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Precision Immuno-Oncology Through Foundation AI Models: Integrating Immune Profiling, Multi-Omics, and Clinical Data

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ABSTRACT:

Immunotherapy has revolutionized cancer treatment by harnessing the host immune system to recognize and eliminate malignant cells. Despite remarkable clinical success across multiple malignancies, only a subset of patients experiences durable therapeutic responses because of the extraordinary biological complexity of tumor–immune interactions. Recent advances in foundation artificial intelligence (AI) models have introduced powerful computational frameworks capable of integrating immune profiling, radiological imaging, digital pathology, genomic sequencing, transcriptomics, proteomics, metabolomics, laboratory biomarkers, electronic health records, and longitudinal clinical information into unified patient-centered representations that support precision immuno-oncology. Unlike conventional machine learning systems designed for isolated predictive tasks, foundation AI models learn generalized biomedical representations through self-supervised learning that can be adapted across numerous oncology applications including immunotherapy response prediction, biomarker discovery, molecular characterization, adaptive treatment planning, digital twins, clinical decision support, and personalized therapeutics. Advances in transformer architectures, multimodal learning, graph neural networks, retrieval-augmented generation, large language models, agentic AI, and generative artificial intelligence have substantially accelerated the development of intelligent immuno-oncology ecosystems capable of comprehensive biomedical reasoning. Nevertheless, important challenges remain regarding multimodal data harmonization, computational scalability, explainability, interoperability, cybersecurity, regulatory validation, and equitable implementation. This review provides a comprehensive overview of precision immuno-oncology through foundation AI models, emphasizing computational principles, clinical applications, implementation challenges, and future perspectives for integrating immune profiling, multi-omics, and clinical intelligence.[1]

Keywords: Immuno-oncology, Foundation models, Artificial intelligence, Precision oncology, Multi-omics, Immune profiling, Computational oncology, Personalized medicine, Clinical decision support, Immunotherapy.

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1.Introduction

Immunotherapy has fundamentally transformed modern oncology by enabling the immune system to recognize and eliminate malignant cells through immune checkpoint inhibition, adoptive cellular therapies, cancer vaccines, bispecific antibodies, and emerging immunomodulatory strategies. Although these therapies have significantly improved survival across numerous malignancies, substantial variability in treatment response remains a major clinical challenge because tumor–immune interactions are highly dynamic and biologically heterogeneous.[2]

The effectiveness of immunotherapy depends upon numerous interconnected biological factors including genomic alterations, tumor mutational burden, immune-cell infiltration, cytokine signaling, stromal remodeling, antigen presentation, metabolic reprogramming, and spatial organization of the tumor microenvironment. Consequently, isolated biomarkers frequently provide insufficient information for accurate prediction of therapeutic outcomes.[3]

Modern immuno-oncology generates enormous quantities of heterogeneous biomedical information through radiological imaging, digital pathology, immune profiling, genomic sequencing, transcriptomics, proteomics, metabolomics, laboratory investigations, wearable technologies, and electronic health records. Foundation artificial intelligence models provide an unprecedented opportunity to integrate these complementary modalities into comprehensive computational representations capable of supporting personalized immunotherapy.[4]

The convergence of foundation AI models, immune profiling, multi-omics, and clinical intelligence is therefore redefining precision immuno-oncology by enabling increasingly adaptive, individualized, and evidence-based cancer immunotherapy.[5]

2.Evolution of Precision Immuno-Oncology

The earliest immunotherapeutic strategies relied primarily on broad immune stimulation without detailed understanding of the biological mechanisms governing tumor immunity. Subsequent discoveries involving immune checkpoint pathways, tumor mutational burden, antigen presentation, and adaptive immune responses transformed immunotherapy into a major pillar of precision oncology.[6]

Parallel advances in genomic sequencing, transcriptomics, proteomics, and single-cell technologies enabled increasingly detailed characterization of the tumor immune microenvironment. Artificial intelligence further expanded these capabilities by integrating heterogeneous molecular datasets with radiological imaging, digital pathology, laboratory biomarkers, and longitudinal clinical information into comprehensive predictive models.

