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NANOMEDICINE-ENABLED CANCER IMMUNOTHERAPY: EMERGING STRATEGIES IN DRUG DEVELOPMENT, MECHANISTIC INSIGHTS, AND CLINICAL PERSPECTIVES

SUNITHA THALUGULA[1], SRIJA REDDY BOLINCHERUVU[2], RAJENDRA PRASAD RAMSHETTY[3], RAJ KUMAR VENISETTY[4]*

[1]University College of Pharmaceutical Sciences, Kakatiya University, Hanamkonda - 506009, Telangana.
[2]School of Pharmacy, Anurag University, Hyderabad-500088, Telangana.
[3]Vaagdevi Pharmacy College, Bollikunta, Warangal - 506005, Telangana.
[4]Jyothishmathi Institute of Pharmaceutical Sciences, Karimnagar-505527, Telangana.

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***Corresponding Author**
Dr. Raj Kumar Venisetty

Abstract

Nanomedicine has emerged as a transformative approach in oncology, integrating nanoscale engineering with immunotherapeutic strategies to address the limitations of conventional cancer treatments. This chapter critically examines the role of nanomedicine in enhancing the specificity, therapeutic efficacy, and safety of cancer immunotherapy. Nanocarriers, typically engineered within the nanoscale range, possess tunable physicochemical properties, high surface-area-to-volume ratios, and versatile surface-functionalization capabilities. These characteristics facilitate targeted drug delivery, improve the solubility and bioavailability of therapeutic agents, optimize release kinetics, and enhance interactions with tumor cells and immune components. The chapter explores the integration of nanomedicine with immune checkpoint blockade, monoclonal antibodies, chimeric antigen receptor T-cell (CAR-T) therapy, oncolytic virotherapy, and cancer vaccines. Through enhanced antigen delivery, improved antigen-presenting cell activation, modulation of immunosuppressive tumor microenvironments, and coordinated co-delivery of immunomodulators, nanomedicine platforms can potentiate antitumor immune responses while minimizing off-target toxicity. Advanced formulations, including liposomes, polymeric nanoparticles, lipid nanoparticles, and stimuli-responsive nanocarriers, offer opportunities for spatiotemporally controlled therapeutic release in response to tumor-associated physicochemical and enzymatic cues. Furthermore, emerging theranostic platforms may integrate diagnostic imaging, therapeutic delivery, and immune modulation to support treatment monitoring and personalized therapeutic strategies. Despite substantial progress, clinical translation remains constrained by biological heterogeneity, variable nanoparticle biodistribution, immune-related adverse effects, tumor immune evasion, manufacturing scalability, regulatory complexity, and limited predictive biomarkers. Addressing these challenges requires rigorous preclinical validation, optimized formulation design, robust clinical evaluation, and patient-stratification approaches. Overall, the convergence of nanomedicine and cancer immunotherapy represents a promising paradigm for developing precision-oriented, multimodal therapeutic interventions with the potential to improve clinical outcomes and advance personalized cancer care.

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INTRODUCTION

Introduction to Nanomedicines and Immunotherapy

Nanomedicine integrates nanotechnology with medical science to improve disease prevention, diagnosis, monitoring and treatment. It employs engineered materials and devices with nanoscale features, frequently within the 1–100 nm range, although many clinically relevant nanocarriers are larger. Compared with bulk materials, nanostructures may exhibit different surface reactivity, optical behaviour, solubility and interactions with biological membranes. These properties support the development of advanced drug-delivery systems, imaging agents, diagnostic platforms and multifunctional therapeutic formulations [1,2]. In oncology, nanomedicine is particularly valuable because conventional cytotoxic agents may have limited aqueous solubility, unfavorable pharmacokinetics and dose-limiting toxicities. Nanocarriers can protect active compounds, alter their circulation and tissue distribution, and regulate drug release. However, improved delivery is formulation- and disease-dependent; nanoscale dimensions alone do not guarantee tumor specificity or clinical benefit.Cancer immunotherapy aims to mobilize innate or adaptive immunity against malignant cells. Its integration with nanomedicine creates opportunities to deliver tumor antigens, immune agonists, nucleic acids and other agents to selected tissues or immune-cell populations. This chapter summarizes

nanoparticle design, major immunotherapeutic strategies, mechanisms of tumor targeting and immune modulation, and the translational challenges associated with combining both fields [3,4].

