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DIGITAL ONCOLOGY 5.0: THE CONVERGENCE OF ARTIFICIAL INTELLIGENCE, DIGITAL TWINS, AND PRECISION MEDICINE

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Abstract: Digital Oncology 5.0 represents the next evolutionary stage of cancer medicine, characterized by the convergence of artificial intelligence (AI), digital twins, multimodal foundation models, precision medicine, and intelligent healthcare ecosystems capable of delivering predictive, preventive, personalized, participatory, and continuously adaptive cancer care. Conventional oncology frequently relies on fragmented diagnostic workflows, episodic clinical assessments, and isolated interpretation of imaging, pathology, molecular diagnostics, and clinical information, limiting comprehensive understanding of the dynamic biological evolution of cancer. Recent advances in foundation AI models, multimodal transformer architectures, graph neural networks, self-supervised learning, reinforcement learning, and generative artificial intelligence have enabled seamless integration of radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, epigenomics, spatial biology, laboratory biomarkers, circulating tumor DNA, wearable physiological monitoring, electronic health records, biomedical literature, and longitudinal clinical outcomes into unified computational frameworks. These intelligent systems support early cancer detection, molecular characterization, biomarker discovery, prognostic prediction, therapeutic optimization, immunotherapy selection, digital twin simulation, adaptive disease monitoring, and evidence-based clinical decision support. Emerging technologies including multimodal large language models, federated learning, retrieval-augmented generation, explainable artificial intelligence, agentic AI, cloud-native healthcare platforms, and Internet of Medical Things (IoMT) technologies further strengthen Digital Oncology 5.0 by enabling collaborative, privacy-preserving, transparent, and continuously adaptive biomedical intelligence. Despite substantial technological advances, important scientific, technical, ethical, and regulatory challenges remain regarding multimodal data harmonization, computational scalability, interoperability, cybersecurity, explainability, clinical validation, and equitable implementation. This review provides a comprehensive overview of Digital Oncology 5.0, emphasizing the convergence of artificial intelligence, digital twins, and precision medicine as a transformative paradigm for next-generation personalized cancer care.[1]

Keywords: *Digital Oncology 5.0, Artificial intelligence, Digital twins, Precision oncology, Foundation models, Computational oncology, Personalized medicine, Clinical intelligence, Multi-omics, Clinical decision support.*

1. Introduction

Cancer remains one of the most complex diseases in modern medicine due to continuous genomic evolution, epigenetic remodeling, immune adaptation, metabolic reprogramming, angiogenesis, tissue remodeling, and intricate interactions among malignant cells, stromal components, immune populations, vascular structures, and host physiology. These interconnected biological processes evolve throughout diagnosis, treatment, recurrence, metastasis, and survivorship, making precision oncology increasingly dependent upon intelligent computational systems capable of integrating heterogeneous biomedical information across multiple biological scales.[2]

Modern healthcare generates unprecedented quantities of biomedical information through radiological imaging, digital pathology, genomic sequencing, transcriptomics, proteomics, metabolomics, epigenomics, spatial biology, laboratory investigations, circulating tumor DNA, wearable physiological monitoring, physician documentation, electronic health records, biomedical literature, and patient-reported outcomes. Although each modality contributes valuable biological insight, isolated interpretation frequently overlooks systems-level relationships governing disease progression, therapeutic response, resistance mechanisms, and long-term clinical outcomes.[3]

Artificial intelligence has emerged as a transformative computational technology capable of integrating these heterogeneous biomedical datasets into unified patient-centered representations. Digital Oncology 5.0 extends these capabilities through convergence of foundation AI models, digital twins, multimodal learning, autonomous reasoning, and continuously adaptive healthcare ecosystems.

