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Review Article

NANOTECHNOLOGY APPLICATIONS IN CANCER RESEARCH: A COMPREHENSIVE REVIEW OF THERAPEUTIC AND DIAGNOSTIC ADVANCES

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ABSTRACT

Nanotechnology has emerged as a transformative approach in cancer diagnosis and therapy, offering precise drug delivery, early detection, and multimodal treatment strategies. The integration of nanoscale materials with molecular oncology enables the development of targeted and stimuli-responsive systems capable of overcoming biological barriers and minimizing systemic toxicity. This review highlights recent advancements in the field of cancer nanomedicine, focusing on passive and active targeting, nanotheranostics, and nano-immunotherapy. The discussion encompasses liposomal, polymeric, and metal-based nanoparticles designed for both therapeutic and diagnostic purposes. Furthermore, the paper outlines translational challenges such as bio-distribution variability, regulatory constraints, and clinical safety. Overall, nanotechnology continues to bridge the gap between experimental oncology and personalized medicine, representing a pivotal direction in future cancer management and drug design.

Keywords: Nanotechnology, Nanomedicine, Cancer therapy, Drug delivery, Theranostics, Immuno-nanotechnology.

INTRODUCTION

Cancer remains one of the leading causes of morbidity and mortality worldwide, demanding innovative strategies for its effective management. Conventional chemotherapy and radiotherapy are often associated with non-specific toxicity, poor bioavailability, and drug resistance. To address these limitations, nanotechnology has evolved as a multidisciplinary field integrating materials science, molecular biology, and pharmacology to develop nanoscale systems for precise cancer diagnosis and therapy. Nanomedicine offers unique advantages due to its ability to exploit the Enhanced Permeability and Retention (EPR) effect, enabling preferential accumulation of nanoparticles in tumor tissue. Moreover, surface-engineered nanocarriers provide targeted delivery through ligands that recognize overexpressed receptors on cancer cells, reducing systemic side effects. Recent advancements have expanded nanotechnology applications beyond drug delivery to include diagnostic imaging, gene therapy, immunotherapy, and theranostics, thereby transforming traditional cancer treatment into a personalized, patient-centered approach.

Nanomedicine and Tumor Targeting Strategies

Recent studies highlight the evolution of nanomedicine as a cornerstone in modern cancer therapy, enabling targeted delivery and enhanced bioavailability of therapeutic agents. Fan *et al*. and Wang *et al*. reported that nanoparticles exploit the Enhanced Permeability and Retention (EPR) effect, allowing passive accumulation within tumor tissue. However, active targeting using ligands such as folic acid, peptides, and antibodies has emerged to improve specificity and reduce systemic toxicity. Giri *et al*. and Nirmala *et al*. reviewed that polymeric, metallic, and lipid-based

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nanocarriers improve pharmacokinetic profiles and reduce multidrug resistance in cancer cells.

Smart Nanomaterials and Functionalized Nanocarriers

Advancements in smart nanomaterials have revolutionized tumor-specific drug delivery and stimuli-responsive release. Kashyap and Sun *et al*. discussed pH-sensitive and thermo-responsive nanoparticles that release drugs selectively in the tumor microenvironment. Springer-based reviews emphasized self-assembling nanoparticles with improved stability and biocompatibility. Nirmala and Aloss demonstrated that surface functionalization of liposomal nanocarriers enhances circulation time and therapeutic efficacy. Recent studies on liposomal formulations such as Onivyde and Doxil have validated these improvements in preclinical and clinical phases.

Nanoparticles in Cancer Immunotherapy

Immuno-nanomedicine has become an emerging field bridging nanotechnology with cancer immunology. Gong *et al*. and Balakrishnan *et al*. highlighted how nanocarriers facilitate T-cell activation**,** antigen presentation**,** and checkpoint inhibition for effective tumor suppression. Yang *et al*. demonstrated multifunctional gold nanoparticles enhancing both diagnostic imaging and immune modulation. Est-Witte *et al*. described nanoparticles as delivery vectors for tumor antigens to generate antigen-specific cytotoxic T-cells. Wang *et al*. predicted that nano-immunotherapy will dominate next-generation cancer therapeutics due to its capability to overcome immune evasion mechanisms.

