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AGENTIC ARTIFICIAL INTELLIGENCE IN PRECISION ONCOLOGY: AUTONOMOUS MULTIMODAL SYSTEMS FOR PERSONALIZED CANCER CARE

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Abstract: Agentic artificial intelligence (AI) represents the next frontier in precision oncology by enabling autonomous computational systems capable of perceiving, reasoning, planning, executing, and continuously learning across the entire cancer care continuum. Unlike conventional AI systems that perform isolated predictive tasks, agentic AI integrates foundation models, multimodal learning, digital twins, reinforcement learning, and clinical reasoning into intelligent ecosystems capable of autonomously coordinating diagnostic workflows, therapeutic planning, longitudinal disease monitoring, and personalized clinical decision-making. Recent advances in multimodal transformer architectures, graph neural networks, self-supervised learning, and generative artificial intelligence have enabled comprehensive 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 real-world clinical outcomes into unified computational frameworks. These intelligent systems support early cancer detection, molecular characterization, biomarker discovery, prognostic prediction, treatment optimization, immunotherapy selection, digital twin simulation, adaptive disease monitoring, and intelligent clinical decision support. Emerging technologies including multimodal large language models, federated learning, retrieval-augmented generation, explainable artificial intelligence, and autonomous planning algorithms further strengthen agentic oncology by enabling collaborative, privacy-preserving, transparent, and continuously adaptive biomedical intelligence. Despite remarkable technological progress, important scientific, technical, ethical, regulatory, and implementation challenges remain regarding multimodal data harmonization, computational scalability, interpretability, interoperability, cybersecurity, clinical validation, human oversight, and equitable implementation. This review provides a comprehensive overview of agentic artificial intelligence in precision oncology, emphasizing autonomous multimodal systems for personalized cancer care and clinical translation.[1]

Keywords: *Agentic artificial intelligence, Precision oncology, Foundation models, Autonomous systems, Multimodal learning, Digital twins, Computational oncology, Personalized medicine, Clinical intelligence, Clinical decision support.*

1. Introduction

Cancer is a biologically dynamic disease characterized by continuous genomic evolution, epigenetic remodeling, immune adaptation, metabolic reprogramming, angiogenesis, tissue remodeling, and intricate interactions among malignant cells, stromal components, immune populations, and host physiology. These interconnected biological processes evolve throughout diagnosis, treatment, recurrence, metastasis, and survivorship, making precision oncology increasingly dependent upon computational systems capable of integrating heterogeneous biomedical information across multiple biological scales.[2]

Modern oncology generates enormous 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

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documentation, electronic health records, 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. Agentic AI extends these capabilities by introducing autonomous reasoning, adaptive planning, intelligent workflow orchestration, and continuous learning that collectively support personalized oncology throughout the patient's clinical journey.
The convergence of foundation AI models, multimodal learning, digital twins, and autonomous intelligent agents therefore establishes a transformative paradigm for next-generation precision cancer medicine.[4]

2. Evolution from Predictive AI to Agentic Oncology Systems

Artificial intelligence in oncology has evolved from statistical analyses toward intelligent computational ecosystems capable of autonomous reasoning. Early machine learning algorithms primarily relied upon handcrafted feature engineering and task-specific predictive models developed for isolated diagnostic or prognostic applications. 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 reinforcement learning, multimodal large language models, digital twins, federated learning, and autonomous planning algorithms have transformed computational oncology into intelligent agentic ecosystems capable of continuous adaptation and autonomous clinical reasoning.[6]

3. Principles of Agentic Artificial Intelligence

Agentic artificial intelligence differs fundamentally from conventional AI because it performs perception, reasoning, planning, execution, reflection, and continual learning within unified computational environments. Rather than generating isolated predictions, agentic systems autonomously coordinate multiple computational tasks supporting precision oncology.
Foundation AI models integrate radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, laboratory biomarkers, wearable physiological monitoring, physician documentation, patient-reported outcomes, and longitudinal clinical trajectories into unified patient-specific computational representations. Multimodal transformer architectures align heterogeneous biomedical modalities within shared embedding spaces, while graph neural networks characterize relationships among genes, proteins, signaling pathways, imaging phenotypes, tissue architecture, therapeutic targets, physiological variables, and clinical outcomes.[7]
Reinforcement learning enables autonomous optimization of clinical strategies, whereas planning modules coordinate diagnostic reasoning, treatment sequencing, evidence retrieval, workflow automation, and adaptive disease surveillance. These computational principles establish intelligent oncology agents capable of supporting personalized precision medicine throughout the cancer care continuum.[8]

4. Computational Architecture of Agentic Oncology Systems

Modern agentic oncology platforms consist of interconnected computational layers responsible for multimodal biomedical data acquisition, preprocessing, representation learning,

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autonomous reasoning, planning, adaptive learning, predictive analytics, digital twin simulation, 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 retrieve current scientific evidence.

