Emerging Paradigms in Personalized Oncology: Role of Nano therapeutics and AI across Liver, Breast, Renal, and Brain Cancers

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Abstract:

Background: Between 2019 and 2024, personalized oncology has rapidly evolved through the integration of **nanotherapeutics and artificial intelligence (AI),** enabling patient-specific interventions that overcome the limitations of conventional therapies. Smart nanocarriers provide targeted, stimuli-responsive, and multifunctional delivery of chemotherapeutics, RNA therapies, and immunomodulators, while AI leverages multi-omics data to guide treatment selection and predict outcomes. **Objectives:** This review examines recent advances in AI-guided nanomedicine across **liver, breast, renal, and neuro cancers,** highlighting innovations in nanocarrier design, payload engineering, tumor microenvironment modulation, and clinical translation. **Methods:** A comprehensive literature survey from 2019–2024 was conducted, focusing on nanoparticle platforms, therapeutic payloads, AI-assisted design, patient stratification, and clinical trials. Comparative insights across the four cancer types were analyzed to elucidate both shared challenges and cancer-specific strategies. **Results:** Smart nanotherapeutics have enabled precise receptor-targeted delivery, RNA-based interventions, nano-immunotherapies, and BBB-penetrating platforms in neuro-oncology. AI integration has optimized nanoparticle properties, predicted patient responses, and facilitated biomarker-guided personalization. While preclinical studies have shown substantial efficacy, translation into clinical practice is ongoing, with challenges in manufacturing, regulatory approval, and long-term safety.**Conclusions:** The synergy of **AI and nanotherapeutics** represents a paradigm shift in personalized oncology. Omics-driven therapy design, AI-guided nanoparticle optimization, and adaptive predictive models promise to accelerate clinical translation and improve patient outcomes. These emerging paradigms are poised to redefine the standard of care across liver, breast, renal, and neuro cancers.

Keywords: Personalized Oncology, Nanotherapeutics, Artificial Intelligence, Liver Cancer, Breast Cancer, Renal Cell Carcinoma, Glioblastoma, RNA Therapeutics, Nano-Immunotherapy, Multi-Omics

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1. Introduction

Between 2019 and 2024, personalized oncology has undergone a remarkable transformation, driven by advances in molecular profiling, high-throughput technologies, and computational modeling. Traditional cancer therapies, often limited by off-target toxicity and variable patient responses, are being increasingly replaced or complemented by approaches that consider the unique molecular and cellular landscape of each tumor. Central to this evolution are **nanotherapeutics,** which enable precise delivery of drugs, gene therapies, and immunomodulators directly to tumor cells while minimizing systemic exposure. By combining these smart delivery systems with **artificial intelligence (AI),** researchers and clinicians can now design, optimize, and predict therapeutic outcomes in a patient-specific manner, integrating large-scale omics data and imaging information to guide decision-making [1-2].

This review focuses on the synergistic role of **nanotherapeutics and AI** in four major cancer types **liver (hepatocellular carcinoma), breast cancer, renal cell carcinoma, and neuro-oncologic tumors (glioblastoma and others).** By examining the trends and innovations from 2019 to 2024, we aim to highlight how these emerging paradigms are reshaping treatment strategies, improving clinical precision, and accelerating the translation of personalized therapies from bench to bedside [3-4].

