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AI-AUGMENTED PRECISION THERAPEUTICS: FOUNDATION MODELS FOR BIOMARKER DISCOVERY AND PERSONALIZED CANCER TREATMENT

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Abstract: Artificial intelligence (AI) is transforming precision therapeutics by enabling comprehensive integration of molecular, imaging, pathological, and clinical information into intelligent computational ecosystems capable of supporting biomarker discovery and individualized cancer treatment. Conventional precision oncology frequently depends upon fragmented interpretation of genomic alterations, histopathological findings, radiological imaging, and clinical information, limiting comprehensive understanding of tumor biology and therapeutic responsiveness. Recent advances in foundation AI models, multimodal transformer architectures, graph neural networks, self-supervised learning, and generative artificial intelligence have enabled generalized biomedical representation learning across radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, epigenomics, spatial biology, laboratory biomarkers, circulating tumor DNA, wearable physiological monitoring, electronic health records, and longitudinal clinical outcomes. These intelligent computational 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, reinforcement learning, retrieval-augmented generation, explainable artificial intelligence, and agentic AI further strengthen AI-augmented therapeutics by enabling collaborative, privacy-preserving, transparent, and continuously adaptive biomedical intelligence. Despite remarkable technological advances, important scientific, technical, ethical, and regulatory challenges remain regarding multimodal data harmonization, computational scalability, interpretability, interoperability, cybersecurity, clinical validation, and equitable implementation. This review provides a comprehensive overview of AI-augmented precision therapeutics, emphasizing foundation models for biomarker discovery and personalized cancer treatment as a transformative paradigm for next-generation oncology.[1]

Keywords: *Precision therapeutics, Foundation models, Artificial intelligence, Biomarker discovery, Precision oncology, Multi-omics, Digital pathology, Clinical decision support, Computational oncology, Personalized medicine.*

1. Introduction

Cancer is a biologically heterogeneous disease characterized by continuous genomic evolution, epigenetic remodeling, immune adaptation, metabolic reprogramming, angiogenesis, tissue remodeling, and dynamic 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 routinely 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 biological 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. Foundation AI models extend these capabilities through generalized multimodal learning that enables knowledge transfer across numerous oncology applications while continuously adapting to evolving biomedical evidence.

The convergence of artificial intelligence and precision therapeutics therefore establishes a transformative computational framework capable of supporting personalized cancer treatment throughout the entire disease continuum.[4]

2. Evolution of AI-Augmented Precision Therapeutics

Precision oncology has evolved from empirical treatment selection toward intelligent computational ecosystems capable of continuously learning from multimodal biomedical information. Early computational approaches primarily relied upon statistical analyses and machine learning algorithms developed for isolated predictive 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 transformed oncology 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, enabling simultaneous integration of imaging, pathology, molecular biology, laboratory medicine, and clinical intelligence while supporting biomarker discovery and personalized therapeutics.[6]

3. Principles of Foundation AI Models

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, molecular characterization, biomarker discovery, therapeutic optimization, disease monitoring, computational pathology, radiomics, immunotherapy, and clinical decision support.[7]

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, laboratory biomarkers, wearable physiological monitoring, physician documentation, patient-reported outcomes, 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, and clinical outcomes, thereby enabling systems-level computational reasoning supporting precision oncology.[8]

4. Computational Architecture

Modern AI-augmented therapeutic platforms consist of interconnected computational layers responsible for biomedical data acquisition, preprocessing, representation learning, multimodal fusion, adaptive learning, predictive analytics, digital twin simulation, biomarker discovery, and intelligent clinical decision support.[9]

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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, and electronic health records. Advanced preprocessing pipelines normalize imaging studies, harmonize molecular datasets, encode clinical narratives using natural language processing, and synchronize temporal patient information.

Foundation AI models subsequently generate generalized multimodal embeddings representing molecular biology, tissue architecture, imaging phenotypes, physiological function, and longitudinal clinical trajectories. These unified computational representations support diagnosis, biomarker discovery, prognostic prediction, therapeutic optimization, adaptive learning, and personalized oncology.[10]

5. Artificial Intelligence for Biomarker Discovery

Biomarker discovery represents one of the most important applications of foundation AI models because computational integration of multimodal biomedical data enables identification of clinically actionable biological signatures that remain difficult to detect using conventional analytical approaches.[11]

Artificial intelligence simultaneously analyzes genomic mutations, transcriptomic profiles, proteomic alterations, metabolomic pathways, epigenetic regulation, immune biomarkers, radiomic features, histopathological morphology, laboratory investigations, and longitudinal clinical outcomes to identify biomarkers associated with early diagnosis, therapeutic responsiveness, disease progression, toxicity, recurrence, and survival.

These computationally derived biomarkers substantially improve molecular subtype classification, patient stratification, clinical trial enrollment, therapeutic target identification, and individualized treatment planning while accelerating translational oncology research.[12]

6. Multi-Omics Integration

Comprehensive molecular characterization represents one of the greatest strengths of AI-augmented precision therapeutics. Artificial intelligence integrates genomics, transcriptomics, proteomics, metabolomics, epigenomics, immunomics, microbiomics, spatial biology, and single-cell sequencing into generalized molecular representations capable of characterizing evolving tumor biology across multiple organizational scales.[13]

Transformer architectures identify latent biological relationships among genes, proteins, signaling pathways, metabolites, immune responses, and therapeutic targets, while graph neural networks model complex biological interaction networks supporting systems-level computational reasoning.