Definition and Principal Applications of Nanomedicine

Nanomedicine describes medical applications of nanomaterials and nanoscale engineering, including therapeutic carriers, diagnostic sensors, contrast agents and regenerative scaffolds. A high surface-area-to-volume ratio permits extensive chemical functionalization and interactions with proteins and cells, but can also increase unintended biological reactivity. Nanomaterial performance therefore depends on composition, size distribution, shape, surface charge, coating, dose and route of administration [1,2].

Targeted drug delivery is a central application. Liposomes, polymeric nanoparticles and related carriers can encapsulate poorly soluble drugs, reduce premature degradation and control exposure to healthy tissues. Active targeting uses surface-bound ligands to promote interaction with selected receptors; passive accumulation depends on physiological transport and clearance. Neither approach produces completely selective distribution.Other important applications include nanosensors for disease biomarkers, nanostructured imaging agents, regenerative biomaterials and theranostics. Theranostic systems combine diagnostic and therapeutic functions to facilitate treatment selection or monitoring. In cancer care, these approaches may support individualized interventions, provided their analytical performance, manufacturing reproducibility, pharmacokinetics and safety are established [3,4].

Overview of Cancer and Its Classification

Cancer comprises heterogeneous diseases characterized by dysregulated cell proliferation, invasion and, in malignant cases, the capacity for metastasis. Genetic and epigenetic changes affecting growth regulation, DNA repair, apoptosis and immune surveillance contribute to tumor initiation and progression. The biological behaviour of a cancer depends on its tissue of origin, molecular alterations, stage and interaction with surrounding stromal and immune cells [5,6].Carcinomas arise from epithelial tissues and include adenocarcinomas, squamous-cell carcinomas and urothelial carcinomas. Sarcomas develop from mesenchymal tissues such as bone, muscle, fat and connective tissue. Leukemias involve hematopoietic cells, whereas lymphomas arise from lymphoid cells and include Hodgkin and non-Hodgkin subtypes. Melanoma originates from melanocytes and can occur in the skin or other sites. These categories contain biologically distinct subtypes with different treatment needs [7,8].

Conventional management includes surgery, radiotherapy, chemotherapy, endocrine treatment and molecularly targeted agents. Selection depends on tumor type, extent of disease, biomarker status and patient condition. Although these modalities remain essential, recurrence, resistance, systemic toxicity and interpatient variability have driven interest in immunotherapy and improved drug-delivery technologies.

Evolution of Cancer Treatment: Cancer treatment evolved from predominantly local surgery to integrated strategies that address both primary lesions and systemic disease. Advances in anesthesia, imaging and surgical technique improved resection and perioperative outcomes. Radiotherapy became an important local and regional modality, while cytotoxic chemotherapy expanded the treatment of disseminated cancers. Each approach offers substantial benefit in appropriate settings but may damage healthy tissue and can be limited by intrinsic or acquired resistance [9–11].Molecular oncology subsequently enabled therapies directed against defined alterations, including HER2 and BCR–ABL. Genomic profiling and biomarker-based selection have improved treatment matching for some tumor types. Immunoth therapy introduced another major shift by enhancing antitumor immune responses rather than exclusively targeting malignant cells directly. Immune checkpoint blockade and engineered cell therapies can produce durable responses in selected patients [12–14].Current oncology increasingly uses multidisciplinary combinations of surgery, radiation, systemic drugs and immune-based approaches. Research priorities include early detection, reliable predictive biomarkers, improved access, reduced treatment toxicity and rational combination regimens. Nanomedicine contributes chiefly by changing the delivery, distribution and release of therapeutic or diagnostic payloads, not by replacing established clinical decision-making.

Introduction to Cancer Immunotherapy: Cancer immunotherapy employs components of the immune system to recognize, control or eliminate malignant cells. Antitumor responses depend on antigen release, processing and presentation, T-cell priming, trafficking to tumors and successful effector activity. Tumors may disrupt these steps by reducing antigen presentation, expressing inhibitory ligands or recruiting immunosuppressive cells. Immunotherapies attempt to restore or amplify one or more stages of this response [15,16].

