Nanoparticles in Targeted Drug Delivery: Role in Early Diagnosis and Drug Discovery

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Abstract

Numerous significant advancements in our understanding of the biological mechanisms underlying the genesis of cancer have occurred in recent years. These developments have enabled the identification of promising new targets for the treatment of cancer. Oncology has been transformed by nanotechnology, which has made site-specific cancer treatments and tailored oncomedicine possible. Nanomedicines increase the effectiveness of treatment by focusing on cancer cells in the tumor microenvironment. Both organic and inorganic nanoparticles are essential for delivering drugs to tumor locations, overcoming delivery obstacles, and improving nanocarriers. By boosting medicine concentration at particular sites and reducing negative effects, targeted drug delivery improves treatment. Targeted therapies are improved, drug-NP interactions are predicted, and biomarker detection is enhanced when artificial intelligence (AI) and nanomedicines are combined. Drug delivery and cancer detection are two applications for nanomaterials like dendrimers and quantum dots. Notwithstanding developments, further study is required to improve medicine delivery and diagnostics with AI and nanoparticles. This chapter highlights the available Nano-formulated therapy in cancer treatment.

Keywords: Cancer, Nanoparticles, Artificial intelligence, Drug delivery system

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Introduction

The global burden of cancer extends beyond health implications, significantly impacting economies and vulnerable populations. In 2022, the United States alone reported 1.9 million new cancer cases, resulting in 609,360 deaths (Siegel et al., 2022). Cancer, a term encompassing a variety of diseases characterized by the transformation of normal cells into malignant ones, remains a leading global health concern, with millions of new cases annually. Its complexity, driven by factors like resistance to apoptosis, angiogenesis, and metastasis, makes it difficult to detect early, with symptoms often manifesting only after metastasis has occurred (Sethi & Kang, 2018). Although chemotherapy, radiation, and surgery are still often used to treat cancer, they have several drawbacks, such as serious side effects and the emergence of drug resistance. For example, systemic toxicity from chemotherapy can impact both diseased and non-cancerous cells, resulting in issues that are frequently permanent if not identified in time (Raghavakaimal et al., 2022).

Conventional cancer treatments, such as radiation, chemotherapy, and surgery, have significant disadvantages, especially in advanced stages. These include low bioavailability and medication toxicity (Olusanya et al., 2018). Chemotherapy often fails due to non-specific targeting and inadequate drug concentration at tumor sites. Research is being done on combination drugs with lower toxicity and synergistic effects to fight multidrug resistance. Targeted treatment still faces challenges with inefficient drug delivery to tumors, which leads to cancer cell resistance and recurrence. These difficulties underscore the need for cutting-edge cancer technology. These problems can be solved by nano-oncology, which does drug delivery, early diagnosis, and treatment by nanoparticles application (Ambrose et al., 2025).

PLGA-PEG/NR7 (for oral squamous cell carcinoma) and Ferumoxtran-10 (for MRI imaging) are two nanoparticles that have been giving increased drug entrance and target delivery. In Europe, lung, breast, and colorectal cancer cases are highly recorded (25% of all types of cancer cases) worldwide (Hofmarcher et al., 2018). Lung cancer is a major cause of cancer-related deaths in poorly developed countries globally. There are various factors that can increase cancer risks like, lack of exercise, not eating properly and smoking (Wang et al., 2015). Scientists have been developing quantum and gold dots that can diagnose and treat cancer in a more accurate and precise way (Adir et al., 2020).

Combination of nanotechnology and artificial intelligence (AI), new, precise, and cost-effective ways are opening for the treatment of cancer. Because AI brings revolution by increasing drug target delivery and synergies, quick data analysis, optimizing material characteristics, and simplifying difficult activities (Adir et al., 2020). While, in the case of nanotechnology, Ag-based and magnetic metallic NPs are treating cancer, by preventing them from growing, and enhancing their appearance during diagnosis (Mirza & Siddiqui, 2014). The fact is that due to some problems like, how NPs can stay in the body for long time, deal with various types of tumors, and reach their specific target tumor site, there is still need for further studies in order to obtain better results in cancer treatment (Mitchell et al., 2017). In order to overcome these problems, there is a need for the experts to work together, successfully link laboratory findings with practical applications, and need of innovative studies. As a result, this chapter examines the significant role that NPs play in cancer treatment, focusing especially on their potential as a targeted delivery system for tumor treatment.

