface charge of nanoparticles is crucial for drug loading. Drugs can be loaded via a variety of techniques, such as encapsulation, charge-charge interaction, hydrophobic contact, and covalent conjugation. The properties of the target molecule and the medicine both influence molecular loading, which alters surface charge. A charged molecule's ability to bind or adsorb on a nanoparticle's surface can be determined.

4.Targeting Drugs:

Targeting tumors enhances chemotherapy, and nanomaterials provide a highly targeted and versatile platform for cancer treatment. Because of fenestrated blood arteries, improved permeability and retention enable preferential localization in tumors spontaneously, just like in the case of drug-loaded liposomes (doxorubicin-liposome complex).. It has been established that nano size liposomes, which target tumours spontaneously due to the fenestrated blood arteries, efficiently increase the selective localisation of small-molecule medicines like doxorubicin in human tumours in vivo. Increased permeability and consequent drug retention are to blame for this [34]. Compared to targeting ligand-drug conjugates, targeting nanomaterials as drug delivery vehicles or nanocarriers for site-specific delivery offers several benefits.

5. Binding to the receptor sites:

When drugs are transported to the MPS (Mono Phagocytic System), which includes the liver, spleen, lungs, and bone marrow, conventional drug carriers alter the drug distribution profile. However, when supplied intravenously, nanoparticles as drug carriers can be recognised by the human immune system, leading to their removal from the circulation by phagocytes [39]. The amount of blood components (such as oponins) that bind to the surface of nanoparticles depends on their size, surface hydrophobicity, and surface coating capabilities, all of which affect the nanoparticles' in vivo destiny. Preventing opsonisation while extending the circulation of nanoparticles in vivo is crucial for improving the likelihood of medication targeting success. The nanoparticles can accomplish this by applying hydrophilic polymers as a pre-coating.

6.Drug Release:

Drug release is the process by which a drug loaded into a nanoparticle diffuses or dissolves in the body, whereas biodegradation is the breakdown of the drug delivery system within the body. Developing a therapeutic delivery system using nanoparticles requires careful consideration of both drug release and biodegradation. The drug's efficiency is also determined by solubility, diffusion, and particle size in addition to its active ingredients. Because of the small particle size, a high surface-to-494 ratio causes rapid drug release at the surface. Larger particles, on the other hand, have larger cores, which enable the encapsulation of more medications per particle and provide slower release.

TYPES OF NANO-PARTICLES:

Micelles:

Lipids and amphiphilic molecules combine to form micelles, which are amphiphilic surfactant molecules. Micelles can be used to integrate hydrophobic therapeutic medicines because they spontaneously aggregate and self-assemble into spherical vesicles with a hydrophilic outer monolayer and a hydrophobic core in aqueous conditions. Because of the special qualities of micelles, hydrophobic medications can become more soluble, increasing their bioavailability. Micelles have a diameter between 10 and 100 nm. Micelles can be used as therapeutic, contrast, imaging, and drug delivery agents, among other things.

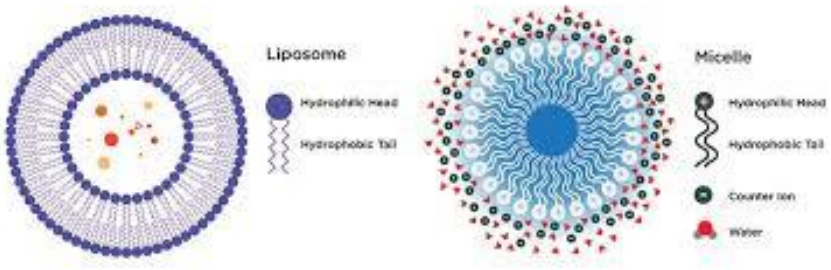

Figure 2: Structure of micelle

Liposomes:

Liposomes are spherical vesicles made of lipid bilayers that range in size from 30 nm to several microns. It is possible to add hydrophilic medicinal chemicals to the liposomes' aqueous phase and hydrophobic substances to the liposomal membrane layer.