This convergence establishes a transformative paradigm capable of reshaping future oncology through predictive, preventive, personalized, participatory, and precision-guided cancer medicine.[4]

2. Evolution Toward Digital Oncology 5.0

The evolution of computational oncology has progressed from isolated statistical analyses toward intelligent healthcare ecosystems capable of continuously learning from multimodal biomedical information. Early computational systems primarily relied upon handcrafted feature engineering and machine learning algorithms developed for isolated diagnostic or prognostic tasks. Although these systems demonstrated important clinical value, they remained constrained by fragmented biomedical information, limited adaptability, and narrow task specialization.[5]

Deep learning substantially expanded computational capabilities through automated representation learning from radiological imaging, digital pathology, genomic sequencing, and electronic health records. Transformer architectures subsequently revolutionized biomedical artificial intelligence by enabling generalized contextual learning across heterogeneous biomedical modalities.

Foundation AI models now acquire transferable biomedical knowledge through large-scale self-supervised pretraining, while multimodal large language models, digital twins, reinforcement learning, federated learning, cloud computing, Internet of Medical Things technologies, and agentic AI have collectively established Digital Oncology 5.0 as a continuously adaptive computational ecosystem supporting precision cancer medicine.[6]

3. Principles of Digital Oncology 5.0

Digital Oncology 5.0 differs fundamentally from previous computational paradigms because it integrates artificial intelligence, digital twins, multimodal learning, autonomous reasoning, and real-time clinical intelligence into unified healthcare ecosystems rather than isolated predictive algorithms. Foundation AI models integrate radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, laboratory biomarkers, wearable physiological monitoring, physician documentation, patient-reported outcomes, biomedical literature, and longitudinal clinical trajectories into comprehensive patient-specific computational representations.[7]

Self-supervised learning enables discovery of latent biological relationships without requiring extensive manual annotation, while multimodal transformer architectures align heterogeneous biomedical modalities within shared computational embedding spaces. Graph neural networks characterize interactions among genes, proteins, signaling pathways, immune populations, imaging phenotypes, tissue architecture, therapeutic targets, physiological variables, environmental exposures, and clinical outcomes.

These computational principles establish adaptive biomedical intelligence capable of continuously supporting predictive precision oncology throughout the patient journey.[8]

4. Computational Architecture

Modern Digital Oncology 5.0 platforms consist of interconnected computational layers responsible for biomedical data acquisition, preprocessing, representation learning, multimodal fusion, autonomous reasoning, adaptive learning, predictive analytics, digital twin simulation, cloud

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integration, and intelligent clinical decision support.[9]
The acquisition layer continuously integrates radiological imaging, digital pathology, genomic sequencing, transcriptomics, proteomics, metabolomics, epigenomics, spatial biology, laboratory investigations, circulating tumor DNA, wearable physiological monitoring, medication history, physician documentation, patient-reported outcomes, biomedical literature, and electronic health records. Advanced preprocessing pipelines normalize imaging studies, harmonize molecular datasets, encode clinical narratives using natural language processing, synchronize temporal patient information, and continuously update computational knowledge.
Foundation AI models subsequently generate generalized multimodal embeddings representing molecular biology, tissue architecture, imaging phenotypes, physiological function, environmental exposures, and longitudinal clinical trajectories. These unified computational representations continuously evolve while supporting precision oncology.[10]

5. Foundation AI Models as the Core Intelligence Engine

Foundation AI models constitute the computational intelligence underlying Digital Oncology 5.0 because they acquire generalized biomedical knowledge from massive multimodal datasets before specialization for individual oncology applications. Unlike conventional task-specific algorithms, foundation models develop transferable computational representations applicable across diagnosis, prognosis, biomarker discovery, therapeutic prediction, disease monitoring, radiomics, computational pathology, immunotherapy, and intelligent clinical decision support.[11]
Transformer architectures enable multimodal attention across imaging, pathology, molecular biology, laboratory investigations, wearable monitoring, and clinical documentation, while graph neural networks characterize interactions among signaling pathways, immune responses, imaging phenotypes, therapeutic targets, physiological variables, and longitudinal clinical outcomes.
These generalized computational capabilities establish foundation AI models as continuously evolving biomedical reasoning engines supporting Digital Oncology 5.0.[12]