Theranostic Nanoplatforms for Cancer Diagnosis and Therapy

Theranostics integrating therapy and diagnostics has gained prominence in cancer nanotechnology. Fernandes and Dutta Gupta reviewed metal-based and mesoporous silica nanoparticles capable of simultaneous imaging and drug delivery. Chavda *et al*. and Khorasani *et al*. demonstrated how metallic nanotheranostics (gold, iron oxide, and gadolinium nanoparticles) provide precise tumor localization through MRI and fluorescence imaging. Azimizonuzi *et al*. and Mao *et al*. discussed the incorporation of precision nanomedicine principles in personalized cancer treatment, enabling real-time monitoring of drug distribution. Hu emphasized translational perspectives for these platforms, encouraging data-driven designs that meet clinical regulatory standards.

Liposomal and Polymeric Nanocarriers

Liposomal nanocarriers remain one of the most clinically validated nanoparticle systems. Aloss and Milano provided comprehensive insights into liposomal irinotecan (Onivyde) and other lipid-based delivery systems that have reached FDA approval. Kizhakkanoodan and Kumar discussed polymeric nanoparticles such as PLGA and PEGylated systems**,** which improve controlled drug release and tumor accumulation. These nanoformulations enhance pharmacokinetics, reduce off-target toxicity, and are suitable for combination therapies with chemotherapeutic or immunotherapeutic agents.

Metal-Based Nanoparticles and Imaging Applications

Metal-based nanoparticles have gained traction due to their dual imaging and therapeutic functionality. Fernandes and Khorasani reviewed gold, silver, and magnetic nanoparticles as photothermal and photoacoustic agents for non-invasive tumor ablation. Chavda *et al*. demonstrated the diagnostic sensitivity of these systems in *in vivo* imaging studies. Bhatia further emphasized translational challenges, focusing on biosafety, long-term accumulation**,** and regulatory limitations in metal-based nanomedicine.

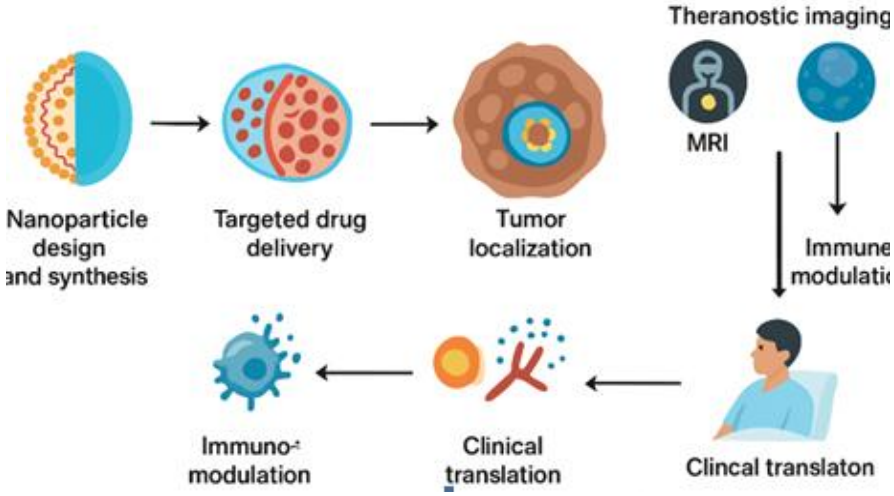

Figure 1. Overview of Nanotechnology Applications in Cancer Therapy and Diagnosis.

NANOTECHNOLOGY- BASED CANCER DRUG DELIVERY SYSTEMS

Nanotechnology-based drug delivery systems have revolutionized cancer therapy by improving the specificity, stability, and therapeutic index of anticancer agents. They allow site-specific delivery and sustained drug release, minimizing systemic toxicity while enhancing therapeutic efficacy. The mechanisms of tumor targeting primarily operate through passive targeting**,** active targeting**,** and enhanced tissue penetration mechanisms.

Passive Tumor Targeting (EPR Effect)

Passive targeting exploits the Enhanced Permeability and Retention (EPR) effect a hallmark of solid tumors that exhibit leaky vasculature and poor lymphatic drainage. Nanoparticles of 100–200 nm size preferentially accumulate within tumor tissues, allowing for enhanced local drug concentration compared to normal tissues. Liposomes, polymeric micelles, and dendrimers have demonstrated significant EPR-mediated drug accumulation in experimental tumor models. However, the EPR effect is often heterogeneous across tumor types and influenced by tumor vascularization, interstitial pressure, and nanoparticle surface charge.

