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INTEGRATIVE CANCER INTELLIGENCE: FOUNDATION MODELS FOR RADIOMICS, PATHOMICS, MULTI-OMICS, AND DIGITAL HEALTH

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Abstract: Integrative cancer intelligence is emerging as a transformative paradigm in precision oncology by combining foundation artificial intelligence (AI) models with multimodal biomedical data derived from radiomics, pathomics, multi-omics, and digital health technologies. Traditional oncology workflows often analyze radiological imaging, histopathology, molecular biomarkers, laboratory investigations, and clinical records independently, limiting comprehensive characterization of tumor biology and individualized therapeutic decision-making. Recent advances in foundation AI models, multimodal transformer architectures, graph neural networks, self-supervised learning, reinforcement 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, digital biomarkers, and longitudinal clinical outcomes into unified computational representations of cancer biology. These intelligent systems support early diagnosis, 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 digital health ecosystems further strengthen computational oncology by enabling collaborative, privacy-preserving, transparent, and continuously adaptive biomedical intelligence. Despite remarkable technological progress, important scientific, technical, ethical, and regulatory challenges remain regarding multimodal data harmonization, computational scalability, interoperability, cybersecurity, clinical validation, regulatory acceptance, and equitable implementation. This review provides a comprehensive overview of integrative cancer intelligence, emphasizing foundation models for radiomics, pathomics, multi-omics, and digital health as transformative technologies for next-generation precision oncology.[1]

Keywords: Integrative cancer intelligence, Foundation models, Radiomics, Pathomics, Multi-omics, Digital health, Precision oncology, Computational oncology, Artificial intelligence, Personalized medicine.

1. Introduction

Cancer is a biologically complex and continuously evolving disease characterized by genomic instability, epigenetic remodeling, immune adaptation, metabolic reprogramming, angiogenesis, stromal interactions, and dynamic communication among malignant cells, 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 computational systems capable of integrating

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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 documentation, electronic health records, biomedical literature, and patient-reported outcomes. Although each modality independently contributes valuable biological insight, isolated interpretation frequently limits comprehensive understanding of tumor biology and therapeutic response.[3]

Integrative cancer intelligence addresses these limitations by combining foundation AI models with multimodal biomedical data to generate unified computational representations capable of supporting adaptive diagnosis, prognostic prediction, biomarker discovery, therapeutic optimization, disease monitoring, and personalized medicine.

2. Evolution of Integrative Cancer Intelligence

Computational oncology has evolved from isolated statistical analyses toward intelligent multimodal ecosystems capable of integrating heterogeneous biomedical information into unified patient-specific computational representations. Early computational approaches primarily analyzed radiological imaging, pathology, or molecular biomarkers independently using conventional machine learning algorithms. Although these systems demonstrated important clinical value, they frequently lacked biological integration and generalizability.[4]

Deep learning substantially expanded computational capabilities by enabling automated representation learning from imaging, pathology, genomics, and electronic health records. Transformer architectures subsequently revolutionized biomedical artificial intelligence through contextual learning across diverse biomedical modalities.

Foundation AI models now acquire transferable biomedical knowledge through large-scale self-supervised pretraining, enabling adaptive diagnosis, biomarker discovery, digital twin simulation, therapeutic optimization, and intelligent clinical decision support across multiple oncology applications.[5]

3. Principles of Foundation Models for Integrative Oncology

Foundation AI models differ fundamentally from conventional artificial intelligence because they acquire generalized biomedical representations from massive multimodal datasets before specialization for individual oncology applications. Rather than learning isolated predictive tasks, these models develop transferable computational knowledge applicable across diagnosis, prognosis, therapeutic optimization, disease monitoring, biomarker discovery, clinical decision support, and translational research.[6]

Self-supervised learning enables discovery of latent biological relationships without requiring extensive manual annotation, while multimodal transformer architectures align radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, epigenomics, laboratory biomarkers, wearable physiological monitoring, physician documentation, patient-reported outcomes, biomedical literature, and longitudinal clinical trajectories within unified computational embedding spaces.

Graph neural networks further characterize interactions among genes, proteins, signaling pathways, immune populations, imaging phenotypes, tissue architecture, therapeutic targets, physiological variables, environmental exposures, and clinical outcomes, thereby enabling systems-level computational reasoning throughout precision oncology.[7]

4. Computational Architecture

Modern integrative cancer intelligence platforms consist of interconnected computational layers responsible for biomedical data acquisition, preprocessing, multimodal representation learning, adaptive inference, predictive analytics, digital twin simulation, knowledge integration, and intelligent clinical decision support.[8]

The acquisition layer continuously integrates radiological imaging, digital pathology, genomic sequencing, transcriptomics, proteomics,

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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 incorporate evolving scientific evidence.

