International Journal of Multidisciplinary Research in Biotechnology, Pharmacy, Dental and Medical Sciences (IJMRBPDMS)

Pan-Cancer Multimodal Intelligence: Integrating Radiomics, Pathomics, Genomics, and Electronic Health Records

Dr.Kavitha Nair[1],Dr.Rohit Agarwal[2],Dr.Simran Kaur[3]

[1]Professor,Department of Community Medicine,Ramaiah Medical College,Bengaluru,India.Kavithanair71@gmail.com
[2]Associate Professor,Department of Pharmacology,Ramaiah Medical College,Bengaluru,India.Rohitagarwal56@gmail.com
[3]Assistant Professor,Department of Microbiology,Ramaiah Medical College,Bengaluru,India.Simrankaur218@gmail.com

ABSTRACT

Cancer represents a heterogeneous group of diseases characterized by diverse molecular alterations, complex tumor microenvironments, variable therapeutic responses, and distinct clinical outcomes across different organ systems. Although advances in molecular biology, targeted therapeutics, immunotherapy, and precision medicine have significantly improved cancer management, effective individualized care increasingly depends upon comprehensive integration of heterogeneous biomedical information rather than isolated diagnostic modalities. Recent developments in artificial intelligence (AI) have introduced the concept of pan-cancer multimodal intelligence, which integrates radiomics, digital pathomics, genomics, transcriptomics, proteomics, laboratory biomarkers, electronic health records (EHRs), and longitudinal clinical data into unified computational frameworks capable of supporting precision oncology across multiple cancer types. Machine learning, deep learning, transformer architectures, graph neural networks, multimodal foundation models, self-supervised learning, retrieval-augmented generation, and generative AI have substantially enhanced multimodal biomedical representation learning while improving diagnosis, prognostic prediction, molecular characterization, therapeutic optimization, immunotherapy response prediction, digital twins, and intelligent clinical decision support. Despite remarkable technological progress, important challenges remain regarding multimodal data harmonization, computational scalability, interoperability, explainability, cybersecurity, regulatory validation, and equitable implementation. This review provides a comprehensive overview of pan-cancer multimodal intelligence, emphasizing computational principles, clinical applications, implementation challenges, and future perspectives for precision cancer medicine.[1]

Keywords: Pan-cancer, Artificial intelligence, Radiomics, Pathomics, Genomics, Electronic health records, Multimodal learning, Precision oncology, Foundation models, Clinical decision support.

Article Info
Received: 05 December 2025, received in revised form: 15 December 2025, accepted: 20 December 2025, available online: 30 December 2025; Volume: 1; Issue: 5; Pages: 71-79.

Citation: Nair K.,2025.Pan-Cancer Multimodal Intelligence: Integrating Radiomics, Pathomics, Genomics, and Electronic Health Records. *International Journal of Multidisciplinary Research in Biotechnology, Pharmacy, Dental and Medical Sciences (IJMRBPDMS) 2(1): 71-79.*

DOI:

1.Introduction

Cancer encompasses more than two hundred distinct malignancies that differ in anatomical origin, molecular biology, histopathology, immune interactions, therapeutic sensitivity, and clinical outcomes. Despite these differences, many cancers share common biological mechanisms including genomic instability, epigenetic dysregulation, metabolic reprogramming, immune escape, angiogenesis, and tumor microenvironment remodeling. Consequently, precision oncology increasingly seeks generalized computational approaches capable of identifying shared biological principles while preserving disease-specific characteristics across multiple cancer types.[2]

Modern oncology generates enormous quantities of heterogeneous biomedical information through computed tomography, magnetic resonance imaging, positron emission tomography, mammography, digital pathology, genomic sequencing, transcriptomics, proteomics, metabolomics, laboratory investigations, wearable biosensors, and electronic health records. Each modality captures complementary aspects of tumor biology; however, isolated analysis frequently limits comprehensive understanding of disease complexity.[3]

Artificial intelligence has emerged as one of the most influential technologies capable of integrating these multimodal datasets into unified patient-specific computational representations. Recent advances in multimodal learning have enabled simultaneous analysis of radiomics, pathomics, genomics, and longitudinal clinical information, giving rise to pan-cancer intelligence systems that support increasingly generalized yet personalized precision medicine.[4]

The convergence of multimodal artificial intelligence with comprehensive biomedical data integration is redefining computational oncology by enabling adaptive clinical reasoning across diverse malignancies while improving individualized diagnosis, prognostic prediction, therapeutic optimization, and survivorship care.[5]

2.Evolution of Pan-Cancer Computational Intelligence

Traditional oncology primarily relied on anatomical classification and histopathological diagnosis to guide treatment decisions. Although these approaches remain fundamental, they often fail to capture the molecular diversity and biological complexity underlying cancer progression and therapeutic response.[6]

The introduction of genomic medicine transformed precision oncology by identifying clinically actionable mutations and enabling targeted therapies across multiple malignancies. Subsequent advances in radiomics, computational pathology, transcriptomics, proteomics, metabolomics, and digital health generated increasingly comprehensive descriptions of tumor biology.

