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Digital pathology and AI in forensic medicine: advances, limitations, and medico-legal utility

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Abstract

Digital pathology (DP) is revolutionizing forensic histopathology through enhanced accuracy, efficiency, and accessibility in post-mortem evaluation. Traditional histopathological evaluations are founded on physical slides and light microscopy, which are time-consuming, susceptible to human error, and limited in remote collaboration. DP, which combines whole-slide imaging (WSI), artificial intelligence (AI), machine learning (ML), and virtual autopsy methods, delivers high-resolution imaging, quantitative evaluation, and telepathology functionalities that significantly improve forensic evaluation. WSI enables pathologists to digitize, store, and share histopathological slides, thus facilitating expert consultation and retrospective evaluation. AI and ML enhance forensic diagnosis by automating tissue classification, identifying pathological features, and optimizing wound age estimation. Virtual autopsy and 3D imaging utilize non-invasive methods like computed tomography (CT) and magnetic resonance imaging (MRI) to assess injuries, fractures, and internal pathology, thus supplementing traditional autopsy methods. Telepathology facilitates global collaboration, ensuring that expertise is readily available in areas with limited resources, and enhances forensic education through digital repositories of challenging cases. DP holds major applications in forensic medicine, including cause-of-death determination, identification of patterns of injury, and toxicology-related investigations. AI-based histopathological evaluations enhance the objectivity and standardization of forensic diagnoses, providing more reliable evidence to support legal proceedings. Challenges notwithstanding, DP presents multiple benefits, including overcoming economic restrictions, addressing technical limitations, and mitigating uncertainties in the admissibility of digital forensic evidence in judicial hearings. This review accentuates DP's technological progress, applications, and limitations in forensic pathology. By integrating DP into forensic protocols, medico-legal evaluations can achieve greater precision, reproducibility, and efficiency, ultimately enhancing forensic investigations and legal proceedings.

Keywords: *digital pathology, virtual autopsy, artificial intelligence, whole-slide imaging, forensic pathology*

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1. Introduction

Forensic histopathology plays a crucial role in routine practice by aiding in determining the cause of death in specific cases. This is accomplished through the microscopic examination of tissue and cell samples collected from major internal organs and any abnormalities identified during the autopsy [1]. Conventional pathology techniques, although effective, are time-consuming, subject to observer variation, and limited in their scope for remote collaboration. Over the last few years, digital pathology (DP), encompassing whole-slide imaging (WSI), image analysis, and artificial intelligence (AI)-based tools, has revolutionized forensic examinations through high-resolution imaging, remote consultation, and quantitative analysis [2]. Forensic pathology has a significant contribution to medico-legal autopsies in the form of establishing the cause of death, victim identification, and assisting judicial proceedings. Traditional histopathological examination, based on glass slides and light microscopy, is time-consuming and prone to human error. It also limits the potential for collaborative examination due to its physical nature. Digital pathology, through WSI conversion of histopathological slides and computational analysis, is a revolution in forensic medicine [3]. The use of DP in forensic environments has numerous benefits. Remote consultations enable experts from geographically remote locations to offer expert opinions, while AI-based diagnostics enhance accuracy and reduce diagnostic variability. DP provides long-term digital storage, preservation, and simple forensic evidence retrieval. Notwithstanding these advantages, the use of DP in forensic centers is hindered by financial, technical, and legal uncertainties regarding the admissibility of digital evidence in court cases [1, 3].

This review examines the current state of digital pathology in forensic pathology, highlighting its technological advancements, utility, and inherent limitations. It also addresses future advancements in

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forensic investigations by stimulating technological development and ultimately enhancing the accuracy, efficiency, and reliability of medico-legal evaluations.