Important modalities include immune checkpoint inhibitors, monoclonal antibodies, therapeutic cancer vaccines, adoptive cell therapies, cytokines and oncolytic viruses. Checkpoint inhibitors block inhibitory signaling through pathways such as PD-1/PD-L1 or CTLA-4. CAR T-cell therapies introduce engineered antigen receptors into T cells and have established roles in selected hematological malignancies. Therapeutic vaccines aim to induce or strengthen antigen-specific immunity, while oncolytic viruses can combine direct tumor destruction with immune stimulation.Responses differ considerably across cancers and patients. Some treatments produce prolonged disease control, whereas others fail because of poor T-cell infiltration, tumor heterogeneity or adaptive resistance. Immune-related toxicities are also clinically important. Nanocarrier strategies are being investigated to improve the spatial and temporal delivery of immune modulators and reduce unnecessary systemic exposure.

ROLE OF NANOMEDICINES IN MODERN ONCOLOGY

Nanomedicine supports modern oncology through formulation improvement, controlled delivery, molecular imaging and combination treatment. Encapsulation can enhance the apparent solubility and stability of hydrophobic anticancer agents, alter their release kinetics and reduce exposure to certain vulnerable tissues. Clinically used liposomal formulations demonstrate the value of formulation engineering, although therapeutic superiority must be evaluated separately for each product and indication [17,18].

Nanoparticles can also carry imaging probes or contrast agents for tracking disease and treatment distribution. Theranostic systems seek to integrate therapy with imaging or biomarker detection, potentially informing dose optimization and treatment response. For immune-based interventions, particles may carry tumor antigens, adjuvants, cytokines, nucleic acids or drugs that remodel the tumor microenvironment.An important limitation is that tumor delivery is heterogeneous. Abnormal vascular permeability, extracellular matrix density, blood flow and phagocytic clearance can all influence deposition. The enhanced permeability and retention effect observed in some experimental tumors is inconsistent across human cancers. Consequently, robust characterization, clinically relevant models and patient stratification are needed before claiming selective tumor accumulation or improved efficacy.

How Nanomedicines Enhance Immunotherapy

Nanocarriers may enhance immunotherapy by protecting sensitive payloads, modifying pharmacokinetics and promoting delivery to antigen-presenting cells or tumor-associated immune populations. Lipid and polymeric carriers can transport nucleic acids, antigens and small-molecule immune modulators. Co-delivery of antigens with adjuvants may improve coordinated immune activation, while local release of immunostimulants may reduce systemic exposure [19,20].Surface functionalization can promote interactions with selected receptors on dendritic cells, macrophages or malignant cells. Responsive carriers can release cargo following changes in pH, enzyme activity or intracellular redox conditions. Such approaches are especially attractive in immunologically suppressed tumors, where a combination of tumor-cell killing and immune activation may be required.Preclinical studies have examined nanoparticles combined with checkpoint blockade, cancer vaccines and agents that reprogram the tumor microenvironment. Promising experimental findings should not be equated with demonstrated clinical efficacy. Key unresolved issues include endosomal escape of nucleic acids, heterogeneous tumor penetration, immune toxicity, scalable manufacturing and the need for validated biomarkers of response.

Fundamentals and Classification of Nanomedicines

Nanomedicines may be classified by application, material composition, structure, mechanism of targeting or administration route. Therapeutic systems transport active agents or exert intrinsic activity; diagnostic systems detect disease-related signals; and theranostic platforms combine both functions. The same carrier may fall into several categories, making classification context-dependent [21–23].Organic carriers include liposomes, lipid nanoparticles, polymeric nanoparticles, micelles and dendrimers. Inorganic platforms include gold, iron oxide, silica and selected semiconductor nanomaterials. Biologically derived systems, such as extracellular vesicles and engineered viral particles, are also under investigation. Structure and composition determine drug-loading capacity, biodegradation, surface functionalization, stability and toxicity [24–28].Nanomedicines may additionally be described as passive-targeted, ligand-directed or stimuli-responsive systems. Release may be diffusion-controlled, degradation-mediated or triggered by environmental changes. Injectable formulations dominate many oncology applications, but oral, topical and other routes are being explored. Selection of a delivery platform should reflect the physicochemical properties of the payload, intended site of action and practical manufacturing requirements [29–32].

