

Nanoparticle-Based Drug Delivery: Current Applications, Challenges, And Future Prospective

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ABSTRACT

Nanoparticle drug delivery is becoming a promising technology that would help to overcome problems associated with the use of traditional drug delivery methods, namely poor bioavailability, lack of stability of the delivered drugs, their non-specific action, and side effects. Due to the specific physicochemical properties of nanoparticles, they allow increasing the solubility of the drugs, protecting the latter from decomposition, and delivering the therapeutic agent in a controlled and targeted manner. Lipid-based nanoparticles, polymer nanoparticles, metallic nanoparticles, mesoporous silica nanoparticles, and dendrimers represent different types of nanocarriers, which show great promise in treating cancer, infections, neurological diseases, cardiovascular diseases, vaccine and gene delivery. However, there are still many issues that hinder their wide implementation, such as toxicity, production on an industrial scale, stability of formulations, and regulatory aspects. The progress in the development of smart nanocarriers, artificial intelligence, and personalized medicine will contribute to improving the efficacy and safety of nanoparticles-based drug delivery systems in the future.

Keywords: Nanoparticles, Nanomedicine, Targeted Drug Delivery, Cancer-cells.

INTRODUCTION

Nanoparticles have brought a change in the field of pharmaceutical science by providing innovative techniques to improve drug delivery and therapeutic outcomes. [2,5] They offer new ways to deliver medications and improve how well treatments work nowadays. [1,8] Specifically, nanoparticle-based drug delivery is getting a lot of attention because it can help people to overcome the problems we used to have with regular drug delivery methods. [3,10,18]

In the past, getting drug delivery to work well was difficult. Drugs sometimes didn't dissolve completely in water, and sometimes the body was unable to tolerate them and they broke down too easily, didn't go to the right places, and caused unwanted side effects. All these issues made treatments less effective. Thus, nanoparticles offer a very effective strategy to overcome these challenges. [4,11,16]

Nanoparticles are tiny particles, usually between 1 and 100 nm (nanometres) in size. [7,12] They have special qualities, like a lot of surface area for their size and surfaces that can be changed. They help the

nanoparticles to carry medicine to specific spots in the body and release it at the specific site. Besides regular medicines, nanoparticles can also deliver larger molecules like proteins, peptides, nucleic acids, and even vaccines. This makes them a flexible option for many different drug treatments. [8,17,13]

A key benefit of using nanoparticles for drug delivery is that they can make treatments work better while causing fewer side effects throughout the body. They do this by shielding drugs from breaking down too early and by helping more of the drug gather where it's needed. This advances how well the treatment works and reduces harm to healthy parts of the body. [9,24]

Researchers have developed various types of nanoparticles for drug delivery, like those made from lipids, polymers, metals, and mesoporous silica. These are used mostly to treat conditions like cancer, infections, brain disorders, and heart disease. They are also being explored for newer uses like vaccine delivery and gene therapy. [10,17,26]

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Even with the good points, it's still tough to use nanoparticle drug delivery in real medical situations. This is because people worry about side effects, long-term health risks, making them in big batches, keeping them stable, and whether they can actually be used everywhere. [15,27,29] So, we need to keep researching to make these systems safer, work better, and be practical to sell.

This article looks at nanoparticle drug delivery in detail. We'll cover the main kinds of nanoparticles, how they deliver drugs, how they're used in medicine now, the problems we face, and what might happen in the future. We want to give a summary of the latest progress in this area and show how nanoparticles could really help improve medical treatments.

2. Types of Nanoparticles used in drug delivery

2.1 Lipid-Based Nanoparticles

Lipid-based nanoparticles, or LNPs, are a common choice for delivering drugs today. They work well because they're safe for the body, break down naturally, and can carry both water-loving and oil-loving drugs. [4,11,26] These tiny particles are mostly made of natural fats, which makes them less harmful and better for medicine than other types of nanocarriers. Depending on what they're made up of and how they're shaped, LNPs can be liposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), or lipid nanoemulsions. [11,26,35]

2.2 Polymeric Nanoparticles

Polymeric nanoparticles are small carriers made up from natural or man-made plastics. These are popular because they're strong, adaptable, and can release medication slowly over time. [6,12,33] Common plastics used include PLGA, PLA, and chitosan, among others. Based on their form, they are either nanospheres, where the drug is mixed throughout the plastic, or nanocapsules, where the drug is held inside a plastic shell.

