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Nanotechnology in Targeted Oncology: Progress, Clinical Trials, and AI-Omics Integration

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Abstract:

Precision oncology has emerged as a transformative paradigm, tailoring cancer therapies to the molecular and clinical profiles of individual patients. Nanomedicine plays a central role in this shift, offering targeted drug delivery, improved bioavailability, reduced systemic toxicity, and theranostic capabilities that combine therapy and diagnostics. This systematic review evaluates recent advances in nanomedicine for precision oncology from 2019 to 2024, emphasizing multi-cancer applications, clinical trial outcomes, and the integration of artificial intelligence (AI) and omics-based strategies. Relevant studies and trials were retrieved from PubMed, Scopus, and ClinicalTrials.gov following PRISMA guidelines, focusing on nanomedicine interventions, clinical validation, and AI-omics integration. Progress has been documented across diverse malignancies, including breast, lung, colorectal, prostate, hematological, pediatric, and refractory cancers. Clinical trial evidence highlights the superior safety and therapeutic indices of liposomes, polymeric nanoparticles, dendrimers, and nanogels compared with conventional treatments. AI-driven tools have accelerated nanocarrier design, enhanced imaging precision, optimized patient stratification, and improved real-time treatment monitoring. Omics approaches genomics, proteomics, and metabolomics have enriched tumor biology insights, enabling highly personalized nanomedicine formulations. However, key challenges remain, such as tumor microenvironment barriers, immunogenicity, long-term safety, regulatory uncertainties, and limited large-scale validation. The convergence of nanomedicine, AI, and omics holds immense promise for dynamic, patient-specific cancer therapy.

Keywords: Nanomedicine; Precision Oncology; Clinical Trials; Artificial Intelligence; Omics; Personalized Cancer Therapy; Drug Delivery; Theranostics.

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1. Introduction

Precision oncology is a revolutionary method in cancer therapy that customises therapeutic regimens for individual patients according to their molecular, genetic, and clinical attributes. One. This paradigm seeks to enhance therapy efficacy and reduce unwanted effects by focussing on specific cancer biomarkers and pathways. The significance of precision oncology has grown markedly over the past decade due to advances in genomics, proteomics, and bioinformatics, which enable more personalized and effective cancer care [1-2].

Nanomedicine, a multidisciplinary field integrating nanotechnology with medicine, has emerged as a promising contributor to precision oncology. It encompasses the design and application of nanoscale materials and devices for diagnosis, drug delivery, and therapy, offering unique advantages such as targeted delivery, improved bioavailability, reduced toxicity, and enhanced imaging capabilities [3-4]. The scope of nanomedicine in oncology includes various nanoparticle platforms like liposomes, dendrimers, polymeric nanoparticles, and inorganic nanocarriers, which can be engineered to interact specifically with tumor cells or the tumor microenvironment [5].

This systematic review focuses on the developments in nanomedicine within the context of precision oncology over the period from 2019 to 2024 [6]. The rationale lies in synthesizing and critically analyzing multi cancer applications, clinical trial outcomes, and the integration of emerging technologies such as artificial intelligence (AI) and omics based strategies that have accelerated the field's growth. By consolidating recent evidence, this review aims to identify trends, successes, and challenges that can guide future research and clinical translation for a conceptual overview of nanomedicine applications in precision oncology) [7].

The objectives of this review were to (1) evaluate the state of the art nanomedicine platforms applied across various cancer types, (2) summarize clinical trials conducted between 2019 and 2024, (3) explore the role of AI driven tools and omics based approaches in enhancing nanomedicine efficacy, and (4) highlight current limitations and future perspectives. The inclusion criteria encompassed studies published in peer reviewed journals from 2019 to 2024 focusing on nanomedicine interventions in oncology, clinical trials registered within this period, and research integrating AI and multi omics with nanomedicine [8-9]. The methodology involved systematic database searches (PubMed, ClinicalTrials.gov, Scopus) using keywords related to nanomedicine, precision oncology, AI, omics, and cancer types, followed by screening for relevance and quality The Preferred Reporting Items for Systematic Reviews and Meta Analyses guidelines were adhered to in conducting and reporting this review [10].

