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REVIEW ARTICLE

Computational Oncology and the Augmented Oncologist: How Implementation-Ready AI and Digital Twins Will Transform Education, Research, and Practice in Precision Oncology—Insights from Theranostics

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Abstract

Theranostics is emerging as a powerful modality in precision oncology, integrating diagnostic imaging with targeted therapies to enable more effective and individualized cancer management. In parallel, Artificial Intelligence (AI) and Digital Twin (DT) technologies are increasingly being explored as enabling frameworks for advancing research, education, and clinical decision support. AI facilitates a range of quantitative and workflow-driven tasks, including organ and lesion segmentation, longitudinal lesion matching and tracking, and absorbed dose estimation, while also contributing to evidence generation, implementation, and evaluation processes. Complementing this, DTs integrate multimodal images, pharmacokinetic models, molecular characteristics, and clinical data to create dynamic, patient-specific representations of disease and treatment response. Together, these technologies improve treatment response and outcome prediction, enhance treatment planning, and support more adaptive and data-informed disease management strategies. In the near term, clinical practitioners and trainees must learn to effectively supervise AI systems, understand algorithmic limitations, and ensure their safe and effective use within clinical workflows. Over time, DT-enabled environments may support immersive, simulation-based learning with continuous feedback and exposure to complex or rare clinical scenarios, reshaping professional training. More broadly, the convergence of AI and DT technologies is driving an evolution in the structure of oncology practice itself. Alongside the four established clinical specialties medical oncology, radiation oncology, surgical oncology, and nuclear oncology a complementary role is emerging: computational oncology. These clinical and computational roles operate synergistically within an integrated health system, advancing data-driven and patient-centered precision oncology.

Keywords: Theranostics; Artificial Intelligence; Digital Twins; Medical Education; Precision Oncology.

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1. Introduction

Theranostics represents an evolving paradigm within modern oncology. By pairing diagnostic imaging with targeted radiopharmaceutical therapy, theranostics provides a seamless bridge between detection and treatment [1]. Successful examples include theranostic pairs for imaging and therapy of neuroendocrine tumors and metastatic prostate cancer [2]. The theranostic approach have improved progression free survival and quality of life compared to conventional systemic therapies in patients with advanced disease [3]. Such developments have rapidly elevated theranostics from a niche subspecialty into a major new frontier in precision oncology.

At the same time, advances in Artificial Intelligence (AI) including Deep Learning (DL), natural language processing (NLP), Large Language Models (LLMs), Graph Neural Networks (GNNs), Reinforcement Learning (RL), and generative modeling approaches are being actively investigated for their potential to enhance biomedical research and, in selected contexts, inform future clinical decision-making [4–6]. The concept of a patient's digital twin, an adaptive computational model that continuously mirrors the biological state of an individual patient based on the available data, is particularly compelling for theranostics [7–10]. By integrating multimodal imaging, pharmacokinetic modeling, molecular biomarkers, and clinical history, digital twins may be able to accurately predict therapeutic response, guide prospective personalized dosimetry, and advance the development of new theranostic agents via virtual clinical trials [11,12].

Recent advances in tumor-scale computational modeling further strengthen this vision by enabling spatially resolved simulation of radiopharmaceutical transport within heterogeneous solid tumors. Three-dimensional image-based spatiotemporal models can incorporate patient-specific vascular architecture, diffusion barriers, receptor heterogeneity, and temporal uptake kinetics, thereby extending digital twins beyond organ-level biodistribution toward intratumoral prediction of dose delivery and treatment response. Such frameworks are particularly relevant in theranostics, where microscale nonuniformity may substantially influence therapeutic efficacy despite similar macroscopic absorbed dose estimates [13].