A big benefit of polymeric nanoparticles is that they defend drugs from breaking down. [12,17] Their surface can also be changed with the help of special molecules to deliver drugs to specific areas and help the cells to absorb better. This can lead to more of the

drug getting into the body, less frequent dosing, and fewer side effects. [6,17,24]

Polymeric nanoparticles have been greatly researched for delivering cancer drugs, antibiotics, proteins, peptides, and genes. They are also useful in tissue repairing and regenerative medicine because they are greatly tolerated by the body and can be broken down. [17,33]

2.3 Metallic Nanoparticles

Metallic nanoparticles are very small (tiny) inorganic carriers made from metals or metal oxides like gold, silver, iron oxide, and zinc oxide. [14,27,32] They have a special optical, magnetic, electrical, and chemical qualities that make them useful for delivering drugs and in biomedical research.

Gold nanoparticles are the favourite because they are safe for our body, easy to change on the surface, and can hold different therapeutic agents perfectly. [14,27] Magnetic iron oxide nanoparticles are also important because they can deliver drugs accurately using outside magnetic fields.

Because metallic nanoparticles have a large surface area relative to their volume, they can load drugs efficiently and be coated with antibodies, peptides, or targeting molecules. [14,23,32] Their surface modifications help improve drug delivery and reduce other harmful side effects. Nanoparticles are also used in photothermal therapy, diagnostic imaging, and combination therapies, making them versatile tools in nanomedicine.

2.4 Mesoporous Silica Nanoparticles

Mesoporous Silica Nanoparticles (MSNs) are porous carriers with a very organized pore structure, a large surface area, and adjustable pore sizes. [16,29] These features allow them to hold many different therapeutic agents, like small-molecule drugs, proteins, and nucleic acids. Their porous structure can hold a lot of drugs and keeps them from breaking down too early.

A major advantage of the MSNs is their ability to release drugs in a controlled way that reacts to different targets. Drug release can be caused by changes in pH, temperature, enzymes, or other biological factors. This helps the therapeutic agents

get delivered precisely to the target location. [16,24,29]

Mesoporous Silica Nanoparticles have shown a great potential in treating cancer, delivering genes, antimicrobial therapy, and diagnostic imaging. Their strong and adaptable structure makes them an attractive choice for drug delivery.

2.5 Dendrimers

Dendrimers are highly branched, tree-like macromolecules with a distinct 3D structural architecture. [17,30] They contain a core, repeating branch units, and various functional groups on the surface, which are chemically modifiable. Such specific structure is responsible for a precise control over the size, shape, and the surface properties of the molecules, making dendrimers good nanocarriers for drug delivery.

The major benefit of dendrimers is associated with their capability to incorporate drugs either in their cavities or through chemical bonding with their surface. Such a two-level drug loading property increases the solubility and stability of drugs and provides a controlled drug release mechanism. Additionally, chemical modification of the surface with targeting agents, antibodies, and polyethylene glycol increases the ability of dendrimers to target the disease site and reduces the systemic toxicity. [5,17,30]

Dendrimers have found application as a carrier of anticancer drugs, antimicrobials, genes, and contrast agents. [17,22,30] Besides, such multi-functional particles are useful for the development of combination therapies and diagnostic techniques. However, the limited clinical applications of dendrimers are due to the issues related to their cytotoxicity, synthesis complexity, and high cost.

3. Mechanism of Drug Delivery

3.1 Passive Targeting

The first drug delivery mechanism that is extensively used in nanotechnology is passive targeting. [3,12,20] This technology depends on the intrinsic properties of diseased tissue, primarily tumour tissue. Tumour tissue tends to have an abnormally developed vascular network, featuring gaps between endothelial cells. As

a result, increased accumulation of the nanoparticles can occur. Moreover, nanoparticles have a prolonged stay at the site due to the enhanced permeability and retention (EPR) effect, which leads to increased concentrations of the drug. Hence, passive targeting increases efficiency of the therapy and decreases the amount of the drug that affects healthy tissue. [3,14,18,24]

3.2 Active Targeting

As opposed to passive targeting, the surface of nanoparticles can be coated with functional groups (ligands) like antibodies, peptides, aptamers and others. [5,7,13] These ligands bind to the specific receptors of the target cells that are overexpressed on their surface. [5,20,24] Further, the nanoparticles are taken up inside the cells via receptor-mediated endocytosis and release the drug in the intracellular environment. As a result, drug specificity increases, making the therapy more effective and preventing the side effects. The active targeting holds great potential in oncology and other conditions, which require targeted delivery of the drug.