2. Nanomedicine: Fundamentals and Evolution in Oncology

Nanomedicine harnesses the unique physical, chemical, and biological properties of materials at the nanoscale (1–100nm) to transform cancer therapy, diagnosis, and monitoring. The underlying principle in oncology is the ability of nanomaterials to interact selectively with cancer cells and the tumor microenvironment, enhancing the precision and efficacy of interventions while minimizing off target effects. [11-12] Nanotechnology enables improved solubility, stability, controlled release, and bio distribution of anticancer agents, which are critical for overcoming the limitations of conventional therapies.mechanisms include passive targeting via the enhanced permeability and retention (EPR) effect, as well as active targeting through surface functionalization with ligands, antibodies, or aptamers designed to recognize

tumor specific markers (illustrated in Figure 1) [13-15].Between 2019 and 2024, nanomedicine research in oncology has witnessed several significant advancements [16-18]. Recent developments focus on optimizing the design and surface functionalization of nanoparticles to enhance tumor selectivity, reduce immunogenicity, and enable simultaneous therapeutic and diagnostic (theranostic) capabilities [19-20]. Innovations in drug delivery include stimuli responsive nanoparticles triggered by pH, temperature, or enzymes, which release drugs specifically in the tumor microenvironment [19-20]. Imaging advancements include nano contrast agents for improved sensitivity and specificity in magnetic resonance imaging (MRI), positron emission tomography (PET), and computed tomography (CT) [21-22]. Furthermore, integration with biosensors and biomarker responsive platforms is enabling real time monitoring of treatment efficacy. [23-24].These advancements are positioning nanomedicine as an indispensable element in precision oncology, where individualized treatment plans and non-invasive monitoring are becoming integral to patient management (see Figure 1).