Foundation AI models subsequently generate generalized multimodal embeddings representing molecular biology, tissue architecture, imaging phenotypes, physiological function, environmental exposures, and longitudinal clinical trajectories, thereby establishing unified computational representations supporting precision oncology.[9]

5. Radiomics Intelligence

Radiomics has transformed precision oncology by enabling quantitative extraction of imaging biomarkers from computed tomography, magnetic resonance imaging, positron emission tomography, ultrasound, and hybrid imaging modalities. Foundation AI models automatically identify subtle imaging characteristics associated with tumor heterogeneity, vascularization, metabolic activity, immune infiltration, therapeutic response, recurrence, and survival.[10]

Multimodal transformer architectures integrate imaging-derived radiomic features with molecular biology, histopathology, laboratory biomarkers, and longitudinal clinical outcomes to generate comprehensive representations of tumor behavior. Self-supervised learning further enables discovery of previously unrecognized imaging biomarkers without extensive manual annotation.

These computational advances substantially improve early diagnosis, prognostic prediction, treatment planning, response assessment, and personalized oncology.[11]

6. Pathomics Intelligence

Digital pathology has become an essential component of integrative cancer intelligence through high-resolution characterization of tumor morphology, tissue architecture, stromal composition, immune microenvironment, vascular organization, mitotic activity, necrosis, and cellular heterogeneity. Foundation AI models analyze whole-slide images using transformer architectures capable of recognizing clinically significant histopathological patterns associated with molecular alterations, therapeutic responsiveness, prognosis, and disease progression.[12]

Graph neural networks further characterize spatial cellular interactions among malignant cells, immune populations, fibroblasts, endothelial cells, extracellular matrix, and signaling pathways, thereby enabling systems-level characterization of tumor ecosystems.

Integration of pathomics with radiomics, multi-omics, and digital health data substantially improves diagnostic precision, biomarker discovery, prognostic modeling, and therapeutic optimization.[13]

7. Multi-Omics Integration

Comprehensive characterization of cancer biology requires integration of complementary molecular technologies including genomics, transcriptomics, proteomics, metabolomics, epigenomics, immunomics, microbiomics, single-cell sequencing, spatial transcriptomics, and spatial proteomics. Foundation AI models harmonize these diverse molecular modalities using multimodal transformers and graph neural networks capable of generating generalized molecular representations of evolving tumor biology.[14]

Artificial intelligence identifies latent biological relationships among genes, proteins, metabolites, signaling pathways, immune responses, epigenetic regulation, and therapeutic targets while simultaneously integrating imaging phenotypes and histopathological information into unified computational frameworks.

These integrated molecular representations substantially improve biomarker discovery, molecular classification, therapeutic selection, precision immunotherapy, adaptive therapeutics, and translational cancer research.[15]

8. Digital Health and Continuous Monitoring

Digital health technologies including wearable biosensors, mobile health applications, remote physiological monitoring, smart medical devices, patient-reported outcomes, and Internet of

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Medical Things (IoMT) platforms continuously generate longitudinal physiological information throughout the cancer care continuum. These technologies extend precision oncology beyond hospital settings by enabling continuous assessment of treatment response, toxicity, medication adherence, functional status, physical activity, sleep quality, cardiovascular function, and quality of life.[16]

Foundation AI models integrate wearable physiological measurements with laboratory biomarkers, molecular biology, radiological imaging, digital pathology, and electronic health records using multimodal transformer architectures. Continuous digital monitoring substantially improves early toxicity detection, adaptive disease monitoring, survivorship management, supportive care optimization, and real-world evidence generation.

Digital health therefore represents an essential component of intelligent precision oncology ecosystems.[17]

9. Unified Multimodal Cancer Intelligence

One of the greatest strengths of foundation AI models is their ability to unify radiomics, pathomics, multi-omics, digital health, laboratory biomarkers, electronic health records, biomedical literature, environmental exposures, and longitudinal clinical trajectories into comprehensive patient-specific computational representations. Rather than analyzing individual biomedical modalities independently, these models generate holistic representations of evolving cancer biology capable of supporting diagnosis, prognostic prediction, therapeutic optimization, disease monitoring, recurrence prediction, survival estimation, and precision clinical decision-making. This multimodal intelligence establishes the computational foundation for adaptive precision oncology, digital twins, intelligent clinical decision support, and continuously personalized cancer care throughout the entire patient journey.[18][19][20]

10. Digital Twins and Integrative Cancer Intelligence

Digital twin technology represents one of the most advanced applications of integrative cancer intelligence by creating continuously evolving virtual representations of individual cancer patients synchronized with their biological counterparts. Foundation AI models integrate serial radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, epigenomics, spatial biology, laboratory biomarkers, circulating tumor DNA, wearable physiological monitoring, medication history, patient-reported outcomes, and longitudinal clinical information into adaptive computational patient models capable of simulating disease progression, therapeutic response, treatment-related toxicity, recurrence, metastatic dissemination, and survival.[21]

Unlike conventional predictive models, digital twins continuously update their computational representations as new multimodal biomedical information becomes available. Integration of radiomics, pathomics, molecular biomarkers, physiological monitoring, and predictive simulation enables virtual patients to evaluate multiple therapeutic strategies before implementation, optimize treatment sequencing, anticipate mechanisms of therapeutic resistance, personalize supportive care, and estimate long-term clinical outcomes according to evolving patient biology.