The convergence of AI and digital twin methodologies with theranostic nuclear medicine presents an opportunity to rethink clinical workflows and to reimagine how future nuclear medicine physicians, physicists, and scientists are educated [14]. In the near term, clinical practitioners will need to understand the capabilities and limitations of modern AI-enabled tools, guide their deployment, and ensure their safe and effective integration into patient care [15]. In the longer term, AI-powered assistants (or agentic-AI) and digital twin frameworks may provide transformative opportunities for education, enabling immersive simulations, adaptive feedback, and continuous learning throughout an oncologist's career [16].

This perspective outlines how the rise of AI and digital twin technologies is poised to reshape education and training in theranostic nuclear medicine, and how this evolution may give rise to a the "augmented oncologist", or more specifically, formation of a new professional identity: a computational oncologist with expertise in AI, digital twins, biological and predictive modeling to aid oncologists in clinical decision making; the same way an engineer can support a pilot in directing a high sophisticated place.

Historically, cancer care has been delivered through collaboration among four primary specialties: medical oncology, radiation oncology, surgical oncology, and nuclear oncology. As AI, DTs, and biological and predictive modeling frameworks become increasingly incorporated into therapeutic planning, complementary roles may emerge, including the role of the computational oncologist (as shown in Figure 1). This role will enable integration of advanced computational modeling into clinical decision-making and planning.

2. AI Tools in Theranostics: From Algorithm Development to Clinical Integration

AI is increasingly being integrated into theranostics as a set of data processing and clinical decision-support tools that require rigorous validation and careful integration into practice. Their clinical impact

Figure 1. The Five Oncology Disciplines: Besides existing four clinical roles, i.e. surgical, medical, radiation, and nuclear oncologists, each contributing domain-specific expertise to patient management, the computational oncologist will enable AI, digital-twins and model-informed decision-making, integrating multimodal imaging, biological, and clinical data with predictive modeling approaches. Together, these roles form a collaborative ecosystem operating within an integrated health system. Responsible AI and computational modeling, coupled with implementation science provide cross-cutting support to ensure safe, effective, and scalable clinical integration

ultimately depends not only on algorithmic performance but also on appropriate adoption, supervision, and interpretation by the clinical community [17,18].

AI-enabled precision oncology is expected to operate within a multidisciplinary ecosystem in which each specialty contributes distinct expertise. Surgical oncologists contribute to local disease control through tumor resection and staging, providing critical tissue-level insights. Medical oncologists manage systemic disease using a spectrum of therapies, including chemotherapy, targeted agents, immunotherapy, and cell-based treatments, while integrating theranostics into broader oncologic care. Radiation oncologists address one or multiple localized lesions using external beam radiotherapy or brachytherapy, contributing expertise in radiobiology and dose planning. Nuclear oncologists (theranosticians) specialize in molecular imaging and radiopharmaceutical therapy, enabling systemic treatment (often guided by patient-specific dosimetry) through unsealed radioactive agents that emit alpha, beta, and Auger particles [19].

Complementing these clinical roles is the computational oncologist, who serves as a translational “bridge” between quantitative modeling and clinical decision-making (Figure 1). These specialists are versed in mathematical modeling and computational sciences, and collaborate closely with biologists, physicists, and other oncology specialties to apply and translate digital, computational, and in silico models of tumor behavior, treatment response, and patient-specific dynamics. They interpret digital twin outputs, integrate PBPK modeling with radiobiological response models, evaluate AI-derived predictions, and support uncertainty-aware clinical decision-making.

Model development is typically carried out by researchers and engineers, with input from clinicians. Computational oncologists will help ensure that models are usable in real-world settings and aligned with clinical needs. They also contribute to education and training through digital learning environments, such as simulation-based platforms, virtual reality–enhanced training, and digital twin–driven educational tools. In addition, they support the clinical application of in silico virtual clinical trials [20] by simulating imaging and treatment scenarios, informing protocol optimization, and incorporating emerging clinical and experimental data, through which the state of the model is updated. Critically, they translate complex model outputs into clinically meaningful insights, including radiobiological response, pharmacokinetics, treatment efficacy, toxicity risk, and associated uncertainties.

