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Review Article

# Artificial intelligence in cancer pathology: Applications, challenges, and future directions

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## ABSTRACT

The application of artificial intelligence (AI) in cancer pathology has shown significant potential to enhance diagnostic accuracy, streamline workflows, and support precision oncology. This review examines the current applications of AI across various cancer types, including breast, lung, prostate, and colorectal cancer, where AI aids in tissue classification, mutation detection, and prognostic predictions. The key technologies driving these advancements include machine learning, deep learning, and computer vision, which enable automated analysis of histopathological images and multi-modal data integration. Despite these promising developments, challenges persist, including ensuring data privacy, improving model interpretability, and meeting regulatory standards. Furthermore, this review explores future directions in AI-driven cancer pathology, including real-time diagnostics, explainable AI, and global accessibility, emphasizing the importance of collaboration between AI and pathologists. Addressing these challenges and leveraging AI's full potential could lead to a more efficient, equitable, and personalized approach to cancer care.

**Keywords:** Artificial intelligence, Cancer pathology, Deep learning, Global accessibility, Machine learning

## INTRODUCTION

The rapid advancement of artificial intelligence (AI) has had a transformative impact across many sectors, and its application in cancer pathology is particularly notable. Cancer remains one of the leading causes of death worldwide, with millions of new cases diagnosed each year. Pathology, especially histopathology, plays a central role in the diagnosis and classification of cancer by examining tissue samples to identify malignant cells and structures. However, traditional pathology is a labor-intensive and time-consuming process that can be prone to subjective interpretation and diagnostic variability between pathologists. The global shortage of skilled pathologists is a pressing issue, particularly in low- and middle-income countries. Research published in *The Lancet* points to a deficit of more than 1 million pathologists worldwide, with many countries having fewer than two pathologists per million people.<sup>[1]</sup> In the United States, there is an estimated shortage of 14,000 pathologists by 2030, and in rural regions, the shortage can be even more severe.<sup>[2]</sup>

AI, particularly deep learning (DL) and machine learning (ML) has emerged as a powerful tool to address these challenges in cancer pathology.<sup>[3]</sup> AI can analyze vast amounts of data,



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including complex medical images, with greater speed and consistency than traditional manual methods.<sup>[4]</sup> AI-driven systems are capable of detecting, segmenting, and classifying tumor cells with impressive accuracy, often matching or surpassing the performance of human pathologists in certain tasks.<sup>[5]</sup> This makes AI an invaluable tool for improving diagnostic accuracy, reducing intra- and inter-observer variability, and enhancing the efficiency of pathology workflows.

AI is not only transforming cancer diagnosis but also contributing to personalized medicine by predicting treatment responses and patient outcomes based on a combination of histopathological, genomic, and clinical data.<sup>[6]</sup> These AI-driven advancements are paving the way for more individualized, precise cancer treatment plans, which are essential in improving patient survival rates and quality of life.<sup>[7]</sup> However, the integration of AI into clinical practice is not without its challenges, such as the need for large, well-annotated datasets, ensuring model interpretability, and addressing regulatory and ethical concerns. This article aims to systematically summarize the various opportunities and challenges associated with AI in cancer pathology by providing insights into the current limitations, ethical considerations, and future directions, offering guidance for both researchers and practitioners in the field.

## OVERVIEW OF AI APPLICATIONS IN CANCER PATHOLOGY

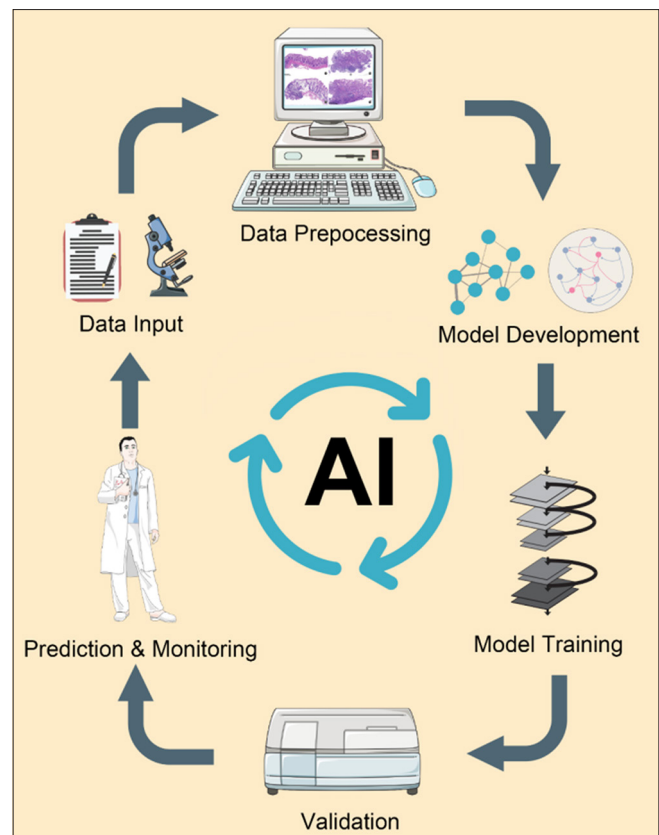
AI has gained significant traction in cancer pathology due to its ability to process vast amounts of data with remarkable accuracy.<sup>[5]</sup> Core AI technologies, such as ML, DL, and computer vision, have been particularly transformative in the analysis of histopathological images. By utilizing convolutional neural networks (CNNs), AI can automatically detect, segment, and classify cancerous tissues, reducing the dependency on manual interpretation by pathologists. One of the primary advantages of AI in pathology is its ability to minimize human error and intra-observer variability, offering consistent and reproducible results.<sup>[3]</sup> In addition, AI can significantly expedite the diagnostic process, enabling real-time or near-real-time analysis that shortens the turnaround time for pathology reports. Moreover, AI algorithms can integrate multiple data types, such as clinical and genomic data, alongside pathology images to provide comprehensive insights into tumor behavior, aiding in precision medicine. While AI is not intended to replace pathologists, it can serve as a valuable tool for augmenting their expertise and reducing their workload in the face of rising cancer cases globally.<sup>[8]</sup> A workflow depicting the integration of AI in cancer pathology is shown in Figure 1.