Major Types of Nanoparticles

Natural nanoscale structures include biological vesicles, viral particles and environmental mineral particles. Synthetic systems are intentionally engineered for defined performance. Metallic nanoparticles offer optical, magnetic or catalytic properties; metal oxides can support imaging or externally triggered therapies; and carbon-based materials have distinctive structural and electronic characteristics, although safety remains an important concern [33–35].Polymeric nanoparticles can encapsulate drugs within biodegradable matrices or associate them with polymer chains. Liposomes consist of phospholipid bilayers enclosing aqueous compartments, while micelles form self-assembled structures with hydrophobic interiors. Dendrimers are branched macromolecules with functionalizable surfaces. Quantum dots possess useful optical properties but some compositions raise concerns about long-term persistence or toxic constituents.Composite and hybrid carriers combine components to achieve multiple functions, such as imaging with drug delivery or improved stability with controlled release. Choice of platform requires balancing drug loading, release, sterility, shelf stability, reproducibility, tissue distribution and long-term biocompatibility. Figure 1 may be retained here as a classification schematic; any historical dates shown in the original figure should be verified before publication.

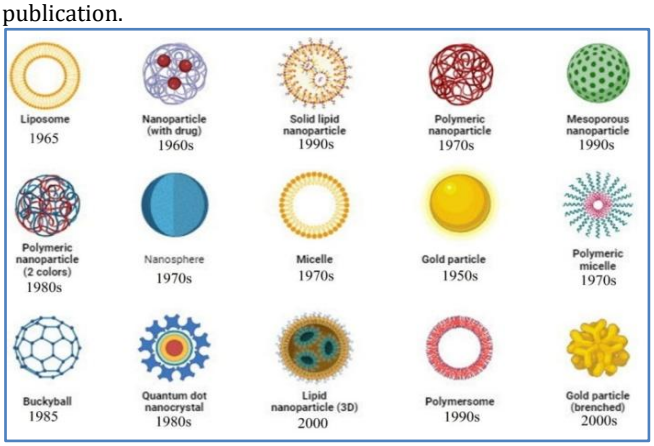

Figure 01: Classification of Major Nanoparticle Platforms Used In Biomedical Applications

Physicochemical Properties and Surface Functionalization

Particle size, shape, polydispersity, surface charge, hydrophobicity and material composition strongly influence biological performance. These features affect aggregation, protein adsorption, membrane interaction, cellular uptake and clearance. In biological fluids, an adsorbed protein corona can change the effective identity of a nanoparticle and alter its targeting behaviour [36].Surface functionalization introduces polymers, antibodies, peptides or other ligands to improve stability or receptor interaction. Hydrophilic coatings such as polyethylene glycol may reduce protein adsorption and prolong circulation for certain formulations, but anti-PEG antibodies and accelerated clearance can complicate repeated administration. Ligand density and orientation must be optimized because excessive surface decoration can increase aggregation, steric hindrance or immune recognition.Formulation characterization should include particle-size distribution, morphology, surface potential, payload loading, release profile, colloidal stability and relevant biological assays. Batch-to-batch consistency is especially important for clinical translation. No single physicochemical property predicts performance independently; safety and efficacy emerge from the combined behaviour of the carrier, payload, dose and biological environment.

Pharmacokinetics and Biodistribution

Nanoparticle pharmacokinetics encompasses absorption or administration, distribution, transformation and elimination. Intravenously administered carriers enter the circulation directly, whereas oral and topical formulations face additional barriers to absorption. Following systemic administration, nanoparticle interactions with plasma proteins and immune cells strongly influence circulation and tissue exposure [37,38].The liver and spleen commonly contribute to uptake and clearance through cells of the mononuclear phagocyte system. Renal elimination is more relevant for sufficiently small particles or degradable components, while larger and persistent structures may remain in tissues for longer periods. Surface chemistry, particle size, shape, dose and repeated exposure all affect these processes. Biodegradable materials may break down into smaller products with different clearance pathways.Tumor accumulation depends on vascular transport, local perfusion, interstitial pressure, extracellular matrix barriers and immune-cell uptake. Passive accumulation cannot

be assumed for every human tumor. Quantitative biodistribution studies should assess both payload and carrier, since they may separate after administration. Understanding these factors is necessary for rational dosing, prediction of off-target toxicity and evaluation of therapeutic index.