6. Multimodal Biomedical Intelligence

Comprehensive Digital Oncology 5.0 depends upon seamless integration of complementary biomedical modalities into unified patient-specific computational representations. Radiological imaging provides anatomical and functional characterization of tumors, digital pathology reveals microscopic tissue architecture, and multi-omics technologies—including genomics, transcriptomics, proteomics, metabolomics, epigenomics, immunomics, microbiomics, and spatial biology—provide comprehensive molecular characterization of evolving cancer biology.[13]
Wearable biosensors continuously monitor physiological parameters including heart rate, sleep quality, physical activity, medication adherence, treatment-related symptoms, and quality-of-life indicators, while electronic health records contribute longitudinal clinical context extending across diagnosis, treatment, recurrence, and survivorship.
Artificial intelligence harmonizes these diverse biomedical modalities using multimodal transformers, graph neural networks, biological knowledge graphs, and cross-modal attention mechanisms capable of generating adaptive computational embeddings representing continuously evolving patient biology.[14]

7. Digital Twins and Virtual Patient Ecosystems

Digital twin technology represents one of the defining innovations of Digital Oncology 5.0 by creating continuously evolving computational replicas of individual cancer patients synchronized with their biological counterparts. Foundation AI models integrate serial radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, laboratory biomarkers, circulating tumor DNA, wearable physiological monitoring, medication history, patient-reported outcomes, and longitudinal clinical information into adaptive computational patient models

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capable of simulating disease progression, therapeutic response, treatment-related toxicity, recurrence, metastatic dissemination, and survival.[15]

Unlike conventional predictive models, digital twins continuously update their computational representations as new biomedical information becomes available. These intelligent virtual patients enable clinicians to evaluate multiple therapeutic strategies before implementation, optimize treatment sequencing, anticipate mechanisms of therapeutic resistance, and personalize supportive care according to evolving patient biology.

Digital twins therefore establish predictive computational ecosystems supporting proactive precision oncology rather than reactive disease management.[16]

8. Intelligent Clinical Ecosystems

Digital Oncology 5.0 extends beyond isolated artificial intelligence by establishing intelligent clinical ecosystems integrating hospitals, pathology laboratories, radiology departments, molecular diagnostics, wearable technologies, cloud computing, biomedical literature, and real-world evidence into continuously connected healthcare networks. Foundation AI models coordinate information exchange across these environments while supporting multidisciplinary collaboration among oncologists, radiologists, pathologists, surgeons, molecular biologists, pharmacists, nurses, biomedical engineers, and computational scientists.[17]

These interconnected ecosystems substantially improve diagnostic consistency, therapeutic planning, workflow efficiency, knowledge dissemination, patient engagement, survivorship management, and adaptive healthcare delivery while strengthening precision oncology across the complete cancer care continuum.[18]

9. Personalized Therapeutic Intelligence

One of the most clinically significant applications of Digital Oncology 5.0 is individualized therapeutic optimization through comprehensive integration of molecular biology, imaging phenotypes, histopathological characteristics, laboratory biomarkers, wearable physiological monitoring, medication history, physician documentation, environmental exposures, and longitudinal clinical trajectories. Foundation AI models continuously predict responsiveness to chemotherapy, targeted therapy, endocrine therapy, immunotherapy, radiation therapy, surgery, and multimodal treatment combinations while adapting therapeutic recommendations according to evolving patient biology, treatment response, toxicity profiles, and continuously expanding biomedical evidence. These adaptive computational ecosystems establish a comprehensive framework for predictive, preventive, personalized, and precision-guided cancer medicine capable of improving patient outcomes across the entire cancer care continuum.[19][20]

10. Intelligent Clinical Decision Support

Digital Oncology 5.0 provides the computational infrastructure for next-generation clinical decision-support systems capable of integrating heterogeneous biomedical information into comprehensive patient-centered recommendations. Rather than interpreting radiological imaging, digital pathology, molecular diagnostics, laboratory investigations, wearable physiological monitoring, medication history, physician documentation, patient-reported outcomes, and evidence-based clinical guidelines independently, foundation AI models synthesize these diverse biomedical information sources into unified computational representations supporting multidisciplinary oncology practice.[21]

Interactive clinical dashboards generate individualized diagnostic summaries, multimodal biomarker analyses, molecular interpretations, digital twin simulations, therapeutic recommendations, toxicity estimates, recurrence probabilities, disease progression forecasts, and survival predictions while facilitating collaboration among oncologists, radiologists, pathologists, surgeons, radiation oncologists, molecular biologists, pharmacists, nurses, genetic counselors, biomedical engineers, and computational scientists.

