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Nanomedicine in Precision Oncology: Engineering Tumor-Specific Nanocarriers for Personalized Therapy

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ABSTRACT

Precision oncology aims to tailor cancer treatments based on individual tumor profiles, yet challenges such as non-specific drug distribution and systemic toxicity hinder therapeutic efficacy. Nanomedicine offers a promising avenue to overcome these limitations through the development of tumor-specific nanocarriers that enable targeted, controlled, and personalized drug delivery. This review explores the convergence of nanotechnology and precision oncology, highlighting the design principles, materials, and functionalization strategies used to engineer tumor-specific nanocarriers. Emphasis is placed on ligand-receptor targeting, stimuli-responsive delivery, and molecular profiling to achieve personalized therapy. Advances in preclinical and clinical translation, challenges such as tumor heterogeneity and immunogenicity, and future perspectives in theranostic integration and artificial intelligence-driven nanocarrier design are discussed. Ultimately, tumor-specific nanocarriers stand at the forefront of next-generation oncology, poised to revolutionize cancer care through precise and individualized treatment strategies.

Keywords: Precision Oncology, Nanocarriers, Targeted Drug Delivery, Tumor-Specific Therapy, Personalized Nanomedicine

INTRODUCTION

Cancer remains one of the most formidable health challenges globally, accounting for millions of deaths each year and representing a major burden on healthcare systems[1–3]. According to recent data from the World Health Organization (WHO), cancer is responsible for approximately 10 million deaths annually, making it the second leading cause of death worldwide[4]. While significant progress has been made in understanding the molecular biology of cancer and developing novel therapeutic strategies, conventional cancer treatments such as chemotherapy, radiation, and surgery are often limited by several critical drawbacks[5]. Chief among these are non-specific targeting, poor pharmacokinetics, multidrug resistance, and severe systemic toxicity, which can significantly compromise treatment outcomes and patient quality of life[1, 6–8].

In recent years, the concept of precision oncology has emerged as a transformative approach to cancer treatment[9]. Unlike the traditional one-size-fits-all methodology, precision oncology aims to tailor therapy to the individual patient based on the molecular and genetic profile of their tumor. This includes identifying specific oncogenic drivers, mutations, or signaling pathways that can be selectively targeted with precision therapeutics[10, 11]. The goal is to maximize treatment efficacy while minimizing collateral damage to healthy tissues. However, even with targeted therapies, issues such as off-target effects, drug resistance, and heterogeneous tumor environments can still pose significant hurdles[12–15]. Therefore, there is a growing need for more sophisticated delivery platforms that can complement and enhance precision medicine strategies.

Nanomedicine, defined as the medical application of nanotechnology, has shown immense potential to revolutionize the field of oncology[16]. By engineering materials at the nanoscale (1–100 nanometers), researchers have been able to develop innovative drug delivery systems that can overcome many of the limitations associated with conventional therapies[17–19]. Nanocarriers such as liposomes, dendrimers, polymeric nanoparticles, metallic nanoparticles, and micelles can encapsulate a wide range of therapeutic agents, from small-molecule chemotherapeutics to nucleic acids, proteins, and immunomodulators[20, 21]. These carriers can be modified with surface ligands or functional groups that allow for tumor-specific targeting, ensuring that the therapeutic payload is delivered precisely to cancer cells while sparing healthy tissues.

A particularly exciting aspect of nanomedicine in the context of precision oncology is the ability to exploit the unique characteristics of the tumor microenvironment (TME)[22]. Tumors often exhibit abnormal vasculature, acidic pH, hypoxia, and overexpression of specific receptors or enzymes. Nanocarriers can be engineered to respond to these cues, thereby achieving stimuli-responsive or "smart" drug release. For instance, pH-sensitive nanoparticles can release their contents selectively in acidic tumor environments, while enzyme-responsive systems can be activated by proteases overexpressed in cancerous tissues. This responsive behavior not only enhances the therapeutic index of anticancer agents but also reduces systemic toxicity and improves pharmacokinetic profiles[23, 24].