Mechanisms of Action in Cancer Treatment

Nanomedicines act through several complementary mechanisms. Passive delivery may exploit tumor-associated vascular abnormalities, whereas active targeting employs ligands that promote binding or uptake by selected cells. Controlled-release formulations alter the rate and location of payload availability. Combination carriers may transport multiple agents to address parallel survival pathways or resistance mechanisms [39–42].Other mechanisms include immune modulation, magnetic guidance, photothermal heating, photodynamic generation of reactive oxygen species and delivery of DNA, messenger RNA or small interfering RNA. Nanoparticles can protect nucleic acids from extracellular degradation, but successful therapy additionally requires cellular uptake, intracellular trafficking and release into the appropriate compartment [43–46].The relative contribution of each mechanism depends on tumor biology and carrier design. For example, ligand binding may improve cellular uptake without substantially increasing the total amount of nanoparticles reaching a tumor. Likewise, stimuli-responsive release may improve spatial control only when the relevant trigger differs sufficiently between diseased and healthy tissues. Figure 02: should illustrate circulation, cellular interaction, endocytosis and intracellular payload release without implying guaranteed tumor-specific delivery.

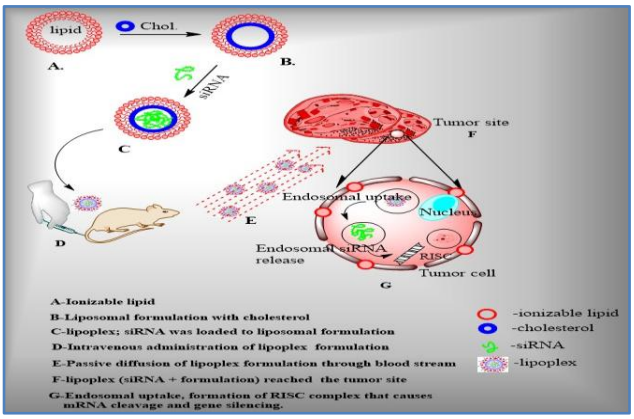

Figure 02: Schematic Illustration of Nanoparticle-Mediated Delivery, Cellular Uptake by Endocytosis and Intracellular Release of Drug or Nucleic-Acid Payloads

Targeted Delivery to Tumors: Targeted nanomedicine aims to increase the therapeutic exposure of tumor cells or relevant stromal and immune cells while limiting unnecessary exposure elsewhere. Passive targeting depends on circulation and tissue transport; active targeting adds recognition elements such as antibodies, peptides or small-molecule ligands. Receptor expression, accessibility and internalization behaviour determine whether a targeting ligand provides meaningful benefit [47].The tumor microenvironment introduces substantial barriers. Irregular blood vessels, high interstitial pressure, dense extracellular matrix and variable perfusion can prevent uniform nanoparticle penetration. Some particles accumulate predominantly in perivascular regions or are taken up by macrophages rather than cancer cells. Tumor heterogeneity and metastatic site differences further complicate delivery.Promising solutions include particle-size optimization, microenvironment-responsive materials, improved penetration strategies and image-guided patient selection. Nevertheless, each design must be evaluated against an appropriate non-targeted comparator. Evidence of receptor binding alone is insufficient to establish improved tumor exposure, safety or survival benefit

Enhancement of Drug Efficacy: Nanoparticle formulations may enhance efficacy by improving apparent solubility, protecting unstable compounds, modifying drug exposure and enabling sustained or triggered release. Encapsulation can be especially useful for poorly water-soluble cytotoxic drugs or biologically fragile nucleic acids. Depending on the formulation, these effects may permit more favourable dosing or reduce selected adverse effects [48–50].Co-delivery of two agents may coordinate their pharmacokinetics and local exposure, supporting combination approaches that attack different pathways. Nanocarriers can also be engineered for cellular uptake and endosomal escape. Such features are important when therapeutic targets are intracellular, as with gene silencing or certain immune signaling pathways.However, improved solubility or higher cellular uptake in vitro does not necessarily translate into better patient outcomes. Nanocarriers can introduce new toxicities, complex clearance behaviour or manufacturing variability. Comparisons should therefore consider efficacy, dose intensity, organ-specific toxicity, pharmacokinetic variability and clinically relevant endpoints rather than relying solely on particle uptake or tumor fluorescence.