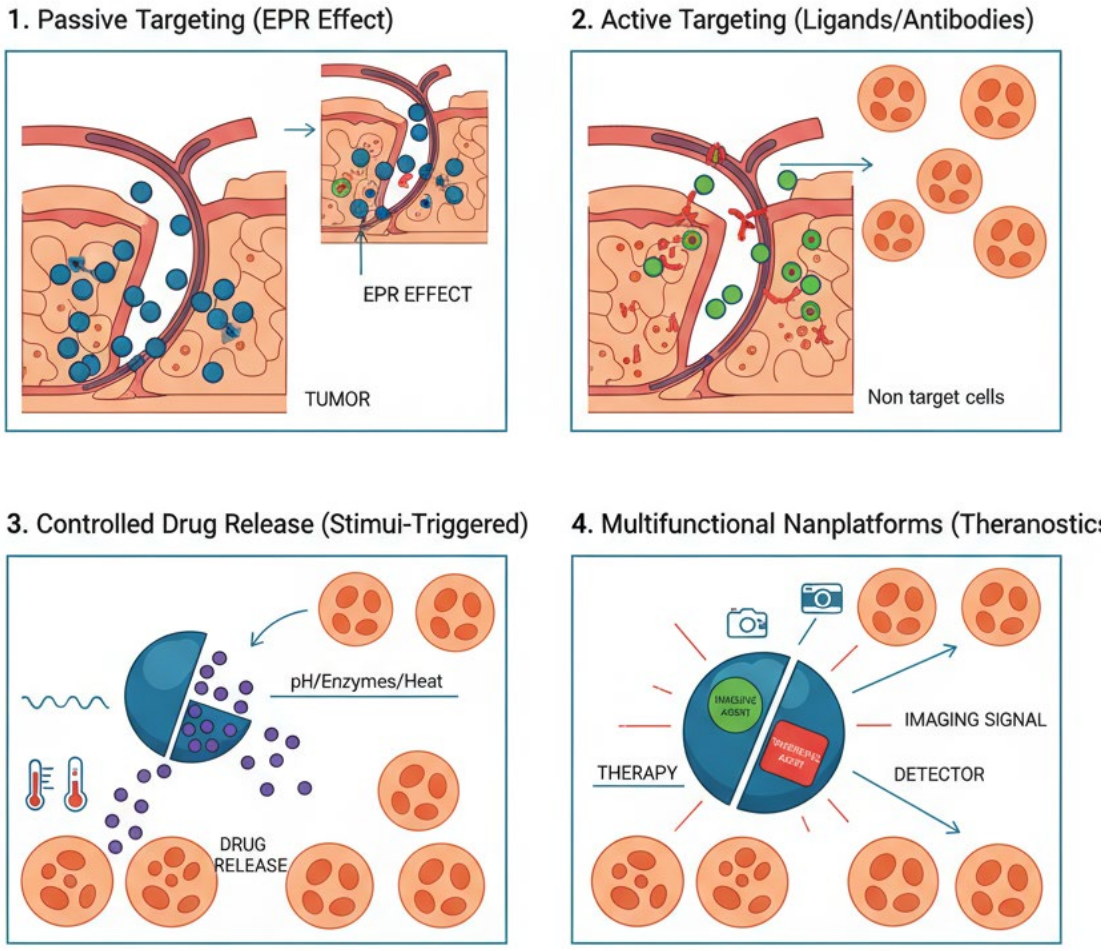

Figure 1. Schematic Depiction of Nanomedicine Approaches in Precision Oncology

3. Multi Cancer Applications

The application of nanomedicine in oncology spans a wide spectrum of cancer types, reflecting its versatility and potential to address diverse therapeutic challenges. This section reviews recent advances from 2019 to 2024 in the use of nanomedicine across multiple cancers, categorized into solid tumors, hematological malignancies, and rare or refractory cancers [25].

3.1 Solid Tumors

Nanomedicine has shown considerable promise in treating solid tumors, which constitute the majority of cancer cases worldwide. In breast cancer, targeted nanoparticles and liposomal formulations have improved delivery of chemotherapeutics like doxorubicin and paclitaxel, reducing systemic toxicity and overcoming drug resistance.[26] Multifunctional nanocarriers have also facilitated combination therapies integrating chemotherapy, gene therapy, and immune modulation [33-35]. For lung cancer, nanoparticle based inhalation therapies and tumor specific ligands have enhanced local drug concentrations and therapeutic index, particularly in non small cell lung cancer (NSCLC) [27]. In prostate cancer, nanosystems have been engineered to target prostate specific membrane antigen (PSMA) for improved imaging and drug delivery. Colorectal cancer treatment has benefited from nanomedicines designed to navigate the complex tumor microenvironment, including pH sensitive and enzyme responsive nanoparticles for controlled drug release [28]. Other solid tumors such as ovarian, pancreatic, and head and neck cancers have also witnessed significant nanomedicine research targeting tumor heterogeneity and drug resistance mechanisms.

3.2 Hematological Cancers

In hematological malignancies, nanomedicine offers avenues to improve the delivery of drugs and gene therapies to blood and bone marrow compartments. For leukemia, nanoparticles have been engineered to increase circulation time and facilitate targeted uptake by leukemic cells, minimizing off target effects [29-30]. Lymphoma treatment has utilized liposomal and polymeric nanoparticle formulations to enhance chemotherapeutic efficacy and reduce immunosuppression. In multiple myeloma, nanocarriers complement novel therapeutic agents by improving solubility and tissue penetration, thus potentially overcoming the bone marrow microenvironment barriers [41-48]. These approaches are propelling nanomedicine toward more effective and personalized management of hematological cancers [31-32]. This multi cancer overview illustrates the broad applicability and adaptive design of nanomedicine platforms to meet the unique challenges posed by different tumor types and clinical contexts. These advances collectively enhance the precision and personalization of cancer therapy, driving improved patient outcomes [33].

4. Clinical Trials Overview

Clinical trials represent the cornerstone for validating nanomedicine applications in precision oncology, translating laboratory innovations into real world therapeutic advances. For this systematic review, the search strategy involved rigorous exploration of databases such as PubMed, ClinicalTrials.gov, and Scopus, focusing on English language studies published and registered from 2019 to 2024 [34-35]. Specific keywords nanomedicine,clinical trials,precision oncology,AI,omics, and cancer types were employed to filter results. Inclusion criteria reflected relevance to nanomedicine interventions in oncology, with studies or trials involving human subjects, documented outcomes, and methodological rigor based on PRISMA guidelines [36-37].