2. Technological advancements in digital pathology

2.1. Whole slide imaging (WSI)

Whole-slide imaging (WSI) has revolutionized forensic pathology by enabling the digital scanning of full glass slides at high resolutions. WSI allows forensic pathologists to visualize tissue samples digitally, replacing physical slides and microscopes in most scenarios. WSI also possesses the ability to facilitate remote consultation by allowing experts from different geographic regions to work together to examine cases without the inconvenience of shipping physical slides. WSI enhances the reliability and reproducibility of forensic analysis by providing detailed and standardized histopathological assessments. The slides can be digitized to enable effective archiving, allowing forensic evidence to be stored in a long-lasting and easily recoverable digital format. This not only facilitates case analysis but also allows for a retrospective analysis and validation of results, thus improving the reliability of forensic conclusions [4].

Creating extensive digital archives of new and challenging-to-diagnose cases is an effective teaching tool for pathology residents and a valuable resource for research investigations. The archives enable trainees to view and learn about an extensive range of forensic specimens, thereby allowing them to fully understand histopathological patterns and forensic analysis. In critical forensic analysis, WSI promises to enable pathologists to obtain second opinions from renowned experts without being burdened by the actual shipping of slides. This technology enhances the validity of autopsy findings and supports expert testimony during court hearings, thus ultimately yielding more potent medico-legal results [5].

Comparative digital vs. traditional pathology analysis identifies substantial diagnostic and business performance gains with digital workflows. Borowsky et al. (2020) concluded in a 2045 case study that digital whole-slide imaging (WSI) was non-inferior to conventional light microscopy for primary diagnosis, with mean review times of 5.20 min for WSI and 4.95 min for glass slides, indicating equal diagnostic efficiency [6]. At the Institute of Molecular Pathology and Immunology of the University of Porto (IPATIMUP), digital pathology supported the management of approximately 25,000 cases annually—around 60,000 slides—with a mean of 326 scanned slides per day, totaling 57,418 slides over 8 months. This enabled a 48 h turnaround for tests that did not require additional techniques [7]. Operationally, digital pathology achieved a 5-year cost saving of USD 1.3 million through reduced slide retrieval times and reduced physical storage space requirements [8, 9]. These efficiencies translated into direct patient benefits, including reduced turnaround times, optimized case assignment between pathologists, and simpler remote consultations through the speedy exchange of digital slides, reducing patient queues and optimizing overall service delivery.

2.2. Artificial intelligence and machine learning

Artificial intelligence (AI) and machine learning (ML) in digital pathology introduced new dimensions into forensic analysis. AI-based image analysis significantly enhances diagnostic accuracy, enabling the detection of subtle forensic tissue sample patterns that may be overlooked by humans. Deep learning is becoming the standard practice in automated tissue classification, the identification of histopathological abnormalities, and the quantification of cellular modifications in the context of forensic analysis [9].

Artificial intelligence programs are critical in automatically identifying pathological features such as traumatic injury, hemorrhage, and toxicological changes. By reducing observer variability, the programs ensure more standardized and credible results in forensic analysis. Machine learning algorithms are particularly well-suited for analyzing intricate or damaged tissue samples, such as those from decomposing or charred bodies, where routine histological analysis is typically challenging. The algorithms can identify delicate patterns indicative of specific injuries or diseases and improve post-mortem diagnosis precision [10].

In addition, AI-aided quantitative analysis has also shown promise for future potential in wound age estimation, offering objective and reproducible results with minimal human bias. AI models can estimate more accurately by examining histological markers and cellular reactions to determine how much time has passed since the injuries were incurred. This renders evidentiary findings from forensic analysis more meaningful during the legal process [11].

Digital pathology, combined with artificial intelligence, has demonstrated remarkable potential in differentiating between healthy and diseased tissues, as well as between benign and malignant tumors, by utilizing large, annotated datasets and sophisticated image analysis methods. For instance, Kather et al. (2019) used deep learning algorithms to differentiate between normal and cancer types of histological images in various cancers with high accuracy, emphasizing the capability of AI to identify subtle morphological variations that human observers might miss [12]. Similarly, Coudray et al. (2018) developed a deep learning algorithm capable of subtype classification of non-small-cell lung cancer and predicting genetic mutations from histopathological images, thereby highlighting the accuracy of AI in tumor classification and determination of malignancy status [13].

