International Journal of Emerging Research in Applied Medical Sciences (IJERAMS)

AI-Driven Radiopathomics: Integrating Radiology and Digital Pathology for Personalized Cancer Care

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ABSTRACT

Cancer remains one of the leading causes of morbidity and mortality worldwide despite remarkable advances in molecular agnostics, targeted therapeutics, immunotherapy, and precision medicine. Modern oncology increasingly relies on ımplementary information derived from radiological imaging and digital pathology to characterize tumor biology, guide erapeutic decision-making, and monitor disease progression. Traditionally, these two domains have been analyzed dependently despite describing different yet interconnected aspects of cancer biology. Recent advances in artificial telligence (AI) have introduced the field of radiopathomics, which integrates radiology, digital pathology, multi-omics, boratory biomarkers, and longitudinal clinical information into unified computational frameworks that support precision ıcology. Machine learning, deep learning, transformer architectures, graph neural networks, multimodal foundation models, ılf-supervised learning, and generative AI have enabled automated extraction of quantitative imaging biomarkers and stomorphological features capable of improving cancer diagnosis, prognostic prediction, molecular characterization, eatment optimization, immunotherapy response prediction, and clinical decision support. AI-driven radiopathomics provides ımprehensive characterization of tumor phenotype by combining macroscopic anatomical information with microscopic ssue architecture, thereby facilitating personalized cancer management. Despite substantial technological progress, challenges main regarding multimodal data harmonization, computational scalability, explainability, interoperability, regulatory ılidation, and equitable clinical implementation. This review presents a comprehensive overview of AI-driven radiopathomics, nphasizing computational principles, current clinical applications, emerging innovations, and future perspectives for ersonalized cancer care.[1]

Keywords: Radiopathomics, Artificial intelligence, Radiology, Digital pathology, Precision oncology, Radiomics, Computational pathology, Multimodal learning, Personalized medicine, Clinical decision support.

Article History

Received: 10 December 2025**;** **Accepted:** 18 December 2025**;** **Published:** 28 December 2025

Citation

Sen B.,(2025).AI-Driven Radiopathomics: Integrating Radiology and Digital Pathology for Personalized Cancer Care.*International Journal of Emerging Research in Applied Medical Sciences (IJERAMS), 1(5), 117-124.*

DOI: https://doi.org/10.65477/ijerams.v1.i5.15

1. Introduction

Cancer is a biologically heterogeneous disease characterized by genomic instability, epigenetic alterations, transcriptional dysregulation, immune diversity, metabolic reprogramming, and continuous interactions between malignant cells and the surrounding tumor microenvironment. Although molecular diagnostics have transformed precision oncology, considerable variability in treatment response and long-term clinical outcomes remains because tumor biology extends far beyond individual molecular biomarkers.[2]

Radiological imaging and histopathology represent two of the most fundamental diagnostic pillars in modern oncology. Medical imaging provides non-invasive assessment of tumor morphology, anatomical extent, vascularity, metabolism, and disease progression, whereas pathology reveals microscopic tissue architecture, cellular morphology, stromal organization, immune infiltration, and molecular characteristics. Historically, these complementary information sources have been interpreted separately despite describing different dimensions of the same biological process.[3]

Artificial intelligence has emerged as a transformative technology capable of integrating heterogeneous biomedical information into unified computational frameworks. Recent advances in multimodal learning have enabled simultaneous analysis of radiological imaging, digital pathology, genomics, laboratory investigations, and longitudinal clinical information, giving rise to the rapidly evolving field of radiopathomics.[4]

By combining macroscopic radiological phenotypes with microscopic histopathological features, AI-driven radiopathomics provides comprehensive characterization of tumor biology while supporting personalized diagnosis, prognostic prediction, therapeutic optimization, and precision medicine.[5]

2. Evolution of Radiopathomics

Traditional oncology relied upon independent interpretation of radiological imaging and histopathology. Radiologists evaluated tumor size, morphology, anatomical relationships, and disease extent, whereas pathologists assessed microscopic tissue architecture, histological grade, cellular differentiation, lymphovascular invasion, and molecular biomarkers. Although both disciplines contributed essential clinical information, limited computational integration restricted comprehensive understanding of tumor biology.[6]