At a complementary level, clinical and workflow integrators (implementation scientists) are responsible for validating, deploying, and optimizing AI systems within theranostic practice. Much like those who refine acquisition protocols for new radiopharmaceuticals, these specialists ensure reproducibility, regulatory compliance, and adaptation to local patient populations, thereby supporting safe, effective, and scalable clinical integration. Implementation science, if practiced in effective collaborations by all stakeholders and particularly by computational oncologists and implementation scientist, will facilitate provision of a structured approach to understanding how innovations are translated into routine practice within complex healthcare systems. Beyond demonstrating technical validity or clinical efficacy, implementation science focuses on the processes and conditions that enable successful adoption, integration, and sustainability in real-world settings. This includes attention to implementation outcomes such as acceptability, feasibility, appropriateness, fidelity, and long-term sustainability, as well as the strategies used to achieve them, including training, workflow redesign, stakeholder engagement, and iterative evaluation.

Closely aligned with this perspective is the concept of integrated knowledge translation (iKT) [21] within implementation science, which emphasizes the co-production of knowledge among researchers, clinicians, and other stakeholders to ensure that innovations are contextually relevant, usable, and responsive to real-world needs from the outset [22]. Within theranostic nuclear medicine, implementation science offers a critical lens for bridging the gap between AI and DT innovation and their effective clinical use. The impact of these technologies depends not only on algorithmic performance or model sophistication, but also on how well they are integrated into clinical workflows, interpreted by practitioners, and adapted across diverse care environments. Key considerations include how AI-generated outputs are incorporated into decision-making processes, how DT models are validated and updated over time, and how clinicians are trained to supervise and critically evaluate these systems. In this context, iKT-informed collaboration among computational scientists, clinicians, physicists, and implementation specialists becomes essential for aligning technological capabilities with clinical realities. This integrated approach ensures that AI and DT systems are not only scientifically robust, but also interpretable, trustworthy, and sustainable. This ultimately enables meaningful contribution of AI and DT to patient-centered, precision oncology.

3. Implementation Pre-requisite in the Short Term: Interprofessional and Stakeholder Educational Collaboration

In the short term, AI tools are most likely to affect routine, repetitive, and quantitative aspects of theranostic workflows. Examples include automated segmentation of organs, segmentation and tracking of tumor lesions on theranostic PET and SPECT images, machine learning–based surrogates for Monte Carlo dosimetry, and natural language processing tools that draft structured reports or integrate imaging findings with treatment recommendations.

Future generation of information scientists should be equipped to contribute to educational programs that prepare clinical trainees to collaborate in algorithm development and application, including equipping future doctors to supervise these tools. Just as residents are taught to recognize imaging artifacts that could compromise a study, future theranostic specialists through interprofessional education and cooperation with information scientists, will need to recognize algorithmic artifacts such as overfitting, bias, or failed segmentation. Competency will require not only knowing how to use AI outputs but also how to judge their reliability in the context of a particular patient, scanner, or disease state. This may not be realized unless information scientists allocate adequate consideration and contribution towards these goals. Training programs therefore face the challenge of how and when to introduce AI into the learning process. If AI systems automatically draft lesion measurements or dose estimates, should trainees still be required to perform these calculations manually before using the tool? The answer is likely yes, at least initially, since manual practice builds foundational understanding. However, as tools become ubiquitous, the real challenge will be ensuring that residents understand both how to leverage AI effectively and how to recognize its limitations. Programs may need to develop standardized teaching sets where AI systems are known to succeed and others where they predictably fail, in order to train residents to critically assess outputs.

4. AI-Supported Competency-Based and Simulation-Driven Training

The integration of AI and digital twins enables a transition from traditional training models defined by fixed duration and case volume toward competency-based education in theranostics [23]. Rather than relying solely on case numbers or training duration, future curricula may increasingly emphasize demonstrated proficiency in interpreting imaging, performing dosimetric analyses, and making therapeutic decisions.