## Comparison with traditional methods in cancer pathology

To recognize the remarkable potential of AI in cancer pathology, it is essential to highlight how it addresses some of the limitations inherent in traditional methods. Traditional cancer diagnosis and staging rely heavily on manual examination of histopathological slides by pathologists, a process that can be time-consuming, subjective, and prone to human error.<sup>[9]</sup> As discussed in the following sections, AI offers several solutions to these issues, enhancing diagnostic accuracy, efficiency, and scalability.<sup>[10]</sup>

## Increased diagnostic speed

Traditional methods often require pathologists to manually examine thousands of tissue samples, which can result in long turnaround times for cancer diagnosis.<sup>[11]</sup> AI systems, however, can analyze large volumes of medical images in a



**Figure 1:** A workflow of artificial intelligence (AI) in cancer pathology (Name: Adobe After Effects; Version: CC 2023; Manufacturer: Adobe Systems Origin: United States/Name: Adobe Photoshop; Version: 2023.25; Manufacturer: Adobe Systems; Origin: United States; the URL of the database referenced by all elements: <https://smart.servier.com/and> and <https://scidraw.io/>. These platforms provide materials under the CC BY 4.0 license, which permits free use with proper attribution.).

fraction of the time, significantly speeding up the diagnostic process.<sup>[12]</sup> For example, AI algorithms have been shown to reduce the time needed for tumor detection in breast cancer and melanoma compared to manual analysis, allowing for quicker treatment decisions and potentially better patient outcomes.<sup>[10,12]</sup>

### Enhanced diagnostic accuracy

Pathologist interpretation can be affected by fatigue, experience, and the complexity of the tissue samples.<sup>[13]</sup> AI can assist in overcoming these limitations by providing consistent and unbiased results.<sup>[14]</sup> Studies have shown that DL algorithms can outperform human pathologists in certain cancer detection tasks, such as detecting lymph node metastasis in breast cancer or identifying early-stage lung cancer lesions.<sup>[10,12]</sup> This consistency ensures that diagnoses are less likely to be missed or misinterpreted, particularly in difficult cases or rare cancer types.

### Reduction of inter-observer variability

In traditional pathology, the interpretation of slides can vary between different pathologists, leading to inconsistent results.<sup>[15]</sup> This inter-observer variability is particularly problematic in cancer grading, where slight differences in judgment can affect treatment decisions. AI can help standardize diagnoses by providing an objective analysis of tissue samples.<sup>[16]</sup> For instance, AI models used in prostate cancer grading have demonstrated greater consistency than human pathologists in assessing Gleason scores, which are crucial for determining the cancer's aggressiveness and treatment options.<sup>[17]</sup>

### Integration with multi-modal data

Unlike traditional methods that primarily focus on histopathological images, AI systems can integrate various forms of patient data, such as genomic sequences, clinical histories, and radiological images, to provide a more comprehensive view of the patient's condition.<sup>[18]</sup> This multi-modal approach allows for more personalized treatment plans and better-informed clinical decisions. For example, AI models that integrate genetic data with pathology slides can help identify patients who are most likely to benefit from targeted therapies or immunotherapy, something that is difficult to achieve using traditional methods alone.<sup>[19]</sup>

### Enhanced access to diagnostics in underserved areas

Traditional pathology services often face shortages, especially in rural or low-resource settings, leading to delays in cancer diagnosis and treatment. AI-driven digital pathology platforms and telepathology can overcome these barriers

by enabling remote diagnostic capabilities. Pathologists can collaborate with AI tools to analyze digital slides from anywhere in the world, improving access to timely and accurate diagnoses even in regions lacking specialized expertise.<sup>[16,20]</sup>

## AI APPLICATIONS IN SPECIFIC CANCER TYPES

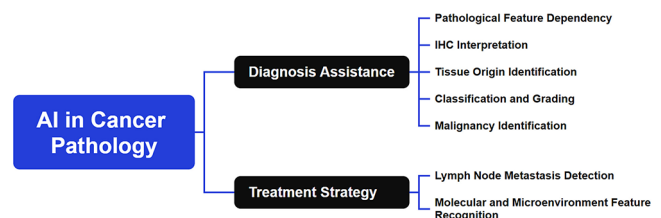
AI has made substantial contributions to cancer pathology by providing automated and highly accurate diagnostic tools tailored to different types of cancers. Each cancer type poses unique challenges, and AI has been adapted to address these needs, leading to a variety of tailored applications across various malignancies. Applications of AI in cancer pathology are shown in Figure 2.

