

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693

ISSN Online: 2617-4707

NAAS Rating (2026): 5.29

IJABR 2026; 10(6): 07-14

www.biochemjournal.com

Received: 08-03-2026

Accepted: 11-04-2026

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Digital pathology in veterinary clinical pathology: From whole-slide imaging to artificial intelligence and precision diagnostics

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6a.8543>

Abstract

Digital pathology has emerged as one of the most transformative innovations in veterinary clinical pathology, revolutionizing diagnostic workflows, education, teleconsultation, laboratory management, and research applications. The integration of whole-slide imaging (WSI), artificial intelligence (AI), machine learning, deep learning, image analysis software, cloud computing, and computational pathology has significantly enhanced diagnostic efficiency and precision. Veterinary clinical pathology increasingly relies on digital systems for hematology, cytology, urinalysis, histopathology, molecular pathology, and comparative pathology investigations. Advances in scanner technologies, image analysis algorithms, and remote diagnostic platforms have enabled rapid sharing of pathological data across geographical boundaries, facilitating global collaboration and One Health surveillance systems. Artificial intelligence-assisted pathology is increasingly capable of automated cell recognition, lesion classification, quantitative morphometry, predictive analytics, and biomarker discovery. Despite these advancements, significant challenges remain regarding standardization, infrastructure requirements, data storage, validation protocols, regulatory considerations, and implementation costs, particularly in resource-limited settings. This review critically examines the current status of digital pathology in veterinary clinical pathology, emphasizing diagnostic applications, artificial intelligence integration, telepathology, computational pathology, molecular diagnostics, educational applications, One Health implications, and future directions. Recent literature published between 2020 and 2026 is comprehensively reviewed, highlighting technological innovations, diagnostic advances, and emerging trends that are reshaping veterinary pathology worldwide.

Keywords: Digital pathology, veterinary clinical pathology, artificial intelligence, computational pathology, telepathology, whole-slide imaging, machine learning, cytology, hematology, one health

Introduction

Digital pathology marks a significant revolution in diagnostic medicine, replacing traditional microscopy-based interpretation with a computational, image-based, and data-driven approach. This trend is especially relevant in veterinary clinical pathology because of increased diagnostic workloads, multispecies heterogeneity, and a growing demand for speedy, distant, and standardized diagnostic services. Traditionally, veterinary pathology has relied on direct microscopic examination of cytological and histological materials, with diagnosis mainly reliant on individual competence and subjective morphological evaluation. Although this remains the diagnostic gold standard, it is constrained by inter-observer variability, workload weariness, and limited access to specialists, particularly in geographically scattered places. These restrictions have fueled interest in digital pathology as a method of improving repeatability, efficiency, and diagnostic accessibility.

Whole-slide imaging (WSI) is at the heart of digital pathology, allowing for the high-resolution digitalization of histology slides into gigapixel-scale images that can be saved, shared, and computationally evaluated. Zuraw and Aeffner (2021) ^[45] highlighted WSI as a key technology for modern pathology processes, particularly in veterinary and toxicologic diagnostics, where it allows for remote consultation and large-scale computational analysis. Between 2021 and 2026, digital pathology grew from a simple imaging tool to an integrated computational ecosystem that incorporated artificial intelligence (AI), machine learning,

cloud computing, and laboratory information system (LIS) integration. Recent studies demonstrated successful implementation of digital pathology in veterinary diagnostic laboratories for routine diagnostics, education, and research (Neal *et al.*, 2025)^[27].

This revolution has been largely driven by artificial intelligence. Deep learning techniques, including as convolutional neural networks (CNNs), multiple instance learning (MIL), and image transformer architectures, have performed well in histopathology classification tasks. Campanella *et al.* (2022)^[5] showed that weakly supervised deep learning models can attain clinical-grade accuracy without extensive pixel-level annotations, emphasizing the scalability of AI-driven pathology systems. Artificial intelligence has been used in veterinary pathology to classify tumors, detect mitotic figures, analyze leukocyte differentials, and identify viral diseases. However, veterinary applications face unique challenges such as interspecies morphological variability, limited annotated datasets, and the lack of standardized diagnostic ontologies, all of which contribute to domain shift and decreased model generalizability across species and laboratories (Piccione *et al.*, 2025)^[31].