Typical Cancer Treatments: Assessing Progress and Unmet Promises

The particular physiology of the diseased organ determines the choice of traditional cancer treatments, such as surgery, chemotherapy, and radiation therapy. Despite clinical success, many treatments continue to have serious limitations that restrict their efficacy (Atlihan-Gundogdu et al., 2020). There are more than 200 forms of cancer, which are categorized either by the type of cell or tissue impacted or by the site of origin, such as the breast, lung, skin, colon, or liver (Carbone, 2020). Sarcoma (from connective tissues like bone, cartilage, or muscle), leukemia (from blood cells), lymphoma and myeloma (from immune cells), carcinoma (from skin or epithelial tissues lining organs), and brain and spinal cord tumors are a few examples. The tumor stage has a major impact on the therapeutic selection, and survival results are greatly impacted by early identification. Cancer at advanced stage IV is usually treatable but incurable (Chidambaram et al., 2011).

One important feature of cancer cells is their fast division, which is the focus of conventional chemotherapy. But a lot of good cells, such as those in the digestive system, bone marrow, and hair follicles, also divide rapidly, which might have negative, non-specific side effects (Tilsed et al., 2022). Organ failure, hair loss, mucositis, immunosuppression, anemia, and thrombocytopenia are a few of these that frequently call for dose modifications, postponements of treatment, or even stopping altogether. Furthermore, solid tumors where cell development slows down close to the tumor core may respond less well to chemotherapy (Senapati et al., 2018). Chemotherapeutic drugs are quickly removed from circulation and frequently do not reach solid tumor cores, which limits their ability to interact with cancer cells. Their inability to dissolve further impairs their capacity to efficiently pass across cellular membranes (Dallavalle et al., 2020). In chemotherapy, drug resistance occurs when cancer cells create defenses against drug accumulation, such as overexpressing P-glycoprotein (Heming et al., 2022). These difficulties highlight the necessity of precise, focused treatments. The next part examines precision cancer medicine, which goes beyond traditional therapies and seeks to customize care to each patient's own genetic and molecular cancer profile for a more individualized and successful outcome.

Using Nanotechnology for Accurate Cancer Treatment

The concept of "precision medicine," popularized around 2010 and advanced by President Obama's 2015 Precision Medicine Initiative (PMI), aims to deliver tailored treatments based on individual genetic and molecular profiles (Terry, 2015). While often used interchangeably with personalized medicine, subtle differences exist, with precision medicine focusing on disease prediction and targeted prevention. This approach not only tailors treatments but also helps reduce tumor development and progression through personalized risk assessments and proactive management (Delpierre & Lefèvre, 2023). Precision medicine tailors treatments based on an individual's genetics, environment, and lifestyle, while targeted drug delivery optimizes drug distribution to disease sites, reducing off-target effects. Together, they enhance therapeutic outcomes and improve cancer treatment efficacy (Manzari et al., 2021). Table 1 gives some of the important NPs used for cancer therapy.

