Journal of Pharmaceutical Research and Integrated Medical Sciences (JPRIMS)
ISSN: 3049-1681 | Vol. 03, Issue-08, August-2026 | pp.-58-72

ORIGINALARTICLE https://jprims.in/

Artificial Intelligence-Powered Translational Nanomedicine in Oncology: Clinical Developments, Multistage Targeting Techniques, And Prospects for Brain, Liver, Breast, and Kidney Cancers

Sudhir Singh Gangwar[1*], Sachin Kumar[1], Meenakshi Verma[1], Yatindra Kumar[1], Mudit Kumar[1]

[1]Department of Pharmacy, GSVM Medical College, Kanpur, UP, 208002, India

***Corresponding Email: sudhirsgangwar@yahoo.com**

Abstract:

The emergence of artificial intelligence (AI) has proved to be an important development in the field of translational nanomedicine, as it has made possible intelligent and personalized applications for precision oncology. The integration of machine learning (ML), deep learning, nanoinformatics, predictive modeling, and computational methods with nano delivery systems has improved carrier design, formulation optimization, multiscale targeting, and therapy monitoring using AI. This article discusses some of the latest developments in the area of AI-assisted translational nanomedicine. It also highlights the use of AI in tumor identification, patient stratification, theranostics, and the application of AI in brain, liver, breast, and kidney cancers. Moreover, cutting-edge developments in digital twins, federated learning, explainable AI, large language models, and intelligent nanorobotics are described for their capacity to speed up clinical translation. While much has been accomplished, there are issues regarding data standardization, clinical validation, scalable manufacturing, regulatory clearance, and algorithm transparency that need to be addressed.

Keywords: Artificial intelligence (AI); Translational nanomedicine; Precision oncology; Multistage targeting; Nanoinformatics; Theranostics; Personalized medicine.

Received: May 11, 2026 **Revised: June 12, 2026** **Accepted: July 19, 2026** **Published: August 17, 2026**

DOI: https://doi.org/10.64063/3049-1681.vol3.issue8.000295

1. INTRODUCTION

AI is revolutionizing oncology by offering ways of diagnosing diseases, developing treatment plans and making precise decisions regarding therapeutic options. However, nanomedicine has advanced the treatment of cancer by way of delivering drugs in a targeted manner, controlling their release, improving pharmacodynamics and pharmacokinetics and decreasing systemic

toxicity[1]. The combination of AI and translational nanomedicine has created a new paradigm for precision oncology through computational and nanotechnological means of optimizing nanoparticles, formulations and personalized medicine. The applications of AI such as machine learning, deep learning and predictive analytics are being applied to nanoparticle discovery and targeted treatment[2].

The recent developments in radiomics, digital pathology, multi-omics data analysis, nanoinformatics, and explainable AI have even further extended the clinical applications of intelligent nanomedicine. Such techniques make it possible to develop multifunctional nanovehicles that are able to address biological obstacles, including tumor heterogeneity, immune clearance, and the blood-brain barrier. In addition, AI-enabled multistage targeting helps ensure the optimization of the delivery of drugs and therapy itself, including toxicity prediction[3]. All these innovations accelerate the development of AI-enabled nanomedicine in the field of precision oncology for different types of cancer.

1.1 Background and Context

Cancer still ranks among the top causes of death in spite of substantial advances made in the field of molecular diagnostics, targeted therapies, immunotherapies, and precision medicine. Traditional approaches to treating cancer are constrained by such problems as nonspecificity of the effect, toxicity, multidrug resistance, and variability among patients[4]. One of the most promising methods of combating the disease is nanomedicine, which employs nanoscale drug carriers that can solve the problems of low solubility, biodistribution, circulation, and release of drugs. Nevertheless, the application of nanomedicine in clinical practice encounters problems associated with designing nanoparticles, reproducible production, biological complexity, and regulation. AI turns out to be an efficient approach for dealing with these issues.

1.2 Objectives of the Review

The primary objectives of this review are:

- To revisit the use of AI in the design and optimization of nanomedicine for precision oncology.
- To look into the computational methods driven by AI in the design of nanocarriers, formulation optimization, nanoinformatics, and predictive modeling.
- To explore multistage AI targeting in enhancing tumor recognition, drug delivery, and treatment monitoring.
- To highlight the latest clinical advances in AI nanomedicine for brain, liver, breast, and kidney cancers.
- To analyze recent developments, translational hurdles, regulatory concerns, and future directions in intelligent cancer nanomedicine.

1.3 Importance of the Topic

The incorporation of AI in translational nanomedicine is indeed a remarkable breakthrough in precision oncology due to its application of computational intelligence along with targeted delivery of drugs[5]. It has helped in optimizing the design of nanoparticles, multistage targeting, personalized treatment decisions, and predictive therapy. The role of AI in the development of precision medicine has immense possibilities as far as future applications are concerned.

