# Chapter 3: Advancements in nanotechnology for drug delivery

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## Abstract:

The practice of nano-technology to deliver drugs has materialized as a viable pathway to overcome obstacles posed by traditional drug delivery. Nanomaterials have unusual physiochemical properties that allow for enhanced drug bioavailability, targeted drug delivery, and increased therapeutic effectiveness. The discussion in this chapter includes: general considerations in nanotechnology and drug delivery, a discussion of nanoparticles as drug-carriers and the practice of nanocarriers in drug-delivery. Applications of nanocarrier drug delivery techniques are illustrated concerning the treatment of cancer, gene therapy, immunotherapy and communicable disease therapy.

**Keywords:**

Nanotechnology, nanoparticles, liposomes, theranostic, PLGA, chitosan, cancer, immunotherapy, gene therapy, carbon-based, stimuli-responsive

## Introduction:

The utilization of nanotechnology for drug delivery appears to be fruitful, because it offers innovative approaches to adapt the obstacles related to conventional drug delivery methods. Nanomaterials have distinct physicochemical properties, and therefore, can improve the therapeutic drugs' bioavailability, targeted delivery, and effectiveness. Nanotechnology delivers systems have the advantage of manipulating materials at the nanoscale and enjoy circumventing the traditional drug delivery.

## 1. Overview of Nanotechnology in Drug Delivery

The distribution of drugs using nanotechnology is a revolutionary method for creating therapeutic pharmacokinetic and pharmacodynamic characteristics of medications. Poor solubility, instability in biological settings, quick bodily clearance, and a lack of selectivity for sick tissues are only a few of the drawbacks of traditional drug delivery techniques. Nanocarriers—engineered materials in the nanometer scale (1–100 nm)—offer innovative solutions to overcome these challenges.

Nanocarriers serve as transport vehicles that encapsulate or bind therapeutic agents, preventing their early deterioration in the circulation and promoting their buildup at the intended location. They can traverse intricate biological settings, including the intestinal mucosa, tumor vasculature, and blood–brain barrier, because to their tiny size and surface-modifiable characteristics.

Furthermore, the tunable nature of nanocarriers allows for precise engineering to suit various therapeutic needs. By extending circulation time, improving drug solubility, enabling sustained release, and facilitating targeted action, nanocarriers contribute to maximizing therapeutic efficacy.

## 2. Types of Nanocarriers

The development of nanocarrier systems has prolonged significantly over the last few times, with a wide variety of nanoscale structures engineered to improve the delivery. These nanocarriers differ in their physicochemical properties, structural architecture, and drug-loading capabilities, good for various clinical applications. Below are some well researched and utilized nanocarrier systems:

**Liposomes**

Liposomes are sphere-like structures having phosphor-lipid bilayers encircling an watery center. Their unique design permits encapsulation of both drugs. Liposomes can improve therapeutic efficacy while lowering drug toxicity because they are biocompatible and biodegradable. Their targeting capabilities and circulation time have been further enhanced by surface modifications such polyethylene glycol (PEGylation).

**Polymeric Nanoparticles**

They are substantial colloidal fragments that generally consist of polymers that decompose like poly(lactic-co-glycolic acid) (PLGA), with sizes that vary from 10 to 1000 nm polylactic acid (PLA), or polycaprolactone (PCL). They are extensively investigated for cancer therapy, vaccine delivery, and treatment of chronic diseases.

**Solid Lipid Nanoparticles (SLNs)**

Tiny colloidal transporters, or SLNs, are composed of solid_lipids that have been stabilized by surfactants. These systems combine the benefits of nanoparticles of polymers and liposomes such as biocompatibility and controlled release, while offering enhanced physical stability and lower toxicity. SLNs are suitable for incorporating both types of drugs and can be used in oral, topical, and parenteral delivery. They are especially promising for dermatological applications and brain-targeted therapies.

**Dendrimers**

Dendrimers are tree-like, monodisperse, highly branching polymers with several functional end groups and a central core. Their exact control over size and form, surface modification. Drugs can be conjugated to surface functional groups or encapsulated in the internal cavities of dendrimers. Due to their versatility, dendrimers are being explored for gene delivery, anticancer therapy, and diagnostic imaging. A common example is poly(amidoamine) (PAMAM) dendrimers used in gene and RNA delivery systems

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**Nanomicelles**

Nanomicelles are nanosized (typically 10–100 nm) self-assembling colloidal carriers in aqueous environments. They have a hydrophilic shell that provides stability in physiological fluids and a hydrophobic core that can dissolve medications that are not very soluble in water. Nanomicelles are perfect for intravenous delivery of hydrophobic anticancer medicines because they improve the solubility, bioavailability, and half-life of medications. Additionally, the improved permeability and retention (EPR) effect made possible by their small size allows passive targeting to tumor tissues. These nanocarrier systems form the foundation of modern drug delivery strategies and are continuously being optimized to improve drug targeting, release kinetics, biocompatibility, and therapeutic outcomes. Their adaptability and functional versatility hold great promise for addressing the limitations of conventional therapies across various disease states.