Targeting Nanoparticles Molecularly and Ligand-Based for Accurate Cancer Treatment

Developments in tumor biology have led to the targeting of cancer-specific proteins, oncogenes, and pathways for targeted drug delivery (Tiwari et al., 2023a). NPs offer ground-breaking approaches to cancer treatment through two targeting strategies: passive targeting, which capitalizes on the enhanced permeability and retention (EPR) effect in tumors, and active targeting, in which ligand-functionalized NPs attach to overexpressed cancer cell receptors (Khan et al., 2023). These techniques enhance receptor-mediated endocytosis, reduce off-target toxicity, and enhance tumor selectivity (Mamnoon et al., 2020). Because of their accessibility, high binding affinity, and specificity, especially in breast cancer, antibodies are frequently utilized in targeted cancer therapy (Sun et al., 2022). Their "Y" structure allows precise antigen binding. Other ligands, like small peptides and proteins, offer advantages such as low molecular weight, reduced immunogenicity, and easy production. Aptamers, synthetic DNA or RNA oligonucleotides, form 3-dimensional structures that tightly bind specific cancer cell markers (Trivedi et al., 2024). Precision medicine has thus advanced therapies targeting tumor-specific antigens, enhancing treatment specificity and effectiveness (Xu & Wang, 2015).

Prostate-specific membrane antigen (PSMA) is highly specific to prostate cancer cells and enables targeted drug delivery. PSMA-targeted nanoparticles like BIND-014, loaded with docetaxel, showed enhanced pharmacokinetics and efficacy in phase I and II trials, selectively targeting tumors with PSMA expression (Wang et al., 2022). In metastatic castration-resistant prostate cancer, BIND-014 improved survival and reduced PSA levels in a subset of patients (Von Hoff et al., 2016). Biomarkers like HER2 in breast cancer enable targeted NPs therapies. MM-302 NPs combined with trastuzumab showed improved safety in early trials but did not increase survival in phase II (HERMIONE trial). Additional targets, such as TfR and EGFR, enhance drug delivery to breast cancer cells, with promising preclinical results, though clinical trials are pending for some NPs (Kumari et al., 2016).

Integrated Cancer Screening and Treatments Using Nanoparticles

Nanotheranostics integrates nanotechnology for personalized cancer imaging and therapy, improving detection, staging, and treatment monitoring (Murar et al., 2022). NPs target tumor cells, deliver higher drug doses with fewer side effects, and track treatment progress. Silica

NPs (C-dots) labeled with 124I PET and Cy5 optical agents showed safety and rapid renal clearance in metastatic melanoma patients (Phillips et al., 2014). Oncogenic biomarkers, including proteins, carbohydrates, and nucleic acids, help detect cancer, predict relapse, and monitor treatment (Das et al., 2023). Protein biomarkers are found by converting signals utilizing QD-based biosensors and interacting with antibodies or aptamers (Kim & Yoo, 2021). Colorectal, liver, prostate, and ovarian cancers are detected using biomarkers such as CEA, AFP, PSA, and CA-125, and lateral flow procedures are made easier by QD-conjugated aptamers and silica NPs (Gumus et al., 2023).

Table 1: Nanoparticle-Encapsulated Drugs for Targeted Cancer Therapy: Current Systems and Limitations