AI-driven learning analytics can continuously assess trainee performance across simulated and real-world cases. Metrics such as segmentation accuracy, dosimetric consistency, pharmacokinetic modeling performance, and treatment planning efficiency may be automatically monitored and benchmarked against expert standards.

Simulation-based training modules powered by DTs can generate personalized learning pathways, e.g. by using generative disease history and progression with synthetic imaging data. Trainees who struggle with organ dosimetry, toxicity prediction, or uncertainty analysis may be automatically assigned targeted virtual cases designed to reinforce these skills. Conversely, advanced trainees may be exposed to rare or complex scenarios that are unlikely to occur during routine clinical rotations. Such an adaptive training paradigm supports deliberate practice, continuous feedback, and individualized progression. By embedding AI-driven assessment within immersive learning environments, training programs can ensure that graduates attain both technical proficiency and clinical judgment before independent practice.

Educational platforms may also incorporate mechanistic case libraries derived from validated computational tumor models. Trainees could explore how modifying vascular permeability, receptor density, radionuclide half-life, or injection schedules changes tumor dose distributions and toxicity trade-offs. This moves training beyond memorization of protocols toward systems-level reasoning, where learners understand why treatment outcomes differ across biological contexts [13,24].

5. Longer-term Transformation through Digital Twins

Looking beyond the immediate horizon, DTs represent a profound opportunity to transform theranostic education. A digital twin of a patient can incorporate imaging data, pharmacokinetics, molecular biology, and radiobiological response models to create a dynamic, evolving computational replica. In research, such models can predict drug distribution, tumor response, and toxicity in silico. In education, digital twins could be deployed as virtual patients that provide trainees with realistic simulations of theranostic decision-making [25].

Emerging optimization studies suggest that therapeutic outcomes may depend not only on total administered activity, but also on the timing and pattern of administration. PBPK-guided strategies may enable personalized metronomic or fractionated schedules to enhance tumor targeting while limiting normal tissue exposure. Within digital twins training environments, such models could allow comparison of standard and individualized regimens before clinical implementation [26].

Imagine a trainee presented with a virtual patient whose digital twin accurately predicts absorbed dose to tumor and critical organs. The trainee could test different activity levels, administration intervals, or combination therapies, and immediately observe the predicted outcomes. Rare or complex cases could be simulated on demand, expanding the breadth of training beyond what any single institution's clinical caseload could provide. In addition, digital twins could offer adaptive feedback, comparing a trainee's therapeutic plan to simulated optimal strategies, thereby accelerating learning.

In practice, digital twins may eventually become continuous learning partners not only for trainees but also for experienced practitioners. Every patient treated would simultaneously serve as a teaching case, with outcomes feeding back into the twin, refining its accuracy and providing cumulative educational value. In this way, digital twins may blur the line between research, education, and clinical care, creating a seamless cycle of continuous improvement and learning.

6. Immersive Theranostic Training Through Extended Reality Platforms

In parallel with the development of digital twins, immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) may play a pivotal role in reshaping theranostic education [27]. These technologies enable the creation of persistent, interactive virtual environments in which trainees can engage with patient-specific digital twins in real time [28].

Such immersive environments may allow trainees to navigate 3D (and 4D, i.e. dynamic) image reconstructions of PET/CT or SPECT/CT, visualize radiopharmaceutical biodistribution, and interactively explore dose deposition patterns within tumors and organs at risk. Unlike conventional workstation-based training, immersive interfaces enhance spatial understanding of radiopharmaceutical kinetics and radiation transport, fostering deeper conceptual learning.

Virtual reality-based simulations may enable residents to rehearse complex treatment scenarios, including multi-cycle radiopharmaceutical therapies, dose-escalation strategies, and toxicity management, within a risk-free environment. Augmented reality may further support clinical training by overlaying digital twin predictions onto real patient images during case discussions or tumor boards, enhancing clinical reasoning and multidisciplinary collaboration [29].