Moreover, nanocarriers can be co-loaded with multiple agents, enabling combination therapy in a single platform. This strategy can synergize the actions of drugs with different mechanisms, reduce the required dosage, and delay or overcome drug resistance. In some designs, diagnostic agents are incorporated into the same nanoparticles for theranostic applications, combining therapy and diagnostic imaging to monitor treatment response in real time[25–28]. Despite the promising preclinical and early clinical results, the translation of tumor-specific nanocarriers into routine clinical practice remains challenging. Issues such as large-scale manufacturing, reproducibility, regulatory approval, and long-term safety need to be addressed. Additionally, tumor heterogeneity and dynamic evolution during treatment necessitate continuous adaptation of therapeutic strategies[29]. This review aims to provide a comprehensive and critical evaluation of the current state and prospects of tumor-specific nanocarriers in personalized cancer therapy. We will discuss the design principles, functionalization strategies, and targeting mechanisms that underpin effective tumor-specific delivery. Furthermore, we will explore recent clinical advancements, ongoing trials, and the translational hurdles that must be overcome to fully harness the potential of nanomedicine in precision oncology. By integrating insights from materials science, cancer biology, and clinical oncology, this review seeks to highlight the pivotal role of engineered nanocarriers in shaping the next generation of personalized cancer treatments.

2. Principles of Precision Oncology

2.1. Molecular Profiling in Cancer

Molecular profiling has become a cornerstone of precision oncology, providing detailed insights into the genetic and molecular landscape of individual tumors[30, 31]. This approach involves the integration of high-throughput technologies such as next-generation sequencing (NGS), transcriptomic analysis, and proteomic profiling to uncover key alterations in cancer-related genes and pathways. For instance, genomic alterations in *HER2*, *EGFR*, *ALK*, and *BRCA1/2* have been successfully exploited as therapeutic targets across various cancer types. These biomarkers not only aid in diagnosis and prognosis but also enable the stratification of patients for targeted therapies, maximizing therapeutic efficacy while minimizing toxicity[32, 33].

By analyzing somatic mutations, gene fusions, copy number variations, and expression patterns, molecular profiling can identify “actionable” mutations—those that are known to be responsive to specific drugs or therapies. Furthermore, proteomic data offer additional layers of information, such as post-translational modifications and signaling pathway activation, which are often missed by genomic methods alone[34, 35]. The integration of multi-omics data enhances the precision of clinical decision-making, allowing oncologists to select the most appropriate therapy tailored to a patient’s unique tumor biology.

Importantly, molecular profiling supports adaptive and dynamic treatment planning. As tumors evolve or develop resistance, repeat profiling can uncover new targets or suggest alternative therapeutic approaches[36]. Thus, molecular profiling not only facilitates initial therapy selection but also supports ongoing disease management, offering a powerful tool for real-time, personalized cancer care.

2.2. Challenges in Conventional Therapies

Despite decades of use and some notable successes, conventional cancer therapies, particularly chemotherapy and radiotherapy, face significant limitations. One of the primary challenges is their lack of selectivity; these treatments target rapidly dividing cells indiscriminately, affecting not only malignant cells but also healthy tissues such as the bone marrow, gastrointestinal tract, and hair follicles[37, 38]. This non-specificity often results in severe side effects, including immunosuppression, fatigue, nausea, and organ toxicity, which can limit dosage and duration of therapy, ultimately reducing efficacy.

Moreover, tumor heterogeneity significantly hampers the success of traditional treatments. Within a single tumor, there can be multiple subpopulations of cancer cells with distinct genetic and phenotypic profiles. This diversity leads to variable sensitivity to drugs, allowing some subclones to survive treatment and drive recurrence or metastasis. Compounding this issue is the frequent development of drug resistance, both intrinsic and acquired, which further undermines the long-term success of standard regimens[39, 40].

These challenges underscore the pressing need for more precise and targeted approaches to cancer treatment. Nanomedicine offers a promising solution by enabling the development of drug delivery systems that can specifically target tumor cells while sparing healthy tissues[22, 41]. Nanocarriers can be engineered to exploit the enhanced permeability and retention (EPR) effect of tumors, incorporate targeting ligands for specific cell surface markers, and provide controlled release of chemotherapeutic agents[42, 43]. As a result, nanotechnology-based interventions are increasingly being explored as adjuncts or alternatives to conventional therapies, aiming to improve treatment outcomes, reduce systemic toxicity, and overcome resistance mechanisms.