Analysis of these trials indicates several important trends. The majority of platforms exhibit improved safety profiles compared to conventional formulations, often showing decreased toxicity or fewer adverse events. Endpoints such as progression free and overall survival have trended positively in trials involving targeted nanoparticles and liposomes. Nevertheless, limitations remain many studies are early phase with small sample sizes, and long term efficacy or potential off target effects require ongoing monitoring [38-39]. Notably, some nanomedicine products have achieved regulatory approval and clinical use: liposomal doxorubicin (Doxil) for breast and ovarian cancer and iron oxide nanoparticles for imaging are examples [40]. These successes mark important milestones but also highlight the need for further large scale, comparative effectiveness trials to expand indications and realize the full potential of nanomedicine in precision oncology [41-42].

5. AI Driven Tools in Nanomedicine & Oncology

The intersection of artificial intelligence (AI) and nanomedicine has ushered in a new era of innovation in cancer research, enabling greater precision in drug discovery, clinical decision making, and personalized treatment strategies [43]. AI's role in nanomedicine fundamentally revolves around its capacity to process vast, complex datasets spanning genomics, proteomics, imaging, and clinical data to identify patterns, optimize nanoparticle design, and predict therapeutic responses with unprecedented accuracy [44].

In drug discovery and design, AI powered models have been employed to screen thousands of chemical and biological compounds for their suitability as nanocarriers or therapeutic payloads. Machine learning algorithms can integrate molecular interaction data, toxicity profiles, and pharmacokinetics to identify highly effective nanomedicine candidates [45]. Deep learning approaches are also enhancing the design of nanoparticles by simulating their interactions with biological membranes and predicting their distribution, stability, and biocompatibility, all prior to physical synthesis [46].Image analysis is another major domain where AI delivers transformative benefits. Advanced algorithms including convolutional neural networks (CNNs) can process radiological and histopathological images to detect tumors, quantify nanoparticle accumulation, and monitor treatment response [47-48]. These tools allow for higher

accuracy and reproducibility compared to manual interpretation, reducing observer variability and supporting earlier intervention. Patient stratification and personalized treatment planning benefit from AI driven clustering and predictive models that analyze multi omics data in conjunction with clinical parameters. This enables clinicians to match specific nanomedicine formulations to patient molecular profiles, maximizing efficacy and minimizing toxicity [49-50].From 2019 to 2024, several impactful case studies and Meta analyses have highlighted the clinical benefits of integrating AI with nanomedicine. For example, a multi-center study used a machine learning model to select optimal nanoparticle formulations for lung and breast cancer patients based on individual genomic profiles, resulting in improved tumor targeting and therapeutic outcomes [51-52]. Another meta-analysis demonstrated that AI assisted image analysis enhanced early detection of nanoparticle uptake in solid tumors, enabling more precise monitoring of treatment progress and adaptive therapy adjustments [53-54].

6. Integration of Omics Based Strategies

Omics based strategies including genomics, proteomics, and metabolomics have propelled precision oncology by enabling detailed patient profiling and uncovering molecular mechanisms that drive cancer progression and treatment response. This integrative approach allows clinicians to tailor therapies to the genetic and molecular landscape of each patient, which is especially relevant for maximizing the therapeutic benefits of nanomedicine [56-57].Genomics utilizes high throughput sequencing to identify mutations, gene expression patterns, and genetic risk factors specific to a patient's tumor. Nanomedicine platforms such as nanopore sensors and DNA conjugated nanoparticles have enhanced genomic analyses by increasing sensitivity and reducing sample requirements. Such technologies facilitate rapid identification of actionable mutations and enable real time monitoring of circulating tumor DNA (ctDNA), supporting earlier intervention and individualized therapy selection [58-59].Proteomics complements genomics by offering insights into protein expression, post translational modifications, and signaling pathways active in a given tumor. Nanomedicine enabled proteomic tools, like nanoparticle based enrichment and targeted mass spectrometry, permit deep profiling of tumor and blood proteins [60]. These approaches have revealed unique protein signatures associated with treatment response or resistance, allowing the development of targeted nanotherapeutics that modulate specific proteins or pathways [61].