The versatility of liposomes allows for the incorporation of macromolecular drugs, including solid metals and nucleic acids, by modifying their surface characteristics using polymers, proteins, and/or antibodies. Poly (ethylene glycol) (PEG)ylated liposomal doxorubicin (Doxil®) is the first FDA-approved nanomedicine for the treatment of breast cancer. It raises the effective drug concentration in malignant effusions without increasing the overall dosage.

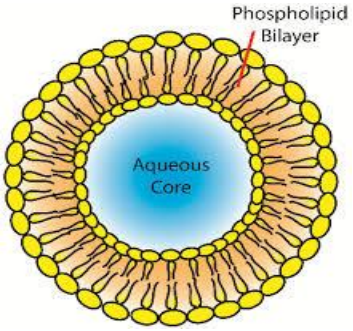

Figure 3: structure of liposomes

Dendrimers:

Dendrimers are macromolecules composed of branched repeating units and external functional groups that extend from a central core. These functional groups, which may be cationic, neutral, or anionic terminals, have the ability to alter the overall structure, as well as the physical and chemical properties. Dendrimers are highly bioavailable and biodegradable due to the fact that medicinal chemicals can be attached to their surface groups or contained within their interior space.It has been demonstrated that dendrimer conjugates with saccharides or peptides have improved antiviral, antibacterial, and antiproton qualities along with increased solubility and stability when therapeutic medications are absorbed. DNA polyamide dendrimer Complexes, also known as dendrimers, have been studied as vectors for gene delivery and show promise in promoting targeted medication delivery, enhancing treatment efficacy, and enabling consecutive gene expression. Because of their transformable characteristics, dendrimers are potential particulate systems for biomedical applications, including medication administration and imaging.

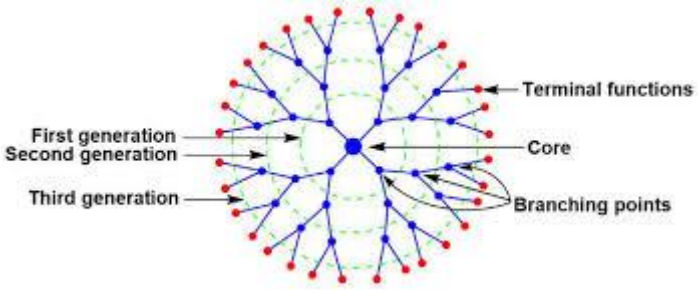

Figure 4: Structure of dendrimers

Carbon nanotubes:

The cylindrical molecules known as carbon nanotubes are made of rolled-up sheets of graphene, a single layer of carbon atoms. They may consist of many concentrically interconnected nanotubes or have one or more walls. Because of their large surface area, carbon. As drug transporters, nanotubes can achieve remarkably high loading capacities. Carbon tubes are also attractive as biological sensors and contrast agents for imaging because of their distinct optical, mechanical, and electrical characteristics.

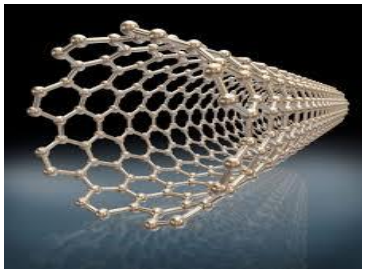

Figure 5: structure of carbon nanotubes

Metallic nanoparticles:

Gold and iron oxide nanoparticles are examples of metallic nanoparticles. Iron oxide nanoparticles are composed of a magnetic core (4-5 nm) and hydrophilic polymers such as PEG or dextran. In contrast, gold nanoparticles are composed of a core of a gold atom surrounded by negative charges. Reactive groups on the surface can be functionalized by adding a monolayer of surface moieties as ligands for active targeting. Metallic nanoparticles have been used in laser-based treatments, medication delivery systems, optical biosensors, and imaging contrast agents.