Recent development of foundation AI models has introduced generalized biomedical reasoning capable of supporting immunotherapy response prediction, biomarker discovery, treatment optimization, and adaptive clinical decision-making across multiple malignancies.[7]

Today, precision immuno-oncology extends beyond isolated biomarkers toward integrated computational ecosystems capable of modeling the complexity of tumor–immune interactions across the entire patient journey.[8]

3.Foundation AI Models in Immuno-Oncology

Foundation AI models differ fundamentally from conventional machine learning algorithms because they are pretrained on extremely large biomedical datasets before adaptation to specialized clinical applications. Rather than learning isolated prediction tasks, these models acquire generalized representations of biological, molecular, immunological, anatomical, and clinical information applicable across diverse oncology domains.[9]

Self-supervised learning enables discovery of latent biomedical relationships without extensive manual annotation, whereas multimodal transformer architectures integrate radiological imaging, digital pathology, immune profiling, genomics, transcriptomics, laboratory investigations, and electronic health records into unified patient-specific representations.

Graph neural networks further strengthen computational reasoning by modeling interactions among immune cells, cytokines, signaling pathways, genes, proteins, metabolites, therapeutic targets, and clinical outcomes. These generalized computational representations substantially improve transfer learning, few-shot learning, zero-shot learning, and generalizability across multiple cancer types.[10]

4.Computational Architecture

Modern immuno-oncology foundation models consist of multiple computational layers responsible for multimodal biomedical data acquisition, preprocessing, representation learning, multimodal fusion, predictive modeling, longitudinal monitoring, and intelligent clinical decision support.[11]

The acquisition layer collects radiological imaging, digital pathology, immune profiling, genomic sequencing, transcriptomics, proteomics, metabolomics, laboratory biomarkers, wearable sensor information, medication history, and longitudinal electronic health records. Advanced preprocessing pipelines normalize imaging studies, harmonize molecular datasets, encode clinical narratives using natural language processing, and synchronize temporal patient information.

Large transformer-based neural networks subsequently generate generalized computational embeddings representing patient-specific biological states. Multimodal fusion mechanisms integrate these embeddings into comprehensive computational representations capable of supporting diagnosis, immunotherapy prediction, toxicity estimation, disease monitoring, and survival prediction.

Continuous incorporation of longitudinal clinical information enables adaptive computational reasoning throughout diagnosis, treatment, follow-up, and survivorship.[12]

5.Immune Profiling and Artificial Intelligence

Comprehensive immune profiling has become essential for precision immuno-oncology because therapeutic response depends upon the composition, function, and spatial organization of immune-cell populations within the tumor microenvironment. Modern immune profiling includes flow cytometry, single-cell sequencing, multiplex immunohistochemistry, imaging mass cytometry, cytokine analysis, immune receptor sequencing, and transcriptomic characterization of immune populations.[13]

Artificial intelligence integrates these diverse immunological datasets into generalized computational representations capable of identifying immune signatures associated with therapeutic responsiveness, resistance, toxicity, and survival. Machine learning identifies complex nonlinear relationships among immune biomarkers, whereas deep learning automatically extracts hierarchical immunological features without requiring manual engineering.

These computational approaches substantially strengthen individualized immunotherapy while improving biological understanding of tumor–immune interactions.[14]

6.Multi-Omics Integration

Precision immuno-oncology increasingly depends upon integration of genomics, transcriptomics, proteomics, metabolomics, epigenomics, immunomics, lipidomics, microbiomics, and single-cell sequencing into unified computational representations of tumor biology. Each molecular layer contributes complementary biological information describing immune activation, antigen presentation, cytokine signaling, metabolic adaptation, and therapeutic response.[15]

Foundation AI models utilize transformer architectures, graph neural networks, multimodal learning, and biological knowledge graphs to identify interactions among genes, immune pathways, proteins, metabolites, signaling networks, and therapeutic targets.

These integrated multi-omics representations improve biomarker discovery, molecular subtype classification, immunotherapy prediction, systems biology research, and personalized treatment planning while strengthening computational precision oncology.[16]

7.Digital Pathology and Immune Landscape Analysis

Digital pathology has become one of the most important modalities supporting computational immuno-oncology because whole-slide imaging enables quantitative evaluation of immune-cell infiltration, stromal remodeling, angiogenesis, lymphovascular invasion, and tissue architecture at microscopic resolution.[17]

Transformer-based pathology foundation models automatically identify tumor-infiltrating lymphocytes, macrophages, dendritic cells, fibroblasts, endothelial cells, necrosis, immune checkpoint expression, and spatial cellular organization while predicting clinically relevant therapeutic biomarkers.