Foundation AI models subsequently generate generalized multimodal embeddings representing molecular biology, tissue architecture, imaging phenotypes, physiological function, and longitudinal clinical trajectories. Agentic reasoning modules autonomously coordinate downstream analytical workflows while continuously refining predictive representations through ongoing interaction with evolving biomedical knowledge.[10]

5. Foundation AI Models as Autonomous Clinical Intelligence

Foundation AI models constitute the computational intelligence underlying agentic oncology because they acquire generalized biomedical knowledge from massive multimodal datasets before specialization for individual clinical 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 capable of supporting autonomous clinical intelligence across oncology practice.[12]

6. Multimodal Biomedical Intelligence

Comprehensive agentic oncology 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. Autonomous Clinical Reasoning and Workflow Orchestration

A defining characteristic of agentic artificial intelligence is autonomous clinical reasoning combined with intelligent workflow orchestration. Agentic systems continuously analyze multimodal biomedical information, formulate diagnostic hypotheses, prioritize additional investigations, retrieve current scientific evidence, generate

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differential diagnoses, evaluate therapeutic alternatives, coordinate multidisciplinary recommendations, and monitor longitudinal patient outcomes while remaining under clinician supervision.[15]

Unlike conventional clinical decision-support tools that simply provide predictions, autonomous oncology agents coordinate multiple interconnected reasoning processes, adapting recommendations according to evolving patient biology, emerging biomarkers, changing clinical guidelines, and newly published evidence.

This intelligent orchestration substantially improves clinical efficiency, reduces cognitive burden, minimizes information fragmentation, and strengthens multidisciplinary precision oncology.[16]

8. Digital Twins and Adaptive Virtual Patients

Digital twin technology represents one of the most transformative components of agentic oncology by creating continuously evolving virtual representations of individual patients synchronized with their biological counterparts. Foundation AI models integrate serial radiological imaging, digital pathology, multi-omics, laboratory biomarkers, circulating tumor DNA, wearable physiological monitoring, medication history, physician documentation, patient-reported outcomes, and longitudinal clinical trajectories into adaptive computational patient models capable of simulating disease progression, therapeutic response, toxicity, recurrence, metastatic dissemination, and survival.[17]

Agentic AI continuously updates these virtual patients, autonomously evaluating alternative therapeutic strategies, identifying optimal treatment sequences, anticipating resistance mechanisms, and refining predictive simulations as new biomedical evidence becomes available.[18]

9. Personalized Therapeutic Optimization

One of the most clinically significant applications of agentic artificial intelligence is individualized therapeutic optimization through autonomous integration of molecular biology, imaging phenotypes, histopathological characteristics, laboratory biomarkers, wearable physiological monitoring, medication history, longitudinal clinical trajectories, and continuously evolving biomedical evidence. Foundation AI models predict responsiveness to chemotherapy, targeted therapy, endocrine therapy, immunotherapy, radiation therapy, surgery, and multimodal treatment combinations while agentic reasoning systems autonomously update therapeutic recommendations according to evolving patient biology, treatment response, toxicity profiles, and current clinical knowledge. These adaptive computational ecosystems establish a continuously learning framework for personalized cancer care capable of improving patient outcomes throughout the cancer care continuum.[19][20]

10. Intelligent Clinical Decision Support

Agentic artificial intelligence 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, autonomous multimodal agents 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, 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, and computational scientists. Agentic systems further coordinate appointment prioritization, clinical documentation, evidence retrieval, multidisciplinary tumor board preparation, and longitudinal patient follow-up while maintaining

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clinician oversight. 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 Adaptation

A defining characteristic of agentic artificial intelligence 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, 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 clinical outcomes. Reflection mechanisms enable autonomous systems to reassess previous decisions, incorporate updated evidence, recognize uncertainty, and modify future recommendations accordingly.

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

12. Federated Agentic Oncology Ecosystems

Development of highly generalizable agentic oncology 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 autonomous agents 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 agentic 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 agentic artificial intelligence 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, 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, human oversight mechanisms, and compliance with evolving international regulatory frameworks governing AI-enabled healthcare technologies.

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Responsible implementation further depends upon patient privacy, informed consent, transparency, accountability, equitable access, responsible data governance, auditability, and continuous post-deployment surveillance to ensure trustworthy integration of autonomous computational systems into routine oncology practice.

14. Emerging Technologies and Future Convergence

The future of agentic precision oncology will be driven by the convergence of multimodal foundation models, multimodal large language models, 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, retrieval-augmented generation, 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, continuously learning, and clinically collaborative medical discipline.

15. Future Perspectives

Future agentic oncology 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, therapeutic planning, survivorship management, and precision prevention under clinician supervision.

These integrated computational ecosystems are expected to support predictive, preventive, personalized, participatory, and continuously optimized oncology on an unprecedented global scale.

16. Discussion

Agentic artificial intelligence represents one of the most significant paradigm shifts in computational oncology by integrating foundation AI models, digital twins, multimodal learning, molecular biology, imaging intelligence, computational pathology, longitudinal clinical reasoning, and autonomous decision support into unified computational ecosystems capable of supporting comprehensive personalized cancer care. Unlike conventional artificial intelligence systems developed for isolated predictive tasks, agentic frameworks simultaneously analyze multimodal biomedical information, autonomously coordinate complex clinical workflows, retrieve evolving biomedical evidence, generate context-aware recommendations, and continuously refine their reasoning while maintaining clinician oversight.[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 agentic AI 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, agentic

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artificial intelligence is expected to become a foundational computational infrastructure supporting intelligent precision oncology worldwide.

17. Conclusion

Agentic artificial intelligence is transforming precision oncology by integrating foundation AI models, digital twins, multimodal learning, radiological imaging, digital pathology, multi-omics, laboratory biomarkers, wearable technologies, electronic health records, and longitudinal clinical intelligence into autonomous 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, retrieval-augmented generation, explainable artificial intelligence, and agentic AI are expected to further strengthen autonomous oncology ecosystems, enabling increasingly accurate molecular characterization, predictive clinical intelligence, adaptive therapeutics, continuous disease surveillance, intelligent workflow orchestration, and continuously personalized cancer 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 agentic artificial intelligence in oncology. 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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