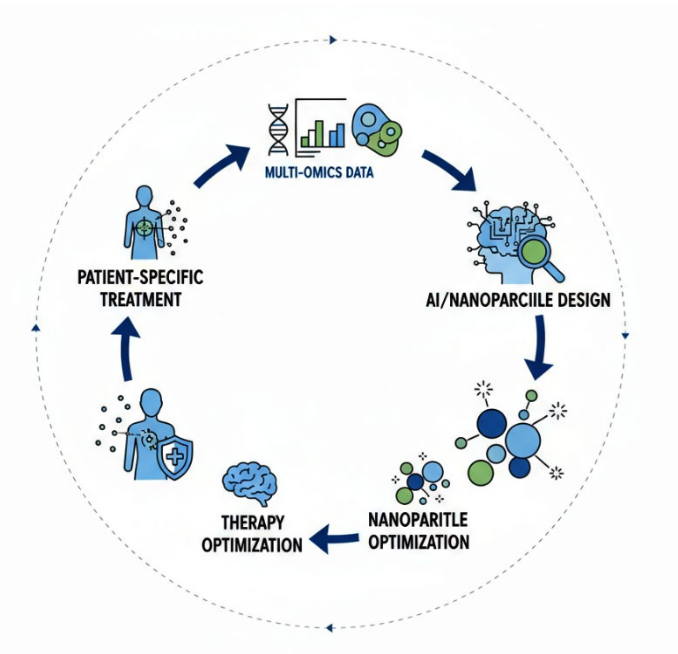

__Figure 1:__ Conceptual overview of personalized oncology integrating nanotherapeutics and AI, illustrating the cycle from omics-driven target identification through nanoparticle design, therapy optimization, and patient-specific precision treatment

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2. Nanotherapeutics in Personalized Oncology

Over the past five years, **nanotherapeutics** have emerged as a cornerstone of personalized oncology, providing highly adaptable platforms for targeted drug delivery and molecular interventions [5]. A diverse array of **nanocarrier platforms** has been developed, including **lipid nanoparticles** and **polymeric nanoparticles,** which offer biocompatibility and controlled release properties. **Inorganic nanoparticles,** such as gold, silica, and magnetic nanostructures, provide unique imaging and photothermal capabilities, while **biomimetic nanoparticles** and **exosomes** leverage natural cellular membranes to evade immune clearance and enhance tumor tropism [6].

The **therapeutic payloads** delivered by these platforms have expanded far beyond traditional chemotherapeutics. Nanocarriers now routinely transport **gene therapies** including siRNA, miRNA, and mRNA to modulate oncogenic pathways, as well as **CRISPR-Cas systems** for genome editing, and **immunomodulators** to stimulate antitumor immune responses [7]. These payloads are further enhanced by **smart design features**, such as **ligand-mediated targeting** to tumor-specific receptors, **stimuli-responsive release mechanisms** triggered by pH, redox gradients, or external energy sources, and **stealth coatings** to prolong circulation and reduce off-target effects [8].

Collectively, these innovations create multifunctional nanoplatforms that integrate targeted delivery, controlled payload release, and compatibility with molecularly guided precision therapy. The convergence of these nanotherapeutic capabilities is accelerating the translation of personalized oncology strategies across diverse cancer types [9].

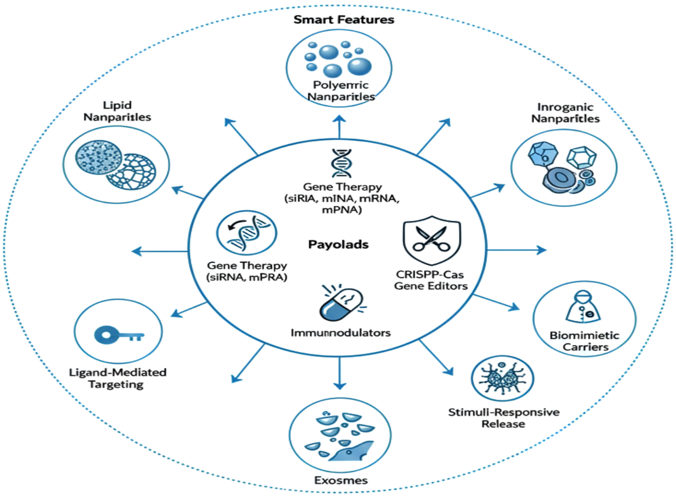

Figure 2: *Overview of nanotherapeutic platforms and functional features in personalized oncology, highlighting nanocarrier types (lipid, polymeric, inorganic, biomimetic, exosomes),*

payloads (chemotherapeutics, gene therapy, CRISPR-Cas, immunomodulators), and smart features.