Artificial intelligence further accelerated this evolution by enabling machine learning, deep learning, transformer architectures, graph neural networks, and multimodal foundation models capable of integrating heterogeneous biomedical information into unified computational frameworks. Rather than analyzing individual cancer types independently, pan-cancer computational intelligence identifies generalized biological representations that support transfer learning and precision medicine across multiple malignancies.[7]

These advances have established multimodal intelligence as one of the central computational paradigms for next-generation oncology.

3.Principles of Multimodal Intelligence

Pan-cancer multimodal intelligence integrates complementary biomedical modalities into unified computational representations that describe individual patients across multiple biological scales. Unlike conventional artificial intelligence systems designed for single-modality analysis, multimodal models simultaneously process imaging, pathology, genomics, laboratory biomarkers, electronic health records, and longitudinal clinical information.[8]

Transformer architectures facilitate cross-modal attention mechanisms that identify latent relationships among heterogeneous biomedical datasets, whereas graph neural networks model interactions involving genes, proteins, signaling pathways, immune responses, therapeutic targets, imaging biomarkers, and clinical outcomes.

Self-supervised learning and multimodal representation learning further enable generalized biomedical embeddings that support transfer learning across diverse cancer types while reducing dependence on manually annotated datasets. These unified computational representations substantially improve diagnosis, molecular characterization, prognostic prediction, and therapeutic decision-making throughout precision oncology.[9]

4.Computational Architecture

Modern pan-cancer intelligence systems consist of multiple computational layers responsible for multimodal data acquisition, preprocessing, representation learning, cross-modal fusion, predictive modeling, and clinical decision support.[10]

The data acquisition layer collects radiological imaging, digital pathology, genomic sequencing, transcriptomics, proteomics, metabolomics, laboratory investigations, wearable sensor information, medication history, and electronic health records from diverse healthcare environments. Advanced preprocessing pipelines normalize imaging, harmonize molecular datasets, encode clinical narratives using natural language processing, align temporal information, and extract quantitative biomedical features.

Large multimodal transformer architectures subsequently generate unified patient-specific embeddings representing complementary biological information across multiple modalities. Predictive modules adapt these generalized representations to downstream oncology applications including diagnosis, molecular subtype classification, therapeutic prediction, recurrence assessment, toxicity estimation, and survival analysis.

Continuous integration of longitudinal patient information enables adaptive precision oncology while supporting dynamic disease monitoring throughout the cancer care continuum.[11]

5.Radiomics in Pan-Cancer Intelligence

Radiomics has become a major contributor to multimodal computational oncology by extracting hundreds of quantitative imaging biomarkers from computed tomography, magnetic resonance imaging, positron emission tomography, mammography, ultrasound, and hybrid imaging modalities. These biomarkers objectively characterize tumor morphology, heterogeneity, vascularity, metabolism, texture, shape, and spatial organization.[12]

Artificial intelligence analyzes radiomic features to estimate disease aggressiveness, molecular subtype, treatment response, recurrence risk, metastatic potential, and overall survival across multiple cancer types. Foundation models further strengthen radiomic analysis by learning generalized imaging representations transferable across diverse malignancies.

Longitudinal radiomics enables continuous monitoring of disease evolution, supporting adaptive therapeutic planning while facilitating early detection of therapeutic resistance and recurrence.[13]

6.Pathomics and Computational Histopathology

Digital pathomics extends traditional histopathology through computational analysis of whole-slide tissue images using artificial intelligence. Deep learning and transformer architectures automatically evaluate millions of microscopic tissue regions, extracting quantitative histomorphological biomarkers describing tumor architecture, cellular differentiation, stromal remodeling, immune infiltration, angiogenesis, necrosis, and tumor heterogeneity.[14]

Computational pathology accurately predicts tumor subtype, histological grade, recurrence risk, lymph node metastasis, therapeutic biomarkers, and molecular alterations across diverse cancer types while improving diagnostic reproducibility.