### Breast cancer

Breast cancer is one of the most studied areas for AI applications in pathology. AI algorithms have shown remarkable capability in analyzing whole-slide imaging (WSI) datasets to identify and grade invasive ductal carcinoma and ductal carcinoma in situ. DL models, such as CNNs, have been employed to automate human epidermal growth factor receptor 2 (HER2) scoring from immunohistochemistry slides, achieving performance comparable to expert pathologists in classifying HER2 status, which is crucial for treatment decisions.<sup>[21,22]</sup> Furthermore, AI has been used to predict Oncotype DX scores directly from pathology images, providing an alternative to expensive gene expression tests.<sup>[6]</sup> By automating processes, AI improves workflow efficiency, providing more reliable diagnoses that lead to better patient outcomes. An example of estrogen receptor quantification by an AI algorithm is shown in Figure 3.<sup>[23]</sup>

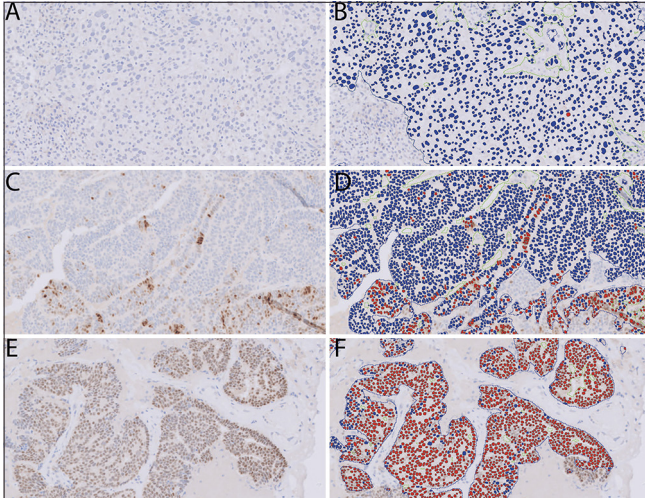
### Lung cancer

Lung cancer, which includes several histological subtypes, poses a significant diagnostic challenge. AI has been utilized to distinguish between small cell lung carcinoma (SCLC) and non-small-cell lung carcinoma (NSCLC) based on complex morphological patterns.<sup>[24]</sup> Cai *et al.* developed a DL model that successfully differentiated between SCLC and NSCLC



**Figure 2:** Applications of artificial intelligence in cancer pathology (Name: Xmind; Version: Xmind 15.0; Manufacturer: BeijingZhitu; Origin: China). Note: IHC: Immunohistochemistry.





**Figure 3:** Example of estrogen receptor quantification by artificial intelligence algorithm.<sup>[23]</sup>

using histopathological images, achieving an accuracy of 91% that outperformed traditional diagnostic methods.<sup>[25]</sup> AI-based systems have shown potential in identifying specific mutations, such as estimated glomerular filtration rate (EGFR) and anaplastic lymphoma kinase alterations directly from histopathological images, which could guide targeted therapy decisions.<sup>[26,27]</sup> Mahajan *et al.* demonstrated that AI-based models could identify EGFR mutations from tissue samples with an accuracy of 88%, providing valuable insights for personalized treatment decisions in lung cancer patients.<sup>[28]</sup> In early-stage lung cancer, AI-based radiomics and pathology integration models have been used to predict lymph node metastasis and patient prognosis, enhancing decision-making for surgical interventions.<sup>[29,30]</sup> These applications show that AI aids in the accurate differentiation between cancer subtypes, which is vital for tailored treatment planning. By identifying genetic mutations and predicting metastasis, AI supports earlier and more precise interventions, improving overall patient prognosis.

### Prostate cancer

Prostate cancer diagnosis and grading have traditionally been highly subjective, leading to inter-observer variability among pathologists. AI has been shown to reduce this variability by providing automated Gleason grading from prostate biopsy images.<sup>[31]</sup> AI models, such as those developed by Arvaniti *et al.*, can distinguish between benign and malignant glands with high sensitivity and specificity and even predict biochemical recurrence based on histological features alone.<sup>[32]</sup> A study demonstrated the application of DL to prostate cancer histopathology slides, achieving high performance in Gleason grading and tumor classification, outperforming pathologists in certain cases.<sup>[33]</sup> Likewise, a study included a DL algorithm that automatically

grades prostate cancer from pathology slides, significantly reducing inter-observer variability and improving diagnostic consistency.<sup>[34]</sup> This level of detail supports more accurate prognostication and risk stratification in prostate cancer management. AI reduces grading variability, which is critical for accurate risk stratification. By automating Gleason grading, AI ensures more reliable results, which aids personalized treatment decisions, leading to better prognostic outcomes.

### Colorectal cancer (CRC)

AI applications in CRC have focused on tumor segmentation, detection of tumor budding, and prediction of lymphovascular invasion. Automated systems have been developed to identify microsatellite instability (MSI) from standard histology slides, providing a cheaper alternative to molecular testing.<sup>[6]</sup> For instance, Qiu *et al.* used DL models to detect MSI directly from hematoxylin and eosin (H&E) stained slides, achieving accuracy comparable to traditional molecular methods.<sup>[35]</sup> Moreover, DL models have shown high accuracy in detecting tumor-infiltrating lymphocytes (TILs), which are important prognostic markers for CRC.<sup>[3]</sup> In a study by Song *et al.*, AI demonstrated strong performance in classifying tumor budding, which is critical for determining patient prognosis and treatment planning.<sup>[36]</sup> AI has also been used to differentiate between adenomatous and hyperplastic polyps in endoscopic biopsy samples, aiding early detection and prevention.<sup>[22]</sup> By identifying TILs and MSI, AI enhances the accuracy of CRC diagnosis and prognosis. This helps in early detection and prevention, reducing unnecessary procedures and improving treatment outcomes.