The emergence of radiomics introduced quantitative extraction of imaging biomarkers describing tumor morphology, texture, heterogeneity, vascularity, and spatial organization. Simultaneously, computational pathology enabled automated analysis of whole-slide histopathological images through deep learning and digital image analysis.[7]

Recent advances in multimodal artificial intelligence, transformer architectures, graph neural networks, and foundation models have enabled simultaneous integration of radiomics and computational pathology into unified computational representations. These technologies facilitate cross-modal biological reasoning while improving diagnosis, prognostic prediction, biomarker discovery, and therapeutic planning.[8]

Radiopathomics therefore represents an important evolution toward integrated computational oncology in which radiology and pathology function as complementary rather than independent diagnostic disciplines.[9]

3. Computational Principles of Radiopathomics

Radiopathomics integrates complementary biomedical information across multiple spatial scales. Radiological imaging captures whole-tumor anatomy, surrounding tissues, vascular networks, metastatic dissemination, and longitudinal disease progression, whereas digital pathology provides microscopic characterization of cellular morphology, tissue architecture, immune infiltration, stromal remodeling, angiogenesis, and molecular alterations.[10]

Artificial intelligence enables harmonization of these heterogeneous datasets through multimodal representation learning. Machine learning identifies statistical relationships among imaging features and pathological characteristics, whereas deep learning automatically extracts hierarchical representations from radiological images and whole-slide pathology specimens.

Transformer architectures provide cross-modal attention mechanisms capable of learning shared representations between radiological imaging and histopathological features. Graph neural networks further model biological interactions among imaging biomarkers, cellular organization, molecular pathways, and clinical outcomes, supporting increasingly comprehensive computational understanding of tumor biology.[11]

4. Artificial Intelligence Technologies in Radiopathomics

Modern radiopathomics relies upon multiple complementary artificial intelligence technologies that collectively support computational integration of radiology and pathology. Machine learning algorithms identify nonlinear relationships between imaging biomarkers, histopathological characteristics, molecular biomarkers, and patient outcomes while supporting diagnosis, prognostic prediction, and therapeutic response estimation.[12]

Deep learning significantly enhances computational performance through automated extraction of complex features from computed tomography, magnetic resonance imaging, positron emission tomography, mammography, ultrasound, and digital pathology. Convolutional neural networks excel in image analysis, whereas transformer architectures efficiently process heterogeneous multimodal biomedical information.

Multimodal foundation models further strengthen generalizability through self-supervised pretraining on large biomedical datasets, while graph neural networks represent interactions among imaging phenotypes, cellular architecture, molecular pathways, and therapeutic targets.

These complementary computational approaches enable increasingly comprehensive patient-specific representations supporting precision oncology.[13]

5. Radiomics: Quantitative Imaging Biomarkers

Radiomics extends conventional medical imaging by extracting hundreds of quantitative biomarkers describing tumor morphology, texture, shape, intensity, vascularity, and spatial heterogeneity from routine radiological examinations. These computational imaging biomarkers provide objective characterization of tumor phenotype beyond visual interpretation alone.[14]

Artificial intelligence analyzes radiomic features derived from computed tomography, magnetic resonance imaging, positron emission tomography, mammography, ultrasound, and hybrid imaging to estimate disease aggressiveness, molecular subtype, therapeutic response, recurrence risk, and survival outcomes.

Longitudinal radiomic analysis further enables continuous monitoring of treatment response through quantitative comparison of sequential imaging studies, allowing earlier identification of therapeutic resistance or disease progression while facilitating adaptive clinical management.[15]

6. Computational Digital Pathology

Digital pathology has become one of the principal components of radiopathomics through conversion of conventional glass slides into ultra-high-resolution whole-slide images suitable for computational analysis. Artificial intelligence evaluates millions of microscopic tissue regions simultaneously, providing objective assessment of tumor morphology, histological grade, stromal remodeling, angiogenesis, immune infiltration, necrosis, and cellular heterogeneity.[16]

Deep learning and transformer-based pathology models accurately classify tumor subtypes, identify prognostic biomarkers, predict lymph node metastasis, estimate recurrence risk, and infer molecular alterations directly from routine histopathological images.

