D&C

Drugs & Clinic | ISSN: 1674-5515

Nanotechnology-Based Drug Delivery Systems: Innovations, Clinical Applications, and Future Prospects

Jitendra Kumar* and Vishal Dubey

Naraina Vidyapeeth Group of Institutions, Faculty of Pharmacy, Panki, Kanpur, (U.P.) –India

ABSTRACT

Nanotechnology has emerged as a transformative approach in clinical therapeutics by enabling targeted, controlled, and efficient drug delivery. Conventional drug delivery systems often suffer from low bioavailability, systemic toxicity, and non-specific distribution, limiting their clinical efficacy. Nanocarrier-based systems such as liposomes, dendrimers, polymeric nanoparticles, and solid lipid nanoparticles offer precise targeting, controlled release, and enhanced pharmacokinetics. This review provides a comprehensive analysis of nanotechnology-based drug delivery in clinical practice, discussing types of nanocarriers, mechanisms of action, current clinical applications, challenges, regulatory considerations, and future perspectives.

Keywords: Nanotechnology, Drug Delivery, Nanocarriers, Targeted Therapy, Clinical Pharmacology, Therapeutics

1. Introduction

Drug delivery is a critical determinant of therapeutic success. Traditional methods such as oral, intravenous, or topical administration are often associated with suboptimal drug distribution, rapid metabolism, and systemic toxicity. Nanotechnology introduces nanoscale drug carriers that can enhance solubility, protect drugs from degradation, allow controlled release, and provide targeted delivery to specific tissues or cells.

Nanomedicine has gained prominence in oncology, infectious diseases, neurology, and cardiovascular therapy. By incorporating drugs into nanocarriers, clinicians can improve efficacy while minimizing adverse effects.

2. Literature Review

Research shows that liposomal formulations of chemotherapeutics, such as doxorubicin, significantly reduce cardiotoxicity. Polymeric nanoparticles and dendrimers enable sustained release and multi-drug encapsulation. Solid lipid nanoparticles enhance oral bioavailability of poorly soluble drugs.
Clinical trials have validated several nanotechnology-based formulations:

- **Doxil® (liposomal doxorubicin)** – reduced systemic toxicity in cancer therapy.
- **Abraxane® (albumin-bound paclitaxel nanoparticles)** – improved tumor targeting and patient survival.
- **Lipid nanoparticles in mRNA vaccines** – showcase rapid translational potential in infectious diseases.

3. Methodology

A systematic narrative review was conducted using PubMed, Scopus, and Web of Science databases (2014–2025). Keywords: “nanotechnology drug delivery,” “nanocarriers clinical applications,” “nanomedicine,” and “targeted drug delivery.” Emphasis was placed on clinical trials, FDA-approved formulations, and emerging preclinical research.

4. Types of Nanocarriers and Mechanisms

4.1 Liposomes

Phospholipid bilayer vesicles encapsulating hydrophilic or lipophilic drugs. Advantages: biocompatibility, reduced systemic toxicity, enhanced circulation time.

4.2 Polymeric Nanoparticles
Biodegradable polymers (PLGA, PLA) used for controlled and sustained drug release. Can be surface-modified for targeted delivery.

4.3 Dendrimers
Highly branched polymers with functional groups for multi-drug loading, targeting ligands, and imaging agents.

4.4 Solid Lipid Nanoparticles (SLNs)
Enhance oral bioavailability of hydrophobic drugs and protect labile molecules.

4.5 Nanocrystals and Nanosuspensions
Increase solubility and dissolution rates of poorly soluble drugs.

5. Clinical Applications
5.1 Oncology
Targeted delivery of chemotherapeutics improves efficacy and reduces toxicity. Nanocarriers enable passive (EPR effect) and active targeting (ligand-receptor interactions).

5.2 Infectious Diseases
Nanoformulations enhance antibiotic delivery to intracellular pathogens, reduce dosage, and minimize resistance risk.

5.3 Vaccines and Gene Therapy
Lipid nanoparticles enable mRNA vaccine delivery. Nanocarriers facilitate CRISPR/Cas9 delivery and gene therapy approaches.

5.4 Neurological Disorders
Nanocarriers cross the blood-brain barrier for targeted delivery in Parkinson's, Alzheimer's, and glioma therapy.

5.5 Cardiovascular Therapy
Nanoformulations of anticoagulants and anti-atherosclerotic agents improve pharmacokinetics and reduce off-target effects.

6. Advantages and Limitations
Advantages:
- Targeted therapy
- Controlled drug release
- Reduced systemic toxicity
- Multi-drug encapsulation

Limitations:
- High manufacturing cost
- Long-term toxicity and immunogenicity concerns
- Regulatory challenges and lack of standardization

Table 1 (Suggested for paper):

Nanocarrier Type	Clinical Application	Advantages	Limitations
Liposomes	Cancer therapy	Reduced toxicity	Short shelf-life
Polymeric NPs	Sustained release	Controlled delivery	Complex synthesis

Nanocarrier Type	Clinical Application	Advantages	Limitations
Dendrimers	Multi-drug delivery	High functionalization	Costly
SLNs	Oral drugs	Increased bioavailability	Drug expulsion

7. Future Perspectives

Emerging trends include:

- Personalized nanomedicine based on patient genomics
- Smart nanoparticles responsive to pH, temperature, or enzymes
- Integration with AI for predictive drug delivery and therapy optimization

8. Conclusion

Nanotechnology-based drug delivery systems have transformed clinical pharmacotherapy. While challenges remain, ongoing research, technological innovation, and regulatory alignment will expand their role in precision medicine.

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