Active Targeting Mechanisms

Active targeting involves surface modification of nanoparticles with ligands such as monoclonal antibodies, peptides, aptamers, folic acid, or transferrin, which selectively bind to receptors overexpressed on cancer cells (e.g., HER2, EGFR, folate receptors). This receptor-mediated endocytosis enhances cellular internalization and drug uptake. Examples include *trastuzumab-conjugated liposomes* targeting HER2-positive breast cancer and *RGD peptide-decorated nanoparticles* targeting integrin receptors in tumor vasculature. Active targeting improves selectivity and can overcome multidrug resistance, although challenges remain in maintaining ligand stability and receptor saturation thresholds.

Transport Across Tissue Barriers

Effective cancer therapy requires nanoparticle penetration across multiple biological barriers vascular, stromal, and cellular. Nanocarriers must evade immune clearance (RES uptake), navigate through extracellular matrices, and penetrate dense tumor stroma. Surface PEGylation improves circulation time and reduces opsonization. Additionally, stimuli-responsive nanoparticles (pH, redox, enzyme, or temperature-triggered) have been developed to release drugs selectively in the tumor microenvironment. Advances in nanoengineering now focus on multistage delivery systems and cell-penetrating peptides (CPPs) to improve intratumoral diffusion and deep tissue transport.

RECENT ADVANCES AND CLINICAL APPLICATIONS

Liposomal Nanocarriers

Liposomal formulations such as Doxil® (liposomal doxorubicin) and Onivyde® (liposomal irinotecan) remain the most successful clinically approved nanomedicines. They offer improved pharmacokinetics, reduced cardiotoxicity, and prolonged circulation time. Current research focuses on dual-drug liposomes and stimuli-responsive liposomes that release drugs under specific tumor microenvironment conditions.

Gold and Magnetic Nanoparticles for Imaging and Therapy

Gold nanoparticles (AuNPs) serve dual roles as therapeutic and diagnostic tools. Their high atomic number makes them ideal for photothermal therapy (PTT) and computed tomography (CT) contrast enhancement**.** Magnetic nanoparticles (Fe_3O_4)**,** on the other hand, facilitate magnetic resonance imaging (MRI) and magnetically guided drug delivery**,** allowing simultaneous imaging and localized treatment (theranostics).

Nano-Immunotherapy

Nano-immunotherapy integrates nanomaterials with immunological strategies to stimulate or modulate immune responses. Nanocarriers can deliver tumor antigens, adjuvants, or checkpoint inhibitors, enhancing T-cell activation and immune recognition of cancer cells. For instance, lipid-based nanoparticles delivering *PD-L1 siRNA* have demonstrated tumor regression in preclinical models. This domain represents the convergence of immunology and nanotechnology for next-generation cancer therapies.

Theranostics: Dual Therapy and Diagnosis

Theranostic nanoplatforms combine therapeutic and imaging functionalities within a single nanostructure. Quantum dots, silica nanoparticles, and mesoporous nanocarriers are being developed for *real-time tracking of drug release and tumor response*. Such systems enable personalized therapy optimization and early detection of treatment resistance.

RESULTS AND DISCUSSION

The collective findings from recent studies demonstrate that nanotechnology-based systems significantly enhance cancer treatment outcomes compared to conventional therapies. Nanocarriers improve drug solubility, bioavailability, and site-specific accumulation**,** achieving superior tumor suppression and reduced off-target toxicity. Comparative analyses reveal that active targeting nanoparticles outperform passive systems in terms of cellular uptake efficiency and therapeutic precision. However, passive EPR-based accumulation still serves as the foundational mechanism in solid tumor targeting.

Hybrid strategies integrating both approaches are now being explored to maximize tumor penetration.