Digital pathology also contributes to One Health programs by facilitating scalable data exchange and multi-species disease surveillance. Neal *et al.* (2025)^[27] highlighted its expanding importance in zoonotic disease monitoring and antibiotic resistance surveillance. Despite these developments, the implementation of fully digital workflows is still constrained by high computational and storage needs, staining variability, scanner heterogeneity, a lack of regulatory uniformity, and poor interpretability of AI-based systems. Most AI models continue to act as "black-box" systems, lowering physician trust and limiting routine application.

Thus, digital pathology should be considered as more than just a replacement for traditional microscopy, but as a shift in diagnostic pathology toward a quantitative approach and computational discipline. According to Lu *et al.* (2023)^[23], new computational pathology frameworks can extract high-dimensional spatial information from tissue pictures, which helps with predicted disease modeling and biomarker development. As a result, this study gives a succinct summary of current achievements in veterinary digital pathology, with an emphasis on technological underpinnings, AI integration, diagnostic applications, limits, and future directions towards interpretable, multimodal, and One Health-oriented diagnostic systems.

Historical Evolution of Digital Pathology

Digital pathology has evolved from conventional microscopy to AI-driven computational pathology systems, transforming veterinary clinical pathology through improved remote diagnostics, workflow efficiency, and analytical accuracy. Initially, pathology relied on optical microscopy and photomicrography, where analog imaging devices captured static microscopic images. Early telepathology enabled remote consultation through image transmission, but limited resolution, incomplete slide coverage, and inadequate network infrastructure restricted its clinical utility. Ribbe *et al.* (2000)^[32] highlighted both the potential and limitations of these early systems.

A major advancement occurred during 2000-2010 with the introduction of Whole-Slide Imaging (WSI), which enabled

high-resolution digitization of complete tissue sections. Improvements in scanner optics, image stitching, compression technologies, and virtual microscopy platforms enhanced diagnostic applications and pathology education. Rojo *et al.* (2006)^[34] demonstrated the clinical feasibility of WSI systems. Between 2010 and 2020, digital pathology became a clinically validated diagnostic tool with developments in cloud storage, slide management systems, telepathology networks, and computational image analysis. Machine learning techniques supported nuclear segmentation, tissue classification, mitotic detection, and quantitative morphometry. Mukhopadhyay *et al.* (2018)^[26] confirmed that digital pathology was comparable to conventional microscopy for primary diagnosis.

Since 2020, artificial intelligence and deep learning have revolutionized digital pathology. CNNs, weakly supervised learning, and transformer-based models now support tumor grading, automated mitotic counting, leukocyte differential analysis, and infectious disease detection. Studies by Campanella *et al.* 2022^[5] and Lu *et al.* 2023^[23] demonstrated improved diagnostic performance and contextual tissue analysis. However, challenges such as limited veterinary datasets, explainability issues, computational costs, and regulatory uncertainty continue to affect widespread veterinary implementation.

Components of Digital Pathology Systems

Digital pathology in veterinary clinical pathology represents an integrated diagnostic ecosystem that converts conventional microscopy into digital, computational, and AI-assisted workflows. These systems combine imaging technologies, computational infrastructure, laboratory information systems, image management platforms, artificial intelligence (AI), and telepathology networks to improve diagnostic efficiency, accuracy, and remote accessibility. Veterinary digital pathology must additionally accommodate multispecies variability, high sample volumes, and rapid diagnostic turnaround times, especially in infectious disease surveillance and toxicologic pathology. Whole-slide imaging (WSI) scanners form the core hardware component of digital pathology. These scanners digitize glass slides into high-resolution virtual images using motorized stages, focusing systems, and image-stitching algorithms. Fitzke *et al.* (2021) demonstrated that modern WSI systems support high-throughput veterinary pathology workflows; however, factors such as staining quality, fixation artifacts, and scanner calibration significantly influence image quality and computational analysis. Supporting computational infrastructure includes high-performance servers, GPUs, cloud storage, and distributed computing systems capable of handling gigabyte-scale slide images. Song *et al.* (2023)^[39] emphasized that such infrastructure is essential for real-time AI-assisted pathology analysis.