3. Artificial Intelligence in Oncology

Artificial intelligence (AI) has rapidly become an indispensable tool in personalized oncology, particularly when integrated with nanotherapeutics. **AI for target identification** leverages high-dimensional data from genomics, transcriptomics, and proteomics to uncover actionable mutations, dysregulated pathways, and potential biomarkers that guide the selection of therapeutic targets [10]. By analyzing these complex datasets, AI enables precision in identifying which molecular abnormalities are most suitable for intervention with nanomedicine.Beyond target selection, **AI in drug and nanoparticle design** is transforming how nanocarriers are engineered. Predictive modeling allows for the optimization of nanoparticle size, surface properties, payload loading, and release kinetics, ensuring efficient delivery to tumors while minimizing off-target effects [11]. AI algorithms can also prioritize the most effective therapeutic payloads ranging from chemotherapeutics to RNA-based therapies tailored to specific molecular profiles of individual patients.Furthermore, **AI in clinical decision support** facilitates patient stratification, adaptive therapy planning, and outcome prediction. By integrating omics data, imaging, and prior clinical outcomes, AI can recommend personalized treatment regimens and anticipate therapeutic responses, enabling dynamic adjustments over the course of therapy [12]. Collectively, these AI-driven approaches synergize with smart nanotherapeutics to create a fully integrated, precision-guided oncology framework. *(Figure 3)*

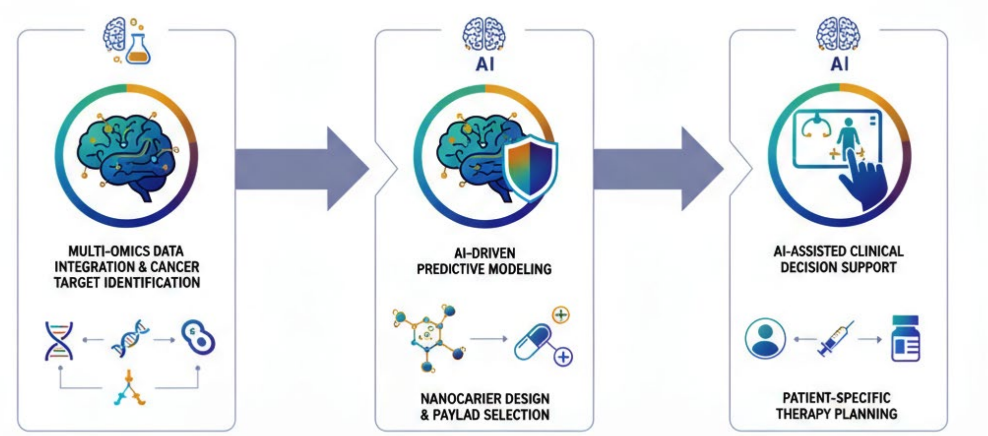

Figure 3: *AI-guided workflow for personalized nanomedicine in oncology, illustrating the integration of multi-omics data for target identification, predictive modeling for nanocarrier*

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design and payload selection, and AI-assisted clinical decision support for patient-specific therapy planning.

4. Liver Cancer (Hepatocellular Carcinoma)

Hepatocellular carcinoma (HCC) remains a leading cause of cancer-related mortality worldwide, and recent advances in personalized oncology have leveraged **nanotherapeutics and AI** to address its clinical challenges [13]. Smart nanoparticles are being engineered to exploit hepatocyte-specific receptors, particularly the **asialoglycoprotein receptor (ASGPR)** and **glypican-3 (GPC3),** allowing precise delivery of therapeutic payloads directly to tumor cells. **Intra-arterial delivery** further enhances local accumulation, maximizing efficacy while reducing systemic toxicity [14].Emerging **RNA- and gene-editing therapeutics,** including siRNA, miRNA, mRNA, and CRISPR-Cas systems, are now being incorporated into these nanocarriers to silence oncogenic drivers or restore tumor suppressor function, offering a molecularly targeted approach beyond conventional chemotherapy [15]. The integration of **AI** plays a pivotal role in patient selection and response prediction, analyzing multi-omics profiles to identify individuals most likely to benefit from specific nanotherapeutic interventions.These combined approaches are rapidly moving through the **translational pipeline**, from preclinical validation to early-phase clinical trials, demonstrating promising safety, targeting efficiency, and preliminary efficacy. By uniting smart nanocarriers with AI-guided personalization, HCC therapy is shifting toward a more precise, patient-specific paradigm [16]. *(Figure 4)*