2.3. Virtual autopsy and 3D imaging

Digital pathology is also significant in the context of virtual autopsies, whereby sophisticated post-mortem imaging devices, including computed tomography (CT) and magnetic resonance imaging (MRI), augment traditional autopsy practice [14, 15]. The aforementioned imaging techniques are non-invasive and enable forensic pathologists to observe internal anatomy in three dimensions, thereby allowing an overall assessment of injury, fracture, and pathological changes without extensive dissection. Integrating AI-based analysis significantly contributes to the objectivity and accuracy of virtual autopsies by detecting subtle pathological features that might not be seen in conventional assessments [14–16].

Forensic use of 3D imaging has numerous advantages. It allows for the reconstruction of complex anatomy, enabling the performance of holistic evaluations of traumatic injuries, including bone fractures, organ injury, and bleeding. Three-dimensional images can also serve as compelling evidence in court, enabling judges and jurors to clearly understand forensic evidence. Virtual autopsies are especially useful in cases where the bodies are badly burned or decomposed and cannot be easily examined by conventional histological analysis. The combination of CT, MRI, and image analysis based on AI enables the detection of internal traumas and pathological changes that would otherwise remain undiagnosed, enhancing the accuracy of post-mortem diagnoses. Three-dimensional imaging also enables the preservation and documentation of criminal evidence, ensuring that digital records can be accessed and re-examined for future reference or re-investigation in court [15–17].

2.4. Telepathology and global collaboration

Telepathology has been further enhanced by digital pathology, enabling real-time consultation and collaboration among forensic experts worldwide. It is particularly conducive for institutions in resource-constrained regions, where expert forensic pathologists may be scarce or inaccessible. Forensic experts can review high-definition digital slides remotely through secure, cloud-based systems, debate complex findings, and collaborate on complex cases. Cross-border collaboration enhances the accuracy and consistency of forensic diagnoses, as well as the overall quality of medico-legal autopsies [18].

Moreover, telepathology enhances the uniformity of forensic practices by allowing expert knowledge to flow across borders. Telepathology enables the procurement of more assessments from international experts, thereby enhancing the reliability of autopsy findings and expert opinions in court. Telepathology also supports collaborative research activity among institutions by procuring unusual and sophisticated forensic cases, enhancing forensic science knowledge, and helping drive standardized procedures in digital forensic pathology [19].

Standardized naming conventions for slides and proper image storage times are key elements of digital pathology for traceability, interoperability, and regulatory acceptability. Following the Digital Imaging and Communications in Medicine (DICOM) standards, Supplement 145, slide identifiers must adhere to a standard nomenclature to enable uniform data management and sharing among systems [20]. For the storage of images, clinical environments often require storage for 10 years or more to meet medical record-keeping statutes, while forensic and research environments may require storage for an indefinite period, particularly when images serve as legal evidence or are part of long-term research data. Cloud-based storage solutions, such as DICOM-compliant standards, provide secure, scalable, and efficient archiving to accommodate these varied requirements [21].

2.5. Specific examples of digitally identified tissue pathology or diagnosis

In digital pathology, there has been significant improvement in diagnostic precision and productivity across different types of tissues. The FDA-cleared Paige Prostate AI platform, for instance, demonstrated high sensitivity (97.7%) and specificity (99.3%) in detecting prostate adenocarcinoma in whole-slide images, enabling rapid diagnosis and reducing reliance on additional immunohistochemical studies [22]. Similarly, deep learning algorithms have been successful in detecting invasive ductal carcinoma (IDC) of the breast with an accuracy of 85% using convolutional neural networks, enabling early diagnosis and precise therapeutic planning [23]. In colonic disease, machine learning algorithms applied to image analysis on CT colonography have accurately distinguished between premalignant and benign polyps. A random forest model, for instance, had an area under the receiver operating characteristic curve of 0.91, thus enhancing non-invasive follow-up and risk stratification protocols [24]. In addition, high-resolution digital imaging has played a critical role in forensic neuropathology in evaluating hypoxic–ischemic damage in infant brain tissue in suspected abusive head trauma to allow for extensive tissue examination and specialist advice, thus enhancing medico-legal diagnostic accuracy [25–27].