2. ARTIFICIAL INTELLIGENCE FOR INTELLIGENT NANOMEDICINE DESIGN

Incorporating AI has helped shift nanomedicine from an empirical science to a data-based engineering framework for precision oncology. The traditional process of formulating nanoparticles entails a lengthy process of experimentation, which is expensive and time consuming. However, use of AI, which includes machine learning, deep learning, generative AI, and predictive modeling, enables quick analysis of complicated biological and physicochemical data to help design nanoparticles and determine their performance[6]. Intelligent nanomedicine design is therefore an integral component of designing safe and efficient cancer therapeutics.

2.1 AI-Driven Nanocarrier Engineering and Material Selection

The efficiency of nanomedicine depends mainly on choosing proper nanocarriers that can carry drugs in an effective manner without inducing any toxic effect in the system. Various nanocarriers like liposomes, polymeric nanoparticles, dendrimers, lipid nanoparticles, inorganic nanoparticles, micelles, exosomes, and hybrids have unique physical and chemical features affecting drug loading capacity, circulation time, cell internalization, degradability, and effectiveness of the therapeutic drugs[7]. The use of AI in choosing these nanocarriers is done through analysis of experimental data sets and identification of their correlation.

The ML algorithms help refine nanocarrier development processes even more by determining the impact of size, shape, surface charge, composition, and hydrophobicity on the performance of nanoparticles in living organisms. The supervised learning models associate certain parameters of the formula with characteristics such as encapsulation efficiency, stability, drug release, circulation time, and cellular uptake. With the use of deep learning, it is possible to analyze complex images and molecular data sets in order to establish non-linear relations which may be ignored otherwise by traditional statistics.

Nanocarrier design using AI for surface engineering is also a crucial field due to the effect that nanoparticle surface plays on biological interactions once administered. AI is useful in selecting the correct polymers, PEGylation, antibodies, peptides, aptamers, and other targeting ligands to ensure high tumor specificity and minimal immune system clearance[8]. Moreover, it is used in determining the suitability of the payload by comparing its physicochemical characteristics with those of chemotherapeutic agents, nucleic acids, proteins, and gene editing molecules.

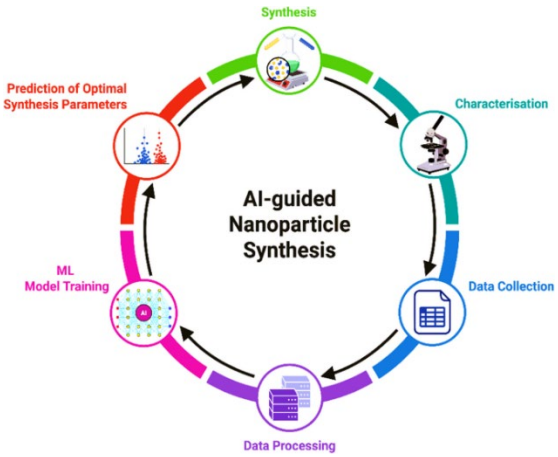

Figure 1. AI-guided nanoparticle synthesis and optimization workflow

2.2 Computational Optimization of Nanomedicine Formulations

In addition to being an important aspect in nanomedicine development in the current times, computational optimization plays a critical role in formulating various types of nanomedicines. Traditional optimization techniques rely on multiple experiments in order to achieve suitable combinations between nanomaterials and loading of drugs[9]. However, through AI, this process is made much easier by analyzing data related to the formulation process and predicting optimal parameters quickly and accurately.

The concepts of machine learning, deep learning, Bayesian optimization, and generative AI are becoming more popular in optimizing important properties of formulations such as particle size, drug loading, surface charge, drug release, and colloidal stability. Moreover, computational methods such as quantitative structure-activity relationship (QSAR), molecular docking, and molecular dynamics help understand the molecular interaction between nanoparticle and drug and the stability of the carriers. Such techniques allow predicting formulation that can be further tested experimentally[10].

Aside from formulation design, the use of AI is essential for optimizing multifactorial objectives including therapeutic efficacy, biocompatibility, toxicity, manufacturability, and cost. AI-powered algorithms can predict pharmacokinetics, stability, and degradation of formulations under various physiological settings. These intelligent approaches increase the robustness of formulations while aiding in the transition from nanomedicine discovery in laboratories to practical uses, hence the necessity of computational design in precision oncology.