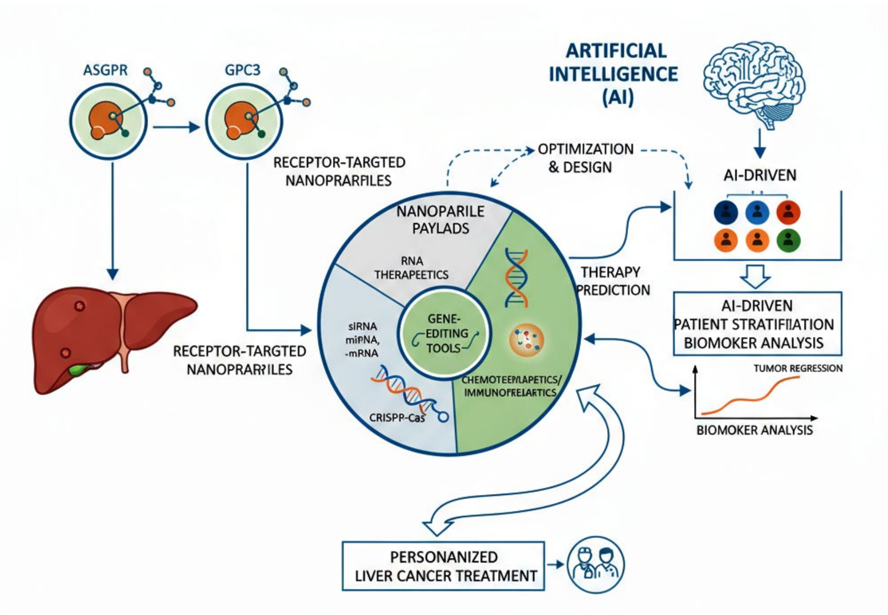

Figure 4: *AI-assisted nanotherapeutic strategies in liver cancer, highlighting receptor-targeted delivery (ASGPR, GPC3), RNA- and gene-editing therapeutics, and AI-guided patient stratification and response prediction.*

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5. Breast Cancer

Breast cancer is a heterogeneous disease, encompassing subtypes such as **estrogen receptor-positive (ER+), HER2-positive (HER2+), and triple-negative breast cancer (TNBC),** each with distinct molecular characteristics and therapeutic vulnerabilities [17]. Recent nanotherapeutic strategies have focused on **subtype-specific delivery,** using smart nanoparticles to target molecular markers unique to each subtype, thereby maximizing therapeutic efficacy while minimizing off-target toxicity [18]. In parallel, **nano-immunotherapy approaches** including nanoparticles carrying checkpoint inhibitors, immune-stimulating cytokines, or tumor vaccines have demonstrated synergistic effects, particularly in TNBC, which often exhibits resistance to conventional therapies.

Artificial intelligence has further enhanced personalized therapy by enabling **biomarker-guided patient stratification,** integrating genomic, transcriptomic, and proteomic data to select the most effective nanotherapeutic regimen. Between 2019 and 2024, multiple preclinical studies and early-phase clinical trials have demonstrated the feasibility, safety, and preliminary efficacy of these AI-guided, nanomedicine-based approaches, marking a significant step toward individualized treatment strategies [19]. *(Figure 5)*

