Review

The Role of Nanotechnology in Revolutionizing Cancer Treatment

Ashutosh Sengar *

Posted Date: 11 March 2025

doi: 10.20944/preprints202503.0713.v1

Keywords: Nanotechnology; Cancer Treatment; Drug Delivery; Targeted Therapy; Precision Medicine

 doi:10.20944/preprints202503.0713.v1

Review

The Role of Nanotechnology in Revolutionizing Cancer Treatment

Ashutosh Sengar

Department of Pharmaceutics, Smt. Vidyawati College of Pharmacy, Smt. Vidyawati Group of Institutions, Jhansi (U. P.); ashutoshsengar26567@gmail.com

Abstract: Nanotechnology has changed the treatment of cancer by providing drug delivery systems with targeted release of drugs that maximizes the therapeutic index and minimizes system toxicity. The application of nanomedicine to cancer therapy, including nanoparticle-based drug delivery, target therapy, and topics for future investigations, is addressed in this review. Polymeric nanoparticles and liposomes provide more solubility, stability, and control of drug release than the limitation of traditional chemotherapy. Active and passive targeting strategies have also optimized the drug concentration within the tumor for optimal selectivity of treatment. Intelligent drug carriers such as stimulus-responsive nanoparticles have controlled release drug systems for the avoidance of off-target effects. Theranostic nanoparticles allowed real-time monitoring and imaging of therapy and advanced personalized medicine protocols. Recent breakthroughs in combination therapy using nanocarriers have been demonstrated to be more efficient in avoiding drug resistance and better patient outcome. New developments in nanoscale imaging also enabled cancer to be diagnosed at its earliest stage and the initial treatment process to commence. These breakthroughs come with, though, equally formidable hurdles to cross before one can access the clinic from nanomedicine. Challenges of long-term toxicity, biocompatibility, and acceptability in the eye of regulatory agencies are hurdles in use of nanomedicines on an extrapolatable level. Manufacturable-on-demand protocols and extensive clinical trials need first to validate nanoparticle-based treatments work as hoped and are safe. With ongoing research, nanomedicine holds vast future potential for advancing precision oncology to unprecedented levels. With advanced formulation techniques, regulatory needs, and clinical evidence attained, nanotechnology can revolutionize cancer therapy by delivering more potent, safer, and highly individualized treatment regimens.

Keywords: nanotechnology; cancer treatment; drug delivery; targeted therapy; precision medicine

1. Introduction to Nanotechnology in Cancer Treatment

Cancer therapy is being transformed from the traditional chemotherapy and radiotherapy to newer, more advanced, target-based therapies. The revolution has been made possible with the input of the science of nanotechnology, which provides controlled drug-delivery systems with zero toxicity and maximum therapeutic effect [1].

1.1. Introduction to Nanotechnology in Oncology

Nanotechnology involves the production of materials at the nanoscale to facilitate drug delivery, diagnosis, and therapeutics. Nanoparticles such as liposomes, polymeric micelles, and metal nanocarriers are used for enhancing drug solubility, stability, and bioavailability. Nanosystems facilitate site-specific deposition of the drug in tumor tissue through passive targeting through the EPR effect [1]. Active targeting methods, where surface modifications include the attachment of ligands or antibodies, allow for additional specificity against cancer cells with lower off-target effects [2].

 doi:10.20944/preprints202503.0713.v1

1.2. Targeted Drug Delivery: Evolution

Traditional chemotherapy is nonselective and tends to produce toxic side effects. Nanotechnology-based drug delivery techniques have surpassed the limitation by maximizing pharmacokinetics and minimizing toxicity. Early studies, including the use of liposome formulations and albumin-bound paclitaxel, delivered enhanced drug retention and controlled release [3]. Advances based on stimulus-responsive nanoparticles offer site-directed delivery of a drug according to pH, temperature, or enzyme concentration and maximize therapeutic yields [4].

2. Nanoparticle-Based Drug Delivery

Nanoparticles have revolutionized drug delivery by enhancing the efficacy and selectivity of cancer treatment. Nanoscale carriers shield therapeutic agents from degradation, increase drug solubility, and allow targeted delivery to tumoral tissues with decreased systemic toxicity and better patient outcomes [5].

2.1. Liposomal Drug Delivery and Its Applications

Liposomal drug delivery systems are one of the most widely studied nanocarriers that are applied in cancer treatments. Liposomes are phospholipid bilayer vesicles that have been discovered to encapsulate hydrophobic and hydrophilic drugs. Liposomes are biocompatible and can be used to alter drug pharmacokinetics, and this has made them capable of effectively minimizing toxicity without negatively affecting therapeutic activity [5].