These computational pathology representations complement radiological imaging by providing detailed microscopic information regarding biological processes responsible for imaging phenotypes observed during radiological evaluation.[17]

7. Multimodal Integration of Radiology and Pathology

The central objective of radiopathomics is seamless integration of radiological imaging and digital pathology into unified computational representations that capture complementary aspects of tumor biology. Artificial intelligence aligns imaging-derived radiomic features with histomorphological characteristics extracted from digital pathology while incorporating genomic sequencing, transcriptomics, laboratory biomarkers, and longitudinal clinical information.[18]

Cross-modal transformer architectures identify latent biological relationships linking macroscopic imaging phenotypes with microscopic cellular organization. These integrated computational representations improve diagnosis, prognostic prediction, molecular characterization, biomarker discovery, therapeutic planning, and disease monitoring.

Radiopathomics therefore enables comprehensive understanding of cancer across multiple biological scales while supporting increasingly personalized precision oncology.[19]

8. Radiopathomics and Molecular Oncology

Integration of radiopathomics with molecular biology substantially enhances precision oncology by connecting imaging phenotypes and histopathological characteristics with genomic alterations, transcriptomic signatures, proteomic pathways, and additional molecular biomarkers. Artificial intelligence identifies relationships among radiological imaging, digital pathology, and molecular biology that facilitate non-invasive prediction of clinically significant genomic alterations and therapeutic biomarkers.[20]

These multimodal computational models improve molecular subtype classification, identification of actionable mutations, prediction of treatment sensitivity, assessment of therapeutic resistance, and personalized clinical decision-making. By integrating radiology, pathology, and molecular biology into unified computational ecosystems, radiopathomics strengthens precision medicine while reducing fragmentation of clinical information across diagnostic disciplines.[21]

9. Radiopathomics in Personalized Therapeutics

One of the greatest clinical advantages of AI-driven radiopathomics is its ability to support individualized therapeutic planning through comprehensive integration of imaging, pathology, molecular biology, and longitudinal clinical information. Unlike conventional treatment planning, which often relies on isolated diagnostic findings, radiopathomics provides a unified biological representation of each patient's tumor.[22]

Artificial intelligence combines radiomic biomarkers, histopathological features, genomic alterations, transcriptomic signatures, laboratory investigations, and clinical characteristics to estimate treatment response, recurrence probability, progression-free survival, overall survival, and treatment-related toxicity.

These predictive models assist oncologists in selecting chemotherapy, targeted therapy, endocrine therapy, immunotherapy, radiation therapy, surgical intervention, and multimodal treatment strategies that are most likely to benefit individual patients while minimizing unnecessary toxicity.

10. Radiopathomics in Immunotherapy and Tumor Microenvironment Analysis

The tumor microenvironment has emerged as one of the most important determinants of therapeutic response, particularly in patients receiving immunotherapy. AI-driven radiopathomics enables simultaneous evaluation of radiological imaging, computational pathology, immunomics, transcriptomics, and laboratory biomarkers to characterize immune activity throughout the tumor ecosystem.[23]

Artificial intelligence quantifies tumor-infiltrating lymphocytes, immune checkpoint expression, stromal remodeling, angiogenesis, inflammatory signaling pathways, vascular architecture, and spatial cellular organization while integrating these findings with imaging-derived biomarkers.

These computational models improve prediction of responsiveness to immune checkpoint inhibitors, CAR-T cell therapies, cancer vaccines, bispecific antibodies, and adoptive cellular therapies while supporting increasingly personalized immunotherapeutic strategies.

11. Radiopathomics in Radiation Oncology and Surgical Planning

Radiation therapy and surgery remain fundamental components of cancer management. Radiopathomics enhances both therapeutic modalities by integrating anatomical imaging with microscopic pathological information into unified computational decision-support systems.[24]

Artificial intelligence assists radiation oncologists by improving tumor contouring, biological target delineation, radiation sensitivity prediction, adaptive treatment planning, and dose optimization using combined radiological and pathological biomarkers.

Within surgical oncology, multimodal computational models predict tumor margins, lymph node involvement, vascular invasion, operative complexity, and postoperative outcomes through simultaneous interpretation of imaging, pathology, and molecular characteristics. These capabilities support individualized surgical planning while improving precision and reducing complications.