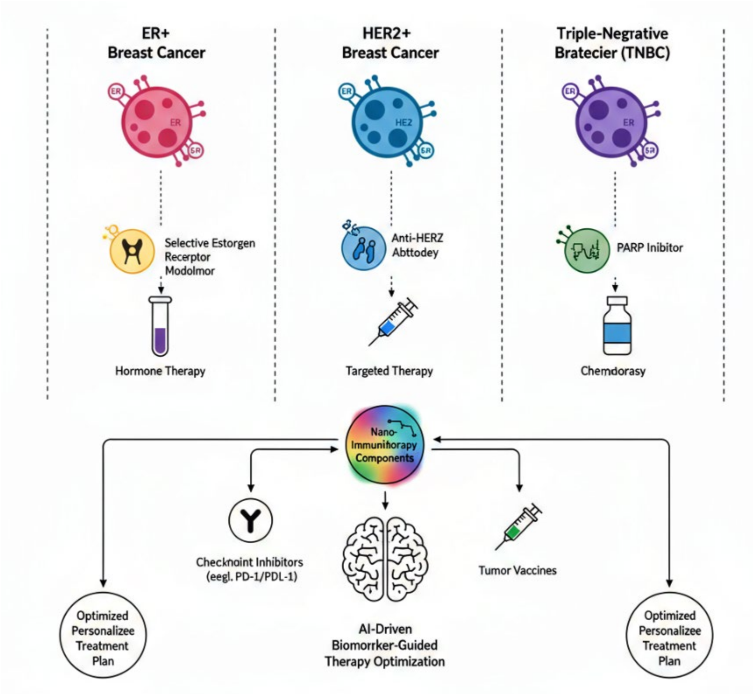

Figure 5: *Personalized nanotherapeutic strategies in breast cancer, illustrating subtype-specific delivery (ER+, HER2+, and TNBC), integration with nano-immunotherapy, and AI-driven biomarker-guided therapy optimization.*

6. Renal Cell Carcinoma (RCC)

Renal cell carcinoma (RCC) presents unique therapeutic challenges due to its highly vascularized tumor microenvironment (TME) and complex immune landscape. Recent advances in nanomedicine have focused on **TME-targeted nanocarriers**, which can modulate angiogenesis, normalize tumor vasculature, and enhance immune cell infiltration, thereby improving therapeutic efficacy [20]. These nanocarriers are increasingly used to deliver **VEGF inhibitors, tyrosine kinase inhibitors (TKIs), and combination therapies,** providing controlled and tumor-specific delivery that reduces systemic toxicity.

Artificial intelligence plays a key role in optimizing these strategies, enabling **biomarker-guided patient selection** and predicting therapeutic responses by integrating multi-omics and clinical data [21]. While preclinical studies have shown promising efficacy, **clinical translation remains challenging,** with hurdles including tumor heterogeneity, reproducibility of nanocarrier performance, and regulatory requirements. Nonetheless, AI-integrated nanotherapeutics represent a critical step toward personalized treatment in RCC, offering the potential for improved outcomes in patients with otherwise difficult-to-treat disease [22]. *(Figure 6)*

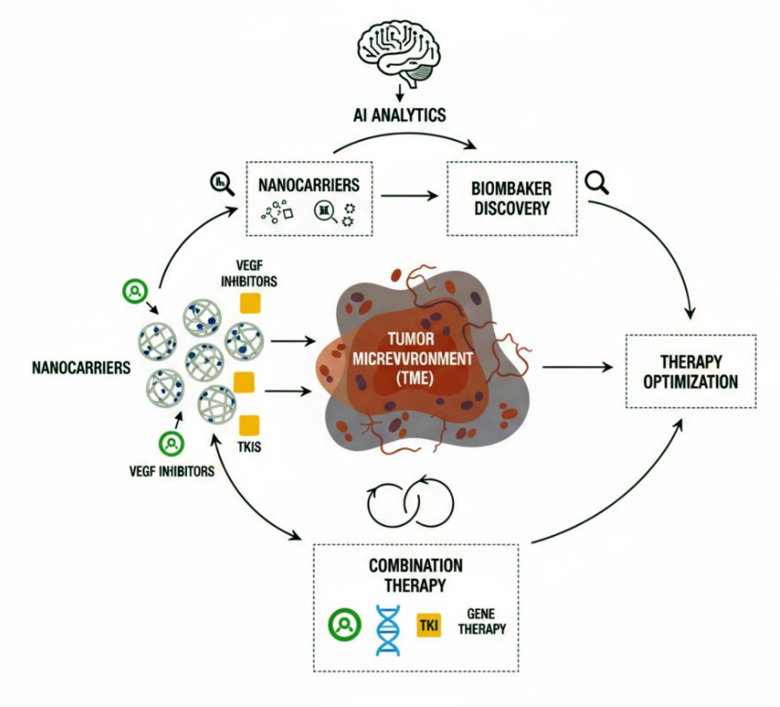

Figure 6: *AI-integrated nanomedicine for RCC, highlighting TME-targeted nanocarriers, VEGF/TKI delivery, combination therapy strategies, and AI-guided biomarker-driven therapy optimization.*