### Skin cancer

Skin cancer, particularly melanoma, is one of the most lethal forms of cancer if not diagnosed early. AI has demonstrated dermatologist-level accuracy in classifying skin lesions from histopathological images, especially for melanomas and basal cell carcinomas. Esteva *et al.* employed a deep neural network to achieve performance on par with dermatopathologists in identifying skin cancers from biopsy images.<sup>[10]</sup> In addition, AI has been used to evaluate Breslow thickness and predict lymph node involvement, which are critical factors in melanoma staging and management.<sup>[37]</sup> Gillstedt *et al.* developed a DL model that accurately predicts Breslow thickness from dermoscopic images, which is vital for assessing melanoma prognosis and treatment options.<sup>[38]</sup> Moreover, Xu *et al.* used AI to assess lymph node involvement in melanoma patients, showing that AI models can predict metastatic risk, thus aiding in personalized treatment planning.<sup>[39]</sup> By achieving dermatologist-level accuracy, AI plays a pivotal role in early skin cancer detection, improving survival rates. Through its ability to predict lymph node

involvement and assess Breslow thickness, AI also helps in personalized treatment planning for melanoma patients.

### **Gastrointestinal cancers (gastric and esophageal cancer)**

Gastric and esophageal cancers are often diagnosed at advanced stages due to subtle histopathological changes in early disease. AI has been applied to detect early gastric cancer from biopsy samples, achieving high sensitivity even in cases with minimal morphological alterations.<sup>[40-42]</sup> Similarly, AI has been used to predict HER2 expression status in gastric cancer from routine H&E slides, assisting in the selection of targeted therapies.<sup>[43]</sup> For esophageal cancer, AI systems have been developed to assess tumor regression grades after neoadjuvant therapy, providing insight into treatment efficacy.<sup>[44-46]</sup> AI enhances early-stage detection of gastric cancer, which is vital for improving survival rates. By predicting HER2 expression status and evaluating treatment response, AI further aids in the selection of appropriate therapies, making it an invaluable tool for personalized cancer care.

### **Brain cancer**

AI has shown promise in the diagnosis and grading of gliomas, which are among the most aggressive forms of brain cancer. DL models have been applied to segment and classify tumor regions from histopathological images, outperforming human experts in some scenarios.<sup>[16,47-50]</sup> In addition, AI-based approaches have been used to identify key genetic mutations (e.g., Isocitrate Dehydrogenase 1/2 status) and predict overall survival, offering comprehensive tools for personalized management of gliomas.<sup>[3]</sup> A DL-based survival prediction model that incorporated radiological and histopathological data provided a more accurate prognosis for glioma patients than traditional methods.<sup>[51]</sup> The above evidence indicates that AI's application in glioma diagnosis enhances the accuracy of tumor grading and genetic profiling, which helps in devising more personalized and effective treatment strategies. By predicting survival and identifying mutations, AI optimizes treatment planning and patient management for glioma cases.

These applications highlight how AI is revolutionizing cancer pathology by providing reliable, reproducible, and clinically actionable insights across various cancer types. As these technologies continue to evolve, they have the potential to fundamentally change how cancer is diagnosed and managed, ultimately improving patient outcomes.<sup>[50]</sup>

## **KEY CAPABILITIES AND TECHNIQUES OF AI IN CANCER PATHOLOGY**

AI in cancer pathology relies on several advanced technological developments that drive its ability to perform

complex image analysis, classification, and prediction. These technologies provide the foundation for automating traditionally manual processes and offer pathologists new tools to enhance diagnostic precision.

### **Image segmentation and classification**

One of the key components of AI applications in pathology is the ability to segment and classify histopathological images accurately. CNNs have become the primary architecture for these tasks due to their ability to capture hierarchical spatial features in images. In cancer pathology, CNN-based models have been applied to detect tumor boundaries, differentiate between cancerous and non-cancerous tissues, and grade tumor malignancies.<sup>[5,24]</sup> The challenge, however, lies in achieving fine-grained segmentation at cellular or sub-cellular levels, especially in densely packed tissue regions. Solutions such as U-Net and Mask R-CNN have been specifically designed for medical image segmentation, enabling the precise delineation of tumor areas in complex tissue environments.<sup>[52]</sup>

### **Super-resolution and image enhancement**

AI algorithms also contribute to improving the quality of low-resolution pathology images. Super-resolution techniques have been applied to enhance images acquired from lower magnification, enabling detailed analysis without the need for high-resolution scanning, which can be time-consuming and resource-intensive.<sup>[53-56]</sup> These approaches are particularly useful for large-scale screening tasks where high-resolution images are not always necessary, but accurate detection is still required.

### **Data annotation and labeling**

Training AI models for cancer pathology requires large, well-annotated datasets. This presents a major challenge, as manually labeling histopathological images is labor-intensive and requires expert knowledge. To address this, AI tools are being developed to assist with semi-automated annotation, allowing pathologists to mark regions of interest more efficiently. In addition, active learning techniques are employed to iteratively improve the AI model by selectively querying new data points for labeling.<sup>[57,58]</sup> This reduces the amount of data that needs to be manually annotated while still improving the model's performance.