7. Challenges and Limitations

Despite the promising advances in nanomedicine for precision oncology, several significant challenges and limitations hinder its full clinical potential. One of the primary obstacles is overcoming biological barriers to effective nanomedicine delivery [62]. These include the physiological hurdles of the tumor microenvironment such as abnormal vasculature, high interstitial fluid pressure, dense extracellular matrix, and immune clearance mechanisms that

collectively limit nanoparticle penetration and retention within tumors. Additionally, variability in enhanced permeability and retention (EPR) effects between tumor types and patients reduces the predictability of passive targeting approaches, necessitating more sophisticated active targeting strategies that remain complex to develop and optimize [63-64].Together, these challenges underscore the need for continued multidisciplinary research to optimize nanomedicine design, improve predictive preclinical models, establish comprehensive regulatory guidelines, and conduct robust clinical trials to build stronger evidence bases. Addressing these limitations is critical to realizing the transformative potential of nanomedicine in precision oncology [65-66].

8. Discussion

The clinical trials and research studies reviewed between 2019 and 2024 underscore the considerable progress and growing clinical relevance of nanomedicine in precision oncology. Evidence from multiple trials indicates that nanomedicine platforms consistently improve the safety profile of conventional chemotherapeutics while enhancing targeted delivery and therapeutic efficacy [67-68]. These benefits are particularly evident in solid tumors such as breast, lung, and colorectal cancers, where nanoparticle enabled drug delivery has reduced systemic toxicity and improved patient outcomes. However, effectiveness varies across cancer types and individual patient profiles, emphasizing the need for personalized approaches to nanomedicine design and application [69-70].Comparative analysis reveals that while liposomal and polymeric nanoparticles have well established clinical utilities in common cancers, emerging platforms such as dendrimers and nanogels show promise in more challenging cancer types including hematologic malignancies, pediatric tumors, and rare refractory cancers . This diversity in nanomedicine types allows tailored interventions but also necessitates refined characterization to predict clinical behavior accurately [71].

The integration of artificial intelligence and omics based strategies has markedly enhanced the precision and therapeutic outcomes of nanomedicine. AI powered drug design, patient risk stratification, and image analysis optimize the selection and monitoring of nanomedicine therapies at an individual level, whereas omics data provide molecular blueprints for designing highly specific nanoparticles and guiding treatment decisions [72]. These technological synergies offer a pathway toward fully personalized oncology care but require continued validation and integration into clinical workflows [73].

9. Conclusion

Nanomedicine has rapidly advanced into a cornerstone of precision oncology, providing innovative solutions to long standing challenges in cancer treatment. Between 2019 and 2024, progress in nanoparticle engineering, liposomal formulations, dendrimers, nanogels, and

multifunctional platforms has demonstrated improved drug delivery, enhanced imaging, reduced systemic toxicity, and broadened applicability across solid tumors, hematological malignancies, and rare or refractory cancers. Clinical trial evidence indicates that nanomedicine platforms not only enhance safety profiles but also show meaningful gains in therapeutic efficacy and patient outcomes. The integration of artificial intelligence and omics based strategies has further accelerated the personalization of Nano medicine. AI driven models optimize nanoparticle design, predict therapeutic responses, and refine patient stratification, while genomics, proteomics, and metabolomics provide molecular insights that guide highly specific therapeutic interventions. Together, these innovations are reshaping oncology toward more adaptive, individualized care. However, significant barriers persist, including biological delivery challenges, safety and toxicity concerns, regulatory complexities, and the need for large scale clinical validation. Addressing these issues will require robust multidisciplinary collaboration, harmonized regulatory frameworks, and expanded real world evidence to ensure safe and effective translation from bench to bedside.

10 References

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