Sr. No	Drug Name	Nanoparticle Type	Active Drug	Cancer Type	Biological Application	Disadvantage	Refrences
1	Linalool Encapsulated Solid Lipid NPs	Solid Lipid NP	Linalool	Hepatocellular carcinoma (HepG2), lung cancer (A549)	Anti-cancer efficacy	Uncertain gelation, low incorporation due to the crystalline nature	(Misra & Sahoo, 2010)
2	PCL-Tween80 Polymeric NP	Polymeric NP	-	General anti-tumor	Improved anti-tumor efficacy	Lack of in vivo studies	(Ma et al., 2011)
3	C225 Antibody Conjugated AuNP	Gold NP	-	Hepatocellular carcinoma	Noninvasive radiofrequency-based treatment	Limited radiofrequency absorption	(Raoof et al., 2012)
4	CD44 Antibody Targeted Liposomal NP	Liposomal NP	-	Hepatocellular carcinoma	Imaging and therapy	Low specificity and efficacy	(Wang et al., 2012)
5	Mit-Loaded Liposome (Mit-GML)	Liposomal NP	Mitomycin	Breast cancer (MCF-7)	Image-guided targeted therapy	Reduced cytotoxicity vs. free drug	(He et al., 2014)
6	HPTOC-DOX Polymeric Micelle	Polymeric Micelle	DOX	General anti-cancer	Enhanced anti-cancer efficacy	Low uptake, short shelf life	(Nam et al., 2015)
7	PP-SS-DTX/DTX Polymeric	Polymeric Micelle	Docetaxel	Breast (MCF-7), melanoma (B16F10)	Anti-cancer activity	Delayed release	(Guo et al., 2016)
8	Curcumin Loaded PMMA-PEG/ZnO	Polymeric NP	Curcumin	Gastric cancer	Anti-angiogenic, anti-proliferative	Limited solubility and stability	(Dhivya et al., 2017)
9	Anti-CD147 Immunoliposomal DOX	Liposomal NP	DOX	Hepatocellular carcinoma	Targeting CD147 overexpressing cells	High production cost, complex synthesis	(Wang et al., 2018)
10	DOPE/CHEMS-based DTX Immunoliposomes	Liposomal NP	Docetaxe	Prostate cancer	Targeted delivery of DTX	Limited cytotoxicity	(Wang et al., 2018)
11	YIGSR-CMCht/PAMAM Dendrimer NP	Dendrimer NP	-	Colorectal cancer	Targeted therapy	Limited validation of affinity	(Carvalho et al., 2019)
12	ICG-Loaded PEGylated BSA-Ag NP	Silver NP	ICG	General photothermal therapy	Photothermal cancer treatment	Ineffective at low concentrations	(Park et al., 2020)
13	TT3-oCB NP@EXOs Exosomal NP	Exosomal NP	-	General tumor treatment	Image-guided photothermal therapy	Toxic degradation products	(Li et al., 2021)
14	Aspergillus Austroafricanus CGJ-B3 AgNP	Silver NP	-	Breast (MCF-7), skin (A431), liver (HepG2)	Antioxidant and cytotoxic against ROS and RNS	Limited toxicity studies in vivo/in vitro	(Danagoudar et al., 2021)
15	Amygdalin Loaded AgNP Chitosan Microcapsules	Silver NP in Chitosan	Amygdalin	Breast cancer	Targeted amygdalin delivery	Lower cytotoxicity vs. free AgNP	(Pandey et al., 2021)
16	Doxil	Liposomal NP	Doxorubicin	Ovarian, Kaposi's sarcoma, Multiple myeloma	Cancer treatment	Costly and complex formulation	(Shafei et al., 2017)
17	Myocet	Liposomal NP	Doxorubicin	Metastatic breast cancer	Anti-tumor therapy	Limited release control	(Batist et al., 2002)
18	Onivyde	Liposomal NP	Irinotecan	Metastatic pancreatic cancer	Tumor-targeted chemotherapy	High production costs	(Ko, 2016)

19	Daunoxome	Liposomal NP	Daunorubicin	HIV-associated Kaposi's sarcoma	AIDS-related Kaposi's sarcoma treatment	Limited tissue penetration	(van Hoogevest et al., 2021)
20	Vyxeos	Liposomal NP	Daunorubicin, Cytarabine	Acute myeloid leukemia	Leukemia treatment	High production cost, limited specificity	(Hristova-Panusheva et al., 2024)
21	Ameluz	Liposomal NP	5-Aminolevulinic acid	Actinic keratosis	Targeted skin cancer therapy	Photosensitivity post-treatment	(Hristova-Panusheva et al., 2024)
22	Abraxane	Polymeric NP	Paclitaxel	Breast, non-small cell lung, pancreatic cancers	Chemotherapy with reduced toxicity	Expensive manufacturing	(Master & Sen Gupta, 2012)
23	Genexol-PM	Polymeric NP	Paclitaxel	Breast, non-small cell lung, ovarian cancers	Targeted anti-tumor therapy	High cost, lack of long-term studies	(Pillai, 2014)
24	NKTR-102	Polymeric NP	Irinotecan	Breast, ovarian, colorectal cancers	Tumor-targeted chemotherapy	Tumor-targeted chemotherapy	(Tripathy et al., 2019)
25	Opaxio	Polymeric NP	Paclitaxel	Lung, ovarian, cervical cancers	Targeted chemotherapy	Potential toxic side effects	(Cryer & Thorley, 2019)