IMMUNOTHERAPY

Major Modalities: Monoclonal antibodies may bind tumor-associated targets, block growth signals or recruit immune effector mechanisms. Immune checkpoint inhibitors, including agents directed against PD-1, PD-L1 and CTLA-4, restore antitumor T-cell activity in selected settings. Clinical benefit depends on tumor type, biomarker status and treatment context [51,52].Therapeutic cancer vaccines seek to elicit responses against tumor antigens; preventive vaccines instead reduce infection-associated cancer risk. Adoptive cell therapy involves collection, expansion or engineering of immune cells before infusion. CAR T-cell therapies are established for certain blood cancers, while tumor-infiltrating lymphocyte and T-cell receptor therapies extend the approach to additional settings [53,54,59].Cytokine treatments can stimulate immune-cell proliferation and function but may cause substantial systemic adverse effects. Oncolytic viruses infect and destroy susceptible tumor cells and can promote immune recognition. Combination regimens integrate these approaches with chemotherapy, radiation or targeted drugs to improve response, although toxicity and sequencing require careful evaluation [55–58].Personalized immunotherapy uses molecular and immunological profiling to guide treatment selection or design patient-specific antigens. Nanoparticles are being studied as delivery vehicles for vaccines, cytokines and nucleic-acid immune modulators, with the goal of improving exposure at relevant immune sites.

Mechanisms of Immune Activation: Effective antitumor immunity requires recognition of tumor-associated antigens and coordination between innate and adaptive immune cells. Dendritic cells process antigens and present peptide fragments through major histocompatibility complex molecules. T-cell activation depends on antigen recognition and appropriate co-stimulatory signaling, followed by clonal expansion and differentiation [60].Activated CD8-positive cytotoxic T cells can kill malignant cells through perforin- and granzyme-mediated mechanisms, while CD4-positive helper cells support immune coordination. B cells may differentiate into antibody-producing

plasma cells. Memory lymphocytes can provide prolonged antigen-specific responsiveness. Cytokines and chemokines regulate cell recruitment, proliferation and effector activity.Immune checkpoints and regulatory T cells limit excessive responses and preserve tolerance. Tumors can exploit these regulatory pathways to evade destruction. Nanoparticle vaccines and immune-modulating formulations seek to improve antigen delivery to antigen-presenting cells, strengthen co-stimulation and support productive T-cell responses without provoking uncontrolled systemic inflammation.

Challenges in Cancer Immunotherapy: Immunotherapy response is variable because tumors differ in antigenicity, immune-cell infiltration, checkpoint signaling and stromal organization. Tumors with impaired antigen presentation or few pre-existing effector T cells may respond poorly to checkpoint blockade. Additional barriers include immunosuppressive macrophages, regulatory T cells, myeloid-derived suppressor cells, metabolic constraints and acquired resistance [61–66].Immune-related adverse events are another major limitation. Checkpoint inhibition can cause inflammatory injury affecting the skin, gastrointestinal tract, liver, lungs, endocrine organs and other systems. These events vary in timing and severity and may occur after treatment has stopped. Management relies on early recognition, severity-based treatment interruption and immunosuppression when indicated, guided by established clinical recommendations [67].High costs, access disparities and incomplete predictive biomarkers further restrict benefit. Nanomedicines might improve the delivery of immune agonists or reduce exposure to selected tissues, but they can also cause complement activation, infusion reactions or unwanted immune stimulation. Translational studies must therefore evaluate both antitumor activity and comprehensive immunological safety.