### **Handling large-scale data and high-throughput analysis**

One of the primary advantages of AI in cancer pathology is its ability to handle large-scale datasets. WSI, which involves scanning entire pathology slides at high resolution, generates enormous amounts of data. DL models continue

to be developed to process these large images efficiently by dividing them into smaller tiles for analysis.<sup>[59]</sup> Techniques like tile-based training, along with cloud computing infrastructure, have enabled high-throughput analysis that can assist pathologists in rapidly identifying areas of concern across thousands of images.

### Training, validation, and model generalization

A significant challenge in the application of AI is ensuring that models generalize well across different datasets and populations. Pathology images can vary greatly due to differences in tissue preparation, staining protocols, and scanner equipment. To mitigate this issue, transfer learning has been adopted, where a pre-trained model is fine-tuned on a smaller, task-specific dataset, improving its performance with limited data.<sup>[60]</sup> Furthermore, techniques such as data augmentation (random rotations, flipping, or color jittering) are used to artificially expand the training dataset and improve model robustness.<sup>[61]</sup>

### Model validation and interpretation

Once trained, AI models must be thoroughly validated before clinical implementation. This often involves multi-institutional validation to test the model's generalization capabilities across different patient populations and clinical settings.<sup>[62]</sup> Explainability is another critical factor in ensuring the adoption of AI in clinical practice. Although DL models, particularly CNNs, are often seen as “black boxes,” efforts are underway to make them more interpretable. Techniques such as Gradient-weighted Class Activation Mapping (Grad-CAM) allow pathologists to visualize which regions of the image contributed most to the model's prediction, fostering trust in AI-generated results.<sup>[63]</sup>

### Integration with multi-modal data

AI models are increasingly being designed to integrate histopathological data with other clinical information, such as genomic data and patient histories, to provide a more comprehensive diagnostic picture. This multi-modal approach helps refine predictions related to cancer prognosis, treatment response, and patient survival.<sup>[64]</sup> The use of multi-modal AI models in cancer pathology represents a shift toward more personalized medicine, where treatment decisions are based not only on pathology images but also on a wide range of patient-specific data.

These technological advancements underscore the complexity of AI applications in cancer pathology. While these models offer considerable potential, ensuring their reliable performance across diverse datasets and making them interpretable for clinicians are key areas that continue to evolve.

## CHALLENGES OF AI IN CANCER PATHOLOGY

Despite the remarkable advancements of AI in cancer pathology, there are significant challenges that must be addressed before it can be fully integrated into clinical practice. These challenges span across various dimensions, including data-related issues, algorithm reliability, ethical concerns, and the practical collaboration between AI systems and pathologists. The main challenges and potential solutions of AI application in cancer pathology are presented in Figure 4.

### Data privacy and security

One of the most critical concerns in AI-driven pathology is the security and privacy of patient data. Cancer pathology requires the use of vast amounts of sensitive, personally identifiable information, including histopathological images, genomic data, and clinical records. The widespread adoption of AI tools necessitates secure storage and transmission of this data, ensuring compliance with regulations such as the Health Insurance Portability and Accountability Act in the United States and the General Data Protection Regulation in Europe.<sup>[10]</sup> Balancing the need for large, diverse datasets to train robust AI models with stringent privacy standards remains a key challenge. Secure data-sharing frameworks and anonymization techniques are, therefore, essential for enabling multi-institutional collaboration without compromising patient confidentiality.<sup>[65]</sup>

### Algorithm reliability and generalization

AI algorithms, particularly DL models, can be highly sensitive to variations in data, such as differences in slide preparation, staining protocols, and imaging equipment across different laboratories.<sup>[3]</sup> This lack of standardization can lead to performance discrepancies when AI models are deployed in real-world clinical settings. Moreover, AI systems are prone to overfitting when trained on limited or highly specific datasets, meaning they may perform well on the data they were trained on but fail to generalize to new, unseen cases.<sup>[66]</sup> Addressing these issues requires larger, more diverse datasets and rigorous external validation across multiple institutions to ensure that AI models are robust and reliable in varied environments.

### Interpretability and the “Black Box” problem

DL models, while effective, often operate as “black boxes” that produce predictions without offering clear insights into their decision-making processes. This lack of interpretability is a significant barrier to clinical adoption, as pathologists and clinicians need to understand how an AI system arrives at its conclusions, especially in high-stakes decisions such



AI in Cancer Pathology		
Challenges	Platform and Equipment	Fully standardizing sample preparation
		Variability in equipment precision
		High manual intervention, large data volume
	Regulatory Issues	Patient privacy protection
		Data security
	Clinical Application	Lack of clear demand
Low acceptance from clinicians and patients		
Countermeasures	Platform and Equipment	Quality control with integrated technology, transfer learning technology for accurate diagnosis
		Quantitative analysis and standardized precision management
		Strongly coupled, high-throughput, unbiased platforms
	Regulatory Issues	Establish standards,
		Ensure data integrity
		Protect patient safety and privacy
	Clinical Application	Integration of multi-level medical data and expansion of application scenarios
		Continuous technology updates and risk-benefit assessment

**Figure 4:** Challenges and solutions of artificial intelligence application in cancer pathology. (Name: Xmind; Version: Xmind 15.0; Manufacturer: BeijingZhitu; Origin: China).

as cancer diagnosis.<sup>[67]</sup> Techniques such as Layer-wise Relevance Propagation and SHapley Additive exPlanations (SHAP) are being developed to improve the transparency of AI models by highlighting which parts of the input data are most influential in the model's predictions.<sup>[68]</sup> However, these methods are still evolving, and achieving full transparency remains an ongoing challenge in AI-driven cancer pathology.

