

AI: Reshaping Pathology from Diagnosis to Prognosis.

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Introduction

The reality of Artificial Intelligence (AI) in pathology is its integration across the entire diagnostic workflow [1].

It's moving beyond simple image analysis to assist in lab operations, quality assurance, and even predicting patient outcomes from slides [1].

This represents a fundamental shift in how pathology is practiced, aiming for higher efficiency and precision [1].

In specific domains like breast pathology, AI's true value isn't just spotting tumors [2].

Its strength lies in quantifying key biomarkers like Ki-67 and evaluating HER2 status with a level of consistency that humans struggle to match [2].

This precision directly informs treatment choices, making AI a critical tool for personalized medicine [2].

Similarly, for prostate cancer, AI's most significant contribution is standardizing Gleason grading [3].

By minimizing the subjective variability between pathologists, these algorithms provide more consistent and reliable prognostic information, which is especially crucial for managing patients with borderline or intermediate-risk disease [3].

The utility of AI also extends beyond tissue sections into cytopathology [8].

For Pap tests and thyroid aspirates, algorithms can function as powerful screening tools, rapidly triaging slides and flagging abnormal cells for human review [8].

This process allows cytologists to concentrate on the most complex cases, boosting overall efficiency and accuracy in diagnoses [8].

Beyond its diagnostic capabilities, AI is evolving into a powerful prognostic tool [6].

Deep learning models can now analyze subtle morphological patterns in a tumor's microenvironment on a standard H&E slide—patterns that are often invisible to the human eye—to predict how a patient will respond to immunotherapy [6].

This effectively transforms a basic slide into a powerful predictive biomarker, opening new frontiers in patient care [6].

Despite these advances, the primary barrier to deploying AI in pathology isn't a lack of powerful algorithms, but a persistent lack of high-quality, generalizable data [4].

Models trained on data from one lab often underperform when exposed to slides from another due to subtle differences in staining and preparation techniques [4].

Achieving true generalizability across different institutions and patient populations remains the central challenge for developers and researchers [4].

Furthermore, pathologists are unlikely to trust a 'black box' diagnosis, making transparency a critical factor for adoption [5].

This is where Explainable AI (XAI) becomes essential [5].

By creating visual aids like heatmaps that highlight the specific cellular features the AI used to make its decision, XAI allows pathologists to verify the algorithm's reasoning, building the trust necessary for clinical adoption and validation [5].

Implementation also involves navigating a complex landscape of regulatory and ethical challenges [7].

Beyond the technology itself, key issues include securing FDA approval for diagnostic tools, establishing clear lines of liability for algorithmic errors, safeguarding patient data privacy, and actively mitigating the risk of bias that could worsen existing health inequities [7].

Ultimately, successful AI implementation in pathology hinges on seamless workflow integration [9].

The goal is to augment, not replace, the pathologist [9].

Optimal systems are designed to operate in the background, pre-analyzing images and presenting quantitative data directly within the pathologist's existing software [9].

This makes the AI function as an indispensable assistant rather than a separate, disruptive step in the diagnostic process [9].

Looking ahead, the influence of AI is expanding beyond image analysis, as Large Language Models (LLMs) are poised to reshape the textual aspects of pathology [10].

These models can assist in drafting standardized diagnostic reports, summarizing complex findings for clinicians, and mining extensive report archives for research purposes [10].

This expands AI's role from the microscope to the final report that guides patient care, completing its integration into the modern pathology practice [10].

Description

Artificial Intelligence (AI) is enacting a fundamental shift in how pathology is practiced. Its integration now spans the entire diagnostic workflow, moving far beyond simple image analysis to assist in core lab operations, quality assurance, and even

the prediction of patient outcomes directly from digital slides [1]. This holistic approach aims to create a more efficient and precise environment, where AI acts as a foundational tool rather than a siloed application. The goal is to augment the pathologist's expertise, not replace it. Optimal systems are designed to operate in the background, pre-analyzing images and presenting crucial quantitative data directly within the pathologist's existing software. This makes the technology function as an indispensable assistant that enhances decision-making without disrupting established diagnostic processes [9]. By weaving AI into the fabric of the daily workflow, its power can be leveraged to handle high-volume, repetitive tasks, freeing up pathologists to focus their skills on more complex and nuanced diagnostic challenges.