By combining multimodal biomedical intelligence with predictive simulation, digital twins transform computational oncology from retrospective analysis toward proactive, continuously adaptive, and individualized precision medicine.

11. Intelligent Clinical Decision Support

Foundation AI models provide 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, these models synthesize diverse biomedical information into unified computational representations supporting multidisciplinary oncology practice.[22]

Interactive clinical dashboards generate individualized diagnostic summaries, radiomic analyses, pathomic interpretations, molecular biomarker profiles, digital twin simulations, therapeutic recommendations, toxicity estimates, recurrence probabilities, disease progression forecasts, survival predictions, and longitudinal treatment response assessments 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.

12. Continuous Learning and Adaptive Intelligence

A defining characteristic of integrative cancer intelligence is the 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, behavioral information, 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.[23]

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. Consequently, integrative cancer intelligence platforms remain synchronized with evolving tumor biology, physiological adaptation, emerging scientific discoveries, changing clinical guidelines, and diverse patient trajectories.

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

13. Federated Multimodal Intelligence Networks

Development of highly generalizable foundation AI models requires access to diverse biomedical datasets representing multiple healthcare systems, imaging platforms, pathology laboratories, molecular technologies, wearable ecosystems, treatment protocols, and patient populations. Federated learning enables collaborative development of multimodal foundation models while preserving patient privacy and institutional governance through decentralized computational training.[24]

Participating healthcare institutions independently train local models using radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, 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 multimodal intelligence 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.

14. Explainability, Validation, and Ethical Governance

Successful implementation of integrative cancer 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, multimodal attention mapping, and

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counterfactual explanations identifying the imaging, molecular, pathological, physiological, and clinical variables responsible for predictive outputs.[25]

Clinical deployment additionally requires standardized multimodal datasets, interoperable computational infrastructure, prospective multicenter validation, external benchmarking, cybersecurity safeguards, continuous monitoring for algorithmic bias, transparent reporting standards, 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 foundation AI models into routine oncology practice.

15. Future Perspectives

Future integrative cancer intelligence ecosystems will increasingly integrate multimodal foundation models, multimodal large language models, agentic artificial intelligence, graph neural networks, reinforcement learning, federated learning, digital twins, spatial multi-omics, single-cell sequencing, liquid biopsy, quantum computing, Internet of Medical Things (IoMT), robotics, cloud-native healthcare infrastructure, and autonomous clinical reasoning systems into unified precision oncology platforms.[26]

These next-generation computational ecosystems will continuously integrate molecular biology, radiological imaging, digital pathology, laboratory medicine, wearable physiological monitoring, environmental exposures, electronic health records, biomedical literature, pharmacological knowledge bases, and real-world clinical outcomes while autonomously coordinating diagnostic workflows, optimizing therapeutic strategies, supporting adaptive clinical trials, generating personalized patient communication, continuously synthesizing biomedical evidence, and identifying emerging biomarkers associated with disease evolution.

Such intelligent ecosystems are expected to transform oncology from fragmented and reactive disease management toward predictive, preventive, adaptive, continuously learning, and precision-guided healthcare across the global cancer community.

16. Discussion

Integrative cancer intelligence represents one of the most significant paradigm shifts in computational oncology by combining radiomics, pathomics, multi-omics, digital health technologies, digital biomarkers, digital twins, and foundation AI models into unified computational ecosystems capable of supporting comprehensive personalized cancer care. Unlike conventional analytical approaches that evaluate biomedical modalities independently, integrative intelligence continuously synthesizes heterogeneous molecular, imaging, pathological, physiological, behavioral, and clinical information into holistic patient-specific computational representations.[27]

Applications spanning computational pathology, radiogenomics, biomarker discovery, digital twins, precision immunotherapy, adaptive therapeutics, remote patient monitoring, continuous learning, federated collaboration, digital health, survivorship management, and intelligent clinical decision support demonstrate the extraordinary potential of foundation AI models 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, and sustained multidisciplinary collaboration.

As biomedical knowledge and healthcare data continue to expand exponentially, integrative cancer intelligence is expected to become one of the foundational computational infrastructures supporting precision oncology worldwide.

17. Conclusion

Integrative cancer intelligence is transforming precision oncology by combining foundation AI models with radiomics, pathomics, multi-omics, digital health technologies, laboratory biomarkers, wearable monitoring, electronic health records, digital twins, and longitudinal clinical intelligence into unified computational ecosystems capable of supporting accurate diagnosis, biomarker

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discovery, prognostic prediction, therapeutic optimization, adaptive disease monitoring, and personalized therapeutics 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, and generative artificial intelligence are expected to further strengthen intelligent oncology ecosystems, enabling increasingly accurate molecular characterization, predictive clinical decision-making, adaptive therapeutics, continuous disease surveillance, 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 integrative cancer intelligence. 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, and continuously learning precision oncology worldwide.[30]

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