## 3. Targeted Drug Delivery

The creation of tailored drug_delivery systems, which seek to give medications to damaged tissues only while preserving healthy cells, is a significant therapeutic innovation made possible by nanotechnology. It is particularly useful in the treatment of cancer, neurological disorders, inflammatory illnesses, and infectious diseases because of its specific localization, which increases therapeutic efficacy and dramatically lowers systemic adverse effects.

**Passive Targeting**

passively targeting takes advantage of the distinct pathophysiological traits of specific diseased tissues —particularly tumors and inflamed areas. Although passive targeting is a foundational strategy, its effectiveness can be variable and is often influenced by tumor type, size, and vascularization.

**Active Targeting**

Active targeting enhances specificity by functionalizing the surface of nanocarriers Upon ligand-receptor binding, the nanocarrier is internalized via receptor-mediated endocytosis, allowing direct intracellular drug delivery. This approach is particularly useful in cancers where certain biomarkers are overexpressed (e.g., HER2, EGFR, folate receptors), and in central nervous system diseases where transcytosis across the blood-brain barrier is needed.

## Advantages and Clinical Relevance

Targeted drug delivery systems at the desired site but also reduce the frequency and dosage required, improving patient compliance and minimizing side effects. In oncology, this can translate to more effective tumor regression with fewer adverse events. In neurology, targeted nanoparticles can facilitate the crossing of the blood-brain barrier a noteworthy task for conventional drugs. Additionally, infectious diseases benefit from targeted systems that concentrate antimicrobial agents at the site of infection, improving efficacy and reducing resistance development.
In summary, targeted drug delivery via nanotechnology marks a shift toward precision medicine, offering individualized treatment strategies that maximize benefit and minimize harm. The combination of passive and active targeting mechanisms holds immense probable in overwhelming the boundaries of conservative medication therapies.

## Theranostic Nanoparticles

Theranostics—a term derived from the combination of "therapy" and "diagnostics"—characterises a groundbreaking improvement in the arena of nanomedicine. It refers to multifunctional nanoparticle which incorporate therapeutic and diagnostic capabilities within a platform.
Theranostic nanoparticles are concocted to encapsulate or conjugate agents alongside imaging moieties such as fluorescent dyes, magnetic_nanoparticles (e.g., iron oxide for MRI), radioisotopes (for PET/SPECT), or quantum dots. These systems can be guided to specific tissues through passive or active targeting strategies, and their accumulation, distribution, and therapeutic effects can be monitored in vivo using non-invasive imaging techniques.

**Key Advantages of Theranostic Nanoparticles:**

- **Simultaneous Diagnosis and Therapy**: Instantaneous drug delivery monitoring is made possible by these devices localization, and release, which helps assess the efficacy of treatment at an early stage.
- **Personalized Treatment Planning**: By correlating imaging data with therapeutic outcomes, clinicians can fine-tune dosing, adjust treatment protocols, and predict prognosis with greater accuracy.

- **Minimized Toxicity**: Targeted delivery combined with real-time imaging allows for precise drug administration, reducing exposure to healthy tissues and improving safety profiles.
- **Overcoming Multidrug Resistance**: Some theranostic systems incorporate mechanisms to bypass drug resistance by co-delivering drugs and siRNA or monitoring efflux pump activity in resistant cells.

**Applications in Clinical Research:**

- In **oncology**, theranostic nanoparticles are being investigated for simultaneous tumor imaging and chemotherapy, enabling the visualization of tumor shrinkage or drug resistance.
- In **neurological disorders**, these systems are made to transport medications across the blood-brain barrier while tracking brain lesions or neuroinflammation.
- In **cardiology and infection control**, theranostic agents can be used to detect and treat inflammation or localized infections, providing both therapeutic and diagnostic feedback.

Although still largely in the preclinical or early clinical trial stages, theranostic nanoparticles represent a promising leap toward precision medicine, where diagnosis, treatment, and outcome monitoring are unified in a single, efficient system. Their continued development may revolutionize how diseases are treated, making healthcare more proactive, personalized, and effective.

