Review

The Role of Liposomal Drug Delivery in Modern Medicine and the Expanding Potential of Nanocarriers

Ashutosh Sengar *

Posted Date: 24 March 2025

doi: 10.20944/preprints202503.1802.v1

Keywords: liposomal drug delivery; nanocarriers; precision medicine; targeted drug release; theranostic liposomes

 doi:10.20944/preprints202503.1802.v1

Review

The Role of Liposomal Drug Delivery in Modern Medicine and the Expanding Potential of Nanocarriers

Ashutosh Sengar *

Assistant Professor, Dept. of Pharmaceutics, Smt. Vidyawati College of Pharmacy, Smt. Vidyawati Group of Institutions, Jhansi (U. P.), ashutoshsengar26567@gmail.com

Abstract: Liposomal drug delivery has transformed contemporary medicine with the supply of targeted, controlled, and effective drug release systems. Liposomal nanocarriers maximize drug bioavailability and reduce systemic toxicity, making them especially beneficial for cancer therapy and precision medicine. The paper points out development and progress in liposomal drug delivery with emphasis on mechanisms for targeted release of drugs and growing application of nanocarriers in contemporary therapeutics. Despite their advantages, the liposomal formulations are subjected to some strong disadvantages including rapid immune system clearance, tumor heterogeneity, and high-scale production. Despite these drawbacks, certain new developments by way of PEGylation, ligand-grafted liposomes, and hybrid lipid-polymer nanocarriers have proved promising and effective in bringing improvements to liposome stability and target specificity. In addition, artificial intelligence predictive modeling is becoming an effective approach for optimizing liposomal formulations to tailor treatment regimens to the patient. Also, liposomal nanoparticle use in the treatment of cancer has provided avenues for the development of new chemotherapy and gene therapy approaches for facilitating precision medicine. The review also illustrates current trends, including theranostic liposomes to facilitate real-time drug delivery and imaging and CRISPR-based liposomal gene therapy. The future is conjugating nanotechnology, bioengineering, and artificial intelligence in formulating the next generation of intelligent nanocarriers. Despite current limitations, liposomal preparations have unmatched promise to revolutionize drug delivery systems and precision medicine.

Keywords: liposomal drug delivery; nanocarriers; precision medicine; targeted drug release; theranostic liposomes

---

1. Introduction to Liposomal Drug Delivery and Nanocarriers

Liposomal drug delivery and nanocarriers are advanced platforms in modern medicine that offer targeted and efficient drug delivery systems. Liposomes are vesicular spheres composed of a lipid bilayer. They enhance drug stability, bioavailability, and therapeutic activity by accommodating active pharmaceutical ingredients within their framework [1]. Their ability to protect drugs from enzymatic degradation and offer controlled release has made them the method of choice in achieving optimal therapeutic gain [2].

Recent developments in nanocarriers have gone a step further from the conventional liposomes and now include smart drug delivery systems that are triggered by physiological stimulus for targeted and controlled delivery of the drug at the action site [3]. Nanocarriers have shown immense potential for circumventing the shortcomings of conventional drug products such as low solubility and systemic toxicity [4]. The union of drug delivery and nanotechnology has also created new platforms for the production of vaccines, gene therapy, and cancer therapy, positioning liposomal systems at the center of modern pharmaceutical science [5].

 doi:10.20944/preprints202503.1802.v1

2. Evolution and Advancements in Liposomal Drug Delivery

Liposomal drug delivery technology has also advanced significantly in the last few decades, moving from investigative studies to clinical applications. During the early years, liposomes were studied merely as drug carriers, but with their stability, biocompatibility, and ability to increase drug solubility, they became valuable delivery systems for therapeutic molecules [6]. Among the landmark advances in the field has been the clearance of Doxil®, the very first FDA-approved liposomal nano-drug, which demonstrated the capability of liposomes in maximizing drug retention, reducing toxicity, and improving the therapeutic effect on cancer therapy [7].

Progress in liposome technology has also focused on ensuring the maximum drug encapsulation, surface engineering, and targeting. Scientists have designed PEGylated liposomes to increase the circulation half-life by reducing the immune recognition and clearance [8]. Liposomal nanocarriers have also been a promising therapeutic platform to treat cancer, with targeted delivery of drugs with few side effects [9]. Despite these advancements, the limitations in mass production, stability, and the regulatory aspect still impede universal acceptance of liposomal drug delivery [10].

Table 1. Evolution and Advancements in Liposomal Drug Delivery.