The clinical applications of this technology are already demonstrating significant impact in specific areas of oncology. In breast pathology, AI's strength lies in its ability to quantify key biomarkers like Ki-67 and evaluate HER2 status with a level of consistency that is difficult for humans to achieve consistently [2]. This precision is not just an academic exercise; it directly informs critical treatment choices and is a cornerstone of advancing personalized medicine. For prostate cancer, AI's most significant contribution has been the standardization of Gleason grading. By minimizing the inherent subjective variability that exists between different pathologists, these algorithms provide more consistent and reliable prognostic information. This reliability is especially crucial for properly managing patients who present with borderline or intermediate-risk disease, where diagnostic ambiguity can lead to suboptimal treatment strategies [3]. Furthermore, AI's utility extends into cytopathology, where algorithms serve as powerful screening tools for Pap tests and thyroid aspirates, rapidly triaging slides and flagging abnormal cells for expert human review, thereby boosting overall throughput and accuracy [8].

However, the path to widespread clinical deployment is fraught with significant challenges, the most pressing of which is not a lack of powerful algorithms but a deficit of high-quality, diverse data. Models that are trained on data from a single institution often underperform dramatically when exposed to slides from another lab. This is due to subtle but critical differences in tissue preparation, staining protocols, and scanning equipment. Achieving true generalizability, where a model performs reliably across different clinical settings, remains the central and most difficult challenge in the field [4]. Beyond the technical hurdles, implementation involves navigating a complex landscape of regulatory and ethical considerations. This includes the rigorous process of securing FDA approval for AI-based diagnostic devices, establishing clear lines of liability when algorithmic errors occur, ensuring robust safeguards for patient data privacy, and actively working to mitigate the risk of inherent biases in algorithms that could perpetuate or even worsen existing health inequities [7].

Building trust between the pathologist and the algorithm is an essential prerequisite for successful clinical adoption. Most clinicians are understandably hesitant to rely on a 'black box' diagnosis where the reasoning is opaque. This is precisely where Explainable AI (XAI) becomes indispensable. XAI techniques create visual aids, such as heatmaps, that explicitly highlight the specific cellular and tissue features the AI used to arrive at its conclusion. This transparency allows pathologists to quickly verify the algorithm's reasoning against their own expertise, fostering the confidence and trust necessary for integrating these tools into routine clinical practice [5]. As this trust grows, the role of AI is also expanding. The technology is transitioning from a purely diagnostic aid to a sophisticated prognostic tool. Deep learning models can now analyze subtle morphological patterns within a tumor's microenvironment on a standard H&E slide—patterns often invisible to the human eye—to predict how a patient will respond to treatments like immunotherapy. This remarkable capability transforms a basic diagnostic slide into a powerful, non-invasive predictive biomarker [6].

Looking forward, the influence of AI is set to broaden even further. Large Language

Models (LLMs) are poised to reshape the textual aspects of the field, moving beyond image analysis entirely. These advanced models can assist in drafting standardized diagnostic reports, summarizing complex findings for other clinicians, and mining vast archives of unstructured text in pathology reports for invaluable research insights. This development effectively expands AI's role from the microscope slide to the final, actionable report that guides all subsequent patient care [10]. The overarching vision is one of synergy, where AI technologies are seamlessly integrated at every step of the pathological process. From initial screening and precise quantification to predicting outcomes and generating reports, AI is becoming an indispensable partner to the pathologist, driving a new era of efficiency, accuracy, and personalized medicine.

Conclusion

Artificial Intelligence (AI) is fundamentally reshaping pathology by integrating across the entire diagnostic workflow, from lab operations to predicting patient outcomes. Its application extends beyond simple tumor detection to provide quantitative precision that humans struggle to match, such as quantifying Ki-67 and HER2 biomarkers in breast cancer and standardizing Gleason grading for prostate cancer. This consistency is crucial for personalized medicine and managing intermediate-risk disease. AI also serves as a powerful screening tool in cytopathology, triaging Pap tests and thyroid aspirates to allow experts to focus on complex cases. A significant evolution is AI's shift from a diagnostic to a prognostic tool, with deep learning models identifying subtle patterns in a tumor's microenvironment to predict responses to immunotherapy. However, widespread adoption faces considerable hurdles. The primary barrier is the lack of high-quality, generalizable data, as models trained in one lab often fail in another due to variations in slide preparation. Building trust is another key challenge, addressed by Explainable AI (XAI), which provides visual aids to help pathologists verify an algorithm's reasoning. Navigating complex regulatory, ethical, and liability issues is also critical for implementation. The future of AI in pathology includes seamless integration into existing workflows to augment pathologists and the use of Large Language Models (LLMs) to automate report generation and data mining, expanding AI's role from the microscope to the final report.

Acknowledgement

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Conflict of Interest

None.

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