### Regulatory and legal issues

The integration of AI into clinical practice presents profound legal and regulatory challenges that need careful consideration. In many jurisdictions, medical devices, including AI software used for diagnostic purposes, must undergo regulatory approval to ensure they meet stringent safety, efficacy, and reliability standards before being used in clinical settings. However, the dynamic nature of AI models complicates this process. Unlike traditional medical devices,

which are typically static once approved, AI systems are often updated or retrained based on new data, making it difficult to maintain consistent regulatory oversight.<sup>[69]</sup> This evolution in AI systems means that their performance can change over time, raising concerns about how regulators can ensure ongoing compliance with safety standards. Moreover, the legal ramifications of AI errors or misdiagnoses remain ambiguous. In the event of an incorrect diagnosis made by an AI system, questions of liability arise – should the responsibility lie with the software developer, the healthcare provider who relied on the system, or the institution that deployed it? This legal gray area can hinder the widespread adoption of AI technologies, as healthcare providers and developers may be hesitant to embrace these tools without clear guidelines. The creation of robust regulatory frameworks, accompanied by ethical guidelines that address issues like accountability, transparency, and patient consent, will be essential to ensure that AI is implemented safely

and responsibly in cancer pathology. Only through such frameworks can the legal, ethical, and practical challenges of AI integration be effectively navigated, fostering greater confidence in its potential to enhance clinical practice without compromising patient safety.<sup>[70]</sup>

### **Ethical considerations and bias**

Ethical issues are also a major concern in AI applications for cancer pathology.

Bias in AI models can arise from imbalanced or historically biased training datasets, which may reflect disparities in previous clinical practices or underrepresentation of certain demographics. For example, the underrepresentation of minority groups in training data can result in algorithms that perform poorly for those populations, perpetuating healthcare inequities.<sup>[71]</sup> To mitigate these concerns, AI developers have an ethical responsibility to ensure fairness and equity using diverse and inclusive datasets, which are crucial for enhancing the generalizability of AI models across all patient groups.

Furthermore, the relationship between AI and pathologists raises important ethical considerations. While AI can reduce human error and improve diagnostic speed, it should complement, not replace, human expertise. Ethical guidelines should emphasize that AI is an augmentation tool – empowering pathologists to make better decisions – but not a substitute for human judgment in complex or ambiguous cases. In addition, issues of accountability and patient consent must be carefully addressed, especially when communicating AI-generated diagnoses and recommendations to patients.<sup>[72]</sup>

### **Collaboration between AI and pathologists**

While AI has the potential to revolutionize cancer pathology, it must be emphasized that AI is not meant to replace human pathologists but to complement their expertise. AI systems can process vast amounts of data quickly and consistently, but pathologists bring contextual understanding and clinical judgment that AI models cannot replicate. The challenge lies in integrating AI into the clinical workflow in a way that enhances the efficiency and accuracy of pathology without diminishing the role of the human pathologist.<sup>[31]</sup> Developing user-friendly AI tools that pathologists can trust and collaborate with is essential for successful implementation.

### **Cost and infrastructure**

Finally, the implementation of AI in cancer pathology requires significant investments in digital infrastructure, training, and maintenance. Pathology labs must adopt WSI technology, cloud storage solutions, and high-performance computing systems to support AI algorithms.<sup>[31]</sup> For many

healthcare institutions, particularly those in resource-limited settings, these costs may be prohibitive. In addition, training pathologists to work with AI tools and ensuring that these systems are maintained and updated regularly poses ongoing challenges. Reducing the cost of AI deployment and making these tools accessible to a wider range of healthcare providers is crucial for the widespread adoption of AI in cancer pathology.

### **Risks of misapplication of AI in cancer pathology**

While AI holds great potential for advancing cancer pathology, there are risks associated with its misapplication.<sup>[73]</sup> One of the most concerning issues is the possibility of false diagnoses resulting from inaccurate AI predictions. This could lead to incorrect treatment plans, delays in diagnosis, or unnecessary treatments, all of which could compromise patient safety and outcomes. Over-reliance on AI systems is another potential danger, where pathologists may defer too heavily to AI suggestions, reducing human oversight and critical thinking. This could be particularly problematic in complex or rare cases where AI models may lack sufficient training data to make accurate predictions.<sup>[74]</sup>

To mitigate these risks, it is essential to maintain a collaborative approach between AI systems and human experts, ensuring that AI serves as a supportive tool rather than a replacement for clinical judgment. Ongoing monitoring, regular validation, and continuous education for pathologists on AI tools are key measures to prevent misapplications and maintain diagnostic quality.

These challenges highlight the complexity of integrating AI into cancer pathology. Addressing issues related to data privacy, algorithm reliability, model interpretability, regulatory frameworks, ethical considerations, and cost will be critical for the successful and responsible implementation of AI in clinical practice.

## **FUTURE DIRECTIONS AND PROSPECTS OF AI IN CANCER PATHOLOGY**

The future of AI in cancer pathology holds significant promise, with ongoing developments expected to transform how cancer is diagnosed, treated, and managed. AI will continue to evolve, integrating more advanced technologies and addressing the current limitations to ensure its broader application and acceptance in clinical settings. Several key trends and future directions are likely to define the trajectory of AI in cancer pathology. Below are some key aspects that will shape the future of AI in this field.