2.3 AI-Based Nanoinformatics and Predictive Modeling

Nanoinformatics is a field that incorporates AI, computational science, and nanotechnology to handle the huge amounts of data created during research in nanomedicine. Data concerning nanoparticle chemistry, physiochemistry, biology, toxicity, pharmacokinetics, and efficacy can be incorporated into databases and analyzed computationally[11]. AI technologies analyze such databases and discover patterns in the data, allowing for data-driven decision-making during nanoparticle design and minimizing the need for empirical experiments.

Additionally, predictive modeling is used to make predictions of nanoparticle behavior in a biological system even before conducting the experiments. Through machine learning, prediction of cellular uptake, biodistribution, interactions with the immune system, protein corona formation, toxicity, pharmacokinetics, and ADME can be made using physicochemical and biological data.

The rising use of explainable artificial intelligence (XAI) has also increased the confidence placed on AI-enabled nanomedicine due to the enhanced transparency and interpretability of these models[12]. Explainable models assist researchers in determining the physicochemical properties that are most significant for determining the performance and toxicity of nanoparticles and their interactions with biological systems. With continued expansion of nanoinformatics databases, predictive modeling using AI is anticipated to be instrumental for the rapid development of intelligent nanomedicine.

Table 1. Artificial Intelligence Techniques and Their Applications in Intelligent Nanomedicine Design

AI Technique	Primary Application	Key Outcomes in Nanomedicine
Machine Learning	Nanocarrier selection, formulation optimization	Improved particle design, encapsulation efficiency, and therapeutic performance
Deep Learning	Image analysis, complex formulation prediction	Enhanced prediction accuracy and identification of nonlinear biological interactions
Bayesian Optimization	Formulation parameter optimization	Reduced experimental iterations and accelerated formulation development
Generative AI	Novel nanoparticle and material design	Discovery of innovative nanocarrier architectures and material combinations
QSAR Modeling	Prediction of nanoparticle properties and biological activity	Improved toxicity assessment and candidate screening
Molecular Docking & Molecular Dynamics	Drug–carrier interaction and structural stability analysis	Optimized payload compatibility, ligand binding, and formulation stability
XAI	Model interpretation and decision transparency	Increased reliability, regulatory confidence, and clinical acceptance of AI-assisted nanomedicine

3. AI-POWERED MULTISTAGE TARGETING TECHNIQUES IN PRECISION ONCOLOGY

Multistage targeting is one of the major approaches to precision oncology which helps tackle the biological obstacles encountered in conventional cancer treatment. In contrast to one-step drug delivery, multistage targeting relies on a series of steps including tumor recognition, navigation of the drug through the body, target accumulation, cellular uptake, and controlled release of the drug inside the cells[13]. By using AI, all of these stages can be further improved through the use of clinical, imaging, molecular, and physicochemical data. Therefore, AI-based multistage targeting is a personalized approach to optimizing drug delivery.

3.1 AI-Assisted Tumor Recognition and Patient Stratification

Accurate tumor characterization serves as the initial stage of success of precision nanomedicine since the effectiveness of treatment greatly depends on patient selection and identification of tumor biological characteristics[14]. The advent of AI has brought a revolution to the field of tumor recognition through radiological images, digital pathology, genome data, and clinical data. Machine and deep learning algorithms enable quicker and more accurate determination of imaging patterns, heterogeneity of tumors, and molecular subtypes.

Radiomics and Pathomics have emerged as significant applications of AI through which quantitative information about tumors can be obtained from medical images and histopathology slides. Radiomics and pathomics are computational tools that characterize tumor morphology, angiogenesis, textures, cell architecture, and metabolism, which are not usually identified during clinical examination. Combination of imaging biomarkers with genomics, transcriptomics, proteomics, and metabolomics provides additional information about tumors.

AI-powered patient stratification involves the use of multimodal clinical data to distinguish those patients who are more likely to respond to specific nanomedicine treatments[15]. Predictive modeling analyzes biomarkers, receptors, immune environment, genetic mutations, and previous treatment experience to enable individualized therapy choice. This is an example of intelligent stratification that increases the accuracy of treatments and raises the clinical response rate.

3.2 Intelligent Multistage Drug Delivery and Targeting

After the patient selection process, AI is used to improve all phases of nanoparticle delivery from the systemic circulation to intracellular drug release. Predictive algorithms help to assess the properties of nanoparticles together with physiological and tumor-specific features to enhance circulation stability, tumor accumulation, and tissue penetration. ML models can predict the protein corona, immune recognition, vascular permeability, and nanoparticle biodistribution to optimize the formulation of nanoparticles even before the clinical use[16].

