Nanotechnology in Drug Delivery: Revolutionizing Medicine

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Abstract

Nanotechnology is changing modern medicine by making it possible for drugs to be safer, more effective and delivered more specifically. Using this strategy, many problems faced by traditional drug delivery systems, including low absorption rate, side effects and little targeting, can be minimized. Delivering drugs like nanocarriers, including liposomes, dendrimers, polymeric nanoparticles and metallic nanostructures, makes it possible to enhance their solubility, control their release and target the drug precisely to a chosen area. Crossing over into cells and shielding cargoes from breakup have allowed these carriers to improve how diseases like cancer, neurological diseases and infections are treated. A focus on multitasking nanocarriers is now helping the theranostics field advance. Moreover, when bioinspired materials and biodegradables are used, the implant becomes safer and less likely to cause lasting toxicity. Invention of cost-effective manufacturing and the use of innovative ingredients are expanding healthcare services around the world. Even if there are difficulties related to scale, approval and safety, it is obvious that nanotechnology can greatly change how drugs are delivered. Because nanomedicine is always improving to meet doctors' demands, it is ready to revolutionize drug treatments and begin a new chapter in personalized and precision medicine.

Keywords: Nano-drug Delivery, Multifunctional Nanocarriers, Biodegradable Materials, Global Healthcare Accessibility

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Introduction

Nanotechnology has brought new ways to deliver drugs, solving the issues faced with old systems. Precise, efficient and targeted drug delivery is possible in modern medicine because of the way nanotechnology makes use of the special properties of small materials (Hsu et al., 2023). Typical drug delivery methods, including oral and intravenous administration, often have issues with poor solubility, low bioavailability, quick degradation and general distribution, causing treatment results that are not ideal and a rise in unwanted effects. Nanotechnology has tackled these problems by introducing nanocarriers that boost drug performance and at the same time reduce negative side effects (Ganta et al., 2014).

Nanotechnology deals with working with materials at a nanoscale—this means between 1 and 100 nanometers. When the materials are at this scale, they display different physical, chemical and biological aspects than they do in bulk forms. Because nanomaterials have all of these properties—high surface area to volume, responsive chemical properties and adjustable ways to function—they form excellent candidates for delivering medicine to patients (Khan et al., 2022). There are several nanocarriers such as liposomes, polymeric nanoparticles, dendrimers and inorganic nanoparticles, created to keep drugs secured and safe from enzymes as they reach their target tissues (Chamundeeswari et al., 2019). Nanotechnology is mostly used in drug delivery to improve how easily and how long drugs remain stable in the body (Liu et al., 2024). Since hydrophobic substances are not easily combined with water, a lot of drugs are not well absorbed in the body. The addition of nanoparticles to drugs helps them dissolve better and transport through biological liquids. Lipid nanoparticles can deliver poorly soluble anticancer drugs and increase their effectiveness at lower doses. The use of polymeric nanoparticles is also effective at maintaining proteins in their natural form and extending drug treatment (Waheed et al., 2024). It represents a complete change in the way drugs are given and how treatment is carried out. These systems commonly use passive or systemic ways which results in both broad coverage and impact on healthy tissues. On the other hand, with nanotechnology, it is possible to use both active and passive targeting which enhances drug precision delivery (Egwu et al., 2024).

Nanotechnology is important for therapeutic delivery, but also for imaging and diagnosis. Such nanocarriers are called theranostics because they bring together therapy and testing in just one system. By combining drug delivery and continuous real-time monitoring, these methods reveal useful information on how well a treatment is working (Hosseini et al., 2023). Gold nanoparticles tagged together with imaging dyes and cancer drugs have been employed to view how tumors respond to treatment and to deliver chemotherapy more precisely (Ghazal et al., 2024). Yet, there are many obstacles to moving from traditional to nanotechnology-based delivery methods for drugs. The fact that nanotechnology can't be scaled easily and is expensive is hindering its widespread use in healthcare. The specialized steps required for making and customizing nanoparticles typically make them too expensive for most to purchase (Malik et al., 2023). Acceptance of nanotechnology by the public is very important for its use. Small-molecule drug delivery is promising, so making sure safety, ethical points and distribution are fair is key to earn users and doctors' trust (Đorđević et al., 2022).