Mixed reality systems may eventually enable hybrid learning environments in which trainees interact simultaneously with physical instruments and virtual models, bridging theoretical knowledge with hands-on clinical experience [30]. Such convergence aligns with emerging frameworks, where digital twins, AI, and immersive visualization operate as unified educational ecosystems [31]. Through these platforms, theranostic training may evolve from episodic classroom-based instruction to continuous, experiential learning embedded within virtual clinical environments.

7. Transformation of Academic Departments

The integration of AI and digital twins into clinical theranostics will require active participation from academic departments. In the short term, this will involve embedding AI tools into workflows while maintaining safeguards to ensure that residents remain central to interpretation and dosimetry. Departments will need to design "training modes" in which AI tools can be used without bypassing foundational traditional learning.

Over time, academic centers will become incubators for AI–theranostic integration. They will be responsible for validating new tools, developing curricula that combine nuclear medicine, physics, and computational sciences, and establishing competency standards for augmented oncologists. Collaborative structures that bring together computer scientists, radiochemists, nuclear medicine physicians, and medical physicists will become increasingly important in both education and research.

8. The Emergence of the Computational Oncologist

As theranostics becomes increasingly model-informed and biologically integrated, a complementary professional role may emerge alongside the four traditional oncology specialties (medical, radiation, surgical, and nuclear oncology): the computational oncologist. This role does not replace the clinical oncologist, nor does it duplicate the traditional responsibilities of a medical physicist, radiobiologist, or data scientist. Rather, it represents a translational bridge, a specialist trained to interpret and operationalize digital twin outputs, pharmacokinetic and radiobiological simulations, AI-derived predictions, and uncertainty analyses within real clinical decision-making contexts. Importantly, this role integrates quantitative modeling with an understanding of tumor biology, molecular heterogeneity, microenvironmental dynamics, and radiation response mechanisms.

Working alongside nuclear medicine physicians and oncologists, the computational oncologist would help contextualize model-driven dose predictions considering biological response variability, interpret PBPK simulations alongside receptor expression patterns, evaluate AI-supported recommendations against known principles of radiobiology and tumor evolution, and anticipate impact of different combination therapy protocols. In this sense, the role functions not merely as a technical consultant, but as a biologically informed computational steward of personalized therapy planning.

Importantly, this role would not require deep software engineering expertise. Instead, it would demand systems-level thinking; literacy in AI and modeling frameworks; familiarity with PBPK modeling; knowledge of radiobiology, tumor biology, and treatment resistance mechanisms; competence in uncertainty quantification; and grounding in implementation science principles.

In the long term, training pathways may evolve to formally prepare such specialists through hybrid curricula integrating radiopharmaceutical science, computational modeling, molecular oncology, radiobiology, data governance, and clinical translation. As digital twin–guided therapy planning matures, computational oncologists may become embedded members of multidisciplinary tumor boards, contributing biologically contextualized, model-informed insights to complex therapeutic decisions.

9. Ethical and Practical Challenges

The road toward augmented theranostics is not without obstacles. Data quantity, quality and standardization remain significant limitations, particularly across institutions and countries. AI models trained on narrow populations may not generalize or handle edge cases well, risking biased outputs [32]. Ethical concerns also loom large: patient-specific digital replicas raise questions about privacy, data ownership, and the transparency of decision-making. A key challenge is how to manage “black box” models generated via machine learning and how to integrate them with deterministic knowledge-driven modeling. From an educational perspective, perhaps the greatest challenge is ensuring that automation does not erode foundational skills. Just as residents must still learn to interpret plain radiographs even in an era dominated by advanced imaging, so too must theranostic trainees master manual dosimetry and pharmacokinetic modeling even as AI tools automate them.

10. Ethical Governance and Responsible AI Education in Theranostics

As AI- and digital twin–driven methodologies gain increasing attention in theranostic nuclear medicine, structured ethical governance must be embedded not only in clinical implementation but also within educational frameworks. Recent work on Theranostic Digital Twins (TDTs) has emphasized that ethical, regulatory, and socioeconomic dimensions are foundational to responsible development rather than secondary considerations [14].