A few of these liposomal formulations have been approved for clinical applications. Doxil, pegylated liposomal doxorubicin formulation, prolongs the half-life of drug circulation and selectively reaches tumors by the EPR effect. This is less cardiotoxic than conventional doxorubicin therapy. Other formulations, liposomal cisplatin and paclitaxel, have demonstrated promise for enhanced drug delivery and reduced side effects [6].

Besides drug delivery, liposomes have been investigated to be utilized for application in gene therapy and vaccine use, thus attracting them to be utilized for cancer treatment. Further modification of the surface by the attachment of ligands has also increased, with increased liposomal target specificity being produced, which has become more viable for targeted drug delivery [6].

2.2. Polymeric Nanoparticles and Dendrimers Role

Polymeric nanoparticles (PNPs) are also nanocarriers with controlled and sustained release of drugs. PNPs are composed of biocompatible polymers such as poly(lactic-co-glycolic acid) (PLGA) and polyethylene glycol (PEG), which support drug stability and half-life of circulation. PNPs are designed to respond to specific physiological stimuli, and drug delivery in the tumor microenvironment [7].

Dendrimers, which are a branched polymer formed by controlled polymerization, give a certain edge in drug delivery by their defined molecular structure. Dendrimers are used for various purposes with the promise of simultaneous loading of drugs, conjugation of ligands with targeting, and imaging. Dendrimer drug formulations have been investigated to deliver chemotherapeutic drugs in a lower form of toxicity and are a new drug delivery vehicle for combination therapy [8].

Polymer nanoparticles and dendrimers are also researched for multifunctional applications, such as the co-delivery of drugs and imaging agents. Their functionality to enhance the solubility, stability, and targeting to tumors is a key priority research topic in nanomedicine research that propels the next wave of targeted anticancer therapy [8].

3. Targeted Therapeutics and Precision Medicine

Nanotechnology has also contributed remarkably to cancer therapy by drug targeting. Whereas in traditional therapies drugs target normal as well as tumoral cells, nanoparticle-based strategies

 doi:10.20944/preprints202503.0713.v1

concentrate drugs at the site of tumors in an attempt to reduce side effects resulting from systemic toxicity and to enhance therapeutic response [9].

3.1. Active vs. Passive Targeting Strategies

Nanoparticles are the cause of two primary mechanisms of targeting: passive and active targeting. Passive targeting is the use of the enhanced permeability and retention (EPR) effect in which the physical features of the tumor vasculature provide a site for the deposition of nanoparticles on the basis of leakiness and poor lymphatic drainage. The effect localizes drugs in the tumor but reduces exposure within normal tissues, improving therapeutic efficacy [9].

Active targeting has the inverse of this, though, through the activation of nanoparticle surfaces with the addition of targeting ligands such as antibodies, peptides, or small molecules. These engage with overexpressed receptors on cancer cells with improved uptake and intracellular drug delivery. Examples include nanoparticles with a coating of folic acid for folate receptor binding, which in most cancers are overexpressed [10]. Active targeting approaches have shown improved penetration of the tumor and reduced off-target toxicity and thus are especially of interest for precision medicine [10].

3.2. Stimuli-Responsive Drug Carriers for Controlled Release

Target stimulus-sensitive drug delivery systems can deliver drugs according to target stimuli in the tumor microenvironment. Internal signal-activated nanoparticles like pH, enzymes, and redox conditions or external-activated nanoparticles like temperature, light, and ultrasound release drugs. pH-sensitive nanoparticles release drugs in the acidic tumor microenvironment, for example, for targeted therapy with a reduced impact on normal cells [11].

Another emerging strategy is multi-functional nanocarriers that contain therapeutic and diagnostic functions (theranostics). These platforms enable real-time tracking of drug delivery and response of cancer, enabling more accuracy in treatment. Also, sequential release of drugs nanoparticles enable combination therapies, where various drugs are released in a controlled fashion to enhance the efficacy of treatment [12]. As investigation continues, use of intelligent nanocarriers in the clinical environment will transform cancer therapy, with improved efficacy and fewer side effects [12].

4. Recent Advancements in Nanomedicine

Cancer treatment is being transformed using nanotechnology, while further advances are still pushing forward the drug effect and the accuracy of diagnosis. Recent advances are targeting combination therapies and enhanced imaging technologies so that more effective and focused treatments are available [13].