Cancer has been connected to the downregulation of microRNAs (miRNAs) that maintain gene expression and cellular functions. Oncogenic viruses can accelerate the formation of growth of cancer by altering the regulation of miRNA (Kandeel, 2023). AuNPs@NIPAm-co-AAc microgel composites and SERS (Nanotechnology platforms) enable the accurate detection of miRNA biomarkers, such as miR-21 and miR-29a (Kamali et al., 2024). Circulating miRNAs present the possibility of correct early treatment and diagnostic monitoring (Treerattrakoon et al., 2022). Circulating tumor cells (CTCs) and circulating tumor DNA (ctDNA) enter the blood circulation as cancer cells expand, helping in successful diagnosis. One important target for liquid biopsy is the surface protein EpCAM on CTCs. For example, the nanotechnologies NG-PEI-COFTAPB-TFPB and Fe-MOF enhance the immunoassay's sensitivity and ctDNA identification (Guo et al., 2022). Microfluidic chips, 30 times quicker than ELISA, giving effective, cost-effective, and low-energy detection (Wang et al., 2021). CoZnFeONPs and other nanotechnology-based immunoarray devices aid in detecting biomarkers. By putting together enzyme-mediated nanoparticles, they are also utilized to find cancer biomarkers and CEA antigens (Yin et al., 2021). Multiplexed imaging is made feasible by semiconductor quantum dots (QDs), which also enable enhanced tissue penetration, photostability, and brightness, primarily for cancer detection (Mousavi et al., 2022). While PEGylated QDs linked with monoclonal antibodies specifically target tumor tissue, surface-modified CdTe QDs increase anti-tumor therapeutic action (Liang et al., 2021).

Nanomaterial-based Formulations for Reversing Multidrug Resistance

Drug resistance, driven by factors like ABC transporter overexpression and tumor microenvironment conditions, limits chemotherapy effectiveness (Sajid et al., 2023). Nanotechnology, including P-GP inhibitors and mesoporous silica NPs, enhances drug delivery and overcomes resistance, even crossing the blood-brain barrier. Selenium- and tellurium-based NPs also show promise in reversing multidrug resistance, improving treatment outcomes (Domínguez-Álvarez et al., 2022). Cancer drug resistance often results from defective apoptosis and dysregulated Bcl-2 and NF-κB pathways. Targeting Bcl-2 with chemotherapeutic drugs and siRNA delivery via NPs, along with pro-apoptotic agents like rubusoside and C6-ceramide, enhances therapy (Sankar et al., 2025). Restoring p53 function using NP-based delivery methods also shows promise in overcoming resistance, especially in lung and breast cancers (Jafari-Gharabaghlou et al., 2023). Gene delivery via viral vectors faces challenges in efficiency and targeting, while nanovehicles offer a safer alternative for cancer gene editing. CRISPR/Cas9, delivered through engineered nanosystems, outperforms Bcl-2 inhibitors and RNAi in targeting oxidative stress and triggering apoptosis. Combining CRISPR/Cas9 with immunotherapy, such as CD47 blockage and IL-12 generation, enhances cancer treatment efficacy (Coelho et al., 2022).

AI's Broad Application in Nanomedicine

AI encompasses machine learning, deep learning, computer vision, and NLP, enabling human-like intelligence in complex tasks. In biomedical research, AI accelerates drug discovery and pharmaceutical operations, aiding in compound identification and compliance. In nanotechnology, AI supports scanning microscopy and simulations, with ANN enhancing spectroscopic analysis and material behavior identification (Zohuri, 2020).

