



Systematic Review Article

Roles of Artificial Intelligence in Enhancing Diagnostic Pathology and Surgical Outcomes in Laboratory Animals: A Systematic Review

Negar Ababaf Shoushtari¹ , Amin Shahinzadeh¹ , Elaheh Mahmoodi² , Bardia Mohammadi¹ , Marziyeh Saki^{2,3} , Safa Najafi^{4,5} and Sirous Rafiei Asl^{6,7,8*}

¹ Doctor of Veterinary Medicine Student, Islamic Azad University of Shoushtar, Shoushtar, Iran

² Doctor of Veterinary Medicine, Graduated, Islamic Azad University of Shoushtar, Shoushtar, Iran

³ Student Research Committee, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁴ Nursing Care Research Center in Chronic Diseases, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁵ Department of Medical and Surgical Nursing, School of Nursing and Midwifery, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁶ Cancer, Environmental and Petroleum Pollutants Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁷ Department of Pathology, Faculty of Medicine, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁸ Alimentary Tract Research Center, Clinical Sciences Research Institute, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

* **Corresponding author:** Sirous Rafiei Asl, Board-Certified Clinical Pathologist, Oncopathology Researcher. Cancer, Environmental and Petroleum Pollutants Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran. Email: rafieiasl-s@ajums.ac.ir

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ABSTRACT

Recent advances in artificial intelligence (AI) have opened new horizons in medical sciences, especially in pathology and surgery. Although AI can enhance diagnostic accuracy and surgical outcomes, its widespread clinical use faces challenges such as validation, interpretability, and ethical and legal issues. The present study aimed to examine recent developments in AI across pathology, including automated recognition of pathological images and surgery (robotic surgical assistant systems and predictive outcome analysis). The present study analyzed current challenges in implementing AI and provided a perspective on how it can become a reliable tool to improve the quality of patient care and treatment outcomes. An initial and extensive search was conducted across reputable scientific databases, including Google Scholar, PubMed, and Scopus, using relevant keywords. Within the clinical pathology section, this review provided a comprehensive examination of how deep learning algorithms and image processing are automating and enhancing data analysis in cytology, hematology, histopathology, and digital pathology. The ability of AI to discover nuanced patterns in vast datasets, greatly improve diagnostic accuracy, and speed up reporting are all impressive capabilities. One of these challenges is the need for large, standardized datasets for algorithm training. Other challenges include clinical validation, ethical concerns, and early costs. In conclusion, this review anticipates that the integration of AI into clinical pathology and surgical workflows promises enhanced quality of care for laboratory animals alongside more accurate and reliable insights.

1. Introduction

Artificial intelligence (AI), as a powerful disruptor in the field of medical sciences, is transforming traditional paradigms of diagnosis and treatment¹. In fields of pathology and surgery, AI provides advanced analytical methods that enable faster, more accurate, and personalized diagnosis²⁻⁴. While aiding clinical decision-making, it paints a clear vision for improving important indicators such as surgical accuracy and patient treatment outcomes. Clinical pathology and surgical pathology are two of the most

significant pillars in the care, monitoring, and evaluation of *in-vivo* studies⁵. The field of clinical pathology provides vital information on health, disease progression, and treatment response by conducting objective studies of biological materials such as blood and tissue⁶. On the other hand, surgical techniques are of utmost significance, whether used to develop complex disease models or deliver therapeutic interventions. It is abundantly clear that the accuracy and precision of these two areas are closely linked to the

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integrity of research data and significant animal welfare indices⁷.

On the other hand, procedures that are considered routine in clinical pathology and veterinary surgery are not without their own intrinsic challenges. In pathology, analyzing large volumes of data from hematology, biochemistry, and histology often involves subjective judgments, staff fatigue, and human error^{8,9}. In addition to the time these treatments require, there is also the possibility that they may result in diagnostic variability. The accuracy of the preoperative pathological diagnosis and the intraoperative assessment (for example, tumor margins) are highly essential aspects in surgery^{10,11}. These parameters are crucial in determining whether an operation is successful and how well the animal recovers afterward. A delayed or inaccurate diagnosis can disrupt the surgical procedure, potentially leading to the failure of the animal and the study design. In recent years, the introduction and development of technologies based on artificial intelligence, notably in the subfields of deep learning and computer vision, have promised to bring about a fundamental transformation in how these challenges are tackled¹². There are two areas in which AI has the potential to dramatically enhance diagnostic sciences in terms of accuracy, speed, and impartiality^{13,14}. These areas include automating repetitive procedures and analyzing exceedingly large, complex data. This might be done with the use of AI. The use of AI for image screening in pathology and radiology is becoming an increasingly important supplementary tool.