Milestone	Description	Reference
Early Research Phase	- Explored as simple drug carriers	[6]
	- Recognized for their biocompatibility and drug solubility enhancement	
First FDA-Approved Liposomal Drug	- Doxil® (liposomal doxorubicin) approved for cancer therapy	[7]
	- Demonstrated enhanced drug retention and reduced toxicity	
Surface Modifications & Targeting	- Introduction of PEGylated liposomes to extend circulation time	[8]
	- Development of ligand-functionalized liposomes for targeted delivery	
Nanocarrier Integration	- Liposomes combined with nanocarriers for improved drug targeting	[9]
	- Enhanced precision in cancer therapy with minimized side effects	
Challenges & Future Directions	- Issues with large-scale production and stability	[10]
	- Regulatory hurdles affecting widespread adoption	

 doi:10.20944/preprints202503.1802.v1

3. Targeted and Controlled Release Mechanisms in Liposomal Nanocarriers

Liposomal nanocarriers were developed to site-specifically and conditionally deliver drugs to enhance therapeutic intervention with little off-target toxicity. The systems were divided into composition, preparation method, and functionalization methods, and they decide whether the systems are capable of delivering and encapsulating drugs [11]. The incorporation of stimuli-responsiveness i.e., temperature-responsive or pH-responsive liposomes makes controlled drug release to target areas with better bioavailability and therapeutic index possible [12].

Although promising, one of the limitations of liposomal drug delivery is the disruption of biological barriers, i.e., endothelial cell tight junctions, to prevent invasion of nanoparticles into target tissue [13]. The recent advancement in lipid nanoparticle (LNP) technology has created organ-specific liposomes for tissue-targeted mRNA delivery, and this is a new era in targeted nanomedicine [14]. The continued evolution of nanoparticles in drug delivery also reflects their groundbreaking influence on modern medicine, with subsequent innovations poised to further increase targeting specificity and therapeutic effectiveness in targeting [15].

4. Applications of Liposomal Nanoparticles in Cancer and Precision Medicine

Liposomal nanoparticles have also been a drug discovery in cancer therapy since they are capable of enhancing drug solubility, prolonging circulation time, and enhancing targeted drug delivery. Nanocarriers utilize the enhanced permeability and retention (EPR) effect to selectively get trapped in tumor tissue and thereby reduce systemic toxicity and enhance therapeutic effects [16]. Liposomal formulations have encapsulated chemotherapeutic agents, which are shielded from premature degradation and clearance and provide better pharmacokinetic and pharmacodynamic profiles.

One of the major advantages of liposomal nanocarriers is that they possess the ability to improve the oral drug bioavailability. The majority of anticancer drugs are water-soluble and undergo enzymatic hydrolysis in the gut very rapidly, thereby become inactive when administered orally. Liposomal entrapment can be utilized to stabilize the drug in the gut that leads to sustained delivery and effective permeation [17]. Polymer-liposome hybrid formulations have also been found promising in enhancing targeted delivery and controlled release, and they provide superior results in the treatment of cancer [18].

Several liposomal drug formulations have received clinical approval for cancer treatment, demonstrating significant advantages over conventional chemotherapy. Notably, liposomal doxorubicin (Doxil®) has been widely used in treating ovarian cancer and Kaposi's sarcoma, with reduced cardiotoxicity compared to free doxorubicin [19]. Likewise, liposomal cisplatin (Lipoplatin™) also showed improved delivery to the tumors with reduced nephrotoxicity, e.g., a less toxic option compared to conventional cisplatin treatment. The addition of liposomal vincristine (Marqibo®) and irinotecan (Onivyde®) further solidified the position of nanomedicine in targeted oncology to deliver more effective anticancer treatments and with less toxicity [20].

 doi:10.20944/preprints202503.1802.v1

Table 2. Comparative Applications of Liposomal Nanoparticles in Cancer Therapy.

Liposomal Formulation	Encapsulated Drug	Therapeutic Application	Advantages
Doxil® (PEGylated Liposomes)	Doxorubicin	Ovarian Cancer, Kaposi's Sarcoma	Reduced cardiotoxicity, prolonged circulation time
Myocet™	Doxorubicin	Breast Cancer	Non-PEGylated, reduced cardiac toxicity
Onivyde®	Irinotecan	Pancreatic Cancer	Improved drug stability and targeted delivery
Marqibo®	Vincristine	Acute Lymphoblastic Leukemia	Enhanced drug penetration and controlled release
Lipoplatin™	Cisplatin	Various Solid Tumors	Reduced nephrotoxicity, improved tumor uptake

5. Recent Advances and Future Directions in Liposomal Drug Delivery for Cancer Therapy

Current studies have emphasized the optimization of liposomal drug delivery systems for targeted therapy, i.e., novel targeting concepts like ligand-modified liposomes, stimulus-responsive nanocarriers, and combination therapy. Ligand-modified liposomes, which are decorated with peptides or antibodies, enable drug targeting to tumors by decorating beyond tumor cell surface-expressed receptors, thus improving the specificity of therapy and minimizing off-target toxicity [18].