3.3 Controlled and Sustained Release of the Drug

One of the key properties of the nanoparticle-based drug delivery system is controlled and sustained release. Instead of delivering the whole dosage, the nanoparticles are designed to deliver the drug gradually during a specified period. [19,24,29] It ensures stable concentrations of the drug, reduces the number of doses and may improve the compliance of the patients. In more advanced designs, the drug release could be controlled by some external stimuli like pH, temperature, enzymes, light and so forth. [19,29,37]

3.4 Internalization of Nanoparticles and Intracellular Drug Release

For the drug delivery to be efficient, the drug-carrying nanoparticles should be taken up by the target cells and then release their cargo. Endocytosis is the most common way of taking up the nanoparticles. [22,24,28] After entering into the intracellular compartment of the cell, the changes in pH or activation of enzymes might cause the release of the encapsulated drug. Optimization of these processes

remains the focus of the research in this area. [9,24,38]

4. Present Applications in Pharmaceuticals

4.1 Cancer Treatment

Cancer continues to be among the major causes of deaths worldwide and is characterized by low drug selectivity, toxicity to other tissues apart from the target sites, and resistance. [2,3,11,40] In this regard, the drug delivery using nanoparticles stands out as an innovative means of addressing these shortcomings by ensuring effective and selective targeting of the disease-causing cells in the body. [3,20,23]

Due to their small sizes and modifiable surfaces, nanoparticles have the ability to selectively concentrate in tumours and cancerous cells as either a result of passive targeting or active targeting that makes use of specific ligands. [12,20,24]

Several nanoparticles including the lipid-based nanoparticles, polymer-based nanoparticles, metal-based nanoparticles, and dendrimers have been considered for delivery of drugs used in the treatment of cancer. [1,21,24,37] Apart from protection against degradation, nanoparticles provide stability in blood, ensuring enhanced concentration of the drugs within the tumour. Combination of nanoparticles with drugs leads to increased efficiency and minimal side effects on normal tissues.

Apart from being used in cancer chemotherapy, nanoparticles have also shown promise in photothermal therapy, photodynamic therapy, and immunotherapy. Nanoparticles have also been considered in the delivery of gene silencing agents including the siRNA. [14,22,25,31]

4.2 Infectious Diseases

The risk possessed by infectious diseases, which are caused by bacteria, viruses, fungi, and parasites, remains significant for public health. Despite the availability of many antimicrobial drugs, there have been various factors affecting the efficiency of their work, including poor bioavailability, fast degradation of the drugs, the low concentration of antimicrobials in the area of infection and the increasing problem of antimicrobial resistance. [1,27,37] Nanotechnology-based drug delivery is one possible way to tackle the

abovementioned problems through the increase of drug stability, targeted delivery, and controlled release. [1,24,37]

There are several types of nanoparticles that could be used for delivery of antimicrobial agents, which include antibiotics, antivirals, and antifungals. Encapsulation in nanoparticles prevents premature breakdown of these agents and helps keep the required level of the drug. Moreover, surface modification of nanoparticles allows enhancing the interaction between infected tissue and nanoparticles and improves treatment efficiency with minimal effect on healthy cells. [17,27,32]

Studies have shown that nanoparticle-based therapy is effective in treating tuberculosis, HIV infection, hepatitis and fungal infections. [17,27,37] Also, there are metallic nanoparticles with antimicrobial characteristics (silver nanoparticles), which can enhance antimicrobial effects of conventional methods of treatment. Currently, the focus of research in this field lies in developing nanoparticles that could overcome the problem of antimicrobial resistance. [26,31,27]