AI helps in the active targeting by selecting appropriate receptors and ligands and optimizing targeting ligands like antibodies, peptides, aptamers, and small molecules. AI-assisted choice of receptor-specific nanocarriers leads to increased uptake of cancer cells and reduced accumulation in healthy cells. Also, computational models help to design stimuli-responsive nanoparticles for the release of drugs under certain biological conditions such as acidic pH, oxidative stress, enzymes, hypoxia, and external stimuli such as ultrasound and magnetic fields[17].

One of the biggest challenges in targeted drug delivery includes overcoming various biological barriers such as the blood-brain barrier and tumor microenvironment. AI-based predictive models predict the passage of drugs through these biological barriers, the process of their intra-cellular transport, and nanoparticle transport efficiency based on imaging and molecular data. Such smart delivery systems help to increase drug penetration into difficult-to-access tumors.

3.3 AI-Integrated Theranostics and Treatment Monitoring

Theranostics is a fusion of diagnostic imaging and drug targeting that allows for disease diagnosis, treatment, and monitoring to be performed concurrently[18]. AI has greatly helped theranostic methods through the combination of data acquired using magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), fluorescence imaging, and molecular biomarkers. AI helps visualize the entire process of treatment from the beginning.

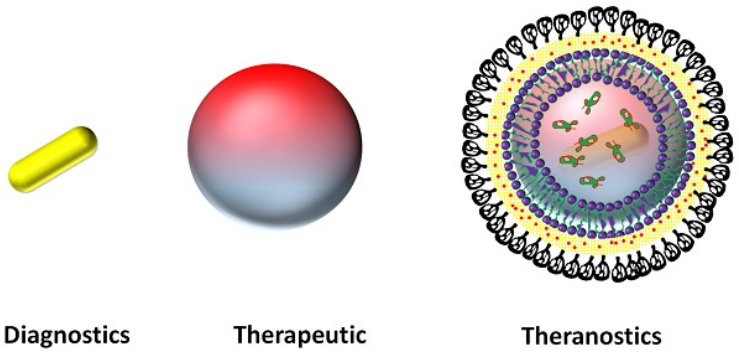

Figure 2. Schematic representation of diagnostic, therapeutic, and theranostic nanoparticles in precision oncology.

AI-based image analysis technology makes real-time monitoring of nanomedicine administration possible since it helps track the dynamics of changes in tumor volume, vasculature, metabolism, and biomarker expression. Prediction algorithms assess the dynamics of therapeutic effects and differentiate between disease progression and treatment effects, allowing for an adjustment of treatment regimens when needed[19]. The combination of digital pathology and multimodal imaging technologies provides additional benefits for clinical decision-making.

Not only treatment monitoring but also treatment adaptation can be facilitated using AI since these intelligent monitoring systems analyze the dynamics of longitudinal clinical, imaging, and

biomarker data. With the help of such algorithms, physicians can perform personalized dose management, detect resistance to therapy and predict toxicity, making the necessary modifications to treatment plans depending on the progression of the disease[20].

Table 2. AI Technologies Supporting Multistage Targeting in Precision Oncology

Targeting Stage	AI Technology	Primary Function	Clinical Benefit
Tumor recognition	Machine Learning, Deep Learning	Tumor detection and molecular classification	Improved diagnostic accuracy and early patient selection
Patient stratification	Radiomics, Pathomics, Multi-omics Integration	Biomarker identification and personalized therapy selection	Enhanced treatment precision and response prediction
Systemic drug delivery	Machine Learning, Predictive Modeling	Protein corona prediction, biodistribution, circulation optimization	Improved nanoparticle stability and tumor accumulation
Active targeting	Deep Learning, Ligand Prediction Models	Receptor–ligand optimization and targeted nanoparticle design	Increased cellular uptake and reduced off-target toxicity
Theranostics	AI-guided PET, CT, MRI, Digital Pathology	Real-time treatment monitoring and response evaluation	Early assessment of therapeutic efficacy
Adaptive treatment	Explainable AI, Predictive Analytics	Dose optimization, toxicity prediction, treatment adaptation	Personalized therapy and improved clinical outcomes

4. CLINICAL DEVELOPMENTS AND FUTURE PROSPECTS OF AI-POWERED NANOMEDICINE

AI has been very instrumental in the development of nanomedicine in the clinical setting through the improvement of the design and optimization of targeted therapy delivery systems in various types of cancer. The combination of computational intelligence with precision drug delivery systems has allowed for accurate patient stratification, personalization of treatments, and real-time tracking of therapies[21]. Progresses made in the field of medical imaging, multi-omics,

prediction modeling, and intelligent engineering of nanocarriers have improved the translational path from basic science to clinical practice[22]. With continued progress in AI technologies, there is hope that such technologies will be critical in addressing biological, technological, and regulatory limitations of nanomedicine in the clinic.