4.1. Nanocarrier-Based Combination Therapies

Combination therapy, whereby several drugs are administered at one time, is very promising in drug resistance and in improving the effectiveness of treatment. Nanocarriers facilitate co-delivery by encapsulating various therapeutic entities in one platform with synchronized release at the tumor site [13].

For example, polymeric nanoparticles have been used for co-delivery of chemotherapeutic drugs and gene therapy elements, and it targets greater than one pathway of cancer at a time. Drug liposome combinations like paclitaxel with doxorubicin maximize synergism without diminishing toxicity. Immunocheology-mediated therapy given along with chemotherapy with immune checkpoint inhibitors is also being identified as a good method to enhance anti-cancer immune response [14].

4.2. Imaging and Diagnostic Advances

Nanotechnology is also enhancing cancer diagnosis by enhancing imaging techniques. Labeled and functionalized gold and iron oxide nanoparticles have significantly enhanced imaging resolution

 doi:10.20944/preprints202503.0713.v1

in imaging modalities such as magnetic resonance imaging (MRI) and computed tomography (CT) [15].

Targeted nanoparticles can facilitate early diagnosis of cancer with molecular imaging due to targeted biomarker identification of the tumor. Quantum dots, for instance, have improved fluorescence imaging ability in order to enable precise localization of the tumor. Therapeutic as well as imaging theranostic nanoparticles facilitate real-time drug delivery imaging as well as tumor response monitoring and pave the way for more site-specific treatment [16].

5. Challenges and Future Perspectives

While showing promising developments in nanomedicine, all these issues are still present while applying such technologies for universal clinical use. Toxicity, biocompatibility, and regulatory issues need to be addressed to effectively and safely deliver nanoparticle-based therapy [17].

5.1. Biocompatibility and Toxicity Issues

One of the most significant challenges in nanomedicine is to render the nanoparticles long-term non-toxic and biocompatible. Although most of the nanocarriers are made up of polymers and biodegradable lipids, quantum dots are experiencing some problem and also some metal-based systems in terms of toxicity as well as accumulation [17].

It has been established by research that size, shape, and surface chemistry of nanoparticles are significant parameters and they play a significant role in deciding their clearance from the body as well as their biodistribution. Polyethylene glycol (PEG) surface modification of the nanoparticles to shield them from detection by the immune system and synthesis of biodegradable carriers, which will degrade to non-toxic degradation products, are some of the processes employed to enhance biocompatibility [18].

5.2. Regulatory and Clinical Translation Issues

Despite the promise in preclinical results of nanomedicine, it is lagging in the clinic owing to regulatory issues and sophisticated manufacturing technologies. There should be proper controls such that efficacy, safety, and long-term effects of nanoparticles should be critically explored before marketing it for use in humans [19].

Scaling up the production at the nanoscale in terms of reproducibility and quality is also a concern. The performance of the nanoparticle can be influenced by the composition of the nanoparticle, and thus standardization has to be done to receive regulatory clearance. The process of production is costly, and large-scale clinical trials are absent, thus hindering extensive applications [20].

Conclusions

Nanotechnology has been a novel technique in cancer treatment, providing targeted, specific, and efficient drug delivery systems. Nanomedicine has also provided newer drug carriers including liposomes, polymeric nanoparticles, and dendrimers, which provide maximum therapeutic effect with minimal systemic toxicity. Passive and active targeting delivery systems have enhanced the delivery of the drug to the cancer site, maximizing the therapeutic impact. Stimuli-responsive smart nanocarriers with regulated drug delivery capacity will pave the way for the era of personalized medicine, yielding more efficient cancer treatments.

More sophisticated tools, such as theranostic nanoparticles and combinational therapy, have always been ahead of the line in advancing the boundary of nanomedicine by combining the therapy and diagnosis on one-platform notion. Multifunctional nanoplatforms allow real-time monitoring of tumor response and therapeutic intervention at a specific site. In addition, the amplification using nanoparticle-amplified imaging technologies has significantly improved cancer diagnosis at an early stage, which allows earlier treatment to survive longer.

 doi:10.20944/preprints202503.0713.v1

Despite these promising developments, limitations exist. Nanoparticle biocompatibility, chronic toxicity, and drug agency licensure are limitations of widespread clinical application. Streamlining large-scale manufacturing processes and optimizing nanoparticle synthesis are most important requirements for sustaining uniform and therapeutic safety of use. These must be improved to move nanomedicine from experimental research to widespread clinical application.