3. Applications of digital pathology in forensic medicine

3.1. Cause of death determination

Digital pathology plays a crucial role in elucidating the cause of death by enabling accurate and reproducible analysis of tissue specimens [28]. In poisoning, infection, and sudden unexpected death, whole-slide imaging (WSI) with artificial intelligence-guided evaluations enables detailed investigations of histopathological changes at the cellular level. Computer-aided quantifying tissue changes, such as inflammatory cell infiltrations, necrosis, or toxic substance deposits, markedly enhances the accuracy of medico-legal diagnosis. Digital archiving also facilitates the preservation of histopathological evidence, enabling retrospective analysis and re-evaluation, which may be decisive in complex or contentious cases [28, 29].

3.2. Injury pattern recognition

WSI with AI-enabled analysis significantly enhances the detection and categorization of injury patterns. The technology can discriminate between post-mortem and ante-mortem injuries by identifying subtle histopathological features, such as inflammatory reactions and tissue responses that reflect vitality. In the evaluation of suspected homicide, abuse, or trauma-related death, image analysis with AI also increases objectivity and standardization of wound evaluation [30]. Digital pathology can be further integrated with 3D imaging modalities to provide paths of injury and enable accurate reconstruction, thereby enhancing the quality of evidence in legal proceedings [28–30].

3.3. Toxicology and drug-related deaths

Digital pathology has emerged as an indispensable tool in the diagnosis of drug abuse-related deaths and poisoning cases. Pathologists can use high-resolution imaging and AI-based image analysis to identify subtle histopathological signs of toxic exposure, including cellular degeneration, tissue hypoxia, and vascular structural changes. Through digital image analysis, it is possible to quantify these changes, thereby enhancing the accuracy and reliability of toxicology-related diagnoses. Digital pathology also allows for the integration of histological findings with toxicological analysis, thereby providing a comprehensive analysis of the causative conditions and circumstances of death in illicit drugs, prescribed medication, and environmental toxins [30].

3.4. Forensic education and telepathology

Digital pathology has transformed forensic training and telepathology by offering access to extensive online databases and virtual case archives. These databases enable pathology trainees and forensic practitioners to access uncommon and challenging cases remotely, thereby enhancing their diagnostic expertise and familiarity with diverse forensic situations. Cloud-based platforms supported by telepathology enable real-time consultation with global forensic experts, facilitating collective case reviews and second opinions. This is especially useful in areas with limited specialized forensic pathology experience availability. Moreover, electronic repositories of intricate forensic cases are helpful teaching resources for training programs, continuing medical education (CME), and research partnerships, ultimately leading to the development of forensic medicine standards and practices [19].

4. Challenges in implementing digital pathology in forensic medicine

At the core of all this, the application of digital pathology (DP) in medical examiners' and coroners' offices has always been a challenging issue. The main obstacles include the admissibility of digital pathology evidence in court cybercrime disputes, which raises difficulties in this area, but primary among them will be the illicit nexus between the two [31]. The Indian legal system, as well as many others, requires courts to use forensic evidence, thereby guaranteeing the credibility, coherence, and reliability of this evidence. Presently, the application of digital slides and AI-assisted histopathological interpretations in courtrooms is met with skepticism due to the lack of protocols that verify the use of digital evidence [32, 33]. These challenges lead to an absence of guiding principles for legal practitioners about accepting digital pathology as a conventional proof of forensic evidence. Regulators and forensic institutions in India must develop coherent procedures for procuring, storing, and displaying digital slides to maintain their reliability in court and medico-legal practice. In addition to this, the specialists should demonstrate their pathology slides are real without editing or counterfeiting them. Therefore, they can be said to have the same diagnostic accuracy as glass slides, satisfying the requirements established by law [31–34].

