Opinion

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Journal of Chemical Biology & Pharmaceutical Chemistry

2025
Vol.8 No.1: 03

Advances in Nanocarrier-based Drug Delivery: Bridging Chemistry and Pharmacology

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Received date: 02 January, 2025; **Accepted date:** 18 January, 2025; **Published date:** 31 January, 2025.

Citation: Foxter D (2025) Advances in Nanocarrier-based Drug Delivery: Bridging Chemistry and Pharmacology. J Chem Biol Pharm Chem Vol. 8 No. 1: 03.

Introduction

The field of drug delivery has undergone a profound transformation with the emergence of nanotechnology, which offers unprecedented opportunities to overcome the limitations of conventional therapeutics. Traditional small-molecule drugs often face challenges such as poor solubility, limited bioavailability, rapid metabolism, and off-target toxicity. Nanocarrier-based drug delivery systems address these issues by enabling precise control over drug encapsulation, protection, transport, and release. Through their ability to traverse biological barriers, prolong circulation time, and selectively accumulate in diseased tissues, nanocarriers bridge the gap between chemical design and pharmacological function. Over the past two decades, multidisciplinary collaborations between chemists, pharmacologists, and clinicians have accelerated the development of innovative nanocarrier platforms, ranging from liposomes and polymeric nanoparticles to dendrimers, micelles, and inorganic nanostructures. These advances not only expand the chemical toolbox for drug formulation but also reshape the therapeutic landscape for cancer, infectious diseases, neurological disorders, and regenerative medicine [1].

Description

At the core of nanocarrier-based delivery lies the rational design of nanoscale materials that integrate chemical tunability with biological compatibility. Liposomes, one of the earliest nanocarriers, are composed of phospholipid bilayers that mimic biological membranes and can encapsulate both hydrophilic and hydrophobic drugs. Advances in lipid chemistry have enabled the modification of liposomes with polyethylene glycol (PEGylation) to evade immune recognition and with ligands for targeted delivery to specific cell types. Polymeric nanoparticles, constructed from biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA) or polycaprolactone, offer controlled release kinetics and structural versatility. Similarly, dendrimers, with their highly branched architecture and tunable surface functionalities, provide a platform for multivalent drug conjugation and diagnostic imaging [2].

A major advance in the field has been the integration of stimuli-responsive nanocarriers, which release their cargo in response to specific biological or external triggers. By exploiting variations in pH, redox potential, or enzymatic activity within diseased tissues, chemists have designed “smart” nanocarriers that remain stable during circulation but selectively release drugs in the tumor microenvironment or at sites of inflammation. External triggers such as light, ultrasound, or magnetic fields further expand the scope of controlled delivery. For example, pH-sensitive polymeric micelles can release anticancer drugs within the acidic tumor milieu, reducing systemic toxicity. These innovations illustrate the synergy between chemical engineering of nanostructures pharmacological exploitation of pathophysiological cues [3].

Nanocarrier-based drug delivery has had a particularly transformative impact on cancer therapy, where overcoming multidrug resistance and minimizing toxicity remain formidable challenges. By enhancing drug accumulation in tumors via the enhanced permeability and retention effect, nanocarriers improve therapeutic indices of cytotoxic agents. Liposomal formulations such as Doxil® represent landmark clinical successes, demonstrating reduced cardiotoxicity compared to free doxorubicin. Active targeting strategies employ nanocarriers conjugated with antibodies, peptides, or aptamers that recognize tumor-specific receptors, enabling selective drug uptake by cancer cells. Multifunctional nanocarriers capable of co-delivering drugs, genes, or immune modulators address the complexity of tumor biology and resistance mechanisms [4].

Beyond oncology, nanocarrier platforms are being extended to diverse therapeutic areas, including infectious diseases, neurological disorders, regenerative medicine. In infectious diseases, nanocarriers improve the delivery of antibiotics with poor solubility or stability, while reducing systemic toxicity. Nanoparticle-based antiretroviral formulations enhance penetration into viral reservoirs, addressing one of the key limitations of HIV therapy. In neurology, crossing the blood–brain barrier remains a major pharmacological challenge, but nanocarriers functionalized with transferrin or lactoferrin ligands have shown promise in delivering drugs to the central nervous system [5].

Conclusion

Advances in nanocarrier-based drug delivery represent a paradigm shift in modern pharmacotherapy, bridging the precision of chemistry with the complexity of pharmacology. By enabling controlled release, targeted delivery, and multifunctionality, nanocarriers overcome longstanding limitations of conventional drugs and open new therapeutic horizons. Nevertheless, significant challenges remain, including large-scale manufacturing, regulatory approval, long-term safety, and potential immunogenicity. Addressing these issues will require continued collaboration across chemistry, pharmacology, materials science, and clinical medicine. As research progresses, nanocarriers are poised to play a central role in the future of precision medicine, offering treatments that are not only more effective but also safer and patient-centric. Ultimately, the convergence of chemical design and pharmacological application through nanocarriers holds the promise of transforming disease management and improving human health on a global scale.

Acknowledgement

None.

Conflict of Interest

None.

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