In veterinary clinical pathology, AI offers a broad range of applications with significant promise¹⁵. It is possible for AI systems to automatically count and classify blood cells in hematological smears, analyze urine samples, and sift through huge volumes of biochemical data in a short period of time. Artificial intelligence can examine scanned tissue slides at speeds beyond human capability in digital histopathology¹⁶. Additionally, AI can recognize specific areas of interest and assist in diagnosing tumor subtypes and subtle clinical signs that may be hidden from the pathologist's view. AI eliminates guesswork, provides clear and quantitative diagnoses, and equips surgeons with the best available information.

Veterinary surgery has evolved significantly with improved diagnostic technologies. When surgeons receive the rapid and accurate pathology results, conducted by AI, they can plan the operation with much greater confidence¹⁷. During cancer surgery, for instance, AI systems trained on histopathology images could aid in the real-time interpretation of frozen sections¹⁸. Surgical margins may also be used to determine whether the tumor has been entirely eliminated using these algorithms. The combination of these techniques often leads to better surgical outcomes and reduces the likelihood of further operations.

Given these circumstances, the purpose of this review article is to conduct a comprehensive review of the most recent developments in AI and their practical applications across various subspecialties of veterinary clinical pathology (hematology, biochemistry, and digital histopathology).

2. Materials and Methods

The methodology was based on an initial and extensive search conducted in reputable scientific databases such as Google Scholar, PubMed, and Scopus from January 2020 to December 2024, using relevant keywords such as artificial intelligence in pathology, deep learning for histological image recognition, robot-assisted surgery, and predictive medicine with artificial intelligence. The present study identified 1282 publications through keyword searching across the databases. 74 studies were included in this study, of which 38 were excluded. A total of 31 full-text articles were reviewed for eligibility. The quantitative synthesis was based on 27 articles selected after duplicates were removed and eligibility screening. After collecting the sources, the data and their findings were categorized, analyzed, and narratively synthesized into main themes including artificial intelligence applications in digital pathology, intelligent surgeon-assistant systems, prediction of postoperative complications, and challenges to clinical implementation.

3. AI in clinical pathology

The paradigms of diagnostic practice in clinical pathology are being completely transformed by this innovation. Deep learning, which employs AI neural networks with multiple layers, can automatically detect subtle and hidden patterns in vast amounts of data, whether numerical or medical imaging^{19,20}. By being trained on thousands of samples (for example, microscopic photographs of normal and abnormal blood cells), these algorithms can learn to extract and classify crucial properties. The process of learning is not based on rules set; rather, it is based on training across thousands of different situations^{21,22}. Because of these qualities, AI is an appealing tool for automating and enhancing the accuracy of repetitive but essential procedures in clinical pathology. Moreover, AI can provide more efficient, accurate results, as human errors and mental fatigue can contribute to diagnostic heterogeneity in clinical pathology. [Figure 1](#) demonstrated a description of the supervised learning flowchart, including training, validation, and prediction²³.

The automated analysis of blood smear pictures is one of the most significant uses of AI in medicine²⁴. More advanced computer vision algorithms can perform differential counts of white blood cells with accuracy comparable to that of certified professionals. In addition, these algorithms are able to recognize abnormalities, such as immature cells, toxic neutrophils, and intracellular parasites^{25,26}. This approach not only enables screening enormous numbers of samples in large-scale research projects, but also significantly speeds up the rate at which diagnoses are produced. In addition, these systems can analyze and quantify subtle morphological traits that may be hidden from human sight. This has led to the discovery of novel biomarkers and increased understanding of the physiological and pathological responses in animal models^{27,28}.