These generalized molecular representations enable discovery of molecular subtypes, therapeutic biomarkers, resistance mechanisms, prognostic signatures, and novel drug targets while substantially improving individualized precision medicine.[14]

7. Imaging and Pathology Intelligence

Radiological imaging and digital pathology provide complementary information describing cancer biology across macroscopic and microscopic organizational scales. Foundation AI models automatically extract generalized imaging and pathomic representations from computed tomography, magnetic resonance imaging, positron emission tomography, ultrasound, and whole-slide pathology images without requiring handcrafted feature engineering.[15]

Artificial intelligence identifies latent imaging and tissue biomarkers associated with molecular alterations, immune infiltration, angiogenesis, fibrosis, hypoxia, therapeutic responsiveness, treatment resistance, and disease progression. Integration of imaging intelligence with molecular biology substantially improves diagnosis, prognostic prediction, biomarker discovery, therapeutic optimization, and longitudinal disease monitoring.

These multimodal computational representations provide comprehensive characterization of

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evolving tumor biology while strengthening precision therapeutics.[16]

8. Clinical Intelligence Through Electronic Health Records

Electronic health records provide one of the richest longitudinal sources of clinical intelligence available in oncology. Structured laboratory investigations, medication history, pathology reports, treatment timelines, physician documentation, hospitalizations, patient-reported outcomes, and survivorship information collectively provide comprehensive patient-level context extending beyond molecular diagnostics.[17]

Foundation AI models employ natural language processing, temporal transformers, and multimodal reasoning architectures to integrate structured and unstructured EHR data with imaging, pathology, molecular biology, laboratory biomarkers, and physiological monitoring into unified patient-specific computational representations.

These integrated clinical embeddings substantially improve prognostic prediction, recurrence surveillance, toxicity estimation, therapeutic optimization, survivorship management, and evidence-based clinical decision-making.[18]

9. Personalized Therapeutic Optimization

One of the most clinically significant applications of AI-augmented precision therapeutics is individualized treatment optimization through comprehensive integration of molecular biology, imaging phenotypes, histopathological characteristics, laboratory biomarkers, wearable physiological monitoring, medication history, physician documentation, 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 real-world clinical outcomes. These adaptive computational systems establish a comprehensive framework for personalized cancer treatment capable of improving patient outcomes across the entire cancer care continuum.[19][20]

10. Digital Twins and Intelligent Therapeutic Simulation

Digital twin technology represents one of the most transformative applications of AI-augmented precision therapeutics 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, 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 biomedical information becomes available. Integration of multimodal molecular biology with predictive simulation enables virtual patients to evaluate alternative therapeutic strategies, optimize treatment sequencing, anticipate mechanisms of therapeutic resistance, and personalize supportive care according to evolving patient biology.

By combining biomarker intelligence with predictive simulation, digital twins transform precision oncology from retrospective therapeutic assessment toward proactive and continuously adaptive cancer management.

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

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

Interactive clinical dashboards generate individualized diagnostic summaries, 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, and computational scientists.

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

12. Continuous Learning and Adaptive Therapeutic Intelligence

A defining characteristic of AI-augmented precision therapeutics 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, patient-reported outcomes, 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 therapeutic recommendations through iterative evaluation of treatment outcomes. Consequently, therapeutic intelligence platforms remain synchronized with evolving tumor biology, 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 Biomarker Discovery Networks

Development of highly generalizable foundation AI models for biomarker discovery 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 AI 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, 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, and generalizability across diverse healthcare environments.

Federated biomarker discovery 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 AI-augmented precision therapeutics 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, biomarker importance ranking, and counterfactual explanations identifying the molecular,

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pathological, imaging, 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, and compliance with evolving international regulatory frameworks governing AI-enabled healthcare technologies.
Responsible implementation further depends upon protection of patient privacy, informed consent, transparency, accountability, equitable access, responsible data governance, and continuous post-deployment surveillance to ensure trustworthy integration of intelligent computational systems into routine oncology practice.

15. Future Perspectives

Future AI-augmented therapeutic 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, and cloud-native healthcare infrastructure 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, and real-world clinical outcomes while autonomously coordinating biomarker discovery, optimizing therapeutic strategies, supporting adaptive clinical trials, generating personalized patient communication, and continuously synthesizing biomedical evidence.
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

AI-augmented precision therapeutics represents one of the most significant paradigm shifts in computational oncology by integrating biomarker discovery, molecular biology, radiological imaging, digital pathology, laboratory biomarkers, wearable technologies, digital twins, and longitudinal clinical intelligence into unified computational ecosystems capable of supporting comprehensive personalized cancer care. Unlike conventional artificial intelligence systems developed for isolated predictive tasks, foundation AI models simultaneously analyze multimodal biomedical information to generate holistic computational representations of evolving cancer biology while enabling individualized therapeutic optimization.[27]
Applications spanning computational pathology, radiogenomics, biomarker discovery, digital twins, precision immunotherapy, adaptive therapeutics, continuous learning, federated collaboration, digital health, survivorship management, and intelligent clinical decision support demonstrate the extraordinary potential of AI-enabled precision therapeutics 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, AI-augmented precision therapeutics is expected to become a central computational infrastructure supporting personalized cancer medicine worldwide.

17. Conclusion

AI-augmented precision therapeutics is transforming personalized cancer treatment by integrating foundation AI models, biomarker discovery, radiological imaging, digital pathology, multi-omics, laboratory biomarkers, wearable technologies, electronic health records, digital twins, and longitudinal clinical intelligence into unified computational ecosystems capable of supporting accurate diagnosis, biomarker discovery, prognostic prediction, therapeutic

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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, and generative artificial intelligence are expected to further strengthen intelligent therapeutic 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 AI-augmented precision therapeutics. 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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