The second potential route is via stimuli-sensitive liposomes, where drug loading is provided based on the tumor-targeting microenvironments of acidic pH, enzymatic, or hyperthermia. Smart liposomal formulations enhance controlled delivery and drug encapsulation and optimize therapeutic efficiency and reduce systemic toxicity [19].

Other than that, combination therapy using liposomal nanoparticles has also gained popularity where more than one drug is co-delivered on a single nanocarrier with the hope of generating synergistic effects. That has proven effective in preclinical and clinical platforms, especially to combat multidrug resistance (MDR) of aggressive tumors [20].

 doi:10.20944/preprints202503.1802.v1

Table 3. Recent Innovations in Liposomal Drug Delivery for Cancer Therapy.

Innovation	Description	Potential Benefits
Ligand-Functionalized Liposomes	Liposomes conjugated with tumor-targeting ligands (antibodies, peptides)	Improved specificity, reduced systemic toxicity
Stimuli-Responsive Liposomes	Liposomes activated by pH, heat, or enzymatic triggers	Controlled drug release at tumor site, enhanced therapeutic efficacy
Polymer-Liposome Hybrid Systems	Combination of liposomes with polymer coatings for stability	Enhanced drug retention and prolonged circulation time
Multi-Drug Liposomal Therapy	Co-encapsulation of multiple drugs in a single liposome	Synergistic effects, reduced multidrug resistance
CRISPR-Liposome Gene Therapy	Liposomal carriers for gene editing in cancer treatment	Potential for personalized, gene-targeted therapies

Non-conventional innovation of liposomal drug delivery is broadening the scope to more effective, targeted, and safer anticancer therapy. Parallel with emerging research in nanocarrier engineering, combination chemotherapy, and gene editing, the future of anti-cancer treatment will increasingly be based on liposomal nanoparticles.

6. Challenges and Future Perspectives in Liposomal Drug Delivery

Liposomal drug delivery has transformed modern medicine but still faces some challenges in preventing it from fulfilling its full potential clinical effects. The biggest challenge is fast MPS-mediated clearance of liposomes and reduced half-life of circulation, leading to failure in drug delivery. While the stability and half-life of liposomes are increased by PEGylation, extended infusion will induce an immune reaction, the ABC effect, reducing the therapeutic effect [21]. Moreover, vascular tumor heterogeneity prevents effective extravasation of liposomal drug, which is a barrier for homogenous and effective cancer therapy to heterogeneous tumors [22].

The second is mass production and reproducibility of liposomal drugs. Liposomal nanocarriers lack strict control over particle size, drug loading, and surface properties compared to conventional drugs, which are hard to reproduce in batches during production. The approval process of nanomedicine is also challenging because the fate of liposomal carriers in the body could not be described using conventional pharmacokinetic models [23].

In spite of such limitations, the prospect of liposomal nanotechnology in the future as a drug carrier is bright. Active targeting approaches such as ligand-functionalized liposomes should have greater tumor selectivity and reduced off-target toxicities. Hybrid nanocarriers derived from liposomes with polymers or inorganic nanoparticles are being investigated to enhance the drug stability and release profile of controlled release [24].

Synergism between machine learning and artificial intelligence will be able to drive optimization and research of liposomal formulations to improve target drug delivery systems. AI can potentially

 doi:10.20944/preprints202503.1802.v1

be employed for liposome composition design by predictive models, to simplify the complexity of dosing regimens, and maximize patient-specific treatment programs [25].

Table 4. Key Challenges and Solutions in Liposomal Drug Delivery.