2. Nanocarriers

Nanocarriers bring an important upgrade to nanotechnology by fixing limitations in traditional drug delivery methods. The flexibility, security and efficiency of nanoparticles make them essential for moving therapeutic drugs to their needed locations. Among the best-known nanocarriers are lipid-based systems, polymeric nanoparticles and dendrimers, as well as inorganic nanocarriers. Each type has its own benefits which support unique medical uses and help create strong and modern treatment plans (Din et al., 2017). Nanocarriers formed using lipids are old subjects of research, as they work safely in living tissue, resemble fluid membranes and can contain drugs that are either polar or nonpolar. Liposomes and solid lipid nanoparticles (SLNs) are the primary types among lipid-based nanoparticles. Liposomes are tiny spheres made when one or several lipid layers encircle a water core. As they are modeled on biological membranes such liposomes can store water-soluble drugs inside their core and water-insoluble drugs in their outer layers (Smith et al., 2020). Liposomes are used by oncology because they help cancer drugs attack cancer cells quickly and with less risk of harming other cells. Stimulation nanotechnology has led to both better results and less harmful reactions in patients treated for breast or ovarian cancer (Zhang et al., 2023). Giving liposomes ligands, antibodies or peptides allows you to deliver cargo specifically to certain body tissues. Because of PEGylation, nanoparticles stay in the body longer, as the immune system does not spot them and they accumulate in tumors via the EPR effect (Brown et al., 2021). Tumors are naturally quite acidic, so nano-medicines have been made to focus on them by reacting to both pH and temperature changes (Suk et al., 2016). Table 1 elaborates applications of nanotechnology in drug delivery.

Table 1: Applications of Nanotechnology in Drug Delivery

Nanotechnology System	Key Features	Applications	Advantages	Challenges
Liposomes	Phospholipid bilayer, biocompatible	Cancer therapy, antifungal drugs, vaccine delivery	Reduced toxicity, enhanced drug solubility	Stability issues, high production costs
Dendrimers	Branched polymer structure	Gene delivery, anticancer therapy	Precise drug loading, multivalency	Toxicity at high generations, complex synthesis
Polymeric Nanoparticles	Biodegradable and tunable polymers	Sustained drug release, vaccine adjuvants	Controlled drug release, biodegradability	Scalability, potential immune response
Gold Nanoparticles	Unique optical properties	Imaging, photothermal therapy, targeted drug delivery	High stability, multifunctional capabilities	Cost of synthesis, potential toxicity
Carbon Nanotubes	Hollow cylindrical carbon structures	Delivery of small molecules, siRNA, and proteins	High surface area, ease of functionalization	Cytotoxicity, poor biodegradability
Silica Nanoparticles	Mesoporous structures	Delivery of anticancer drugs, imaging agents	High loading capacity, biocompatibility	Long-term safety concerns
Quantum Dots	Semiconductor nanocrystals	Imaging and diagnostics, drug tracking	Bright fluorescence, stability	Potential toxicity, environmental impact
Nanogels	Hydrophilic polymer networks	Delivery of hydrophilic drugs, protein therapeutics	High water content, responsive behavior	Limited stability, complex manufacturing
Micelles	Amphiphilic block copolymers	Delivery of poorly soluble drugs	Enhanced solubility, selective drug delivery	Limited stability in vivo
Exosomes	Natural extracellular vesicles	Gene therapy, drug delivery for cancer, neurodegenerative diseases	Natural origin, immune evasion	Scalability, variability in isolation

SLNs are next-generation lipid-based nanocarriers that adopt features of liposomes and make them stronger for use. An SLN consists of a combination of solid lipids surrounded by surfactants as its solid form for drugs. Although liposomes take time to release their drug, SLNs provide better safety by safeguarding them against fast degradation (Mitchell et al., 2020). They find use in helping poorly-water soluble drugs and in shielding sensitive substances such as proteins and nucleic acids from harm (Viegas et al., 2023). One important example of SLN use is found in developing vaccines for cancer as well as vaccines against COVID-19 infection. Polymeric nanocarriers are made from biocompatible and biodegradable polymers and include poly (lactic-co-glycolic acid) (PLGA), chitosan and polyethyleneimine (PEI) as examples. There are numerous ways these carriers can be used, allowing release to be controlled, high loads of drugs placed and targeting to specific areas (Wu et al., 2024).

Hydrophilic, hydrophobic and biological medications are easily contained in Polymeric Nanoparticles. Clinical use of PLGA-based nanoparticles is allowed because they are safe, biocompatible and break apart into non-harmful materials. This controlled and steady release means patients don't have to take as many doses which improve both compliance and their health. PLGA nanoparticles have been used in this way to deliver medicines that help people with inflammatory illnesses such as rheumatoid arthritis (Danhier et al., 2012).