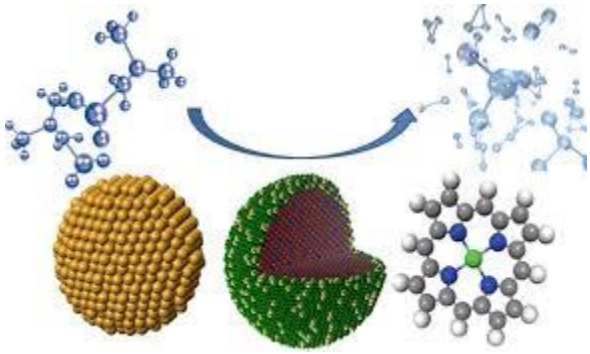

Figure 6: structure of metallic nanoparticles

Quantum dots:

Fluorescent semiconductor nanocrystals with a wavelength of 1–100 nm, quantum dots (QDs) have demonstrated promise for a number of biological uses, including cellular imaging and medication administration. The structure of quantum dots is shell-core, with the core structure usually made comprised of elements from the periodic table's II–VI or III–V groups. Quantum dots have been used in medical imaging because of their unique optical characteristics, compactness, high brightness, and stability.

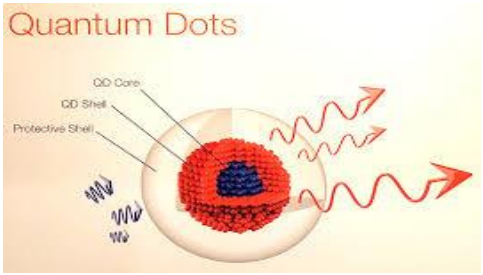

Figure 7: Structure of quantum dots

Recent Trends:

I. **Nanoparticle-Based Gene Delivery:** Researchers are exploring the use of nanoparticles for gene delivery, which could potentially treat genetic diseases.
II. **Stimuli-Responsive Nanoparticles:** Nanoparticles that respond to specific stimuli, such as pH or temperature, are being developed for controlled drug release.
III. **Nanoparticle-Based Combination Therapies:** Researchers are investigating the use of nanoparticles to deliver combination therapies, which could improve treatment outcomes.
IV. **Targeted Nanoparticles for Cancer Therapy:** Nanoparticles are being designed to target specific cancer cells, reducing side effects and improving treatment outcomes.
V. **Nanoparticle-Based Diagnostic Tools:** Researchers are developing nanoparticles for diagnostic applications, such as imaging and biosensing.

Future Directions:

1. Personalized Nanomedicine: Researchers are working towards developing personalized nanomedicines that can be tailored to individual patients' needs.
2. Nanoparticle-Based Regenerative Medicine: Scientists are investigating the potential of nanoparticles for tissue engineering and other regenerative medicine applications.
3. Nanoparticle-Based Immunotherapy: Scientists are looking at using nanoparticles for immunotherapy purposes, like treating cancer.
4. Nanoparticle-Based Gene Editing: Scientists are investigating the use of nanoparticles for CRISPR-Cas9 and other gene editing applications.

5. Nanoparticle-Based Synthetic Biology: Scientists are looking into the creation of new biological systems and other uses for nanoparticles in synthetic biology.

Emerging Technologies:
1. 3D printing using nanoparticles: Scientists are investigating the use of nanoparticles for 3D printing uses, like producing intricate tissue architectures.
2. Nanoparticle-Based Microfluidics: Scientists are examining the application of nanoparticles in microfluidics, including the development of miniature medical equipment.
3. Nanoparticle-Based Synthetic Biology: Scientists are investigating the potential of nanoparticles for applications in synthetic biology, including the creation of novel biological systems.
4. Biohybrid Systems Based on Nanoparticles: Scientists are looking into the formation of artificial cells and other biohybrid systems using nanoparticles.
5. Nanoparticle-Based Nanorobotics: Scientists are investigating how nanoparticles can be used in nanorobotics applications, like building tiny robots for use in medicine.