### **Integration of multi-modal data**

One of the most promising future directions for AI in cancer pathology is the integration of multi-modal data.



As discussed previously, in addition to histopathological images, AI systems can incorporate clinical data, genomic sequencing, and radiological images to provide a more comprehensive understanding of cancer biology. By combining these data types, AI can offer more personalized and precise diagnostic and prognostic information, moving toward the ideal of precision oncology.<sup>[6,64]</sup> For example, AI models could link tumor morphology with genetic mutations, such as TP53 or KRAS, and suggest targeted therapies based on these molecular profiles. Multi-modal AI systems will likely play a crucial role in the early detection of cancers, prediction of treatment responses, and monitoring of disease progression.

### Real-time AI-assisted diagnostics

The future of AI in cancer pathology is heading toward real-time diagnostics, where AI models can process pathology slides instantaneously during biopsies or surgeries. Such systems would allow pathologists to obtain AI-generated insights in real-time, assisting with intraoperative decision-making, such as determining clear surgical margins.<sup>[75,76]</sup> This rapid feedback loop could significantly reduce diagnostic turnaround times and improve surgical outcomes. Cloud-based solutions and edge computing, combined with AI, will enable real-time processing even in low-resource settings, making AI more accessible globally.

### AI in early detection and cancer screening

Early cancer detection is a key factor in improving survival rates, and AI is poised to enhance cancer screening programs by detecting subtle patterns that may be missed by the human eye. AI models for screening are particularly promising in cancers where early-stage detection is difficult, such as ovarian, pancreatic, and lung cancers.<sup>[77]</sup> AI can be integrated with screening modalities such as mammography, computed tomography scans, and even blood-based liquid biopsies to detect cancer biomarkers at earlier stages than traditional methods.<sup>[18,78]</sup> These AI-powered screening tools could significantly improve early diagnosis and lead to better outcomes for cancer patients through earlier intervention.

### Telepathology and remote diagnostics

Telepathology and AI-based remote diagnostics are poised to address the disparity in access to high-quality pathology services across the world, particularly in low-resource or rural areas. With AI-driven digital pathology platforms, pathologists can remotely analyze digitized slides and collaborate with AI tools to provide accurate diagnoses without being physically present.<sup>[79]</sup> As AI models become more robust, remote pathology services will be able to deliver

quicker and more reliable results, bridging gaps in healthcare infrastructure. This approach has already gained momentum in some regions, and as digital pathology becomes more widespread, AI will enhance the efficiency of remote consultations.

### Explainable AI (XAI) for greater trust and adoption

The development of XAI models is a critical future direction that will enhance trust in AI systems among clinicians and pathologists. XAI refers to AI models designed to make their decision-making processes transparent and interpretable, which is essential in clinical settings where human oversight is crucial. Pathologists need to understand why an AI model has made a particular recommendation or diagnosis to ensure its appropriateness for each patient. As XAI techniques such as Grad-CAM and SHAP improve, AI models will become more interpretable, providing visual explanations for decisions that align with human reasoning.<sup>[63,80]</sup> This transparency will be pivotal in increasing AI's acceptance in pathology and ensuring patient safety.

### Self-learning and continual learning AI models

AI models capable of self-learning or continual learning – adapting and evolving as new data become available – are another exciting area of future development. Traditional AI models are static once trained, but self-learning models can update themselves by learning from new cases or user feedback, improving their accuracy over time without needing full retraining from scratch.<sup>[81-83]</sup> In cancer pathology, this could lead to more adaptive systems that stay current with the latest clinical insights, evolving treatment protocols, and newly discovered biomarkers. These adaptive models would be highly valuable for rare cancers or newly emerging cancer subtypes where limited historical data are available.

### AI-driven drug discovery and predictive modeling

Another major future direction is the use of AI in drug discovery and predictive modeling for cancer treatment. By analyzing pathology data, AI can help identify novel drug targets, predict patient responses to various treatments, and simulate the effects of new drugs. In oncology, AI models are being developed to predict which patients are likely to respond to immunotherapies based on the tumor microenvironment and genetic markers.<sup>[84]</sup> AI can also facilitate virtual clinical trials, where drug efficacy is tested on AI models before moving to human trials, significantly reducing costs and time in drug development.<sup>[85]</sup> These predictive tools will allow oncologists to personalize cancer treatment regimens, enhancing patient outcomes while reducing unnecessary treatments.<sup>[77]</sup>

## Global application and resource distribution

A significant future prospect of AI in cancer pathology is its potential to democratize access to high-quality diagnostic services globally. Many developing countries and rural areas face a shortage of pathologists and diagnostic tools, which leads to delayed or inaccurate cancer diagnoses. AI-driven pathology systems can help bridge this gap by providing highly accurate, cost-effective, and scalable diagnostic solutions.<sup>[86]</sup> As AI systems improve in terms of cost, speed, and robustness, they could be deployed in resource-limited settings to improve cancer detection rates and provide equitable healthcare access worldwide.