4.1 Clinical Applications in Brain, Liver, Breast, and Kidney Cancers

The implementation of AI-based nanomedicine depends on the biological properties and obstacles associated with each specific type of cancer[23]. The case of brain cancer is an example where imaging technologies combined with the predictive modeling capabilities of AI are used to develop nanoparticles that can better penetrate the blood-brain barrier for the delivery of drugs. In the case of liver cancer, AI technologies are employed to model loco-regional and systemic strategies for the development of nanomedicines using imaging biomarkers, liver function, and tumor heterogeneity[24]. One of the types of cancer where the development of nanomedicines is the most advanced is breast cancer where AI helps classify subtypes and develop personalized drug delivery approaches.

There are many nanomedicine techniques that have been clinically proven to be successful, such as liposome drugs, nanoparticle drug bound to albumin, polymers as drug carriers, and drugs based on lipids. AI can also improve the performance of these therapeutic techniques, since it is capable of predicting individual responses, dosage optimization, and biomarkers for efficacy[25].

More clinical trials utilizing AI and more clinical studies involving nanomedicine point to the translational prospects offered by intelligent oncology. Contemporary clinical research involves the use of AI in imaging, molecular analysis, and predictive analytics in assessing the efficacy of nanoparticles, tracking the course of treatment, and fine-tuning treatment regimens. The described trend may be seen as the development of personalized nanomedicine guided by computational intelligence.

4.2 Emerging Technologies Accelerating Clinical Translation

Advances in digital technologies are increasing the functionality of AI-based nanomedicine in addition to the application of traditional machine learning[26]. Digital twins are created in order to create virtual patients that help to mimic the progress of diseases, nanoparticles distribution, pharmacodynamics, and the results of therapy before initiating therapy. In a similar way, federated learning allows for joint creation of models among several healthcare organizations without breaching patient confidentiality.

Large language models, intelligent AI agents, and complex decision-making systems are also starting to aid in oncology research as tools for literature analysis, biomarkers identification, data analysis, and treatment planning[27]. Such technologies allow for fast knowledge synthesis, data analysis, and help physicians determine personalized therapeutic approaches. Their use in nanomedicine research is expected to facilitate scientific advancements and increase translational efficiency.

Future developments may include more complex integration of AI with robotics, smart nanorobots, wearable biosensors, and therapeutic monitoring technologies. Intelligent nanorobotic systems able to navigate within the human body, control the release of drugs, and monitor vital signs in real time can be transformative in precision oncology. With the help of multi-modal imaging techniques and adaptable algorithms, such technology might become a personalized therapeutic system[28].

4.3 Challenges, Regulatory Perspectives, and Future Clinical Adoption

Despite great achievements, several scientific and regulatory issues prevent wide-scale implementation of AI-driven nanomedicine into routine clinical practice. Such issues include standardization of nanoparticles characterization, variability of biological data sets, lack of external validation of AI models, problems with reproducibility of manufacture, and lack of multicenter clinical evidence. Furthermore, integration of heterogeneous clinical, radiological, molecular, and pharmacological data sets needs advanced computational technologies and standardized approaches to reporting.

Regulatory clearance of AI-based nanomedicine is especially challenging since it requires assessment of pharmaceutical drugs, medical devices, AI algorithms, and companion diagnostics at once[29]. Regulatory authorities focus on such aspects as explainable AI, algorithm transparency, continuous validation of AI models, cybersecurity, and quality-by-design manufacture. Harmonized international regulatory frameworks will thus be key for clinical application and commercial success.

Successful integration of intelligent nanomedicine in the clinic will require the interplay of experts from fields such as oncology, nanotechnology, computer science, regulatory agencies, and pharmaceutical industry. Further research on nanoinformatics databases, clinical trials, explainability in AI and manufacturing techniques will build trust in intelligent nanomedicine. Addressing these challenges will pave the way for intelligent nanomedicine to emerge as a critical element of advanced precision oncology.

Table 3. Comparative Analysis of Recent Studies on AI-Powered Translational Nanomedicine

Author(s) & Year	Study Focus	Approach	Key Findings	Research Gap
Tagde et al. (2022)[30]	Breast cancer nanomedicine	Targeted nanoparticle drug delive	Improved drug delivery, tumor targeting, and reduced toxicity.	Limited AI integration and personalized optimization.
Tran et al. (2017)[31]	Cancer nanomedicine	Conventional nanoparticle delivery	Demonstrated clinical benefits of	Lacks AI-driven design and

			nanomedicine in oncology.	precision medicine concepts.
Wang et al. (2024)[32]	AI in cancer nanomedicine	ML, DL, AI-assisted imaging	Improved diagnosis, nanoparticle optimization, and treatment monitoring.	Limited focus on multistage targeting and clinical translation.
Wang et al. (2021)[33]	Multistage-targeting nanoparticles	Sequential chemo/chemodynamic delivery	Enhanced tumor penetration and therapeutic efficacy.	Minimal AI-based optimization and predictive modeling.
Wang et al. (2018)[34]	Magnetic multistage targeting	Magnetic nanoparticle drug delivery	Achieved effective chemo-photothermal therapy.	No AI integration for targeting or treatment planning.