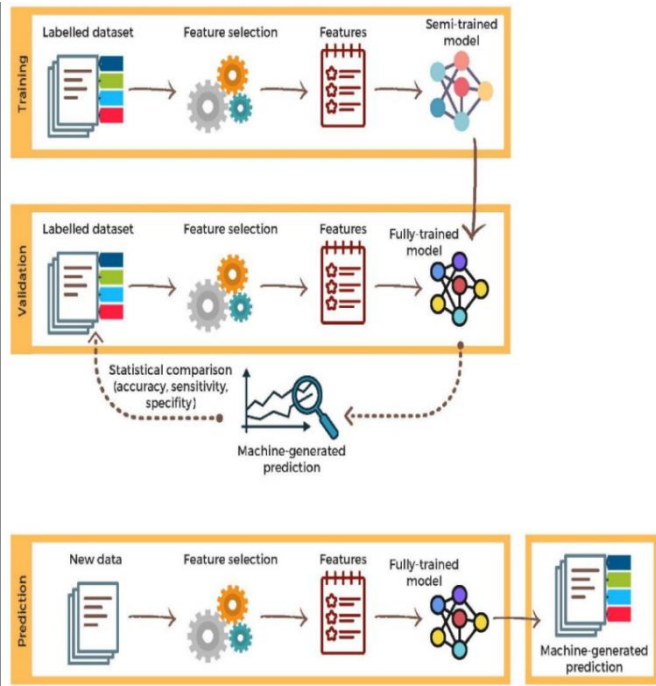


Figure 1. A brief description of the supervised learning flowchart, including training, validation, and prediction (Source: MDPI Copyright, 2022; Bouhali et al.²³)

In addition to its use in the field of image analysis, AI has a great deal of potential for the interpretation of complex biological data. In the field of clinical biochemistry, machine learning algorithms can detect patterns in multiparameter biochemical panels, which may include liver enzymes, electrolytes, and renal indicators, and uncover complex, nonlinear relationships among these parameters²⁹. This skill may lead to the creation of intelligent decision support systems that can comprehend not only a single aberration but also the full pattern of abnormalities, thereby assisting in making a more accurate differential diagnosis. As an example, these methods could make it easier to differentiate between the many distinct liver diseases or organ failure syndromes. This kind of analysis can provide a more comprehensive assessment of a laboratory animal's health and identify the effects of research treatments with greater sensitivity and specificity.

In the field of clinical pathology, digital pathology and histopathology section analysis has emerged as one of the most cutting-edge and promising applications of AI^{30,31}. The digitization of tissue slides using high-resolution scanners has enabled deep learning algorithms to analyze these images at resolutions nearly equal to those of the originals. At the moment, these algorithms are being trained to carry out complex tasks. These tasks include accurately identifying and counting mitoses, which is an important indicator of tumor aggressiveness; classifying and grading neoplasia (for example, adenocarcinoma versus sarcoma); and even identifying microscopic areas of necrosis, inflammation, or fibrosis. The diagnostic procedure is not only made more effective as a result of this, but it also becomes more consistent and objective.

4. AI integration in veterinary surgery

Artificial intelligence is a revolutionary tool in many fields of medical science, such as disease prevention,

control, and treatment³²⁻³⁵. Regarding surgery, an intelligent and responsive cycle that covers the perioperative period, starting with preoperative planning and concluding with postoperative monitoring, is replaced by a rather linear approach to surgical operations^{36,37}. This cycle begins with preoperative planning and ends with postoperative monitoring. This change is achieved through this integration. For the purpose of making strategic decisions, pathological data that has been improved by AI, developed with incredible accuracy and speed, serves as the basis³⁸. The accurate identification of the tumor's type, grade, and stage is of utmost significance in cancer surgery performed on laboratory animals. The reason for this is that the accuracy of the evaluation has a direct impact on the entire surgical procedure. Surgeons can determine how much tissue should be removed, whether lymph node dissection is needed, and which adjuvant therapies to use. By providing a quantitative, clear diagnostic, AI accelerates and refines the surgery procedure, giving the surgeon confidence that the surgical plan is based on the most comprehensive and reliable information currently available^{39,40}.

As the preoperative planning phase approaches, AI evolves from a simple diagnostic report into a powerful predictive tool. Predictive models trained on clinical and pathological data from thousands of operations that are fairly similar to one another can provide a unique estimate of the likelihood of specific issues^{41,42}. The surgical team can take targeted preventive measures, such as prescribing a stronger antibiotic regimen or using more effective hemostatic procedures, for a case expected to be at high risk of infection. Not only does this proactive, customized strategy enhance Patient safety, but it also helps reduce waste of research resources by minimizing the loss of essential Case specimens due to anticipated concerns (Figure 2).