Integration of pathomics with radiomics and genomics substantially strengthens precision oncology by linking microscopic tissue architecture with macroscopic imaging phenotypes and molecular biology.[15]

7.Genomics and Multi-Omics Integration

Genomics remains a fundamental component of pan-cancer intelligence because genomic alterations influence tumor initiation, progression, therapeutic response, and resistance mechanisms across multiple malignancies. High-throughput sequencing technologies characterize inherited susceptibility variants, somatic mutations, copy-number alterations, structural rearrangements, and molecular pathways associated with cancer biology.[16]

Artificial intelligence further integrates transcriptomics, proteomics, metabolomics, epigenomics, lipidomics, immunomics, and single-cell sequencing into unified multi-omics representations that capture biological interactions extending beyond genomic information alone.

These multimodal molecular representations improve biomarker discovery, molecular subtype classification, systems biology research, therapeutic prediction, and individualized precision medicine while supporting increasingly comprehensive characterization of cancer biology.[17]

8.Electronic Health Records and Longitudinal Intelligence

Electronic health records constitute one of the most valuable yet underutilized resources in computational oncology because they capture longitudinal patient trajectories across diagnosis, treatment, recurrence surveillance, survivorship, and end-of-life care. Clinical documentation, laboratory investigations, medication history, physician notes, pathology reports, radiology reports, and patient-reported outcomes collectively describe evolving disease processes over time.[18]

Large language models and transformer architectures extract clinically relevant information from structured and unstructured EHR data while integrating these temporal clinical records with radiomics, pathomics, genomics, and laboratory biomarkers into unified computational representations.

Longitudinal clinical intelligence substantially improves prediction of disease progression, therapeutic response, treatment-related toxicity, recurrence, and survival while enabling adaptive precision oncology throughout the entire cancer care continuum.[19]

9.Multimodal Fusion and Pan-Cancer Representation Learning

A defining feature of pan-cancer multimodal intelligence is its ability to combine heterogeneous biomedical information into generalized patient-specific computational representations. Cross-modal transformer architectures align radiomics, pathomics, genomics, laboratory biomarkers, and electronic health records through shared embedding spaces that preserve complementary biological information while identifying latent relationships across diverse modalities.[20]

These generalized representations facilitate transfer learning across multiple malignancies, allowing computational knowledge acquired from one cancer type to improve diagnostic and therapeutic performance in others. Such pan-cancer representation learning substantially strengthens precision medicine by identifying shared biological mechanisms while preserving disease-specific characteristics required for individualized clinical decision-making.[21]

10.Radiopathomics in Precision Diagnosis and Prognostic Prediction

One of the most important clinical applications of AI-driven radiopathomics is precision diagnosis through simultaneous interpretation of radiological imaging and digital pathology. Artificial intelligence integrates imaging-derived radiomic biomarkers with histopathological characteristics, molecular biomarkers, laboratory investigations, and longitudinal clinical information to generate comprehensive patient-specific diagnostic profiles.[22]

Machine learning algorithms improve tumor detection, disease classification, molecular subtype prediction, cancer staging, recurrence risk estimation, and prognostic stratification by analyzing complementary macroscopic and microscopic tumor features. Unlike conventional diagnostic workflows that interpret radiology and pathology separately, radiopathomics provides unified computational reasoning that reflects the biological complexity of individual tumors.

This integrated diagnostic approach improves clinical consistency, reduces observer variability, and supports multidisciplinary oncology teams through evidence-based computational decision support.

11. Personalized Therapeutics and Treatment Response Assessment

Personalized cancer treatment depends upon accurate prediction of therapeutic response and disease evolution. Radiopathomics enhances treatment planning by integrating radiological imaging, computational pathology, genomic sequencing, transcriptomics, laboratory biomarkers, treatment history, and patient-specific clinical characteristics into unified predictive models.[23]

Artificial intelligence estimates treatment response, recurrence probability, progression-free survival, overall survival, and treatment-related toxicity across chemotherapy, targeted therapy, endocrine therapy, immunotherapy, radiation therapy, surgery, and multimodal treatment combinations.

Longitudinal integration of imaging and pathology enables continuous monitoring of tumor evolution throughout therapy. Changes in imaging biomarkers together with microscopic tissue alterations provide early indicators of therapeutic effectiveness or emerging resistance, facilitating timely modification of treatment strategies.

12.Radiopathomics in Immunotherapy and Tumor Microenvironment Analysis

The tumor microenvironment plays a central role in determining responsiveness to immunotherapy. AI-driven radiopathomics enables comprehensive evaluation of immune-cell infiltration, stromal organization, angiogenesis, vascular remodeling, inflammatory signaling pathways, and spatial cellular interactions through simultaneous analysis of radiological imaging and digital pathology.[24]

Artificial intelligence identifies relationships between imaging phenotypes and microscopic immune architecture, enabling prediction of responsiveness to immune checkpoint inhibitors, CAR-T cell therapies, cancer vaccines, bispecific antibodies, and adoptive cellular therapies.