3. Nanocarriers in Cancer Therapy

3.1. Types of Nanocarriers

Nanocarriers are engineered nanoscale delivery systems designed to transport therapeutic agents specifically to diseased tissues while minimizing off-target effects. Among the most extensively studied are **liposomes**, which are spherical vesicles comprising one or more phospholipid bilayers[44–46]. Their biocompatibility and capacity to encapsulate both hydrophilic drugs (in their aqueous core) and hydrophobic drugs (within their bilayer membrane) make them highly versatile. Liposomes are used in several FDA-approved formulations for cancer and other diseases, demonstrating their clinical utility[44].

Polymeric nanoparticles represent another major class of nanocarriers[47–50]. These particles are made from biodegradable and biocompatible polymers such as PLGA (poly(lactic-co-glycolic acid)) and PEG (polyethylene glycol). Their structural integrity allows for sustained or controlled drug release profiles, and their surfaces can be modified to improve targeting or cellular uptake. The degradation rate of polymeric nanoparticles can be tailored to match therapeutic needs[48].

Dendrimers are highly branched, tree-like macromolecules with a well-defined architecture and multiple terminal functional groups[51]. Their unique structure offers a high degree of surface modification for drug loading, targeting ligands, or imaging agents. Dendrimers are especially promising for gene delivery due to their ability to condense nucleic acids efficiently[51].

Inorganic nanoparticles, such as gold, silica, and iron oxide, are widely used due to their inherent physical properties[52, 53]. Gold nanoparticles, for example, offer photothermal effects; iron oxide nanoparticles are suitable for magnetic resonance imaging (MRI), and silica nanoparticles provide excellent stability and loading capacity for drugs and dyes[54, 55].

Lastly, **exosomes** are natural, cell-derived nanovesicles involved in intercellular communication[24, 56, 57]. They carry proteins, lipids, and nucleic acids, and inherently possess targeting capabilities based on their cellular origin. Their biocompatibility and ability to evade immune detection position them as ideal candidates for personalized, cell-based drug delivery strategies in precision oncology.

3.2. Design Parameters

The success of nanocarriers in precision oncology largely depends on meticulous engineering that ensures optimal delivery, targeting, and safety. One of the most critical design features is **size**[58]. Nanocarriers typically range between 10 to 200 nanometers in diameter. This size range is crucial for exploiting the enhanced permeability and retention (EPR) effect observed in tumor vasculature, allowing nanocarriers to preferentially accumulate in tumor tissues while limiting their diffusion into healthy tissues[58].

Surface charge is another determinant of nanocarrier biodistribution and cellular uptake. Slightly positive or neutral charges may facilitate interaction with negatively charged cell membranes, promoting endocytosis[59]. However, highly charged particles may be rapidly cleared by the mononuclear phagocyte system (MPS), reducing therapeutic efficacy. Hence, fine-tuning the zeta potential is necessary to balance circulation time and cellular interaction[59].

Stealth properties, often conferred through PEGylation (surface modification with polyethylene glycol), help nanocarriers evade immune surveillance. This prevents rapid opsonization and clearance by macrophages, prolonging the circulation half-life of the nanocarriers and enhancing the probability of tumor accumulation[60].

Biodegradability is another essential parameter, particularly for minimizing long-term toxicity. Nanocarriers should ideally degrade into non-toxic byproducts that can be easily metabolized or excreted from the body. This is especially important for repeated or high-dose administration in chronic diseases such as cancer[61]. Incorporating targeting ligands (e.g., antibodies or peptides) and stimuli-responsive elements (e.g., pH or temperature-sensitive components) further refines nanocarrier performance, enabling on-demand drug release in the tumor microenvironment[62]. Collectively, these design parameters are fundamental to the development of safe, effective, and personalized nanomedicine platforms.