These intelligent systems improve workflow efficiency, strengthen multidisciplinary communication, reduce fragmentation of biomedical information, and promote evidence-based personalized cancer management throughout the cancer care continuum.

11. Continuous Learning and Autonomous Healthcare Intelligence

A defining characteristic of Digital Oncology 5.0 is its ability to continuously evolve as new biomedical information becomes available. Artificial intelligence incorporates serial imaging examinations, computational pathology, circulating tumor DNA, laboratory biomarkers, wearable physiological monitoring, medication adherence, physician documentation, patient-reported outcomes, biomedical literature, and real-world clinical evidence into adaptive computational frameworks capable of continuously refining predictive accuracy throughout the patient's clinical journey.[22]

Continual learning algorithms enable incremental refinement of computational knowledge without catastrophic forgetting of previously acquired information, while reinforcement learning optimizes diagnostic and therapeutic recommendations through iterative evaluation of treatment outcomes. Agentic AI systems further coordinate evidence retrieval, clinical documentation, workflow automation, treatment planning, and longitudinal disease surveillance with minimal manual intervention while remaining under clinician oversight.

This adaptive computational paradigm transforms oncology into a continuously learning healthcare ecosystem capable of supporting real-time precision medicine.

12. Federated Digital Oncology Ecosystems

Development of highly generalizable Digital Oncology 5.0 platforms requires access to diverse biomedical datasets representing multiple healthcare systems, imaging platforms, pathology laboratories, molecular technologies, treatment protocols, and patient populations. Federated learning enables collaborative development of foundation AI models while preserving patient privacy and institutional governance through decentralized computational training.[23]

Participating healthcare institutions independently train local models using radiological imaging, digital pathology, genomics, transcriptomics, laboratory investigations, wearable monitoring, liquid biopsy, electronic health records, and longitudinal clinical records while securely exchanging encrypted model parameters rather than identifiable patient information. This collaborative learning strategy substantially improves algorithm robustness, fairness, external validity, transparency, and generalizability across diverse healthcare environments.

Federated Digital Oncology 5.0 ecosystems therefore establish international computational oncology networks capable of accelerating scientific discovery, improving equitable access to precision medicine, and supporting global cancer research while maintaining responsible biomedical data stewardship.

13. Explainability, Validation, and Ethical Governance

Successful implementation of Digital Oncology 5.0 requires transparent, interpretable, reproducible, and rigorously validated computational systems capable of supporting clinician confidence, patient trust, and regulatory approval. Explainable artificial intelligence (XAI) enables clinicians to understand computational reasoning through attention visualization, saliency maps, SHAP (Shapley Additive Explanations), feature attribution analysis, uncertainty estimation, multimodal attention mapping, and counterfactual explanations identifying the imaging, molecular, pathological, physiological, and clinical variables responsible for predictive outputs.[24]

Clinical deployment additionally requires standardized multimodal datasets, interoperable computational infrastructure, prospective multicenter validation, external benchmarking, cybersecurity safeguards, continuous monitoring for algorithmic bias, and compliance with evolving international regulatory frameworks governing AI-enabled healthcare technologies.

Responsible implementation further depends upon patient privacy, informed consent, transparency, accountability, equitable access, responsible data governance, continuous post-deployment surveillance, and multidisciplinary oversight to ensure trustworthy integration of intelligent

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computational systems into routine oncology practice.

14. Emerging Technologies and Future Convergence

The future of Digital Oncology 5.0 will be driven by the convergence of multimodal foundation models, multimodal large language models, agentic artificial intelligence, graph neural networks, reinforcement learning, federated learning, digital twins, spatial multi-omics, liquid biopsy, quantum computing, robotics, Internet of Medical Things (IoMT), cloud-native healthcare infrastructure, edge computing, and autonomous clinical reasoning systems.[25]

These emerging technologies will continuously integrate molecular biology, radiological imaging, digital pathology, laboratory medicine, wearable physiological monitoring, environmental exposures, electronic health records, biomedical literature, and real-world clinical outcomes into unified computational ecosystems capable of autonomous reasoning, adaptive therapeutic optimization, intelligent clinical trial matching, precision prevention, personalized survivorship management, and continuous evidence synthesis.