Polymeric nanoparticles are valuable for use in genetic medicine. Gene modification was enabled in target cells by transporting both siRNA and plasmid DNA using PEI nanoparticles (Piotrowski-Daspit et al., 2020). Surface coating with PEG makes them more stable and safer since the body will not react to them (Padín-González et al., 2022).

Dendrimers are special nanocarriers since they are built with branches and end in a central core. Such an architecture offers maximum options for controlling size, shape and structure on their surfaces (Soliman et al., 2024). Chemists usually favor dendrimers because they can be filled with drugs in their center or can have drugs attached to their outside. Nanoparticles give the chance to introduce different drugs, genetic material and imaging compounds at the same time (Abbasi et al., 2014). Dendrimers can deliver drugs through the blood-brain barrier and reach the central nervous system, as shown by Zhu et al. (2019). People are developing this technique to treat Alzheimer's and Parkinson's disease. Designed dendrimers are able to deliver their cargo to particular cells, making it easier to target cells precisely and lowering the risk of problems. Because of these features, inorganic nanocarriers can support imaging, diagnostics and theranostic applications. Among all these materials, the most studies have been conducted on gold nanoparticles (AuNPs) and quantum dots (QDs) (Ashique et al., 2023).

Gold Nanoparticles (AuNPs) are valuable nanocarriers appreciated for being friendly to living organisms, simple to make and having tunable surfaces. Adding therapeutic compounds, targeting substances and imaging materials to AuNPs creates possibilities for their drug delivery and diagnostic use. Their ability to penetrate small areas makes these particles good for carrying drugs and CRISPR-Cas9-based gene-editing tools (Jadhav & Mandlik, 2024). Using photothermal therapy, AuNPs in cancer treatment absorb light and change it into heat that destroys cancer cells in the tumor area. Being both a delivery system and a therapeutic agent is evidence of their place in theranostics (Jadhav & Mandlik, 2024). AuNPs are being investigated as vaccine ingredients, as their immunosupportive properties advance antigen uptake and boost the immune system (Ferrando et al., 2020).

QDs are tiny semiconductors with optical properties that allow them to give off high light, not fade quickly and their brightness can be adjusted by their size. The first use for QDs is usually imaging and diagnostics, yet they are growing in use for drug delivery by nanocarriers (Mitchell et al., 2020). Through their fluorescence, experts can see how the drug moves and where it has an effect, helping to measure treatment success (Hamidu et al., 2023). Still, people are concerned about QDs that have toxic metals which has caused scientists to research biodegradable and safer types of fluorescent materials. Carbon quantum dots have recently been made in a way that provides biocompatibility and light emission that matches their optical equivalents. Such improvements broaden the range of QDs used in drug delivery and various biomedical tasks (Sahu & Sahoo, 2024).

3. Comparative Advantages and Challenges

The different kinds of nanocarriers have advantages of their own and also face particular challenges. Lipid-based systems are very safe for use in the body, but their poor stability and lack of drug-loading space limit their use. The use of polymeric nanoparticles and dendrimers is useful because they provide precise release and many properties, yet they are usually difficult to make (Alshawwa et al., 2022). Even though nanocarriers such as AuNPs and QDs have outstanding optical and therapy-related properties, they still raise some doubts about safety and environmental impact (Prasad and Selvaraj, 2024). Meeting these obstacles involves exploring various areas of science to prototype better nanocarriers, produce them in large amounts and obey rules. Improvements in how materials are coated, responsiveness to stimuli and biodegradable products are likely to help nanocarriers achieve even more in modern medicine (Aswini et al., 2024). Nanotechnology has helped improve drug delivery by getting around the challenges of previous methods and making therapies easier for people. Compared to other delivery methods, nano-based approaches give the best results in making drugs more soluble, giving more control and helping to deliver drugs to their targets. This allows them to support the success of treatments while reducing the risks of side effects which is why nano-based systems play a key role in current medical research (Sim & Wong, 2021).

4. Enhanced Drug Solubility and Bioavailability

Drug delivery is a major challenge since a lot of therapeutic agents do not dissolve easily or cannot be absorbed properly into the blood. Such drugs are less effective because water does not dissolve them well enough for our bodies to make use of them. These systems solve the problem by placing hydrophobic drugs in carriers that improve their solution and their stability (Xie et al., 2024). These nanoparticles are designed to solve the issue of water insoluble medicines by turning them into soluble forms. Their structure traps water-fearing molecules within, helping the drugs to be mixed with water. Packaging paclitaxel which breaks down in lipids, within liposomes vastly enhances its solubility and provides better outcomes for certain patients (Mehta et al., 2023).