Image visualization software and Image Management Systems (IMS) further enhance digital pathology by enabling slide viewing, zooming, annotation, case comparison, and collaborative telepathology. IMS platforms organize, archive, retrieve, and share digital slides along with clinical metadata, improving workflow automation and diagnostic reproducibility. Integration with Laboratory Information Systems (LIS) and Picture Archiving and Communication Systems (PACS) ensures traceability, standardized reporting, and regulatory compliance. Cloud-

based IMS solutions also facilitate remote consultation and multi-institutional collaboration.

Artificial intelligence and computational pathology now represent the most transformative aspects of digital pathology. Deep learning models, particularly convolutional neural networks (CNNs), enable automated tissue classification, tumor grading, infectious disease detection, leukocyte differential analysis, and quantitative morphometry. Weakly supervised multiple instance learning (MIL) frameworks reduce the requirement for extensive manual annotations, while transformer-based architectures improve contextual tissue analysis and capture spatial heterogeneity more effectively than conventional CNNs. AI systems increasingly integrate histopathology with genomic, transcriptomic, and clinical data to support predictive diagnostics and precision medicine. Despite these advancements, veterinary computational pathology continues to face challenges including limited annotated datasets, interspecies variability, infrastructure costs, standardization issues, and limited explainability of AI predictions. Nevertheless, integrated AI-driven pathology systems are expected to become essential components of future veterinary diagnostics and One Health surveillance programs.

Digital Cytology in Veterinary Clinical Pathology

Digital cytology is an emerging branch of digital pathology that combines high-resolution imaging, computational analysis, telecytology, and artificial intelligence (AI) to improve cytological diagnosis in veterinary clinical pathology. It replaces or supplements conventional microscopic examination of cytological smears with digital workflows, increasing diagnostic efficiency, accessibility, reproducibility, and workflow standardization. Digital cytology is especially important in veterinary medicine because cytology is widely used as a rapid, minimally invasive, and cost-effective diagnostic method for inflammatory, infectious, and neoplastic diseases.

Digital cytology systems begin with the digitization of cytological preparations such as fine-needle aspirates, impression smears, exfoliative samples, and body cavity effusions using whole-slide imaging (WSI) scanners or high-resolution digital microscopy systems. These technologies allow pathologists to visualize, archive, annotate, and remotely share slides while preserving cellular morphology comparable to conventional microscopy. Telecytology has become a major advantage of digital systems by enabling remote consultation between geographically distant veterinary clinics and specialists, thereby reducing diagnostic turnaround time and improving clinical decision-making. Rogers *et al.* (2024) ^[33] highlighted the importance of telepathology and telecytology systems in expanding access to veterinary expertise.

Advancements in scanner optics, autofocus systems, and image stitching technologies have significantly improved the reliability of digital cytology despite challenges such as uneven cellular distribution, overlapping cells, and staining inconsistencies. Modern image viewing and management software further support diagnostic accuracy through zoom-based navigation, annotations, measurements, and side-by-side slide comparisons. These tools are especially important in veterinary cytology, where subtle species-specific cellular variations may influence diagnosis.

Artificial intelligence and machine learning now represent the most transformative components of digital cytology. Deep learning algorithms, particularly convolutional neural networks (CNNs), enable automated detection of abnormal cells, leukocyte differentiation, infectious agents, and neoplastic changes. Multiple instance learning (MIL) frameworks reduce the need for detailed annotations by learning from slide-level labels, making them suitable for veterinary datasets with limited annotations. Advanced object detection and segmentation algorithms also allow quantitative assessment of nuclear size, chromatin texture, nuclear-cytoplasmic ratio, and cellular clustering patterns. Transformer-based models further enhance diagnostic performance by capturing global spatial relationships across entire cytology smears.

Despite these advances, digital cytology faces challenges including lack of standardized veterinary datasets, species variability, infrastructure costs, computational demands, and limited explainability of AI systems. Nevertheless, digital and AI-assisted cytology are rapidly becoming essential components of modern veterinary diagnostic workflows and precision medicine.