NANOMEDICINE TARGETING THE IMMUNE SYSTEM

Immune modulation involves increasing or suppressing selected immune functions through cellular interactions and signaling pathways. Dendritic cells, macrophages, T lymphocytes and regulatory populations contribute to the balance between immune activation and tolerance. Cytokines such as IL-1, IL-6 and TNF participate in inflammatory signaling, whereas IL-10 and TGF-β often contribute to suppressive or resolving pathways, depending on context [68–70].Immune responses are also shaped by epigenetic regulation, host microbiota, nutrition and environmental exposures. These influences may affect treatment response, although their use as routine determinants of nanomedicine selection remains investigational [71–74]. Nanoparticles can be engineered to deliver antigens and adjuvants to dendritic cells, reprogram tumor-associated macrophages or release immune modulators within the tumor microenvironment.An effective immune-targeting carrier must balance uptake by intended cells with avoidance of harmful systemic inflammation. Design decisions include material composition, biodegradability, particle size, ligand specificity, cargo release and route of administration. Biological testing should assess cytokine production, antigen presentation, immune-cell phenotype and functional antitumor responses, alongside toxicity and biodistribution [75].

Surface-Modified and Smart Nanoparticles: Surface modification can enhance interactions between nanocarriers and immune-cell receptors. Antibodies, peptides and other ligands are attached using covalent chemistry or noncovalent assembly. Their density, orientation and accessibility affect binding, internalization and stability. Particle size, charge and protein-corona formation may alter the intended targeting behavior after administration.Smart nanoparticles incorporate

release mechanisms sensitive to local conditions, including pH, enzymes, redox status, temperature or externally applied energy. Multi-responsive systems seek to combine triggers to improve control over payload release. For nucleic-acid delivery, carrier stability must be balanced against efficient endosomal escape and intracellular cargo availability [76].Although these approaches show promise, manufacturing and translational challenges are substantial. Formulations must remain stable during storage and administration, meet quality standards and demonstrate consistent biological activity. PEGylation and related coatings may prolong circulation in some contexts but can also influence immune recognition. Rigorous in vitro and in vivo testing remains necessary before clinical application.

TARGETED DELIVERY AND COMBINATION THERAPIES

The tumor microenvironment comprises malignant cells, cancer-associated fibroblasts, endothelial cells, immune populations and extracellular matrix. Its growth-factor networks, hypoxia, abnormal vasculature and immunosuppressive signaling influence tumor progression and treatment response. Nanomedicines are being investigated to deliver agents that modify these components, inhibit angiogenic pathways or enhance immune-cell access [77,78].Clinical examples illustrate the broader importance of molecular targeting and formulation engineering. Trastuzumab in HER2-positive disease, imatinib in BCR–ABL-driven leukemia, CAR T-cell products and checkpoint inhibitors demonstrate the value of mechanism-based cancer treatment, but these are not themselves examples of nanoparticle therapy. Pegylated liposomal doxorubicin is an established nanomedicine that alters doxorubicin distribution and toxicity; its comparative benefit varies by indication and should not be described as universally superior [79-80].Combining chemotherapy with radiotherapy can improve tumor control in selected cancers through complementary cytotoxic mechanisms and radiosensitization. Integration with immunotherapy or nanoparticle delivery may add further opportunities, but treatment timing, dose, toxicity, hypoxia and tumor heterogeneity complicate optimization. Rational combination regimens require mechanistic justification, validated biomarkers and clinical evidence rather than assumptions of synergy [80-86].

CONCLUSION

Nanomedicine provides adaptable platforms for improving the formulation, distribution and controlled release of therapeutic agents used in oncology. Lipid, polymeric, inorganic and biologically derived carriers offer different advantages for drug delivery, imaging and immune modulation. Their performance is governed by particle composition, physicochemical properties, biological interactions and tumor-specific transport barriers. Importantly, selective delivery and reduced toxicity are potential benefits that must be demonstrated for individual formulations rather than assumed from nanoscale size.Cancer immunotherapy has changed the treatment of selected malignancies through checkpoint inhibition, engineered immune cells, therapeutic vaccines and related strategies. Nanocarriers may extend these advances by delivering antigens, nucleic acids, adjuvants and immune modulators to relevant tissues or cell populations, enabling localized release and rational combination approaches. Experimental findings are encouraging, but many nanoparticle-enabled immunotherapies remain investigational. Future progress will depend on reproducible manufacturing, robust safety

assessment, realistic models of human tumor delivery, predictive biomarkers and carefully designed clinical trials.

The most valuable contribution of nanomedicine will be to improve measurable patient outcomes through better therapeutic exposure, manageable toxicity and more individualized treatment selection.

AUTHOR CONTRIBUTIONS

All authors contributed to equally.

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Not Applicable

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