Oncologists will not merely use computational tools but will operate within multidisciplinary ecosystems that involve data governance, model validation, interoperability standards, and regulatory compliance. Training programs should therefore include formal education in data privacy regulations (e.g., GDPR and HIPAA) [33,34], federated learning approaches for privacy-preserving multi-institutional collaboration [35], and algorithmic transparency and bias mitigation [36].

As highlighted in the TDT framework, reliability, robustness, validation, and verification are not abstract technical attributes but measurable prerequisites for clinical trustworthiness [14]. Educational curricula should therefore introduce trainees to concepts such as silent trial validation, longitudinal model monitoring, and post-deployment auditing, consistent with broader research ethics frameworks for clinical AI translation [37].

Ethical instruction must also address practical tensions inherent to digital twin deployment, including cross-border data sharing constraints, regulatory heterogeneity (EU AI Act), liability allocation in interconnected systems, and the risk of automation bias [14,38]. Furthermore, trainees must appreciate that equitable model development requires diverse and representative datasets to mitigate demographic bias and promote fairness in treatment recommendations [39,40].

Finally, governance structures should clearly delineate boundaries between research-grade digital twin experimentation and validated clinical decision-support systems. As cautioned in the recent ethical analysis of TDTs, technological advancement must proceed alongside robust regulatory oversight, transparent validation, and sustained stakeholder engagement to ensure socially responsible implementation [14]. Embedding governance literacy within digital twin–based education ensures that computational competence is balanced with professional accountability and societal responsibility.

11. Toward an Integrated Health System in Theranostics

The convergence of AI, digital twins, immersive technologies, and networked data infrastructures supports the emergence of an integrated health system in theranostics. In such systems, every patient encounter contributes to collective knowledge, and every training experience is informed by real-world outcomes. Clinical data, imaging, dosimetry, toxicity profiles, and treatment responses continuously feed into digital twin models, refining predictive accuracy over time, which will require adaptive regulatory frameworks to ensure ongoing validation, safety, and accountability as models evolve. These evolving models, in turn, inform educational simulations, case libraries, and decision-support tools. Trainees become participants in a feedback-rich ecosystem where learning, research, and practice are inseparable. This closed-loop framework accelerates knowledge translation, reduces practice variation, and promotes evidence-based personalization of therapy. Within this paradigm, the augmented oncologist functions as both clinician and system-steward, contributing to model refinement while maintaining critical oversight of automated processes. In this emerging ecosystem, cancer care may increasingly rely on collaboration among five complementary oncology domains, where computational oncology serves as the bridge between biological knowledge, clinical expertise, and data-driven modeling.

12. Conclusion

Theranostic nuclear medicine is entering a new era in which precision radiopharmaceuticals can converge with artificial intelligence and digital twin frameworks. These technologies promise not only to enhance clinical care but also to fundamentally transform education and research. In the short term, theranostic specialists must learn to effectively use AI tools and oversee them, understand their capabilities and limitations, and ensure their safe integration into practice. In the longer term, AI-powered assistants, human assistants using AI, or AI agents, and patient-specific digital twins may enable immersive simulations, adaptive curricula, and continuous lifelong learning, giving rise to a new type of professional identity: the augmented oncologist. For this future to be realized, academic departments, training programs, and professional societies must anticipate these changes and build the infrastructure, both technical and educational, to support them. If successful, the next generation of nuclear medicine specialists will not only master radiopharmaceuticals and imaging but will also harness computational intelligence, bridging human expertise with digital innovation to advance patient-centered care. In parallel, the integration of immersive technologies, VR platforms, and AI-driven competency assessment systems will further expand the educational impact of digital twins. By enabling experiential learning, personalized feedback, and global knowledge exchange, these systems will cultivate a generation of theranostic specialists capable of navigating increasingly complex clinical environments. The future of theranostic education will therefore be defined not by the replacement of human expertise, but by its systematic augmentation through ethically governed, data-driven, and immersive computational frameworks.

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