Digital Hematology

Digital hematology is an advanced branch of digital pathology that combines digital imaging, computational analysis, and artificial intelligence (AI) to evaluate peripheral blood smears, bone marrow aspirates, and hematological specimens in veterinary clinical pathology. It transforms traditional microscopy-based hematology into a quantitative and AI-assisted diagnostic system, improving diagnostic accuracy, reproducibility, and efficiency. Conventional hematological examination relies heavily on manual smear interpretation, which is time-consuming and subject to inter-observer variability. Digital hematology overcomes these limitations through automated imaging, standardized analysis, and computational interpretation across multiple animal species.

The foundation of digital hematology is the digitization of blood smears using whole-slide imaging (WSI) scanners or automated digital microscopy systems. These devices generate high-resolution images that allow storage, remote sharing, and computational analysis of erythrocytes, leukocytes, and platelets. AI-driven systems, particularly convolutional neural networks (CNNs), are widely used for automated white blood cell differential counting and classification based on nuclear morphology, cytoplasmic texture, and staining patterns. Esteva *et al.* (2021) ^[10] demonstrated that deep learning systems can achieve expert-level image classification performance, supporting their application in hematology diagnostics.

Digital hematology also supports quantitative red blood cell morphology analysis, enabling objective detection of abnormalities such as anisocytosis, poikilocytosis, polychromasia, and spherocytosis. Automated platelet analysis further improves diagnostic consistency by identifying platelet counts, aggregates, and morphological changes associated with coagulation and immune-mediated disorders. Advanced segmentation and classification models such as U-Net and ResNet improve cellular identification, even in densely packed smear regions. AI-assisted systems additionally help identify leukemic blasts, circulating tumor cells, and blood-borne parasites including *Babesia*, *Ehrlichia*, and *Mycoplasma*.

Automated blood smear analysis is a major application of digital hematology. The process includes image preprocessing, cell segmentation, morphological characterization, leukocyte classification, and platelet assessment. AI-powered decision-support systems can prioritize abnormal samples and highlight suspicious findings for pathologist review. These technologies significantly reduce manual workload while increasing throughput and standardization in veterinary laboratories. Comparative hematology further extends digital hematology by enabling quantitative cross-species analysis of blood cell morphology and disease patterns. Digital systems facilitate standardized comparison of erythrocytes and leukocytes among species and support zoonotic disease surveillance and One Health initiatives.

Despite these advantages, challenges remain, including species variability, lack of standardized veterinary datasets, staining inconsistencies, computational demands, and limited AI generalizability across laboratories. Nevertheless, digital hematology is becoming an essential component of modern veterinary diagnostics and precision medicine.

Telepathology in Veterinary Medicine

Telepathology in veterinary medicine is the remote transmission of pathological images and diagnostic data for consultation, diagnosis, education, and collaboration. It is one of the most important applications of digital pathology because it improves access to veterinary specialists, particularly in rural and resource-limited regions. Telepathology uses digital imaging systems such as whole-slide imaging (WSI) scanners and digital microscopy to convert glass slides into high-resolution digital images that can be securely transmitted and interpreted remotely. Unlike traditional microscopy, telepathology enables real-time and asynchronous consultations without physical slide transport, thereby improving accessibility, workflow efficiency, and collaborative diagnosis.

Telepathology systems are broadly classified into static telepathology, dynamic telepathology, and WSI-based telepathology. Static telepathology involves capturing selected microscopic images and sharing them for remote evaluation. It is affordable and easy to implement, especially in field diagnostics and small veterinary clinics, but suffers from sampling bias because only selected areas are examined. Dynamic telepathology uses robotic microscopes that allow remote pathologists to navigate slides in real time, closely mimicking conventional microscopy. Although it improves diagnostic accuracy and collaboration, it requires high-speed internet connectivity and expensive infrastructure. WSI-based telepathology is considered the most advanced approach because it digitizes entire slides at high resolution, enabling comprehensive tissue examination and asynchronous consultation using virtual slide viewers.