## Various nanotechnology aspects used in drug delivery:

**Using nanoparticles to deliver drugs**

In drug delivery, nanoparticles, which measure one to 100 nanometers, are gaining much attention. Nanoparticles can encapsulate and protect many different types of therapies. Nanoparticles might be engineered to improve medication solubility, boost cellular absorption, and deliver drugs to certain tissues or cells with precision.

a) **Lipid-based Nanoparticles:**
   Some great examples are "liposomes," which have been extensively studied and primarily consist of phospholipids, one of the fundamental components of biological membranes. (15 -17)

b) **Polymer-based Nanoparticles:** Polymeric nanoparticles are generated from biodegradable polymers including poly (lactic-co-glycolic acid) (PLGA), and

chitosan (2. Polymeric nanoparticles are available as versatile platforms that allow tuning to maximize drug loading, release kinetics, and targeting. Polymeric nanoparticles can be utilized for different types of therapeutic agents including proteins, peptides, and small molecules (3).

c) **Carbon-based Nanoparticles:** These have demonstrated tremendous potential for use in drug delivery. Carbon-based nanoparticles can also be functionalized to increase drug loading, enhance cellular uptake, and target delivery (4,5).

d) **Stimuli-responsive Nanoparticles:** In reaction to particular ecological signals, such as temperature, stimuli-responsive nanoparticles are made to release their payload. These intelligent nanocarriers can increase drug delivery's selectivity and efficiency. (6).

e) **Theranostic Nanoparticles:** Therapeutic capabilities within a single nanoparticle platform has given rise to the concept of theranostic nanoparticles. These multifunctional nanoparticles can be used for disease diagnosis, real-time monitoring of drug delivery, and targeted therapeutic interventions (7).

## Claims of Nanocarriers in Drug Delivery

Nanocarriers used in various applications, including:

- **Cancer therapy**: Nanocarriers used to deliver anti-cancer agents, to target tumor cells and reduce side effects (9). Some marketed nanoparticles used in cancer therapy are a) Organic nanoparticles like Liposomal paclitaxel (ES-SSL-PTX), Liposomal (PLAD-MLP), PLGA-PEG (GEM+BA) Polymeric nanoparticles, etc. b) Inorganic nanoparticles like Au Nanoparticle Au-SMCC-DOX, Carbon nanotube (DTX-CNTP-Tf ), Silica nanoparticle, Magnetic Nanoparticle ( FeO NPs coated with silica). c) (10)
- **Gene therapy**: they used to deliver genes, such as pDNA and siRNA, to target cells and tissues (11). With the increasing understanding of cancer, it is evident that low-toxicity gene delivery using nanovectorization of genes is essential for successful cancer therapy.
- **Immunotherapy**: Nanocarriers have been used to deliver immunomodulatory substance like cytokines and vaccines, to target immune cells and enhance the immune response (12). Nanomaterials used as a goal of modulating innate immune cells for immunotherapy are like Liposomes, Carboxylated polystyrene. Glucomannan polysaccharide, Hyaluronic acid-protamine@cationic liposome, etc. for tumor-associated macrophages (TAM).
- **Infectious disease therapy**: Nanocarriers have been used to deliver antimicrobial agents, such as antibiotics and antiviral agents, to target infected

cells and tissues (13). For example, Solutal®HS15 nanocapsules loaded with the HIV protease inhibitor, Indinavir, Nanospheres for the treatment of Herpes simplex virus, Hepatitis B virus, and Influenza. Silver nanoparticles and various other metallic nanoparticles like titanium, zinc and copper also iron oxide, zinc oxide and titanium oxide have demonstrated specific anti-viral activities. (14)

## Benefits of Nanocarriers in Drug_Delivery

Nanocarriers offer several benefits above conventional medication delivery techniques, including:

- **Improved pharmacokinetics**: Nanocarriers can alter the pharmacokinetics of drugs, providing sustained release and reducing dosing frequency.
- **Enhanced efficacy**: Nanocarriers can enhance the efficacy of therapeutic agents by providing targeted delivery and reducing side effects. the potential for drug encapsulation, functionalization through stable structure formation.

## Conclusion:

Nanotechnology has made a considerable impact possibly drug delivery. There are now many types of nanoparticle platforms, from lipid-based, polymer-based, and carbon-based nanoparticles, making available so many different therapeutics. The incorporation of stimuli-responsiveness and theranostics have made the drug delivery more selective and effective. Looking to the future of this field, as technologies continue to be improved and developed, there is substantial potential for successful transformation of nanotechnology drug_delivery systems to clinical settings to improve patient management and to offer high impact clinical translation to treatment for diseases.

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