Use of AI techniques has been increasingly used to resolve nanotechnology issues, with a focus on creating nanocomputing, useful nanoscale stimulation to decrease processing time, nanosystems, and improve parameter accuracy and estimation (Elemento et al., 2021). AI increases the medical efficacy of drug delivery, facilitating processes such as preparation, customized transport, and stability of bioactive components (Liao et al., 2023). Modern developments in AI assist in the development, characterization, and formation of drug delivery nanosystems through the analysis of biological and genetic data to accelerate drug development and estimate drug behaviors (Sherani et al., 2024). By evaluating immense databases, especially patient DNA and molecular profiles, AI creates customized treatments for cancer. In addition, artificial intelligence accelerates pharmacokinetic modeling and offers more customized dispersion across complicated biological barriers by incorporating various kinds of inputs, like drug and molecule interactions (Cheng & Zhao, 2014).

Cancer biomarkers are important for prognosis, surveillance, risk assessment, diagnosis, and therapeutic response in oncology (Das et al., 2023). Genetic and protein examinations aid in discovering the best medicines, and diverse biomarker profiles permit customized care. To accurately treat cancers without harming healthy tissues, nanomaterials that boost drug delivery the selectivity, and biomarker detection, such

as gold nanoparticles and quantum dots, are crucial (Sajid et al., 2023). Real-time studying of the distribution of drugs and efficiency becomes possible by outstanding imaging, which is crucial for treatment planning. AI-enhanced NP tracking devices, like Malvern's NTA, facilitate imaging and evaluation, providing individualized care and boosting the impact of nanomedicine (Zdobnova et al., 2011).

Advances in nanorobotics now allow microrobots to perform tasks like targeted drug delivery, cellular targeting, and microsurgeries, though challenges in design and biocompatibility remain (Taha et al., 2024). A recent study showcased mesoporous silica NPs with urease and gold NPs functioning as radiolabeled nanomotors, enabling PET imaging for real-time tracking and new therapeutic possibilities (Neague et al., 2024). Nanorobots' integration of AI, sensors, and power sources has improved molecular production even further. AI simulations enhance the design of nanorobots for regulated medication delivery; DNA-based nanorobots exhibit potential for accurate drug delivery and biosensing (Kong et al., 2023). Artificial neural networks enhance tumor detection, while fuzzy logic optimizes intracellular dosing for greater precision (Hassanzadeh et al., 2019).

Nanomedicine has both benefits and drawbacks, even while technological developments, particularly artificial intelligence, have accelerated drug development and optimization (Tiwari et al., 2023b). The consequences of increased permeability and retention (EPR), toxicity, dose accuracy, drug system design, and biocompatibility are all significant factors to take into account. Precise drug administration in nanorobotics is difficult due to issues including noise interference and the ability to distinguish between healthy and malignant cells (Giri et al., 2021). However, by evaluating complex data, improving drug development, and guaranteeing precise dose delivery, AI can assist in resolving these problems (Hassanzadeh et al., 2019). Artificial intelligence (AI) is especially important for genetic programming and cancer genomics, where techniques like fuzzy logic, decision trees, and artificial neural networks (ANNs) aid in the identification of new drugs (Quazi, 2022). Artificial neural networks (ANNs) are excellent at classification and prediction, fuzzy logic improves automated medication scheduling, and supervised associating networks enable response surface techniques. In silico medicine, reinforcement learning is beneficial and might adapt (Mak & Pichika, 2019).

Conclusion

AI-powered strategies enhance medication targeting and biomarker identification, resulting in a more customized treatment regimen. The study highlights the expanding use of cutting-edge nanoparticles that improve therapeutic efficacy and clinical imaging capabilities, such as dendrimers and quantum dots. The concept of nanotheranostics, which combines therapeutic and diagnostic qualities in nanoparticles, enables real-time treatment progress monitoring. Additionally, it has been shown that the production of nanoparticles functionalized with ligands improves the precision of targeting for specific cancer receptors. Despite these advancements, problems with multidrug resistance and ensuring effective tumor accumulation still exist, necessitating additional development of therapies based on nanoparticles.

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