4. Engineering Tumor-Specific Nanocarriers

4.1. Active Targeting Strategies: Active targeting strategies in nanomedicine involve the functionalization of nanocarriers with ligands that bind selectively to overexpressed receptors on tumor cells, thereby enhancing specificity and reducing off-target effects. One common approach includes the use of folate, a vitamin whose receptor is significantly overexpressed in various cancers such as ovarian, breast, and lung cancers[63]. By attaching folate to the surface of nanocarriers, researchers can improve cellular uptake through receptor-mediated endocytosis in tumors while sparing healthy cells. Similarly, transferrin receptors, often elevated in gliomas and other rapidly dividing tumor types, are exploited by attaching transferrin molecules to the nanocarrier surface to facilitate enhanced delivery across the blood–brain barrier. In HER2-positive breast cancers, nanocarriers are conjugated with HER2-specific monoclonal antibodies like trastuzumab, providing both targeted delivery and therapeutic effects[64]. Moreover, aptamers and peptides are emerging as versatile ligands for active targeting. Aptamers are short, single-stranded nucleic acids with high binding affinity and specificity, while peptides offer the advantages of easy synthesis, low immunogenicity, and efficient tumor penetration[65, 66]. These ligands allow nanocarriers to selectively bind tumor-specific antigens, improving therapeutic indices and minimizing toxicity. Active targeting thus holds the potential to revolutionize drug delivery by enhancing the therapeutic payload's precision in cancer treatment.

4.2. Stimuli-Responsive Nanocarriers: Stimuli-responsive nanocarriers are engineered to respond to the unique microenvironmental cues found within tumors, allowing for the selective release of therapeutic agents at the disease site[62]. The tumor microenvironment often exhibits distinct characteristics such as acidic pH, elevated glutathione levels, hypoxia, and the presence of specific enzymes like matrix metalloproteinases (MMPs). pH-sensitive nanocarriers, such as liposomes modified with acid-labile bonds, remain stable in the bloodstream but disassemble in the acidic extracellular matrix of tumors, thereby releasing their drug cargo precisely where needed. Redox-responsive systems utilize disulfide bonds that cleave in the presence of high intracellular glutathione concentrations commonly found in cancer cells, leading to controlled release within the cytoplasm[67]. Another advanced design involves enzyme-triggered nanocarriers that degrade or transform upon contact with overexpressed tumor enzymes like MMP-2 or cathepsin B, allowing for highly specific release[68]. These smart delivery systems reduce systemic toxicity and enhance therapeutic efficacy by synchronizing drug release with tumor-specific physiological conditions. Overall, stimuli-responsive nanocarriers represent a promising direction in precision oncology, as they enable controlled, site-specific drug delivery while minimizing harm to healthy tissues and improving patient outcomes.

4.3. Multi-Modal and Theranostic Systems: Multi-modal and theranostic nanocarriers represent a cutting-edge frontier in cancer nanomedicine, combining therapeutic and diagnostic functionalities within a single platform[69]. These systems are designed to simultaneously deliver drugs and enable real-time imaging, offering a comprehensive approach to cancer treatment and monitoring. Gold nanoparticles are a prime example of this dual capability; their high atomic number and surface plasmon resonance properties allow them to function both as photothermal agents, heating and destroying tumor cells upon near-infrared light exposure and as contrast enhancers in computed tomography (CT) imaging[52, 70]. Similarly, quantum dots, which are semiconductor nanocrystals, exhibit strong fluorescence and photostability, making them ideal for high-resolution imaging of tumors. These can be further functionalized to carry therapeutic agents, thus serving dual roles in imaging and treatment. Other examples include iron oxide nanoparticles for magnetic resonance imaging (MRI) and magnetic hyperthermia, or polymeric nanoparticles embedded with both chemotherapeutic drugs and fluorescent dyes[55, 71]. The integration of diagnostic and therapeutic capabilities enables real-time tracking of drug distribution, therapeutic efficacy, and disease progression. This multifunctionality is particularly valuable for personalized oncology, as it allows for dynamic adjustment of treatment strategies based on imaging feedback, ultimately improving the precision and success of cancer therapies.

5.1. Patient-Specific Nanocarrier Design: Personalized nanomedicine emphasizes the customization of nanocarriers based on the individual molecular and genetic profile of each cancer patient[72]. Advances in genomics and proteomics have made it possible to characterize tumor heterogeneity at an unprecedented level, allowing the integration of this data into the rational design of nanocarriers. For instance, nanocarriers can be tailored to target specific biomarkers that are overexpressed in a patient's tumor, such as mutant KRAS, HER2, or EGFR. This biomarker-guided targeting enhances therapeutic selectivity and minimizes adverse effects. Additionally, personalized payload selection becomes feasible, wherein the therapeutic agents whether small-molecule drugs, siRNA, or CRISPR-Cas systems are chosen based on the patient’s unique mutation profile[72]. For example, RNA interference strategies targeting specific oncogenic mutations can be incorporated into lipid or polymer-based nanoparticles for gene silencing. Furthermore, pharmacogenomic data can inform optimized dosing regimens, accounting for metabolic variations among patients that affect drug absorption and clearance[72]. This personalized approach ensures that the nanocarrier system not only targets the right cells but also delivers the most appropriate therapeutic agent most effectively. As a result, patient-specific nanocarrier design holds immense promise in advancing precision oncology and improving clinical outcomes.