4.3 Neurological Diseases

The treatment of neurological diseases continues to be challenging because many therapeutic agents do not possess the ability to enter into the blood-brain barrier (BBB). [18,28,29] As a result, many drugs are not able to reach an effective concentration level in the brain, which limits the efficiency of these drugs. Thus, nanoparticle drug delivery has been proposed as a novel way to overcome this challenge, because it allows for delivery of drugs through the BBB and increasing the levels of these drugs in the target area. [18,24,28]

There are a number of different nanoparticle systems, which can be used to deliver drugs to the central nervous system, including lipid nanoparticles, polymer nanoparticles, and dendrimers. Such nanoparticles increase stability of drugs, their circulation period, and provide additional drug uptake by brain tissues. Surface modification of nanoparticles increases their ability to pass the BBB and delivers drugs selectively to diseased nerve cells. [17,18,30]

Nanoparticle drug delivery demonstrates considerable efficiency in the treatment of neurological diseases, such as Alzheimer's disease, Parkinson's disease, brain tumours, epilepsy, and multiple sclerosis. [18,28,29] At the same time, nanoparticles are actively researched as gene or neuroprotectant delivery agents for the purpose of slowing down disease progression. Though these approaches are mostly studied in clinical trials, they represent an important step in developing new methods for the treatment of neurological diseases. [22,29,31]

4.4 Cardiovascular Diseases

There are several cardiovascular diseases including coronary artery disease, hypertension, heart failure, and stroke among others which continue to pose serious challenges concerning health morbidity and mortality across the world. [16,27,30] Common treatments for CVDs are faced with such difficulties like poor drug distribution, short circulation time, and undesired side effects. The application of drug-loaded nanoparticles for enhanced CVDs treatment is based on the ability to provide drug stabilization, increased bioavailability, and specific targeting to affected tissue sites. [16,24,30]

Among the existing types of nanoparticles, lipid-based, polymeric, and magnetic nanoparticles can be applied in delivery of different cardiovascular drugs and thrombolytics. Such nano-carriers can increase drug targeting efficiency, decrease side effects and improve controlled release of drugs. Apart from delivering the therapeutic payload, nanoparticles can be used for diagnostic imaging and the early detection of CVDs. [14,30,32] Although further clinical studies are required, it should be noted that nanoparticle technology opens new perspectives for the prevention, diagnostics and treatment of cardiovascular diseases. [16,27,30]

4.5 Vaccine and Gene Delivery

Nanoparticles have opened up novel ways for vaccine and gene delivery due to the ability to serve as carriers of biological material and protection of such therapeutics from degradation and instability. [8,22,26] In addition, nanoparticles provide effective intracellular transport of such labile molecules. Modification of nanoparticles can increase their

cellular uptake and gene transfection efficiency. [8,17,22]

Lipid nanoparticles have gained international recognition due to their contribution to mRNA vaccine development. In case of gene therapy, nanoparticles can be used for delivery of DNA, mRNA, and siRNA in order to treat various genetic disorders, infectious diseases and cancer. [22,25,31] Compared to viral vectors, nanoparticle systems possess such benefits as reduced immunogenicity, increased safety, and enhanced formulation flexibility. Current research efforts are focused on developing more efficient delivery systems. [8,22,38]

5. Challenges and Limitations

5.1 Toxicity and Biocompatibility

While there have been some considerable breakthroughs in drug delivery using nanoparticles, the problem of toxicity and biocompatibility still remains the main limitation on the widespread clinical use of such formulations. [15,25,36] The interaction of nanoparticles with the organism depends on the nanoparticle size, morphology, surface charge, composition, dose, etc. Sometimes nanoparticles provoke an immune response, oxidative stress, inflammation or unwanted accumulation of nanoparticles in vital organs such as liver, spleen and kidneys. [15,25,36]

Therefore, it is important to assess the safety of this technology both in the short term and in the long run. [9,27,36] The development of biodegradable and biocompatible nanocarriers can be considered a fruitful direction of research aimed at reduction of the negative effects of nanoparticles and preservation of their effectiveness. [6,17,36]