Integration of computational pathology with immune profiling substantially improves

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characterization of the tumor immune microenvironment while strengthening personalized immunotherapy planning across multiple cancer types.[18]

8.Multimodal Clinical Intelligence

The principal advantage of foundation AI models lies in their ability to integrate heterogeneous biomedical information throughout the immunotherapy workflow. Radiological imaging, digital pathology, immune profiling, multi-omics, laboratory investigations, medication history, wearable technologies, physician documentation, and longitudinal clinical outcomes are harmonized into unified patient-centered computational representations.[19]

These multimodal computational ecosystems enable comprehensive reasoning regarding diagnosis, immunotherapy selection, toxicity prediction, treatment monitoring, recurrence estimation, and survivorship care while reducing fragmentation of biomedical information across traditional diagnostic disciplines.

By continuously learning from multimodal biomedical data, foundation AI models support adaptive precision immuno-oncology that evolves alongside changing patient biology and immune responses.[20]

9.Foundation AI Models for Immunotherapy Response Prediction

One of the most important clinical applications of foundation AI models is the prediction of immunotherapy response through comprehensive integration of immune profiling, radiological imaging, digital pathology, multi-omics, laboratory biomarkers, and longitudinal clinical information. Unlike conventional predictive systems based on isolated biomarkers, foundation models generate unified patient-specific computational representations that capture the complex biological interactions governing tumor immunity.[21]

Artificial intelligence estimates responsiveness to immune checkpoint inhibitors, CAR-T cell therapies, cancer vaccines, bispecific antibodies, adoptive cellular therapies, and emerging immunotherapeutic strategies by simultaneously analyzing tumor mutational burden, PD-L1 expression, immune-cell infiltration, cytokine signaling, transcriptomic profiles, and clinical characteristics.

These multimodal computational models substantially improve patient selection while reducing unnecessary treatment-related toxicity and optimizing individualized immunotherapy.

10.Tumor Microenvironment Modeling

The tumor microenvironment represents one of the most complex biological ecosystems in oncology, comprising malignant cells, immune populations, fibroblasts, endothelial cells, extracellular matrix components, vascular networks, cytokines, and numerous signaling molecules that collectively influence disease progression and therapeutic response.[22]

Foundation AI models integrate radiological imaging, computational pathology, spatial biology, immunomics, transcriptomics, proteomics, laboratory biomarkers, and longitudinal clinical outcomes into comprehensive computational representations of tumor–immune interactions.

Graph neural networks model communication among immune cells, stromal compartments, signaling pathways, angiogenesis, and therapeutic targets, enabling increasingly accurate prediction of treatment response while supporting adaptive precision immunotherapy based on each patient's unique immune landscape.

11.Personalized Immunotherapeutic Planning

Precision immuno-oncology requires individualized therapeutic planning that continuously adapts to evolving tumor biology and immune responses. Foundation AI models integrate imaging, pathology, genomics, immune profiling, laboratory investigations, treatment history, and longitudinal patient trajectories into unified computational frameworks capable of supporting personalized immunotherapeutic strategies.[23]

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Artificial intelligence estimates treatment response, recurrence probability, progression-free survival, overall survival, immune-related adverse events, and mechanisms of therapeutic resistance while evaluating multiple immunotherapeutic options individually or in combination with chemotherapy, targeted therapy, radiation therapy, or surgery.

Continuous incorporation of updated clinical information enables adaptive therapeutic recommendations that evolve alongside changes in tumor biology and immune function throughout treatment.

12.Digital Twins and Adaptive Immuno-Oncology

The convergence of foundation AI models with digital twin technology is creating continuously evolving virtual patient ecosystems capable of integrating immune profiling, radiological imaging, digital pathology, multi-omics, laboratory biomarkers, wearable technologies, medication history, and longitudinal clinical information into adaptive computational models.[24]

Artificial intelligence continuously synchronizes these virtual patients with evolving biological systems, enabling simulation of immune activation, therapeutic response, toxicity, disease progression, recurrence, and survival before clinical intervention.

These adaptive computational ecosystems support evidence-based precision immunotherapy while allowing clinicians to evaluate multiple treatment strategies and optimize individualized patient management throughout the cancer care continuum.