One of the major advantages of telepathology is rapid access to specialist consultation for emergency diagnostics, outbreak investigations, zoonotic disease surveillance, oncology, and One Health programs. It also enhances consultation pathology, second-opinion diagnosis, and collaborative research among veterinary institutions. In veterinary education, digital slide libraries and annotated virtual slides improve teaching and training by providing access to diverse pathological cases across multiple species. Integration with image management systems (IMS) and laboratory information systems (LIS) further supports

efficient case tracking, workflow automation, and secure data management.

Modern telepathology systems increasingly incorporate artificial intelligence (AI) and computational pathology tools. AI-assisted platforms can identify abnormal regions, prioritize urgent cases, and support lesion detection and quantitative analysis. Whole-slide imaging systems also facilitate computational pathology applications such as tumor classification, inflammatory scoring, and infectious disease detection. However, telepathology faces challenges including high infrastructure costs, large image storage requirements, internet dependency, image standardization issues, and limited veterinary-specific validation studies. Despite these limitations, telepathology is rapidly becoming a central component of modern veterinary pathology and digital diagnostic infrastructure.

Artificial Intelligence in Veterinary Pathology

Artificial intelligence (AI) is transforming veterinary pathology by integrating computational algorithms with digital pathology systems to improve diagnostic accuracy, reproducibility, and workflow efficiency. Rather than replacing veterinary pathologists, AI acts as an assistive technology that enhances interpretation of histopathology, cytology, hematology, and whole-slide imaging (WSI). This advancement is driven by developments in machine learning (ML), deep learning (DL), digital imaging, and high-performance computing. Machine learning algorithms are trained using annotated digital slides to identify patterns associated with inflammation, tumors, infections, and degenerative diseases. Deep learning, especially Convolutional Neural Networks (CNNs), has become highly important because it automatically extracts features such as tissue architecture, nuclear morphology, and staining characteristics. Esteva *et al.* (2021)^[10] demonstrated expert-level performance of deep learning systems in medical image classification, supporting their use in pathology diagnostics.

AI-assisted pathology commonly follows a multi-stage workflow. Whole-slide images are digitized and divided into smaller image patches for computational analysis. AI systems then identify diagnostically important features such as neoplastic clusters, inflammatory infiltrates, infectious organisms, and cellular abnormalities. Multiple Instance Learning (MIL) has become particularly valuable because it enables slide-level diagnosis without requiring extensive pixel-level annotations, making it suitable for veterinary datasets where annotated images are limited. Campanella *et al.* (2022)^[5] showed that weakly supervised MIL systems can achieve clinical-grade performance with limited annotation requirements.

AI applications in veterinary pathology are extensive. In oncology, AI assists with tumor detection, grading, invasion assessment, and neoplasm classification. In infectious and inflammatory diseases, AI quantifies inflammatory infiltrates and detects microorganisms such as bacteria, fungi, and parasites. In hematology and cytology, AI improves leukocyte classification, atypical cell identification, differential counts, and morphometric analysis. Advanced CNN architectures such as Faster R-CNN, YOLO, RetinaNet, U-Net, and Mask R-CNN are widely used for object detection, segmentation, and tissue classification. More recently, transformer-based models and attention mechanisms have improved global tissue analysis

by capturing long-range spatial relationships. Lu *et al.* (2023)^[23] demonstrated that vision transformers outperform conventional CNNs in complex computational pathology tasks.

AI also enhances workflow efficiency through automated slide triaging, suspicious region detection, and prioritization of urgent cases. Integration with image management systems (IMS), laboratory information systems (LIS), and cloud-based computing platforms supports large-scale storage and analysis of pathology data. However, veterinary AI still faces challenges including species variability, lack of standardized datasets, domain shift between laboratories, infrastructure costs, and limited interpretability of deep learning models. Explainable AI techniques such as saliency maps and Grad-CAM are increasingly used to improve transparency and clinical trust. Despite these limitations, AI-powered systems are rapidly becoming essential tools in modern veterinary pathology and precision diagnostics.