5.2. Artificial Intelligence (AI) and Machine Learning: Artificial intelligence (AI) and machine learning (ML) are revolutionizing the field of nanomedicine by enabling data-driven design, prediction, and optimization of nanocarrier systems for oncology[73]. These computational tools can analyze large datasets derived from biological, chemical, and clinical studies to uncover patterns and correlations that would be difficult to detect through conventional methods[73]. For instance, AI algorithms can predict nanoparticle biodistribution based on physicochemical properties such as size, shape, surface charge, and hydrophobicity, thereby facilitating the selection of optimal design parameters for enhanced tumor targeting. Machine learning models can also be employed to identify the best combinations of ligands for active targeting, enhancing specificity by simulating interactions between nanocarriers and cell surface receptors[73]. Furthermore, AI can be used to stratify patients into subgroups based on their molecular profiles, thereby identifying those most likely to benefit from specific nanotherapeutics. These models improve clinical trial design and reduce development timelines by predicting efficacy and toxicity profiles in silico. Overall, AI and ML serve as powerful tools in personalizing nanomedicine, enhancing the precision, efficiency, and scalability of cancer treatment development while paving the way for more responsive and adaptive therapeutic strategies.

6. Challenges and Limitations

Despite the transformative promise of nanocarriers in cancer therapy, tumor heterogeneity remains a significant challenge[74]. Tumors are not uniform masses but consist of diverse populations of cells with distinct genetic, epigenetic, and phenotypic profiles. This variability leads to inconsistent uptake of nanocarriers, as not all cancer cells express the same surface receptors or respond similarly to targeted ligands[74]. Consequently, a nanocarrier that effectively targets one subpopulation may fail to reach or affect others, diminishing therapeutic efficacy. Furthermore, the tumor microenvironment, including factors such as vascular density, pH, and interstitial pressure, varies across different tumor regions and among different patients. These differences can alter the penetration and distribution of nanocarriers, making it difficult to achieve uniform drug delivery throughout the tumor. Addressing tumor heterogeneity requires the development of adaptive or multi-targeted nanocarriers capable of recognizing diverse tumor markers or responding to the dynamic tumor milieu to ensure a more comprehensive therapeutic effect[75].

Another major limitation to effective nanocarrier-based therapy is the presence of biological barriers that impede targeted delivery. Chief among these is the mononuclear phagocyte system (MPS), which identifies and eliminates foreign particles from the bloodstream[76]. Nanocarriers, especially those not adequately coated or functionalized, are often recognized and sequestered by macrophages in the liver, spleen, and other reticuloendothelial organs before they can reach tumor sites. This leads to reduced bioavailability and therapeutic efficacy. Additionally, vascular endothelial barriers and abnormal tumor vasculature can hinder nanocarrier extravasation into tumor tissues. While strategies such as PEGylation, surface modification with "stealth" coatings, or receptor-mediated targeting have shown some success in evading immune detection and enhancing tumor accumulation, these approaches are not universally effective across all tumor types or patient populations[76]. Therefore, overcoming these systemic and local biological barriers remains essential to improve delivery efficiency and achieve meaningful clinical outcomes with nanocarrier-based therapies.

Immunogenicity and long-term safety concerns further complicate the clinical translation of nanocarrier systems[77]. The immune system may perceive certain nanocarriers or their surface modifications as foreign, triggering an immune response that can result in rapid clearance, hypersensitivity reactions, or even long-term immunotoxic effects. This is particularly important when repeated dosing is required for chronic cancer treatment. Moreover, the biodegradation products of some synthetic nanomaterials may accumulate in vital organs, leading to toxicity or interference with normal physiological functions over time [77]. Long-term safety data are limited for many nanocarrier platforms, and comprehensive preclinical and clinical studies are necessary to assess their biocompatibility, metabolism, and excretion pathways. Regulatory agencies demand thorough safety evaluations before approving these systems for clinical use, emphasizing the need for well-characterized, standardized materials[77]. Addressing these concerns through the development of biodegradable, non-immunogenic nanocarriers with predictable clearance profiles is crucial for fostering trust and facilitating broader acceptance of nanomedicine in oncology practice.