These computational models improve patient selection for immunotherapy while supporting development of personalized therapeutic strategies based on the biological characteristics of each patient's tumor microenvironment.

13.Digital Twins and Clinical Decision Support

The convergence of radiopathomics with digital twin technology is creating continuously evolving virtual representations of individual cancer patients capable of integrating radiological imaging, pathology, genomics, laboratory biomarkers, wearable technologies, and longitudinal clinical information into adaptive computational ecosystems.[25]

Artificial intelligence continuously updates these virtual patient models as new imaging and pathological information becomes available, enabling simulation of disease progression, therapeutic response, toxicity, recurrence, and long-term survival before clinical intervention.

Within routine oncology practice, radiopathomics-powered clinical decision-support systems provide individualized diagnostic summaries, therapeutic recommendations, toxicity predictions, recurrence estimates, and survivorship planning through interactive multidisciplinary dashboards while maintaining physician oversight.

14.Explainable Artificial Intelligence and Clinical Translation

Successful implementation of radiopathomics requires transparent computational reasoning that clinicians can interpret and validate. Explainable artificial intelligence (XAI) enables visualization of imaging regions, histopathological structures, molecular biomarkers, and clinical variables contributing to AI-generated predictions using saliency maps, Grad-CAM, SHAP (Shapley Additive Explanations), attention mechanisms, feature attribution analysis, and counterfactual explanations.[26]

These explainability techniques improve clinician confidence while facilitating multidisciplinary communication among radiologists, pathologists, oncologists, surgeons, molecular biologists, and radiation oncologists.

Despite remarkable technological progress, challenges remain regarding multimodal data harmonization, interoperability, computational scalability, regulatory validation, cybersecurity, algorithmic bias, and equitable implementation. Standardized validation frameworks and prospective multicenter studies will be essential for routine clinical adoption.

15.Emerging Innovations and Future Perspectives

Rapid advances in computational oncology continue to expand the capabilities of radiopathomics. Multimodal foundation models, large language models, graph neural networks, digital twins, federated learning, agentic artificial intelligence, reinforcement learning, spatial multi-omics, liquid biopsy, single-cell sequencing, and cloud-native healthcare infrastructure are expected to substantially strengthen integrated computational oncology ecosystems.[27]

Future radiopathomic systems may continuously integrate imaging, pathology, genomics, laboratory medicine, wearable biosensors, and real-world clinical outcomes into adaptive computational platforms capable of personalized diagnosis, dynamic therapeutic planning, autonomous knowledge synthesis, and continuous disease monitoring.

These intelligent ecosystems have the potential to transform multidisciplinary oncology by providing comprehensive patient-centered computational intelligence across every stage of cancer care.

16.Discussion

AI-driven radiopathomics represents one of the most significant advances in computational oncology by integrating radiological imaging and digital pathology into unified multimodal representations of tumor biology. Unlike conventional workflows that evaluate imaging and pathology independently, radiopathomics combines complementary macroscopic and microscopic information to provide more comprehensive diagnosis, prognostic prediction, molecular characterization, treatment optimization, and disease monitoring.[28]

Applications spanning precision diagnosis, immunotherapy prediction, personalized therapeutics, digital twins, biomarker discovery, and intelligent clinical decision support demonstrate the remarkable potential of this emerging discipline to improve patient-centered cancer care.

Nevertheless, successful implementation requires continued advances in multimodal artificial intelligence, explainable computational reasoning, standardized interoperability, secure computational infrastructure, prospective validation, and interdisciplinary collaboration among radiologists, pathologists, oncologists, biomedical engineers, computer scientists, and regulatory agencies.

17.Conclusion

AI-driven radiopathomics is redefining personalized oncology by integrating radiological imaging, digital pathology, molecular biology, laboratory biomarkers, and longitudinal clinical information into comprehensive computational frameworks capable of supporting precision cancer medicine.[29]

Advances in multimodal learning, transformer architectures, foundation models, graph neural networks, digital twins, federated learning, generative artificial intelligence, and computational pathology are expected to further strengthen radiopathomic systems, enabling increasingly accurate diagnosis, adaptive therapeutics, continuous disease monitoring, and evidence-based clinical decision-making.

Although important scientific, technical, ethical, and regulatory challenges remain, ongoing interdisciplinary collaboration will accelerate responsible clinical translation of radiopathomics into routine oncology practice, ultimately improving diagnostic accuracy, therapeutic precision, and patient outcomes while advancing the future of precision cancer care.[30]

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