Computational Pathology

Computational pathology integrates digital pathology, artificial intelligence (AI), machine learning, bioinformatics, and high-performance computing to transform veterinary pathology into a quantitative, reproducible, and data-driven discipline. Unlike conventional microscopy, computational pathology converts histopathological, cytological, and hematological images into numerical datasets that can be computationally analyzed for diagnosis, prognosis, biomarker discovery, and disease prediction across multiple animal species. Whole-slide imaging (WSI) forms the basis of computational pathology by digitizing tissue sections into high-resolution virtual slides. These images undergo preprocessing steps such as color normalization, artifact correction, stain deconvolution, and noise reduction to improve image consistency and reduce variability between laboratories and species. Komura and Ishikawa (2022)^[20] emphasized that computational image analysis enhances diagnostic objectivity and minimizes subjective interpretation.

Computational pathology systems extract quantitative image features including nuclear size, shape, chromatin texture, tissue architecture, and cellular spatial distribution. These features are analyzed using machine learning and deep learning models to classify diseases, predict prognosis, and identify pathological patterns. Convolutional Neural Networks (CNNs) are widely used because they automatically learn hierarchical image features without manual feature engineering. Esteva *et al.* (2021)^[10] demonstrated expert-level performance of deep learning algorithms in medical image interpretation. Whole-slide images are typically divided into smaller image patches for computational processing, and Multiple Instance Learning (MIL) frameworks enable accurate slide-level predictions without extensive pixel-level annotations. Campanella *et al.* (2022)^[5] showed that weakly supervised MIL systems can achieve clinical-grade diagnostic performance, especially useful in veterinary datasets with limited annotations.

Computational pathology also supports predictive pathology, quantitative image analysis, and spatial tissue analysis. AI systems assess tumor microenvironments, inflammatory infiltrates, vascular structures, and tissue organization to predict metastasis risk, treatment response, survival outcomes, and disease progression. Transformer-based architectures further improve analysis by capturing

long-range spatial relationships within tissues. Quantitative image analysis uses segmentation algorithms such as U-Net to identify nuclei, cytoplasm, inflammatory cells, and lesion regions for objective morphometric assessment. Integration of imaging data with genomic, transcriptomic, proteomic, and clinical information enables precision medicine and One Health research.

Despite its advantages, computational pathology faces challenges including species variability, lack of standardized veterinary datasets, domain shift between laboratories, infrastructure costs, and limited interpretability of AI models. Nevertheless, it is rapidly becoming a fundamental component of modern veterinary diagnostics and precision medicine.

Molecular Pathology and Digital Integration

Molecular pathology and digital integration combine molecular diagnostics, digital pathology, artificial intelligence (AI), and computational analysis to create a multidimensional approach to veterinary clinical pathology. This integration links traditional histopathology with genomics, transcriptomics, proteomics, and bioinformatics, shifting pathology from a morphology-based discipline to a precision-driven diagnostic system. In veterinary medicine, this approach is particularly important because it improves understanding of complex diseases across multiple animal species with diverse genetic and pathological variations.

Traditionally, molecular pathology used techniques such as polymerase chain reaction (PCR), immunohistochemistry (IHC), in situ hybridization (ISH), and sequencing-based diagnostics to detect infectious agents, mutations, and tumor biomarkers. However, these methods often lacked direct morphological context. Digital pathology and AI now allow molecular information to be integrated with high-resolution histopathological images, enabling simultaneous evaluation of molecular and structural tissue changes. Esteva *et al.* (2021)^[10] emphasized that integrating imaging and molecular data significantly improves diagnostic precision and supports predictive and personalized medicine.

Modern digital pathology systems integrate molecular information into image management systems (IMS) and laboratory information systems (LIS), allowing pathologists to analyze histological images alongside genomic, immunophenotypic, and biomarker data. This integration enhances diagnostic accuracy and enables spatial mapping of molecular markers such as Ki-67, p53, HER2, and c-KIT directly onto tissue sections. Such spatial analysis improves understanding of tumor heterogeneity, disease progression, and treatment response. Computational image analysis and AI-based tools further improve biomarker quantification, reproducibility, and prognostic assessment.

Artificial intelligence and deep learning play a central role in molecular-digital integration. Convolutional neural networks (CNNs) and transformer-based models can identify molecular patterns directly from histopathological images and support multimodal disease prediction. Integration of imaging, genomic, transcriptomic, and proteomic datasets enables comprehensive disease modeling and precision medicine applications in veterinary oncology, infectious diseases, toxicologic pathology, and comparative pathology. Spatial molecular pathology further enhances analysis by preserving tissue architecture while evaluating gene and protein expression patterns within tissue microenvironments.