5. DISCUSSION

Intelligent design of nanoparticles, targeted delivery, and personalized treatment strategies have been facilitated through the integration of AI with translational nanomedicine[35]. This article aims at reviewing recent developments in AI -driven computational methods, multistage targeting, and clinical application, as well as the challenges that hinder its extensive clinical use. The following is a discussion of the key discoveries, their clinical relevance, existing research gaps, and future directions[36].

5.1 Interpretation and Analysis of Findings

From the results obtained, it is clear that the use of AI has improved nanomedicine through better designing of nanoparticles, optimal formulation, multitargeting, and customized therapy planning[37]. The application of AI in integrating imaging, molecular, and clinical information allows for better tumor profiling, intelligent drug delivery, and treatment monitoring. Examples of clinical applications include tumors of the brain, liver, breast, and kidneys[38].

5.2 Implications and Significance

There are major implications of AI in nanomedicine that can significantly affect precision oncology since it allows for rapid development of nanocarriers, selection of individual therapy, and evidence-based decisions in clinical practice[39]. Predictive models used in collaboration with AI allow increasing targeting efficacy, ensuring safety and monitoring of treatment, as well as avoiding toxicity[40].

5.3 Research Gaps and Limitations

However, there are still many obstacles that hinder the clinical implementation of nanomedicine powered by AI despite the huge number of advancements. Some of the major problems are that AI models are created using inadequate and heterogeneous data, while differences in characterization of nanoparticles, imaging process, and clinical reporting affect model generalization. Besides, prospective clinical validation and manufacturing, regulation, explainability, and data privacy are still obstacles that need further research.

5.4 Future Research Directions

Future research directions need to consider the integration of nanoinformatics, multi-omics, radiomics, and real-world clinical data within AI-driven platforms for precision oncology. Advancing technologies like digital twins, federated learning, explainable AI, intelligent nanorobots, and adaptive decision-support systems will contribute to the further advancement of nanoparticles and personalized treatments. Clinical studies involving multicenter trials and frameworks for data sharing and regulatory harmonization will play an important role in realizing clinical use of AI-driven nanotechnology.

6. CONCLUSION

AI-assisted translational nanomedicine has revolutionized the field of precision oncology through the incorporation of intelligent computing methodologies in tandem with cutting-edge nanocarrier systems to achieve improved targeted delivery, drug monitoring, and personalized cancer therapy. The present review article brings to the forefront the role of AI-enabled nanocarrier design, computational formulation design, nanoinformatics, multistage targeting, and theranostics to hasten the process of clinical translation of nanomedicine applications for the treatment of brain, liver, breast, and kidney cancers. Even though substantial gains have been made so far, issues such as data standardization, clinical validation, regulatory approval, manufacturing scalability, and explainable AI need to be addressed before clinical implementation becomes possible. Further advances in the area of digital health and evidence-based clinical studies will only enhance the convergence of AI and nanomedicine.

REFERENCES

1. Akhtar, M., Nehal, N., Gull, A., Parveen, R., Khan, S., Khan, S., & Ali, J. (2025). Explicating the transformative role of artificial intelligence in designing targeted nanomedicine. Expert Opinion on Drug Delivery, 22(7), 971-991.