Data security and privacy are additional concerns, especially when handling sensitive post-mortem data. The Digital Personal Data Protection Act (DPDPA) of 2023 in India mandates stringent provisions regarding the collection, storage, and processing of personal data, including forensic evidence. Compliance with such provisions is necessary to avoid unauthorized usage, breaches, and covertly destroying the integrity and security of personal locked-away forensic data [35]. Modern digital pathology methods need the most potent encryption technology, access control mechanisms, and data trail auditing to protect the confidentiality and integrity of forensic data. Moreover, cloud-based telepathology apps used in online consultations must adhere to strict data-sharing regulations to avoid cross-border issues that could compromise the legal admissibility of evidence [30, 32].

The cost and infrastructure limitations of digital pathology are substantial and specific to forensic institutions in low-resource settings, such as those in India. The initial investment in whole-slide imaging (WSI) scanners, high-end servers, and artificial intelligence-based diagnostic software is significant. In addition, the requirement for continuous software updates, increased data storage capacity, and maintenance contributes to the total operational costs [36]. Forensic institutions supported by public funding often face financial constraints, which limit their ability to fully adopt digital pathology (DP) technologies. To overcome this challenge, government programs and funding are essential to offset the costs of digitization for forensic laboratories. In addition, public–private partnerships (PPPs) could overcome the financial hurdles, making the widespread adoption of DP in forensic medicine feasible [15–17].

Another major challenge is the reluctance of traditional pathologists to embrace digital pathology, as they remain comfortable with conventional microscopy methods. Switching from glass slides to digital media requires a paradigm shift in forensic practice, which is often met with suspicion [2]. Pathologists may feel that this change compromises haptic feedback and direct visual interaction, which they equate with diagnostic accuracy and precision. In addition, the steep learning curve associated with learning new digital tools, such as whole-slide imaging (WSI) platforms and artificial intelligence-based image analysis, can further contribute to resistance to embracing digital pathology workflows [4, 5]. To counter this resistance, it is essential to implement all-encompassing training programs coupled with ongoing professional development (CPD) programs. Indian forensic hospitals and medical schools are encouraged to incorporate digital pathology into their curriculum to acclimatize future forensic pathologists to this technology from an early stage. Practical workshops and certification programs in digital forensic streams can further underpin acceptance and skill acquisition among practicing pathologists.

5. Future directions of digital pathology in forensic pathology

The future evolution of digital pathology in forensic medicine is expected to undergo a revolutionary shift with the convergence of artificial intelligence (AI), blockchain technology, multi-omics data, and global forensic networks. These technologies have the potential to significantly enhance the accuracy, efficiency, and reliability of forensic investigations, thereby overcoming current limitations.

The ongoing development of AI-assisted forensic analysis and automation will have a profound impact on the future of digital pathology. Deep learning models are designed to enable cause of death determinations through automated analysis by identifying complex histopathological patterns that correlate with a wide range of pathological processes. Through reduced workload for forensic pathologists, AI-fortified systems can accelerate diagnostic procedures and reduce the frequency of human error. Additionally, predictive models are being developed to estimate the time since death more accurately by evaluating large datasets of post-mortem histopathological and biochemical alterations. These AI-assisted tools are poised to provide objective, data-driven insight into post-mortem examinations, thereby enhancing the accuracy of forensic diagnoses [37].