Despite its advantages, molecular-digital integration faces challenges including high infrastructure costs, species variability, lack of standardized veterinary molecular databases, and limited explainability of AI systems. Nevertheless, it is rapidly becoming a key component of modern veterinary precision diagnostics and One Health research.

Digital Pathology in Veterinary Oncology

Digital pathology in veterinary oncology combines whole-slide imaging (WSI), artificial intelligence (AI), computational pathology, and molecular data integration to improve the diagnosis, grading, and prognosis of neoplastic diseases in animals. It transforms traditional morphology-based cancer diagnosis into a quantitative, reproducible, and predictive discipline. In veterinary oncology, where tumor heterogeneity, species variability, and limited standardized datasets often reduce diagnostic consistency, digital pathology provides an objective and scalable diagnostic framework. Deep learning systems can analyze histopathological images to identify clinically significant oncologic features, supporting precision-based diagnostic and prognostic approaches.

Traditional microscopic evaluation of tumors is often subjective and prone to inter-observer variability. Digital pathology addresses these limitations through whole-slide digitization, quantitative morphometric analysis, automated tumor detection, and AI-assisted grading systems. Whole-slide imaging enables comprehensive assessment of tumor architecture, invasive margins, necrosis, vascular invasion, and tumor heterogeneity while supporting remote consultation and long-term digital archiving. Computational pathology also facilitates large-scale comparative oncology research and retrospective analysis using digitized datasets.

Artificial intelligence, particularly convolutional neural networks (CNNs) and transformer-based models, plays a major role in digital oncology pathology. These systems assist in tumor detection, classification, grading, metastasis prediction, and survival outcome analysis by evaluating thousands of image patches from digital slides. Digital pathology also improves evaluation of the tumor microenvironment by analyzing immune infiltrates, stromal density, angiogenesis, and spatial cellular interactions. Quantitative analysis of nuclear pleomorphism, mitotic index, tissue organization, and necrosis enhances tumor grading accuracy and reduces variability between pathologists.

Integration of molecular oncology further strengthens digital pathology by linking histological patterns with genetic mutations, immunohistochemical markers, transcriptomics, and proteomic data. This multimodal integration supports precision veterinary oncology, prognostic modeling, biomarker discovery, and personalized treatment strategies. Despite challenges such as species diversity, limited annotated datasets, infrastructure costs, and computational demands, digital pathology is rapidly becoming an essential component of modern veterinary cancer diagnostics and comparative oncology research.

Challenges and Limitations

Despite rapid advancements in digital pathology, including whole-slide imaging (WSI), artificial intelligence (AI), and computational pathology, several challenges continue to limit its widespread implementation in veterinary clinical

pathology. These challenges involve technical, biological, infrastructural, financial, and regulatory factors, which are further complicated by species diversity and variability in veterinary laboratory practices. Although AI systems demonstrate high diagnostic performance in controlled settings, their clinical applicability is often restricted by dataset bias, poor generalizability, and workflow integration difficulties.

One of the major barriers is the high cost of infrastructure. Digital pathology requires expensive scanners, high-performance computing systems, large-scale data storage, secure networking, and specialized software platforms. Whole-slide images generate massive datasets that demand cloud-based storage and GPU-enabled computational resources, significantly increasing operational costs. McGenity *et al.* (2023) ^[25] emphasized that scalability and storage remain major limitations in computational pathology deployment.

Another important challenge is the lack of standardization across workflows. Variability in slide preparation, staining protocols, scanning resolution, image formats, and annotation methods reduces reproducibility and affects AI model reliability. Veterinary pathology faces additional complexity because tissue architecture and disease patterns vary greatly between species. Limited availability of well-annotated veterinary datasets further restricts AI model development and increases the risk of overfitting and poor cross-species generalization.