2. Albukhari, A. F. (2025). AI-Driven Marine Bioactives for Cancer Therapy: A Systematic Review of Drug Discovery, Resistance Overcoming Strategies, and Precision Drug Delivery. Pharmacognosy Reviews, 19(38), 175-185.
3. Bhange, M., & Telange, D. (2025). Convergence of nanotechnology and artificial intelligence in the fight against liver cancer: a comprehensive review. Discover Oncology, 16(1), 77.
4. Chen, B., Dai, W., He, B., Zhang, H., Wang, X., Wang, Y., & Zhang, Q. (2017). Current multistage drug delivery systems based on the tumor microenvironment. Theranostics, 7(3), 538.
5. Cheng, H. B., Cheng, Y., Wang, J., Liu, H., Zhang, K., Wu, R., ... & Yoon, J. (2025). Protein-based nanomedicines for cancer theranostics: From supramolecular self-assembly to AI-driven design and applications. Chem, 11(10).
6. Chou, W. C., Canchola, A., Zhang, F., & Lin, Z. (2025). Machine learning and artificial intelligence in nanomedicine. Wiley interdisciplinary reviews: Nanomedicine and nanobiotechnology, 17(4), e70027.
7. Cun, X., Chen, J., Ruan, S., Zhang, L., Wan, J., He, Q., & Gao, H. (2015). A novel strategy through combining iRGD peptide with tumor-microenvironment-responsive and multistage nanoparticles for deep tumor penetration. ACS applied materials & interfaces, 7(49), 27458-27466.
8. Fan, Y., Yuan, S., Huo, M., Chaudhuri, A. S., Zhao, M., Wu, Z., & Qi, X. (2017). Spatial controlled multistage nanocarriers through hybridization of dendrimers and gelatin nanoparticles for deep penetration and therapy into tumor tissue. Nanomedicine: Nanotechnology, Biology and Medicine, 13(4), 1399-1410.
9. Garg, P., Pareek, S., Kulkarni, P., Salgia, R., & Singhal, S. S. (2024). Nanoengineering solutions for cancer therapy: bridging the gap between clinical practice and translational research. Journal of Clinical Medicine, 13(12), 3466.
10. Glaser, T., Han, I., Wu, L., & Zeng, X. (2017). Targeted nanotechnology in glioblastoma multiforme. Frontiers in pharmacology, 8, 166.
11. Habeeb, M., Vengateswaran, H. T., You, H. W., Saddhono, K., Aher, K. B., & Bhavar, G. B. (2024). Nanomedicine facilitated cell signaling blockade: difficulties and strategies to overcome glioblastoma. Journal of materials chemistry B, 12(7), 1677-1705.
12. He, H., Liu, L., Morin, E. E., Liu, M., & Schwendeman, A. (2019). Survey of clinical translation of cancer nanomedicines—lessons learned from successes and failures. Accounts of chemical research, 52(9), 2445-2461.
13. Hu, C., Yang, X., Liu, R., Ruan, S., Zhou, Y., Xiao, W., ... & Gao, H. (2018). Coadministration of iRGD with multistage responsive nanoparticles enhanced tumor targeting and penetration abilities for breast cancer therapy. ACS applied materials & interfaces, 10(26), 22571-22579.
14. Ji, C., Li, J., Mei, J., Su, W., Dai, H., Li, F., & Liu, P. (2023). Advanced nanomaterials for the diagnosis and treatment of renal cell carcinoma. Advanced NanoBiomed Research, 3(2), 2200079.

15. Joyce, P., Allen, C. J., Alonso, M. J., Ashford, M., Bradbury, M. S., Germain, M., ... & Santos, H. A. (2024). A translational framework to DELIVER nanomedicines to the clinic. Nature nanotechnology, 19(11), 1597-1611.

16. Kapoor, D. U., Sharma, J. B., Gandhi, S. M., Prajapati, B. G., Thanawuth, K., Limmatvapirat, S., & Sriamornsak, P. (2024). AI-driven design and optimization of nanoparticle-based drug delivery systems. Science, Engineering and Health Studies, 24010003-24010003.

17. Kumar, D. K. (2025). Clinical Translation of Nanomedicine in Oncology: A Comprehensive Analysis of Developments, Obstacles, and Prospects in Brain, Hepatic, Renal, and Breast Cancers. Journal of Emerging Pharmaceutical and Medical Research (JEPMR), 25-52.

18. Lammers, T. (2024). Nanomedicine tumor targeting. Advanced Materials, 36(26), 2312169.

19. Mao, X., Wang, G., Wang, Z., Duan, C., Wu, X., & Xu, H. (2025). Theranostic lipid nanoparticles for renal cell carcinoma. Advanced Materials, 37(31), 2306246.

20. Meng, J., Jin, Z., Zhao, P., Zhao, B., Fan, M., & He, Q. (2020). A multistage assembly/disassembly strategy for tumor-targeted CO delivery. Science Advances, 6(20), eaba1362.

21. Metselaar, J. M., & Lammers, T. (2020). Challenges in nanomedicine clinical translation. Drug delivery and translational research, 10(3), 721-725.

22. Naz, S., Wang, M., Han, Y., Hu, B., Teng, L., Zhou, J., ... & Chen, J. (2019). Enzyme-responsive mesoporous silica nanoparticles for tumor cells and mitochondria multistage-targeted drug delivery. International journal of nanomedicine, 2533-2542.

23. Parodi, A., Kolesova, E. P., Voronina, M. V., Frolova, A. S., Kostyushev, D., Trushina, D. B., ... & Zamyatnin Jr, A. A. (2022). Anticancer nanotherapeutics in clinical trials: The work behind clinical translation of nanomedicine. International Journal of Molecular Sciences, 23(21), 13368.