12. Drug Discovery and Clinical Decision Support

AI-driven radiopathomics has become increasingly valuable in oncology drug discovery by integrating imaging biomarkers, histopathological characteristics, molecular biology, pharmacology, and clinical outcomes into unified computational frameworks. Machine learning identifies novel therapeutic targets, predicts drug-target interactions, estimates toxicity profiles, and models mechanisms of therapeutic resistance.[25]

Generative AI further accelerates pharmaceutical research by designing candidate molecules, simulating biological interactions, and prioritizing compounds for laboratory validation.

Within routine clinical practice, radiopathomic decision-support systems integrate imaging studies, pathology reports, laboratory investigations, genomic sequencing, medication history, and electronic health records into interactive dashboards providing individualized diagnostic summaries, therapeutic recommendations, toxicity prediction, recurrence surveillance, and survivorship planning.

13. Explainable Artificial Intelligence and Clinical Translation

Clinical implementation of radiopathomics requires transparency, interpretability, and clinician confidence because diagnostic and therapeutic recommendations directly influence patient management. Explainable artificial intelligence (XAI) enables clinicians to understand computational reasoning through saliency maps, attention visualization, SHAP (Shapley Additive Explanations), feature attribution methods, and counterfactual explanations.[26]

Visualization of radiological regions, histopathological structures, molecular biomarkers, and clinical variables contributing to model predictions allows physicians to verify AI-generated recommendations using established biological knowledge and clinical expertise.

Several important implementation challenges remain, including multimodal data harmonization, computational infrastructure requirements, interoperability, cybersecurity, regulatory approval, algorithmic bias, and equitable healthcare access. Addressing these barriers will require standardized validation protocols, transparent governance frameworks, and multidisciplinary collaboration.

14. Emerging Innovations and Future Perspectives

Rapid advances in computational oncology continue to expand the capabilities of radiopathomics. Multimodal foundation models, digital twins, agentic artificial intelligence, federated learning, spatial multi-omics, large language models, quantum computing, liquid biopsy, wearable biosensors, and cloud-native healthcare infrastructure are expected to substantially strengthen multimodal cancer intelligence.[27]

Future radiopathomic systems may continuously integrate radiological imaging, digital pathology, genomics, transcriptomics, proteomics, metabolomics, laboratory biomarkers, wearable technologies, and longitudinal clinical information into adaptive virtual patient ecosystems capable of supporting real-time therapeutic optimization.

These intelligent computational platforms may ultimately function as continuously learning precision oncology systems that coordinate diagnosis, treatment planning, disease monitoring, and survivorship care across multidisciplinary healthcare environments.

15. Discussion

AI-driven radiopathomics represents one of the most significant advances in computational oncology by integrating radiology and digital pathology into unified multimodal artificial intelligence frameworks. Unlike conventional diagnostic approaches that evaluate imaging and pathology independently, radiopathomics provides comprehensive biological representations capable of supporting diagnosis, molecular characterization, prognostic prediction, therapeutic optimization, immunotherapy selection, drug discovery, and intelligent clinical decision support.[28]

Its ability to bridge macroscopic imaging with microscopic pathology substantially enhances understanding of tumor biology while improving multidisciplinary collaboration and personalized cancer care. Nevertheless, successful implementation requires continued advances in explainable artificial intelligence, multimodal foundation models, interoperability, computational infrastructure, prospective validation, and regulatory science before widespread clinical adoption.

16. 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 diagnosis, prognostic prediction, therapeutic planning, and disease monitoring.[29]

Advances in multimodal learning, transformer architectures, graph neural networks, digital twins, foundation models, federated learning, generative artificial intelligence, and computational pathology are expected to further strengthen these intelligent systems while improving scalability, robustness, and clinical applicability.

Although important scientific, technical, ethical, and regulatory challenges remain, continued interdisciplinary collaboration among radiologists, pathologists, oncologists, molecular biologists, computer scientists, biomedical engineers, and regulatory agencies will accelerate responsible translation of radiopathomics into routine clinical practice, ultimately improving patient outcomes and advancing the future of precision cancer medicine.[30]

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