When used, polymeric nanoparticles boost how well drugs are soluble and can be used by the body. PLGA and similar biodegradable polymers shield the drug, avoiding its breakdown in the gut or in the blood while it is in the body. The drug level in the body remains even which improves how well it is absorbed. Nanocrystals are an example of nano-nanotechnology because they shrink drugs to the nanoscale which boosts surface area and allows faster drug dissolution (Herdiana et al., 2022). A better solubility level in the body provides better chances for drugs to achieve desired effects at the target tissues. Due to this advantage, people can take smaller amounts of myelinated oral and intravenous drugs which cuts the danger of possible toxicity and side effects. With nano-based systems, optimal drug action is obtained while also reducing the chance of side effects (Bhalani et al., 2022).

5. Controlled and Sustained Release Profiles

One more advantage of using nano-based drug delivery methods is that they allow controlled and regular drug release. Adhering to older dosing schedules can result in you having both low and high levels of medication which may make patients less willing to take the drugs as required. Because of nano-based systems, medications are slowly released, so patients always get the therapeutic effects they need (Cheng et al., 2023). Polymeric nanoparticles make it highly possible to control drug release. Because these carriers break down inside the body slowly, they can release their substances at the right time. Using PLGA nanoparticles, a single dose of anti-inflammatory medicine for arthritis can work for up to several weeks which helps patients take medication regularly and live better (Begines et al., 2020).

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) are highly effective for controlled release applications. Using SLNs to give antiviral drugs for chronic infection treatment helps keep a regular amount of medicine in the body and diminishes the chance of resistance (Ghasemiyeh & Mohammadi-Samani, 2018). A different path to controlled release involves using nanoparticles made from hydrogels. Because these systems respond to changes in pH, temperature and enzymes, drugs can be released only at the desired location in the body. For example, pH-sensitive nanoparticles are designed to release their lethal anticancer cargo only when the microenvironment in the tumor becomes acidic. This minimizes the drug's effect on other parts of the body and guarantees enough drug is present for the therapy to work. These types of medicines make dosing less regular, lower the threat of loss of balance and result in better care outcomes (Adepu & Ramakrishna, 2021).

6. Improved Targeting and Reduced Side Effects

Nano-based systems focus on targeted drug delivery which is an important advantage over older systems. Most of the time, transporting medicine this way means the drugs reach all over the body, impacting both sick and healthy cells. Because drugs are not precise enough, they are less effective and can cause major side effects. Nano-based systems achieve this by offering both passive and active targeting, so drugs are delivered to the right places with little disturbance to other tissues (Li et al., 2023).

Turbulent vasculature and an insufficient draining system in tumor tissue cause passive targeting using the enhanced permeability and retention (EPR) effect, where nanoparticles congregate. In oncology, this feature has made it possible for nanoparticles to treat cancer by bringing chemotherapeutics only to the tumor, not to nearby healthy tissues. A liposomal formulation of doxorubicin was found to improve results in treatment and decrease the risk of heart side effects, compared to traditional doxorubicin (Bazak et al., 2014).

Active targeting counts on adding ligands, antibodies or peptides that bind to receptors found on the wanted cells to the nanoparticles. Using such a method improves how medicines are sent which ensures the drugs are only sent to the site where they work. Nanoparticles that bind to folate are drawn to cancer cells with lots of folate receptors which helps deliver drugs directly to the cancer, improving their capability (Davis et al., 2020). Inflamed parts of autoimmune diseases are also being treated by using antibody-covered nanoparticles, avoiding many adverse effects according to (Al-Thani et al. 2024).

Targeted delivery helps personalized medicine by making treatments specific to each patient's gene and body composition. Designing systems at the nano level means they can interact with particular biomarkers, leading to safer and more specific therapies for cancer, genetic disorders and infections. With such specific doses, the risk of harmful reactions is decreased and treatment works better. Besides making drugs more suitable for a target, nano-systems cut down on systemic exposure and the resulting side effects. By confining drug activity to specific sites, these systems protect healthy tissues from off-target effects, lowering the risk of toxicity and complications. For example, nanoparticle-mediated delivery of chemotherapy drugs has significantly reduced common side effects such as nausea, hair loss, and immune suppression, improving the quality of life for cancer patients (Dash et al., 2024).