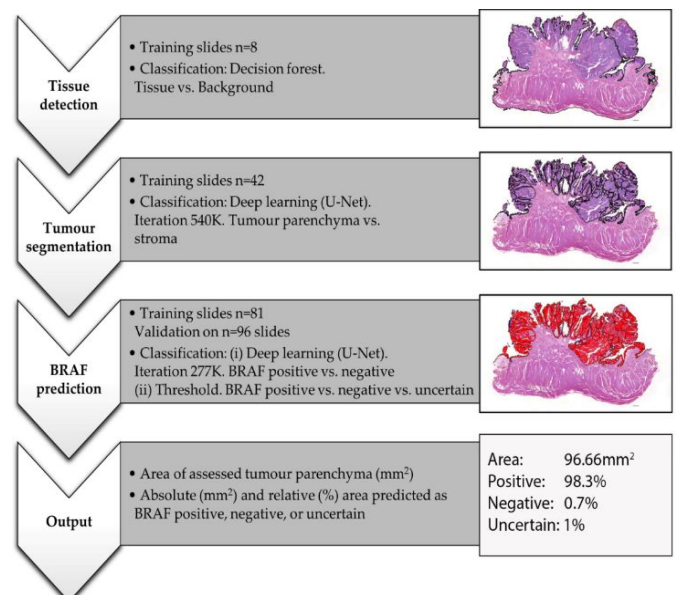


Figure 2. Workflow of the performed AI training and analysis for BRAF mutation prediction on whole slide images of hematoxylin and eosin-stained canine urothelial carcinomas. The images represent a case of bladder UC from an 11-year-old female neutered Jack Russell Terrier with positive BRAF PCR. (Source: MDPI Copyright, 2023; Küchler et al.⁴³)

With the arrival of artificial intelligence in the operating room, it can be noted that the landscape of surgery has undergone a complete and comprehensive

transformation^{44,45}. By deploying cameras in the operating room, computer vision-based surgical support systems can detect anatomy during surgery^{46,47}. It is also possible for these technologies to display additional information within the surgeon's field of vision through augmented reality. By way of illustration, these systems can highlight significant blood vessels or tumor margins that are somewhat difficult to see with the naked eye⁴⁸. Nevertheless, the examination of intraoperative specimens (frozen sections) via the use of algorithms that are driven by AI is now one of the most significant applications of this technology⁴⁹. Determining whether the margins excised from the tumor are free of cancer cells is of the utmost significance in tumor surgery. The images of these frozen specimens can be evaluated by algorithms driven by artificial intelligence in a fraction of a second, and the findings can achieve excellent accuracy in determining the presence or absence of neoplastic cells at the edges of the specimens⁵⁰. Because of this speed and accuracy, the surgeon can quickly decide if removing the additional tissue is necessary during the surgery, thereby reducing the risk of subsequent treatments (Figure 3).

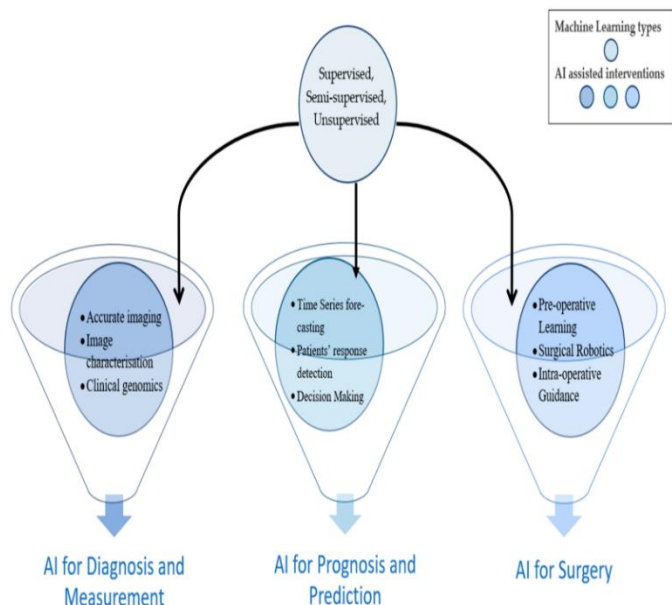


Figure 3. Popular AI techniques for diagnosis, measurement, prediction, prognosis, and surgery (Source: MDPI Copyright, 2022; Taha et al.⁵¹)

After surgery, the role of AI continues. It monitors recovery in patients by tracking temperature, heart rate, and activity levels. Additionally, algorithms can evaluate the outcomes of pathological follow-up tests, such as blood inflammatory indicators.