Challenge	Description	Potential Solutions
Rapid Clearance by Immune System	Recognition by macrophages leading to fast elimination	PEGylation, stealth liposomes, immune evasion strategies
Heterogeneous Tumor Vasculature	Uneven drug distribution in different tumor types	Targeted liposomes, tumor-specific ligands
Manufacturing and Scalability Issues	Difficulty in maintaining batch-to-batch consistency	Advanced nanofabrication techniques, AI-driven quality control
Regulatory Hurdles	Complex approval process for nanomedicines	Standardized characterization methods, regulatory framework development
Drug Leakage and Stability	Premature drug release affecting efficacy	Hybrid lipid-polymer nanocarriers, pH-sensitive liposomes

Emerging Trends and Future Directions

Current research in liposomal nanotechnology is focused on precision medicine and targeted drug delivery. The future generation of liposomes is being engineered with multiple functions, including imaging agents for real-time monitoring as well as theranostic uses. In addition, stimuli-responsive liposomes responding to specific biological stimuli, like pH or enzymes, are also being engineered for improved drug release at the site of action [24].

Gene therapy medications with liposomal vectors are also being used more and more, especially in the treatment of rare genetic disorders and cancer. CRISPR/Cas9 liposomal delivery systems are also being investigated for gene editing in diseased tissue, with a potential to cure diseases that were previously considered to be incurable [25].

 doi:10.20944/preprints202503.1802.v1

Table 5. Future Prospects in Liposomal Drug Delivery.

Future Innovation	Potential Impact
Stimuli-Responsive Liposomes	Controlled drug release at tumor sites for enhanced efficacy
Hybrid Lipid-Polymer Nanocarriers	Improved stability, targeting, and prolonged drug release
AI-Driven Liposome Design	Optimized formulations for personalized medicine
Liposomal Gene Therapy	CRISPR-based gene editing for genetic disorders
Theranostic Liposomes	Integration of imaging agents for real-time treatment monitoring

7. Conclusions

Liposomal drug delivery represents a new science in modern medicine with the ability for enhanced bioavailability, site-specific drug delivery, and minimizing systemic toxicity. Science of liposomes has proceeded significantly improved by passing years in terms of more effective drug entrapment, stability, and sustained release schemes. Therapeutic relevance of liposomes has also been further established due to being enriched with the presence of nanocarriers, particularly targeting therapy and also therapy of cancer. But issues like immune system-mediated fast clearance, heterogeneity of tumor vasculature, and scalability will still deter liposomal drug formulations from mass clinic uptake.

Methods to tackle such issues are PEGylation, active targeting methods, and hybrid carriers maximizing drug delivery effectiveness and confining toxicity to off-target tissues. Artificial intelligence technology will also determine personalized liposomal drugs to be designed and tailored delivery schedules to be programmed. Theranostic liposomes, gene therapy target delivery, and stimulus-responsive carriers are some of the concepts heralding the dawning of the wonderful epoch of liposomal nanomedicine.

Though intimidating, more recent developments in liposomes are vast in their potential to revolutionize drug delivery systems in medicine. Liposomal drug carriers will be the stars of personalized medicine as research and development continue to make safe, effective, and targeted therapy against a broad spectrum of disease possible.

References

1. Sengar, A. (2025). Liposomal Nanocarriers From Concept to Clinical Applications. Preprints. https://doi.org/10.20944/preprints202503.0837.v1
2. Sengar, A. (2025). Enhancing Therapeutic Outcomes with Smart Drug Carriers. Preprints. https://doi.org/10.20944/preprints202503.0921.v1
3. Sengar, A. (2025). Advancements in Drug Delivery Systems from Chewable Tablets to Nanomedicine. Preprints. https://doi.org/10.20944/preprints202503.1322.v1
4. Sengar, A. (2025). Advancements in Liposomal and Nanoparticle-Based Targeted Drug Delivery. Preprints. https://doi.org/10.20944/preprints202503.1397.v1
5. Sengar, A. (2025). Advancements in Liposomal Drug Delivery Systems and Their Therapeutic Applications. Preprints. https://doi.org/10.20944/preprints202503.1540.v1
6. Allen, T. M., & Cullis, P. R. (2013). Liposomal drug delivery systems from concept to clinical applications. Advanced Drug Delivery Reviews, 65(1), 36-48. https://doi.org/10.1016/j.addr.2012.09.037