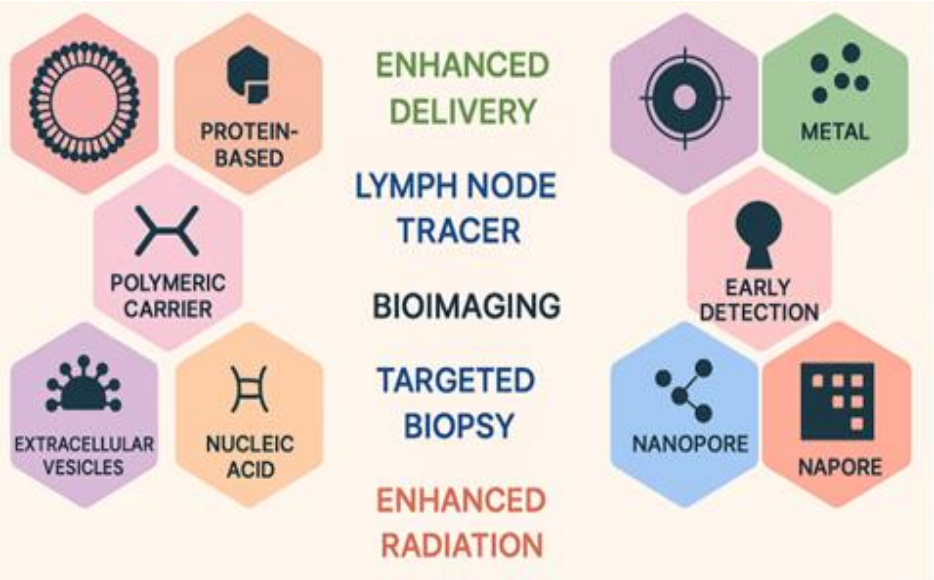

Figure 2. Clinical applications of Nanomaterials.

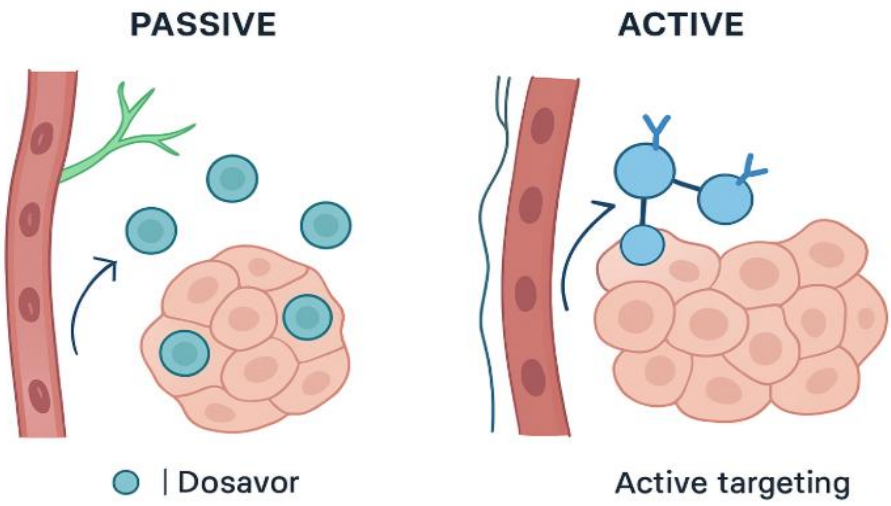

Figure 3. Tumor targeting.

Despite encouraging results, limitations persist. The biodistribution variability, immune recognition, and potential long-term toxicity of some inorganic nanoparticles remain critical concerns. Clinical translation also faces barriers such as scale-up synthesis, cost, and regulatory standardization. Nevertheless, FDA-approved nanomedicines (Doxil, Onivyde, Abraxane) validate the clinical potential of nanotechnology in oncology. Ongoing trials continue to explore theranostic agents and nano-immuno modulators, indicating a strong trajectory toward precision nanomedicine.

CONCLUSION

Nanotechnology has established itself as a cornerstone of modern oncology, bridging the gap between molecular biology and clinical therapeutics. The multifunctional capabilities of nanoparticles including targeted delivery,

imaging, and immune modulation make them invaluable for personalized and minimally invasive cancer treatment. Future research should focus on Molecular-level understanding of nanoparticle–cell interactions.AI-driven nanoinformatics for predictive drug design. Integration of omics-based diagnostics for precision nanotherapy. Toxicological and pharmacokinetic standardization for clinical safety. Development of biodegradable and patient-specific nanocarriers**.** The convergence of artificial intelligence, bioengineering, and nanomedicine promises to accelerate the translation of nano-oncology from experimental models to effective, patient-centered therapies. With continued innovation and regulatory collaboration, nanotechnology is poised to redefine cancer diagnosis and treatment in the coming decade.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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