Blockchain technology is a significant step in preserving the integrity and traceability of digital pathology data during forensic analysis. With the creation of immutable digital slides and chain-of-custody records, blockchain enhances the integrity and legal acceptability of digital evidence presented in court. Blockchain technology provides a secure channel for authenticating expert consultations, peer review, and forensic reports [38]. Furthermore, applying blockchain to timestamp digital slides enables protection from data tampering, thereby providing uniform reliability of forensic evidence in the long term. The application of blockchain technology to forensic medicine promises increased transparency and fosters increased trust in digital forensic processes [38, 39].

Integrating digital pathology and multi-omics data is a paradigm shift in forensic medicine. Multi-omics methods enable broader analysis of post-mortem alterations, encompassing genomics, proteomics, and metabolomics [40]. Through the correlation of histopathological information with molecular data, forensic pathologists can better understand the mechanisms of death, toxicological effects, and individual susceptibility to trauma [1, 9–11]. For example, integration of metabolomic profiles with histology of liver tissue can increase the detection rate of drug-related deaths. In contrast, proteomic profiling of heart tissue can enable myocardial infarction identification as a cause of death. Integrating histopathology and molecular science can potentially enable more accurate and personalized forensic examinations, which are more advanced than traditional morphological examinations [41].

Establishing global digital forensic networks and cloud-based collaboration platforms is most likely to fundamentally revolutionize cross-border forensic investigations. Cloud-based repositories can serve as centralized digital forensic case file databases, enabling the real-time sharing of digital slides, AI-based analyses, and expert reports. Such an integrated system would be especially valuable in mass disaster scenarios, where rapid and coordinated forensic interventions are essential. International cooperation would also aid efforts towards standardization by enabling the sharing of forensic expertise and the establishment of standardized diagnostic criteria [30–33, 36–40]. These networks can also aid forensic training by providing access to rare and complex case collections, thus enhancing knowledge sharing and continuous professional development among forensic professionals worldwide. Key technologies currently used in digital pathology and applicable to forensic medicine are listed in **Table 1**.

Table 1 • Key technologies used in digital pathology.

Technology	Core application	Reference
Whole-Slide Imaging (WSI)	High-resolution digitization of slides for analysis and sharing	Kumar N et al. (2020) [4]
Artificial Intelligence and ML	Automated tissue classification, injury recognition, wound aging	Hanna MG et al. (2025) [9]
3D Imaging and Virtual Autopsy	Non-invasive internal visualization of trauma and pathology	Cergan R et al. (2025) [17]
Telepathology	Remote consultation and collaborative diagnosis	Parwani AV et al. (2025) [18]
Cloud Storage and Digital Archiving	Secure, scalable, and retrievable storage of digital slides	Matias-Guiu X et al. (2025) [36]
Blockchain for Data Integrity	Tamper-proof chain of custody and authentication of forensic digital evidence	Xie Y et al. (2025) [39]
Multi-Omics Integration	Linking histology with genomics/proteomics to improve cause-of-death analysis	Spooner A et al. (2025) [40]

6. Conclusions

Digital pathology is revolutionizing forensic medicine, offering increased diagnostic accuracy, process efficiency, and improved coordination. With high-definition imaging, AI-based analysis, and telepathology, it optimizes forensic processes and enhances the consistency of medico-legal evaluations. However, problems such as legal admissibility, data security concerns, and inadequate infrastructural facilities are slowing its wider adoption. A key part would be to create standard operating procedures, legal guidelines, and specialized training modules to ensure the admissibility and reliability of digital forensic evidence in a legal process.

New technologies, such as AI-based diagnostics, blockchain-based data integrity, and multi-omics integration, will further enhance the potential of digital pathology. These technologies will aid in more accurate post-mortem analysis, enhance the determination of cause of death, and improve the quality level in forensic investigations. With the advancement of the field, the application of these technological innovations will be the key for the forensic agencies to respond to the increasing demands of contemporary medico-legal practice and provide reliable and accurate forensic services.

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Conflict of interest

The authors declare no conflicts of interest.

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