Such technological convergence is expected to redefine oncology as an intelligent, adaptive, connected, and continuously evolving healthcare discipline.

15. Future Perspectives

Future Digital Oncology 5.0 ecosystems will progressively evolve beyond isolated decision-support systems toward comprehensive intelligent healthcare platforms capable of continuously modeling individual patient biology throughout diagnosis, treatment, recurrence, survivorship, and long-term follow-up.[26]

Digital twins will increasingly simulate alternative therapeutic pathways, foundation AI models will autonomously incorporate newly published biomedical evidence, multimodal learning systems will integrate emerging biological modalities, and intelligent clinical agents will coordinate diagnostic workflows, multidisciplinary communication, patient education, clinical documentation, precision treatment planning, survivorship management, and preventive oncology under continuous clinician supervision.

These integrated computational ecosystems are expected to support predictive, preventive, personalized, participatory, precision-guided, and continuously optimized oncology on a global scale.

16. Discussion

Digital Oncology 5.0 represents one of the most significant paradigm shifts in computational cancer medicine by integrating foundation AI models, digital twins, multimodal learning, molecular biology, imaging intelligence, computational pathology, longitudinal clinical reasoning, cloud-native infrastructure, and intelligent healthcare ecosystems into unified computational platforms capable of supporting comprehensive personalized cancer care. Unlike conventional artificial intelligence systems developed for isolated predictive tasks, these intelligent frameworks simultaneously analyze multimodal biomedical information, coordinate complex clinical workflows, continuously assimilate emerging biomedical evidence, and refine clinical recommendations while supporting multidisciplinary collaboration.[27]

Applications spanning computational pathology, radiogenomics, biomarker discovery, digital twins, precision immunotherapy, adaptive therapeutics, autonomous workflow management, continuous learning, federated collaboration, digital health, survivorship management, and intelligent clinical decision support demonstrate the extraordinary potential of Digital Oncology 5.0 to redefine future oncology. Nevertheless, successful implementation requires continued advances in multimodal data harmonization, explainable artificial intelligence, interoperability, computational infrastructure, cybersecurity, regulatory science, ethical governance, human–AI collaboration, and sustained multidisciplinary research.

As biomedical knowledge and healthcare data continue to expand exponentially, Digital Oncology 5.0 is expected to become the foundational computational infrastructure supporting intelligent precision oncology worldwide.

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17. Conclusion

Digital Oncology 5.0 is transforming personalized cancer medicine by integrating artificial intelligence, foundation models, digital twins, radiological imaging, digital pathology, multi-omics, laboratory biomarkers, wearable technologies, electronic health records, and longitudinal clinical intelligence into unified computational ecosystems capable of supporting accurate diagnosis, biomarker discovery, prognostic prediction, therapeutic optimization, adaptive disease monitoring, and individualized clinical decision-making throughout the cancer care continuum.[28]

Advances in transformer architectures, multimodal learning, graph neural networks, self-supervised learning, federated learning, reinforcement learning, digital twins, multimodal large language models, agentic AI, cloud-native healthcare systems, and generative artificial intelligence are expected to further strengthen Digital Oncology 5.0 ecosystems, enabling increasingly accurate molecular characterization, predictive clinical intelligence, adaptive therapeutics, continuous disease surveillance, autonomous workflow orchestration, and continuously personalized oncology care.[29]

Although important scientific, technical, ethical, regulatory, and implementation challenges remain, sustained collaboration among oncologists, radiologists, pathologists, molecular biologists, biomedical engineers, computer scientists, healthcare organizations, policymakers, industry partners, and regulatory agencies will accelerate the responsible implementation of Digital Oncology 5.0. These innovations have the potential to improve patient outcomes, enhance healthcare efficiency, reduce disparities in cancer care, accelerate translational research, and establish a new era of intelligent, adaptive, autonomous, and continuously learning precision oncology worldwide.[30]

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