In future years, further nanotechnology development and interdisciplinarity studies will determine the future of precision oncology. With greater biocompatibility, better regulation conditions, and adequate clinical evidence in huge numbers, nanomedicine is able to transform cancer therapy with safer, more effective, and more potent drugs for patients worldwide.

References

1. Sengar, A. (2025). Innovations in Drug Delivery and Advanced Therapeutics. Preprints. https://doi.org/10.20944/preprints202502.0156.v1
2. Sengar, A. (2024). Precision in Practice: Nanotechnology and Targeted Therapies for Personalized Care. Preprints.
3. Sengar, A. (2025). Personalized Medicine and Nanotechnology: Transforming Modern Therapeutics. Preprints. https://doi.org/10.20944/preprints202502.0744.v1
4. Sengar, A. (2025). Advancements in Drug Delivery Systems: Targeting Strategies, Nanotechnology, and Vesicular Innovations. Preprints. https://doi.org/10.20944/preprints202502.0849.v1
5. Allen, T. M., & Cullis, P. R. (2004). Drug delivery systems: Entering the mainstream. Science, 303(5665), 1818-1822. https://doi.org/10.1126/science.1095833
6. Davis, M. E., Chen, Z. G., & Shin, D. M. (2008). Nanoparticle therapeutics: An emerging treatment modality for cancer. Nature Reviews Drug Discovery, 7(9), 771-782. https://doi.org/10.1038/nrd2614
7. Farokhzad, O. C., & Langer, R. (2009). Impact of nanotechnology on drug delivery. ACS Nano, 3(1), 16-20. https://doi.org/10.1021/nn900002m
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. Wang, A. Z., Langer, R., & Farokhzad, O. C. (2012). Nanoparticle delivery of cancer drugs. Annual Review of Medicine, 63, 185-198. https://doi.org/10.1146/annurev-med-040210-162544
10. Koo, H., Huh, M. S., Sun, I. C., Yuk, S. H., Choi, K., Kim, K., & Kwon, I. C. (2011). In vivo targeted delivery of nanoparticles for theranosis. Accounts of Chemical Research, 44(10), 1018-1028. https://doi.org/10.1021/ar2000277
11. Lammers, T., Kiessling, F., Hennink, W. E., & Storm, G. (2012). Drug targeting to tumors: Principles, pitfalls and (pre-) clinical progress. Journal of Controlled Release, 161(2), 175-187. https://doi.org/10.1016/j.jconrel.2011.09.063
12. Shi, J., Kantoff, P. W., Wooster, R., & Farokhzad, O. C. (2017). Cancer nanomedicine: Progress, challenges and opportunities. Nature Reviews Cancer, 17(1), 20-37. https://doi.org/10.1038/nrc.2016.108
13. Mitragotri, S., Burke, P. A., & Langer, R. (2014). Overcoming the challenges in administering biopharmaceuticals: Formulation and delivery strategies. Nature Reviews Drug Discovery, 13(9), 655-672. https://doi.org/10.1038/nrd4363
14. Kumar, P., & Banik, B. L. (2013). Nanotechnology-based drug delivery systems for the treatment of cancer. International Journal of Nanomedicine, 8, 4719-4730. https://doi.org/10.2147/IJN.S48924
15. Zhang, L., Gu, F. X., Chan, J. M., Wang, A. Z., Langer, R. S., & Farokhzad, O. C. (2008). Nanoparticles in medicine: Therapeutic applications and developments. Clinical Pharmacology & Therapeutics, 83(5), 761-769. https://doi.org/10.1038/sj.clpt.6100400
16. Koo, H., & Park, K. (2013). Nanotechnology in drug delivery and tissue engineering. Journal of Controlled Release, 190, 1-3. https://doi.org/10.1016/j.jconrel.2014.03.002
17. Liu, Y., & Miyoshi, H. (2007). Nanomedicine for drug delivery and imaging: A promising avenue for cancer therapy and diagnosis using targeted functional nanoparticles. International Journal of Cancer, 120(12), 2527-2537. https://doi.org/10.1002/ijc.22709

 doi:10.20944/preprints202503.0713.v1

18. 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
19. 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
20. Wang, J., & Gao, S. (2014). Advances in nanoparticle-based drug delivery systems for cancer treatment. Journal of Biomedical Nanotechnology, 10(9), 2341-2372.