## Potential timeline and steps for achieving future directions

The realization of AI's potential in cancer pathology will likely unfold in phases. In the short term, the focus will be on improving the accuracy and generalization of AI models for clinical applications, especially in real-time diagnostics and multi-modal data integration. During this phase, regulatory bodies will finalize guidelines and frameworks for AI adoption in clinical settings. In the medium term, AI tools will be more widely used in routine diagnostics and personalized treatment planning. Key developments will include enhanced data-sharing agreements and the creation of more robust, diverse datasets for AI training. Finally, in the long term, AI is expected to become integral to personalized oncology, with continuous learning models and broader deployment in global healthcare, particularly in underserved regions.<sup>[4,20]</sup>

## Steps for achieving future goals

To achieve these goals, several steps are essential. First, regulatory support is crucial to establish clear standards for AI's safety and efficacy in clinical practice. Second, data sharing across institutions and countries will be necessary to build diverse, representative datasets. In addition, continued advancements in technology development, especially in AI algorithms and computational power, will be critical. The success of AI integration into clinical workflows will also depend on education, ensuring healthcare professionals are trained to effectively work with AI tools. Finally, significant investment in infrastructure, particularly in low-resource settings, will be needed to facilitate the widespread adoption of AI technologies globally.<sup>[14,50]</sup>

These future directions point toward an increasingly collaborative relationship between AI and pathologists, where AI enhances diagnostic capabilities without replacing the human expert. By integrating AI into routine cancer diagnostics and care, the field of pathology will move toward more personalized, efficient, and accessible cancer management strategies.

## DISCUSSION

The integration of AI in cancer pathology represents a significant paradigm shift in how cancer is diagnosed, treated, and managed. AI has already demonstrated immense potential in enhancing diagnostic accuracy and workflow efficiency, thus providing vital support to precision medicine. Through its capacity to automate the analysis of histopathological images, AI has not only contributed to faster diagnostics but has also ensured higher consistency and reduced intra- and inter-observer variability. As AI technology continues to evolve, its role in cancer pathology will expand, creating new opportunities for early detection, real-time diagnostics, and more personalized treatment strategies. AI's strength lies in its ability to process vast amounts of data quickly and accurately, identifying complex patterns that may be challenging for human pathologists to detect. For example, AI algorithms have been shown to match or even exceed human performance in detecting various types of cancer, such as breast cancer, lung cancer, and melanoma, and in predicting treatment outcomes.<sup>[10,24]</sup> However, despite these advancements, the successful implementation of AI in clinical practice hinges on addressing several key challenges, such as data privacy, algorithm transparency, and regulatory compliance.

Moreover, the future of AI in cancer pathology is likely to be shaped by the continued development of XAI, which will increase trust among pathologists and clinicians by providing clear, interpretable outputs. Collaboration between AI systems and human pathologists will be essential, as AI is not intended to replace human expertise but to enhance it, enabling pathologists to focus on more complex cases and improve patient outcomes.<sup>[72]</sup> In addition, the use of AI in multi-modal data integration – combining histopathological images with genomic, clinical, and radiological data – will provide a more holistic view of each patient's cancer, supporting the shift toward personalized oncology.<sup>[64]</sup>

Furthermore, AI-driven telepathology and remote diagnostics are expected to play a critical role in reducing healthcare disparities by providing high-quality diagnostic services to underserved and remote areas.<sup>[79]</sup> As AI becomes more accessible and its deployment costs decrease, these technologies could be scaled globally, democratizing access to advanced cancer diagnostics and improving outcomes for patients worldwide.

However, for AI to reach its full potential in cancer pathology, several hurdles must still be overcome. Ensuring the reliability and generalizability of AI models across diverse populations and healthcare settings is crucial to avoid the perpetuation of bias and inequity in healthcare.<sup>[71]</sup> Likewise, the ethical implications of AI must be carefully considered, ensuring that human pathologists remain in control of

clinical decision-making and that patients receive the most personalized, safe, and effective care possible.

## SUMMARY

AI holds immense promise in revolutionizing cancer pathology by improving diagnostic accuracy, streamlining workflows, and enabling personalized treatment strategies. While AI's capabilities in automating tasks such as tumor detection and prognosis prediction are clear, the integration of AI into clinical practice must be approached carefully to overcome challenges related to data quality, model interpretability, and regulatory compliance. The future of AI in cancer pathology depends on the continued development of AI models that are both accurate and transparent, as well as on establishing clear guidelines and frameworks to ensure safe, equitable, and effective use in clinical settings. With concerted efforts from researchers, clinicians, and regulatory bodies, AI has the potential to transform the landscape of cancer diagnosis and treatment, ultimately improving patient outcomes on a global scale.

## AVAILABILITY OF DATA AND MATERIALS

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

## ABBREVIATIONS

AI: Artificial intelligence  
 CNNs: Convolutional neural networks.  
 DL: Deep learning  
 Grad-CAM: Gradient-weighted Class Activation Mapping  
 HER2 score: Human epidermal growth factor receptor 2 score  
 IHC: Immunohistochemistry  
 ML: Machine learning  
 MSI: Microsatellite instability  
 TILs: Tumor-infiltrating lymphocytes  
 WSI: Whole-slide imaging  
 XAI: Explainable AI

## AUTHOR CONTRIBUTIONS

BC, DMS and JLW: Contributed to the conceptualization and design of the study; JLW and TW: Wrote the original draft manuscript; JLW and RH: Reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript. All authors meet ICMJE authorship requirements.

## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Ethical approval and consent to participate is not required as this article does not contain any studies on animals or patient, performed by any of the authors.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## EDITORIAL/PEER REVIEW

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