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7. Neuro Cancers (Glioblastoma & Others)

Neuro-oncology faces unique challenges due to the **blood–brain barrier (BBB),** which severely restricts the delivery of conventional therapeutics. Recent nanotherapeutic strategies have focused on overcoming this barrier using **ligand-mediated transcytosis, exosome-based carriers, and ultrasound-assisted nanoparticle delivery**, enabling targeted accumulation of drugs and gene therapies in gliomas and other aggressive brain tumors [23]. In parallel**, nano-immunotherapy approaches** have emerged, leveraging nanoparticles to deliver immune-modulating agents, checkpoint inhibitors, or tumor vaccines, stimulating localized and systemic antitumor immune responses in the brain's specialized immune environment [24].The incorporation of **AI-assisted multi-omics analysis** has further enhanced personalization in neuro-oncology. By integrating genomic, transcriptomic, and proteomic profiles, AI can identify key tumor-specific targets such as **IDH mutations, MGMT methylation, and immune landscape features,** guiding the design of nanotherapeutics for maximal efficacy [25]. Despite preclinical success, **clinical translation** remains challenging, with ongoing trials (2019–2024) focused on evaluating safety, pharmacokinetics, and early therapeutic outcomes. Collectively, these strategies underscore the potential of AI-guided, nanotherapeutic platforms to transform the management of glioblastoma and other neuro cancers [26].

8. Future Perspectives

The future of personalized oncology is poised for transformation through the integration of **AI-guided next-generation nanotherapeutics** and **multi-omics-driven adaptive personalization**. Artificial intelligence will enable the design of highly optimized nanoparticles, predicting optimal size, surface chemistry, and payload combinations tailored to individual tumor profiles. Coupled with real-time **omics analyses,** these smart nanotherapeutics will allow dynamic adaptation of therapy based on tumor evolution, resistance mechanisms, and patient-specific responses [27-28].

Furthermore, the incorporation of **real-world data and digital twins** virtual models representing individual patients will facilitate predictive simulations of therapy outcomes, enabling clinicians to refine treatment strategies and anticipate adverse events before administration [29]. These innovations collectively form a **roadmap for global clinical adoption,** streamlining the translation of nanotherapeutics from bench to bedside while ensuring safety, efficacy, and personalized treatment optimization. By combining AI, multi-omics insights, and advanced computational modeling, the next decade promises a truly individualized and precision-guided oncology landscape [30].

9. Conclusion

From 2019 to 2024, personalized oncology has been increasingly shaped by the synergy between **nanotherapeutics and artificial intelligence (AI),** offering new avenues for precise, patient-specific cancer treatment. Smart nanocarriers engineered for receptor-mediated targeting, stimuli-responsive release, and multifunctional payload delivery have demonstrated enhanced therapeutic efficacy and reduced systemic toxicity across liver, breast, renal, and neuro cancers. AI-driven analyses, leveraging multi-omics datasets, have enabled refined target identification, patient stratification, and predictive modeling of therapeutic responses, accelerating the design and optimization of nanomedicine interventions.Despite remarkable progress, challenges remain in large-scale manufacturing, regulatory approval, long-term safety, and broad clinical translation. Looking forward, the integration of **AI-guided nanotherapeutics, real-time omics-driven personalization, and digital twin-based predictive modeling** is poised to transform oncology practice. By uniting engineering innovation with computational intelligence and molecular precision, these emerging paradigms promise to deliver highly individualized therapies, improve clinical outcomes, and establish a new standard of care in liver, breast, renal, and neuro-oncology.

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