5.2 Stability and Storage

Another important issue is maintaining the stability of nanoparticle formulations throughout the process of manufacturing, storing and transporting. Changes in temperature, pH, humidity and light can change the properties of nanoparticles such as size, drug-loading and drug-release. [24,27,39] Besides, aggregation may reduce the effectiveness and shelf-life of nanoparticles. Thus, the research in developing new approaches to formulation and protecting of

nanoparticles, and finding optimal conditions for storing nanoparticle formulations, is an urgent problem. [19,24,34]

5.3 Large-Scale Manufacturing

Though there are numerous examples of nanoparticle formulations with good laboratory results, it is quite difficult to translate these results into commercial drugs. Large-scale production requires processes which are reliable, economically efficient and allow maintenance of consistency in the quality of the product. [9,27,39] Variability in size, encapsulation efficiency and formulation stability can affect the therapeutic effectiveness and ability to get approval. Moreover, large-scale manufacturing requires expensive equipment and strict quality control, thus increasing costs. Therefore, the development of manufacturing technology suitable for large-scale production is very important for commercialization of nanoparticle-based drugs. [15,35,39]

5.4 Regulatory and Clinical Challenges

Nanoparticle-based drug delivery systems require more thorough evaluation than conventional pharmaceutical products because of their unique physicochemical characteristics. It is necessary to provide extensive data on safety, efficacy, pharmacokinetics and long-term toxicity to get the approval. Besides, in many countries the development of guidelines for evaluation of nanomedicines continues. The clinical translation of nanoparticle-based drug delivery systems is hindered by high costs of clinical trials, long approval times and necessity of long-term safety monitoring. The close cooperation of researchers, pharmaceutical industry and regulatory agencies is crucial in overcoming these difficulties.

6. Future Perspectives

6.1 Smart and Stimuli-Responsive Nanoparticles

The future of research is about creating smart nanoparticles that can react to things like changes in pH, temperature, enzymes, light or magnetic fields. [19,24,37] These nanoparticles are designed to release drugs where they are needed, which means fewer side effects and better results. As research continues, nanoparticles can be engineered to deliver drugs more precisely and efficiently. [9,24,39]

6.2 Artificial Intelligence in Nanomedicine

Artificial intelligence is becoming a useful tool in making nanoparticles that can deliver drugs. It can analyse large amounts of data and predict how nanoparticles will behave, which makes research and development faster and cheaper. [9,38,39] We are also using machine learning to figure out which drugs work well with nanoparticles and how to make them work better. As computers get better, artificial intelligence will help us make more effective nanomedicines. [9,38]

6.3 Personalized Medicine

Personalized medicine is about giving people treatments that're just right for them based on their genes, molecules and medical history. [7,22,38] Nanoparticles can help with this by delivering drugs to the cells or tissues that need them without hurting healthy parts of the body. By combining nanotechnology with genetics, molecular diagnostics, and precision medicine, we can make treatments better for diseases like cancer, genetic disorders and brain conditions. We still need to do research and testing but personalized nanomedicine is a promising idea for the future of medicine. [17,38,39]

CONCLUSION

Nanoparticle drug delivery has significantly transformed pharmaceutical research. Instead of relying on outdated methods, scientists now use these tiny carriers to improve how drugs work in the body. [1,3,9] They help medicines dissolve better, stay stable longer, reach the right spots, and even control how fast the active ingredient gets released. It doesn't matter if they're made from lipids, polymers, metals, mesoporous silica, or even dendrimers—these systems are getting a lot of attention. Researchers are exploring them for everything from cancer and infections to brain and heart diseases, not to mention vaccines and gene therapy. [8,17,26]

However, several challenges remain. Some nanoparticles can be toxic, and the truth is, we still don't know enough about their long-term safety. Scaling up production isn't straightforward, either. [15,25,36] Getting regulatory approval and making sure these new drugs stay stable outside the lab just adds more to the to-do list. The finish line isn't in sight

yet. Scientists and engineers still have tough problems to solve before these treatments show up in every doctor's office. [9,15,39]

Still, even with all these bumps in the road, nanoparticle drug delivery continues to advance rapidly. Smarter nanocarriers, artificial intelligence, and personalized approaches are making these systems more accurate and effective than ever. In the end, all this work means better care for patients and a stronger outlook for healthcare. [22,38,39]

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