24. Pearce, A. K., & O'Reilly, R. K. (2019). Insights into active targeting of nanoparticles in drug delivery: advances in clinical studies and design considerations for cancer nanomedicine. Bioconjugate chemistry, 30(9), 2300-2311.

25. Rana, A., Adhikary, M., Singh, P. K., Das, B. C., & Bhatnagar, S. (2023). "Smart" drug delivery: A window to future of translational medicine. Frontiers in Chemistry, 10, 1095598.

26. Ruan, S., Zhang, L., Chen, J., Cao, T., Yang, Y., Liu, Y., ... & Gao, H. (2015). Targeting delivery and deep penetration using multistage nanoparticles for triple-negative breast cancer. Rsc Advances, 5(79), 64303-64317.

27. Samathoti, P., Kumarachari, R. K., Bukke, S. P. N., Rajasekhar, E. S. K., Jaiswal, A. A., & Eftekhari, Z. (2025). The role of nanomedicine and artificial intelligence in cancer health care: individual applications and emerging integrations—a narrative review. Discover Oncology, 16(1), 697.

28. Šamec, N., Zottel, A., Videtič Paska, A., & Jovčevska, I. (2020). Nanomedicine and immunotherapy: a step further towards precision medicine for glioblastoma. Molecules, 25(3), 490.

29. Sharma, G. (2025). Clinical Translation of Nanomedicine in Oncology: Advances, Challenges, and Future Directions in Hepatic, Renal, Breast, and Brain Malignancies. Journal of Emerging Pharmaceutical and Medical Research (JEPMR), 53-85.

30. Tagde, P., Najda, A., Nagpal, K., Kulkarni, G. T., Shah, M., Ullah, O., ... & Rahman, M. H. (2022). Nanomedicine-based delivery strategies for breast cancer treatment and management. International Journal of Molecular Sciences, 23(5), 2856.

31. Tran, S., DeGiovanni, P. J., Piel, B., & Rai, P. (2017). Cancer nanomedicine: a review of recent success in drug delivery. Clinical and translational medicine, 6(1), e44.

32. Wang, J., Liu, G., Zhou, C., Cui, X., Wang, W., Wang, J., ... & Cui, D. (2024). Application of artificial intelligence in cancer diagnosis and tumor nanomedicine. Nanoscale, 16(30), 14213-14246.

33. Wang, N., Liu, C., Yao, W., Zhou, H., Yu, S., Chen, H., & Qiao, W. (2021). A traceable, sequential multistage-targeting nanoparticles combining chemo/chemodynamic therapy for enhancing antitumor efficacy. Advanced Functional Materials, 31(26), 2101432.

34. Wang, Y., Wei, G., Zhang, X., Huang, X., Zhao, J., Guo, X., & Zhou, S. (2018). Multistage targeting strategy using magnetic composite nanoparticles for synergism of photothermal therapy and chemotherapy. Small, 14(12), 1702994.

35. Wilson, B., & Km, G. (2020). Artificial intelligence and related technologies enabled nanomedicine for advanced cancer treatment. Nanomedicine, 15(5), 433-435.

36. Wójcik, B., Zawadzka, K., Jaworski, S., Kutwin, M., Sosnowska, M., Ostrowska, A., ... & Wierzbicki, M. (2023). Dependence of diamond nanoparticle cytotoxicity on physicochemical parameters: comparative studies of glioblastoma, breast cancer, and hepatocellular carcinoma cell lines. Nanotoxicology, 17(4), 310-337.

37. Yao, W., Lin, Y., Weng, Y., Wu, Y., Zheng, L., Zheng, D., ... & Zhao, J. (2025). Lipid-based nanoparticles in cancer therapy: advances in targeted drug delivery and therapeutic potential for renal cell carcinoma. Advanced Science, 12(36), e07666.

38. Yi, H., Liu, P., Sheng, N., Gong, P., Ma, Y., & Cai, L. (2016). In situ crosslinked smart polypeptide nanoparticles for multistage responsive tumor-targeted drug delivery. Nanoscale, 8(11), 5985-5995.

39. Zhang, P., Xiao, Y., Sun, X., Lin, X., Koo, S., Yaremenko, A. V., ... & Tao, W. (2023). Cancer nanomedicine toward clinical translation: Obstacles, opportunities, and future prospects. Med, 4(3), 147-167.

40. Zhou, J., Wang, M., Han, Y., Lai, J., & Chen, J. (2019). Multistage-targeted gold/mesoporous silica nanocomposite hydrogel as in situ injectable drug release system for chemophotothermal synergistic cancer therapy. ACS Applied Bio Materials, 3(1), 421-431.