13.Intelligent Clinical Decision Support

Foundation AI models provide the computational foundation for intelligent clinical decision-support systems within precision immuno-oncology. These systems integrate radiological imaging, digital pathology, immune profiling, genomic sequencing, laboratory investigations, wearable technologies, medication history, physician documentation, and electronic health records into unified computational environments.[25]

Interactive clinical dashboards generate individualized diagnostic summaries, immunotherapy recommendations, toxicity estimates, recurrence predictions, survival probabilities, and adaptive clinical pathways while facilitating multidisciplinary collaboration among oncologists, immunologists, radiologists, pathologists, molecular biologists, and pharmacists.

These intelligent systems substantially improve evidence-based clinical decision-making while reducing fragmentation of biomedical information throughout immunotherapy workflows.

14.Explainability, Ethics, and Clinical Translation

Successful implementation of foundation AI models within immuno-oncology requires transparency, interpretability, and clinician confidence. Explainable artificial intelligence (XAI) enables healthcare professionals to understand computational reasoning through attention visualization, saliency maps, SHAP (Shapley Additive Explanations), feature attribution analysis, uncertainty estimation, and counterfactual explanations identifying the immunological variables contributing most strongly to therapeutic recommendations.[26]

Several implementation challenges remain. Foundation AI models require standardized multimodal datasets, secure computational infrastructure, interoperability among healthcare systems, prospective multicenter validation, continuous monitoring for algorithmic bias, and robust cybersecurity.

Patient privacy, regulatory approval, equitable implementation, transparent governance frameworks, and internationally standardized reporting methodologies remain essential for responsible translation into routine clinical practice.

15.Future Perspectives

Future precision immuno-oncology will increasingly incorporate multimodal foundation models, large language models, agentic artificial intelligence, digital twins, federated learning, reinforcement learning, spatial multi-omics, liquid biopsy, quantum computing, cloud-native healthcare infrastructure, and Internet of Medical Things (IoMT) technologies into unified intelligent oncology ecosystems.[27]

These next-generation computational platforms will continuously integrate immune profiling, molecular biology, radiology, pathology, laboratory medicine, wearable technologies, electronic health records, and real-world clinical outcomes while supporting adaptive immunotherapeutic optimization, autonomous workflow coordination, personalized patient communication, and continuous evidence synthesis.

Foundation AI models are expected to evolve from predictive algorithms into comprehensive biomedical reasoning systems capable of transforming immunotherapy into an increasingly individualized and dynamically adaptive treatment modality.

16.Discussion

Precision immuno-oncology through foundation AI models represents one of the most significant advances in computational cancer medicine by integrating immune profiling, multi-omics, radiology, pathology, and longitudinal clinical information into unified patient-centered computational representations. Unlike conventional immunotherapy prediction based on isolated biomarkers, these intelligent systems model the complex biological interactions governing tumor immunity across multiple organizational levels.[28]

Applications spanning immune profiling, immunotherapy response prediction, computational pathology, digital twins, biomarker discovery, adaptive therapeutics, intelligent clinical decision support, and systems immunology demonstrate the extraordinary clinical potential of these technologies.

Nevertheless, successful implementation requires continued advances in explainable artificial intelligence, computational infrastructure, interoperability, regulatory science, cybersecurity, ethical governance, and multidisciplinary collaboration to ensure safe, effective, and equitable deployment.

17.Conclusion

Foundation AI models are redefining precision immuno-oncology by integrating immune profiling, multi-omics, radiological imaging, digital pathology, laboratory biomarkers, wearable technologies, electronic health records, and longitudinal clinical information into unified computational frameworks capable of supporting individualized immunotherapy throughout the cancer care continuum.[29]

Advances in transformer architectures, multimodal learning, graph neural networks, large language models, digital twins, federated learning, agentic AI, and generative artificial intelligence are expected to further strengthen intelligent immuno-oncology ecosystems, enabling increasingly accurate prediction of therapeutic response, adaptive treatment planning, continuous immune monitoring, and evidence-based clinical decision-making.

Although important scientific, technical, ethical, and regulatory challenges remain, continued interdisciplinary collaboration among oncologists, immunologists, radiologists, pathologists, molecular biologists, biomedical engineers, computer scientists, healthcare organizations, and regulatory agencies will accelerate responsible implementation of foundation AI models, ultimately improving patient outcomes and advancing the future of personalized cancer immunotherapy worldwide.[30]

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