Biological variability, algorithmic bias, and limited interpretability of AI systems also hinder clinical adoption. Many deep learning models function as “black-box” systems, reducing clinician trust and complicating regulatory approval. Integration into existing laboratory workflows is another challenge because many veterinary laboratories still depend on conventional microscopy and legacy information systems. Additional concerns include limited internet connectivity in rural areas, cybersecurity risks, data privacy, and lack of unified global regulatory frameworks for veterinary AI diagnostics.

Overall, successful implementation of digital pathology in veterinary medicine requires improved infrastructure, standardized protocols, larger multispecies datasets, explainable AI systems, and stronger regulatory frameworks to ensure reliable and scalable clinical adoption.

Future Perspectives

The future of digital pathology in veterinary clinical pathology lies in the integration of artificial intelligence (AI), robotics, molecular diagnostics, cloud computing, and precision medicine into a unified diagnostic ecosystem. Future systems are expected to move beyond simple image digitization toward autonomous and predictive platforms capable of combining histological, molecular, spatial, and clinical data for advanced diagnostic decision-making. Artificial intelligence will remain the central driving force, evolving from assistive tools into highly sophisticated systems capable of automated tumor detection, grading, disease prediction, and comparative pathology across multiple species. Transformer-based and foundation AI models are expected to improve contextual understanding and cross-species generalization in histopathological analysis.

Robotics and laboratory automation will further transform veterinary pathology by automating slide preparation,

staining, scanning, sorting, and labeling processes. Integration of these automated workflows with AI-based diagnostic systems will improve efficiency, reduce human error, and support high-throughput diagnostic laboratories. Simultaneously, integration of digital pathology with genomics, transcriptomics, proteomics, and spatial transcriptomics will enable multidimensional disease characterization and precision veterinary medicine. This multimodal integration will improve tumor classification, biomarker discovery, disease prediction, and individualized therapeutic planning.

Cloud computing will serve as the foundation for future global telepathology networks by enabling centralized data storage, remote consultation, AI deployment, and cross-border collaboration. These systems will improve access to veterinary expertise, particularly in geographically isolated regions, and support One Health initiatives through rapid disease surveillance and data sharing. AI-assisted telepathology platforms will also support automated lesion detection, slide triage, and report generation to optimize workflow efficiency.

Another major advancement will be the development of precision and personalized veterinary medicine through integration of pathology, molecular data, and clinical information. Computational models and digital twins may simulate disease progression and treatment response in individual animals, enabling predictive diagnostics and tailored therapies. Despite these advancements, challenges such as high infrastructure costs, computational demands, lack of standardization, data privacy concerns, and ethical issues surrounding autonomous diagnostics remain important barriers. Nevertheless, digital pathology is expected to become a central component of future veterinary precision healthcare systems.

Conclusion

Digital pathology has transformed veterinary clinical pathology by shifting diagnostics from conventional microscopy to digitally integrated and computationally enhanced systems. This transformation is driven by the integration of whole-slide imaging (WSI), artificial intelligence (AI), telepathology, computational pathology, and molecular diagnostics. WSI enables glass slides to be converted into high-resolution digital images for remote access, long-term storage, and computational analysis, supporting global collaboration and telepathology networks. Artificial intelligence and machine learning are among the most impactful developments in digital pathology. AI systems support automated screening, lesion detection, histopathological classification, quantitative image analysis, and disease prediction, thereby improving diagnostic accuracy, reproducibility, and workflow efficiency. Computational pathology further enhances diagnostics by extracting quantitative and clinically relevant information from tissue images, shifting pathology from subjective interpretation to objective analysis.

Molecular diagnostics add another important dimension by integrating genomic, transcriptomic, and proteomic information with histopathological findings. This multimodal approach supports precision veterinary medicine by improving disease classification, prognosis, and therapeutic decision-making. Telepathology and cloud-based systems also strengthen global collaboration,

education, and disease surveillance, particularly in areas with limited specialist access.

Despite these advances, challenges such as high infrastructure costs, lack of standardization, limited interoperability, cybersecurity concerns, and variability in imaging protocols continue to restrict widespread implementation. However, ongoing developments in AI, cloud computing, computational pathology, and precision medicine are expected to overcome many of these limitations. Overall, digital pathology is becoming a central component of modern veterinary diagnostics and One Health surveillance systems.

Acknowledgments

There is no conflict of interest related to the work.

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