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Research Paper

Nanoparticle-Based Drug Delivery Systems in Cancer Therapy: A Comprehensive Review

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ABSTRACT

Cancer continues to be a major global health issue with high mortality rates due to limitations of conventional chemotherapy, such as non specific drug distribution and systemic toxicity. Nanoparticle based drug delivery systems offer promise for improved cancer therapy by enabling targeted delivery, controlled drug release, and enhanced bioavailability. This review critically examines various nanocarrier platforms, including liposomes, polymeric nanoparticles, solid lipid nanoparticles, and metallic nanoparticles. Mechanisms of both passive and active targeting, advantages, clinical applications, limitations, and regulatory challenges are discussed. Recent developments from 2020–2025, such as biomimetic and stimuli responsive nanocarriers, are also evaluated. Prospects for future research and clinical translation are highlighted.

INTRODUCTION

Cancer is defined by uncontrolled cell proliferation and the potential to invade adjacent tissues and metastasize to distant organs. Conventional chemotherapy remains a frontline treatment strategy; however, its effectiveness is often compromised by systemic toxicity, poor selectivity, and the development of multidrug resistance. These limitations underscore the need for more effective and safer drug delivery methods.

Nanotechnology has revolutionized the field of drug delivery by enabling nanoscale carriers that improve drug solubility, prolong circulation time, and facilitate targeted delivery to tumor tissues. Nanoparticles, typically 1–100 nm in diameter, exhibit unique physicochemical properties, including high surface-to-volume ratio and modifiable surface chemistry, which improve tumor targeting via enhanced permeability and retention (EPR) and functional ligand attachment.

2. Types of Nanoparticles

2.1 Liposomes

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Liposomes are phospholipid vesicles capable of carrying both hydrophilic and hydrophobic drugs. Liposomal formulations such as Doxil® have significantly reduced cardiotoxicity compared to free drugs.

2.2 Polymeric Nanoparticles

These nanoparticles are fabricated from biodegradable polymers such as PLGA, providing controlled drug release and protecting encapsulated agents from degradation.

2.3 Solid Lipid Nanoparticles (SLNs)

SLNs combine the stability of polymeric nanoparticles with high drug loading capacity, offering controlled drug release and improved stability over traditional systems.

2.4 Metallic Nanoparticles

Gold and silver nanoparticles possess unique optical and electronic properties used in imaging, diagnostics, and photothermal therapies.

3. Mechanisms of Drug Targeting

3.1 Passive Targeting (EPR Effect)

Passive targeting leverages the Enhanced Permeability and Retention effect, where nanoparticles accumulate preferentially in tumor tissue due to leaky vasculature and deficient lymphatic drainage.

3.2 Active Targeting

Active targeting involves functionalizing nanoparticle surfaces with ligands such as antibodies, peptides, or aptamers, which bind selectively to receptors overexpressed on cancer cells.

4. Advantages of Nanoparticle-Based Systems

Nanoparticle-mediated delivery offers several benefits over conventional chemotherapy, including:

- Enhanced tumor targeting
- Reduced systemic toxicity
- Improved bioavailability
- Controlled and sustained drug release
- Enhanced pharmacokinetics

5. Applications in Cancer Therapy

Nanoparticle systems have shown promise in both clinical and experimental settings. Examples include:

- **Liposomal Doxorubicin (Doxil®):** Reduced cardiac toxicity and improved targeting
- **Albumin-bound Paclitaxel (Abraxane®):** Enhanced solubility and tumor uptake
- **Lipid nanoparticles (LNPs):** Widely used in gene delivery and immunotherapy

Recent studies (2023–2025) focus on:

- Stimuli-responsive nanoparticles
- Biomimetic nanocarriers (cell membrane-coated)
- Exosome-based delivery systems

Lipid-based systems dominate due to favorable safety and delivery efficiency.

6. Limitations and Challenges

6.1 Toxicity Concerns

Accumulation of nanoparticles in organs such as liver and spleen can cause long-term toxicity and unpredictable biological interactions.

6.2 Biological Barriers

Tumor heterogeneity and the presence of physiological barriers restrict effective nanoparticle penetration.

6.3 Manufacturing Challenges

High production costs, difficulties in scale-up, and batch variability hinder commercialization.

6.4 Regulatory Challenges

Regulatory authorities (FDA, EMA) require comprehensive evaluation of pharmacokinetics, toxicity, and reproducibility. The lack of standardized regulatory criteria for nanomedicines remains a significant obstacle.

7. Future Perspectives

Future research is steering toward:
- Smart and stimuli-responsive nanoparticles
- Personalized nanomedicine
- Multifunctional combination therapies
- AI-assisted nanocarrier design

CONCLUSION

Nanoparticle-based drug delivery systems hold transformative potential in cancer therapy by enabling targeted treatment, improved efficacy, and reduced toxicity. Continued advancements in nanocarrier design and regulatory frameworks are essential to realize widespread clinical adoption.

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