7. Targeted Drug Delivery with Nanotechnology

Targeted drug delivery represents one of the main effects nanotechnology provides in medicine. It makes it possible to send medicines accurately, efficiently and securely to chosen body parts or cells. Authentication of standard drug delivery often results in the medication affecting healthy as well as diseased tissues. Not being specific in doses means drugs don't work as well and can cause more side effects. Through its use of active and passive methods, nanotechnology aims the delivery of drugs precisely at the intended location. Using the special biological and physical traits of nanomaterials, scientists can make medicines more effective with less risk of side effects (Ma et al., 2024).

8. Active Targeting Using Ligands and Antibodies

Active targeting means adding molecules to nanoparticles that bind selectively to receptors displayed by specific cells. When medicines are delivered with this approach, they precisely reach the treatment site, avoiding problems with other parts and making drugs, work more efficiently (Elumalai et al., 2024).

9. Ligand-Functionalized Nanoparticles

Many treatments for diseases use small molecules, peptides or vitamins to bind to a specific receptor found in distressed cells. In one example, using nanoparticles that bind to folate has allowed targeting of many cancers that commonly overproduce these receptors. Chemotherapeutics delivered through these nanoparticles are directed to cancer cells and enter these cells without harming normal healthy tissue. It helps the treatment become safer in many respects because it reaches the target location more precisely (Ebrahimnejad et al., 2022). An additional class of ligands that plays a role in active targeting are peptides. Using RGD peptides that connect to extra integrins in tumor blood vessels, nanoparticles are now being used to bring the drugs directly to the cancer. These functional nanoparticles have superior tumor accumulation and greater effectiveness for treating tumors than non-targeted systems (Hosseinikhah et al., 2024).

10. Antibody-Functionalized Nanoparticles

Antibodies have a much greater ability to bind to precise parts of the cell because they can tell antigens apart. The monoclonal antibody trastuzumab (Herceptin) has been attached to nanoparticles for use in targeting HER2-positive breast cancer cells. Together, this method provides higher sensitivity, better delivery and superior results for therapy When antibodies recognizing CD44, common in tumor cells, are joined with nanoparticles, chemotherapy can be delivered, increasing tumor-selectivity and decreasing damage to healthy tissues (Montaseri et al., 2020; Sitia et al., 2022).

11. Dual-Functionalized Nanoparticles

Nanotechnology advances now allow for designing dual-functionalized nanoparticles packed with several types of ligands or antibodies to help them target the right cells. They simultaneously interact with several targets, helping to address the differences between cells in the tumor and improve treatment results. In particular, combing folate and transferrin ligands on nanoparticles can improve the delivery of drugs to cancer cells that express these receptors (Fan et al., 2023).

Helping personalized medicine, active targeting aims treatments for diseases based on a patient's own unique biomarkers. Choosing ligands or antibodies that match the biomarkers seen in a patient's disease makes the therapy both tailored and accurate (Al-Thani et al., 2024).

12. Passive Targeting Through Enhanced Permeability and Retention (EPR) Effect

Passive targeting exploits the distinct traits of tumors so that more nanoparticles are found nearby. Passive targeting relies mainly on the enhanced permeability and retention (EPR) effect. The large holes in tumor blood vessels and few lymphatic channels cause nanoparticles to be attracted into the tumor (Bazak et al., 2014).

13. Advantages of Passive Targeting

Cancer therapy which relies on the EPR effect, means that nanoparticles will move to the tumor on their own, without requiring a device to guide them. For these reasons, creating nanoparticles is simpler, so medication delivery becomes much more affordable and convenient. Furthermore, integrating passive targeting with active targeting gives many advanced systems stronger and more accurate results (Rosenblum et al., 2018).

Conclusion

In short, nanotechnology has transformed the field of drug delivery by giving us thorough, precise and focused drug treatments that handle the challenges inherent in traditional methods. A variety of nanocarriers, including liposomes, dendrimers, polymeric nanoparticles and inorganic systems, have made drug solubility, bioavailability, controlled release and targeted delivery possible through nanotechnology. As a result, therapy is more effective and patients suffer fewer systemic side effects which is a big step forward for custom and safe treatments. By blending diagnostic and treatment features into multifunctional nanocarriers, it is now possible to see the progress of treatments in real time. Although these new findings show great promise, difficult challenges in scaling, high costs of production, strict regulations and possible long-term side effects must be managed so that clinical translation is safe. The rise of biodegradables, the use of AI in drug design and new methods in green synthesis are opening doors to improved nano-drug systems. The growth of interdisciplinary work is helping nanotechnology become the backbone of future medicine, providing the world with more secure, better performing and accessible healthcare.

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