Finally, despite significant laboratory success, scaling up the production of nanocarriers with consistent quality remains a formidable obstacle. Reproducibility is vital for clinical translation, yet many nanocarrier synthesis protocols involve complex, multistep procedures that are difficult to standardize across large batches[77]. Slight variations in raw material properties, synthesis conditions, or purification techniques can lead to inconsistencies in size, drug loading, surface characteristics, and overall functionality. These inconsistencies can affect safety and efficacy, undermining regulatory approval and clinical reliability. Additionally, large-scale manufacturing must comply with Good Manufacturing Practice (GMP) guidelines, requiring stringent quality control and assurance systems[78]. The need for specialized equipment, high production costs, and challenges in ensuring long-term stability and storage further complicate commercialization efforts. To overcome these hurdles, efforts must be made to simplify fabrication techniques, employ scalable production technologies such as microfluidics or self-assembly methods, and develop robust protocols that ensure batch-to-batch consistency without compromising therapeutic performance.

7. Future Directions

Future directions in nanomedicine are increasingly exploring biomimetic nanocarriers, such as cancer cell membrane-coated nanoparticles, to enhance specificity and therapeutic efficacy. These innovative systems exploit homotypic targeting, where nanoparticles coated with membranes from the same tumor type can recognize and bind to similar cells in the body. This strategy reduces off-target effects and promotes selective drug delivery, minimizing damage to healthy tissues. Furthermore, the natural surface proteins retained on these membranes help the nanocarriers evade immune surveillance, prolong circulation time, and increase tumor accumulation. Such biomimetic approaches represent a leap toward more efficient and intelligent drug delivery systems in oncology.

Microfluidic organ-on-a-chip technologies are poised to transform the preclinical testing landscape. These miniaturized platforms simulate human physiological conditions more accurately than traditional 2D or even 3D cultures. By integrating vascularization, mechanical cues, and cellular heterogeneity, organ-on-a-chip systems can better predict drug responses and toxicities. When combined with nanocarrier testing, these platforms provide a high-throughput, cost-effective, and ethically favorable alternative to animal models. Their ability to replicate the tumor microenvironment and its interactions with nanomedicines offers invaluable insights for optimizing nanoparticle design and delivery. Consequently, these systems promise to bridge the translational gap between laboratory findings and clinical applications in precision oncology.

Another promising avenue involves integrating nanocarrier-based therapy with immune checkpoint inhibitors. Immune checkpoint blockade has shown remarkable success in treating various cancers, but response rates remain suboptimal. Nanocarriers can enhance immunotherapy efficacy by co-delivering antigens, adjuvants, or modulators directly to the tumor microenvironment, thereby boosting anti-tumor immunity. This combination may help overcome immune resistance, promote immunogenic cell death, and foster durable responses. Additionally, nanocarriers can be engineered to target immune cells or tumor-associated macrophages, further amplifying the synergistic effect. This approach heralds a new era of immuno-nanomedicine that offers hope for more effective and personalized cancer treatments.

Artificial intelligence (AI) holds transformative potential in advancing precision nanomedicine. By analyzing vast datasets—including genomics, proteomics, pharmacokinetics, and patient-specific tumor profiles—AI can identify optimal nanoparticle compositions and delivery strategies tailored to individual patients. Machine learning algorithms may also predict therapeutic responses, toxicity, and off-target effects, thus improving treatment planning and reducing trial-and-error. Furthermore, AI-guided design can accelerate the development of multifunctional nanocarriers with enhanced targeting, controlled release, and adaptive responses to tumor signals. As AI and nanotechnology converge, the vision of individualized, smart nanomedicine becomes increasingly attainable, paving the way for breakthroughs in cancer diagnosis and therapy.

CONCLUSION

The fusion of nanomedicine with precision oncology represents a transformative frontier in cancer treatment. Tumor-specific nanocarriers provide the means to bypass biological barriers, deliver drugs directly to malignant tissues, and reduce systemic toxicity. Through intelligent design, molecular targeting, and incorporation of patient-specific tumor profiles, these nanoplatforms are ushering in a new era of personalized cancer therapy. Continued interdisciplinary research and technological innovation are critical to fully realize their clinical potential.

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