7. Barenholz, Y. (2012). Doxil®—the first FDA-approved nano-drug Lessons learned. Journal of Controlled Release, 160(2), 117-134. https://doi.org/10.1016/j.jconrel.2012.03.020
8. Torchilin, V. P. (2005). Recent advances with liposomes as pharmaceutical carriers. Nature Reviews Drug Discovery, 4(2), 145-160. https://doi.org/10.1038/nrd1632
9. Peer, D., Karp, J. M., Hong, S., Farokhzad, O. C., Margalit, R., & Langer, R. (2007). Nanocarriers as an emerging platform for cancer therapy. Nature Nanotechnology, 2(12), 751-760. https://doi.org/10.1038/nnano.2007.387
10. Sercombe, L., Veerati, T., Moheimani, F., Wu, S. Y., Sood, A. K., & Hua, S. (2015). Advances and challenges of liposome assisted drug delivery. Frontiers in Pharmacology, 6, 286. https://doi.org/10.3389/fphar.2015.00286
11. Akbarzadeh, A., Rezaei-Sadabady, R., Davaran, S., Joo, S. W., Zarghami, N., Hanifehpour, Y., Samiei, M., Kouhi, M., & Nejati-Koshki, K. (2013). Liposome Classification, preparation, and applications. Nanoscale Research Letters, 8(1), 102. https://doi.org/10.1186/1556-276X-8-102
12. Bozzuto, G., & Molinari, A. (2015). Liposomes as nanomedical devices. International Journal of Nanomedicine, 10, 975-999. https://doi.org/10.2147/IJN.S68861
13. Barua, S., & Mitragotri, S. (2014). Challenges associated with penetration of nanoparticles across cell and tissue barriers A review of current status and future prospects. Nano Today, 9(2), 223-243. https://doi.org/10.1016/j.nantod.2014.04.008
14. Wang, X., Liu, S., Sun, Y., Yu, X., Lee, S. M., Cheng, Q., Wei, T., Gong, J., Robinson, J., Zhang, D., Lian, X., Basak, P., & Siegwart, D. J. (2023). Preparation of selective organ-targeting (SORT) lipid nanoparticles (LNPs) using multiple technical methods for tissue-specific mRNA delivery. Nature Protocols, 18(1), 265-291. https://doi.org/10.1038/s41596-022-00755-x
15. Couvreur, P. (2013). Nanoparticles in drug delivery past, present and future. Advanced Drug Delivery Reviews, 65(1), 21-23. https://doi.org/10.1016/j.addr.2012.04.010
16. Fenske, D. B., & Cullis, P. R. (2008). Liposomal nanomedicines. Expert Opinion on Drug Delivery, 5(1), 25-44. https://doi.org/10.1517/17425247.5.1.25
17. Zhang, L., Wang, S., Zhang, M., & Sun, J. (2013). Nanocarriers for oral drug delivery. Journal of Drug Targeting, 21(6), 515-527. https://doi.org/10.3109/1061186X.2013.789033
18. Kieler-Ferguson, H. M., Fréchet, J. M., & Szoka, F. C. Jr. (2013). Clinical developments of chemotherapeutic nanomedicines Polymers and liposomes for delivery of camptothecins and platinum (II) drugs. Wiley Interdisciplinary Reviews Nanomedicine and Nanobiotechnology, 5(2), 130-138. https://doi.org/10.1002/wnan.1209
19. Fenske, D. B., Chonn, A., & Cullis, P. R. (2008). Liposomal nanomedicines An emerging field. Toxicologic Pathology, 36(1), 21-29. https://doi.org/10.1177/0192623307310948
20. Allen, T. M., & Cullis, P. R. (2012). Drug delivery systems entering the mainstream. Science, 303(5665), 1818-1822. https://doi.org/10.1126/science.1095833
21. Moghimi, S. M., Hunter, A. C., & Murray, J. C. (2001). Long-circulating and target-specific nanoparticles Theory to practice. Pharmacological Reviews, 53(2), 283-318. https://doi.org/10.1124/pr.53.2.283
22. Wang, J., Byrne, J. D., Napier, M. E., & DeSimone, J. M. (2011). More effective nanomedicines through particle design. Nature Reviews Drug Discovery, 10(7), 511-523. https://doi.org/10.1038/nrd3503
23. Park, K. (2017). Facing the truth about nanotechnology in drug delivery. ACS Nano, 11(12), 10452-10453. https://doi.org/10.1021/acsnano.7b07994
24. Danhier, F., Feron, O., & Préat, V. (2010). To exploit the tumor microenvironment Passive and active tumor targeting of nanocarriers for anti-cancer drug delivery. Journal of Controlled Release, 148(2), 135-146. https://doi.org/10.1016/j.jconrel.2010.08.027
25. Shi, J., Votruba, A. R., Farokhzad, O. C., & Langer, R. (2010). Nanotechnology in drug delivery and tissue engineering From discovery to applications. Nano Letters, 10(9), 3223-3230. https://doi.org/10.1021/nl102184c

 doi:10.20944/preprints202503.1802.v1

disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.