5. Future prospects

The use of AI in clinical pathology and surgical medical sciences, despite its great promise, offers significant benefits and practical limitations⁵². Artificial intelligence, on the other hand, has the potential to deliver significant improvements in precision and repeatability. Deep learning algorithms can analyze complex data, even from compromised damages, and can identify patterns that humans might overlook⁵³. As a result, diagnoses can be

made with greater sensitivity and specificity. This poses a substantial issue in the context of research, which is characterized by the highest priority placed on impartiality and data integrity. Another benefit of AI is that it notably accelerates analysis, enabling the management of large volumes of samples in a fraction of the time required by traditional methods^{54, 55}. This allows experts to focus on complicated cases, planning surgeries and studies, and developing new initiatives. Artificial intelligence introduces a new degree of standardization worldwide, eliminates differences between laboratories and individuals, and makes it considerably easier to compare findings across different locations^{56, 57}.

Despite the incredible progress achieved, many challenges remain. One of the most critical challenges is making strong, evidence-based decisions. It is essential to have access to large, high-quality datasets that have been thoroughly annotated to design reliable, robust algorithms⁵⁸. Across a wide variety of strains and species, these databases ought to cover a broad spectrum of disorders that can affect laboratory animals. The lack of such standard databases is a significant barrier in the work process⁵⁹. Additionally, the issue of generalizability is a pervasive concern that has to be addressed. When an algorithm trained on data from one species, such as mice, is exposed to data from another species, such as dogs, or even a different breed of the same species, it may lose accuracy⁶⁰. This occurs when the algorithm is subjected to data from a different breed of the same species.

Additionally, there are challenges with the data, as well as significant hurdles in validation and technology⁶¹. Before being implemented in a clinical setting representative of the real world, every AI algorithm must undergo thorough, independent clinical validation⁶². This is necessary to establish beyond a doubt that it is both practical and safe.

6. Conclusion

Artificial intelligence has significant potential to transform clinical and surgical pathology in medical sciences. The ultimate success of this technology may depend not only on further technical advances but also on collaboration between experts from a wide range of professions, such as veterinarians, clinicians, scientists, regulators, and ethicists. Among the most important steps to overcome these challenges are the creation of consortia to produce standardized datasets, the development of transparent validation frameworks, and the development of ethical and legal standards. Artificial intelligence has the potential to fulfill its promise of improving the quality of human and animal care, increasing the reliability of research data, and accelerating scientific discovery in medicine and veterinary medicine. Despite the incredible progress achieved, there are still many challenges to overcome before AI can be fully realized. It is recommended and essential to have access to large, high-quality datasets that have been thoroughly notated to design reliable, robust algorithms.

Declarations

Authors' contributions

All authors contributed to the conceptualization and methodology of this study. The formal analysis and investigation were conducted by Negar Ababaf Shoushtari, Amin Shahinzadeh, Elaheh Mahmoodi, Bardia Mohammadi, Marziyeh Saki, Safa Najafi, and Sirous Rafiei Asl, who also prepared the original draft. The writing was reviewed and edited by Elaheh Mahmoodi, Bardia Mohammadi, and Marziyeh Saki. Sirous Rafiei Asl supervised the project. All authors contributed to the revision steps and approved the final edition of the manuscript for publication in the present journal.

Availability of data and materials

All datasets related to this study are available in the present study and the reference list.

Competing interests

The authors declared that they have no competing interests.

Ethical considerations

The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the preparation, writing, data analysis, or editing of this manuscript. All sections of the present study were conducted and written entirely by the authors and were not submitted or published before. The source of any data used in this review is mentioned, and the authors did not produce any false or fabricated data.

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