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The evolving role of DICOM in digital pathology

Toby C. Cornish [a,*], Shubham Dayal [b], David Ferber [b], Joseph Chiweshe [b], Robert Monroe [b]

[a] Department of Pathology, Medical College of Wisconsin, Milwaukee, WI 53226, USA
[b] Leica Biosystems Richmond Inc., Deer Park, IL 60010, USA

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ABSTRACT

Digital pathology has emerged as a technology with the potential to transform anatomic pathology by enabling remote consultation, computational analysis, streamlined workflows, and more efficient archival of histopathology slides. Interest in digital pathology has steadily grown as health practitioners increasingly recognize its potential to enhance patient care. In the United States, at least 10 whole slide scanners have been cleared or approved by the Food and Drug Administration (FDA), reflecting a growing confidence in this technology. However, widespread adoption has been hampered by the continued proliferation of proprietary, vendor-specific whole slide image formats that limit interoperability between systems. Whereas commonly used whole slide image formats, such as SVS, iSyntax, BIF, MRXS, and NDPI, have proven adequate for siloed deployments, they are less well-suited for integration into enterprise imaging solutions. The Digital Imaging and Communications in Medicine (DICOM) standard, which revolutionized radiology over three decades ago, offers a vendor-neutral whole slide image format that enables seamless exchange of images and metadata across systems, supporting efficient workflows, accurate diagnosis, and secondary use such as artificial intelligence research. This article discusses the use of DICOM in digital pathology, the key benefits it provides, the clear need for digital pathology vendors to adopt it as a native storage format, and other opportunities and barriers to adoption. As digital pathology matures and computational pathology applications proliferate, DICOM adoption represents a critical step toward an interoperable, vendor-neutral imaging ecosystem.

Background

Central to the practice of anatomic pathology is the microscopic examination of stained tissue sections to diagnose disease. For over a century, this process remained fundamentally unchanged: tissue specimens were fixed, sectioned, mounted on glass slides, and examined using a conventional light microscope. In the late 1990s, a new technology—whole slide imaging—permitted a glass slide to be digitized in an automated fashion, creating a high-resolution image.[1] The application of whole slide imaging to clinical practice subsequently became known as "digital pathology," which the Digital Pathology Association (DPA) defines as "a dynamic, image-based environment that enables the acquisition, management, and interpretation of pathology information generated from a digitized glass slide."[2]

Whole slide images (WSIs) offer significant advantages over glass slides. Digital pathology facilitates diagnostic consultation by allowing pathologists across institutions to readily share and analyze the same WSI, enabling access to expert opinion and increasing diagnostic confidence. Additionally, digital images are easier to store, retrieve, archive, and track than physical slides. Finally, WSIs provide a substrate for the development and adoption of artificial intelligence (AI) and other types of advanced computational techniques to support diagnosis, prognosis, quality assurance, and biomarker analysis. While ereas the potential impact of whole slide imaging was recognized early, initial iterations of the technology were not ready for clinical deployment. Instead, slide scanning hardware and software for storing, transmitting, and viewing WSIs matured in the research setting, where it became a well-established and valued technique for reviewing, sharing, and analyzing slides.

Demand for digital pathology has increased significantly in the last decade. This growth has been driven in part by the first Food and Drug Administration (FDA) approval[3] of a digital pathology system in 2017 and subsequent validation studies demonstrating the non-inferiority to conventional light microscopy for routine diagnosis.[4–8] Adoption accelerated further during the COVID-19 pandemic, as pathologists turned to telepathology for remote case review, with the support of regulatory bodies such as the FDA and Centers for Medicare & Medicaid Services, who provided temporary Clinical Laboratory Improvement Amendments waivers and enforcement discretion for remote case sign-out.[9,10] The digital pathology market continues to grow steadily[11] with a global revenue of approximately $550 million in 2020 and projected revenue of $2 billion in 2027[12]—a 260% increase.

* Corresponding author at: Department of Pathology, Medical College of Wisconsin, 9200 W. Wisconsin Avenue, Milwaukee, WI 53226, USA.
E-mail address: tcornish@mcw.edu (T.C. Cornish).

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As the digital pathology industry grew, each vendor entering the market developed its own WSI file format. Whereas most vendor-specific formats offer similar capabilities, none of them are directly interoperable, making sharing and working with WSIs unnecessarily difficult.[13] For example, training robust machine learning (ML) algorithms requires large datasets comprising thousands of images; when these are acquired from different scanning systems, format heterogeneity must be resolved before training can proceed. Similar issues affect inference from trained models. Likewise, laboratories integrating scanners from multiple vendors must accommodate disparate file formats within their clinical systems. Furthermore, if WSIs must be shared externally between institutions, proprietary image formats may complicate or even preclude exchange.[14–17] Faced with these challenges, the digital pathology community, like radiology before it, recognized the need for a vendor-neutral framework to share, view, archive, retrieve, and analyze whole slide digital images.[18,19]

The radiology community confronted analogous challenges in the 1980s as digital imaging modalities proliferated and became essential to the standard of care.[20–22] The solution, the Digital Imaging and Communications in Medicine (DICOM) standard, has since become ubiquitous, enabling seamless image exchange across vendors and institutions worldwide. Digital pathology now faces a similar inflection point. This review examines the application of DICOM to whole slide imaging, assessing its technical implementation, clinical workflow integration, current adoption status, and remaining barriers to widespread use.

Historical development of the DICOM standard

The widespread adoption of digital imaging modalities in radiology, including magnetic resonance imaging (MRI), computed tomography (CT), and digital radiography, created an urgent need for interoperability. Images produced by one manufacturer's equipment could not be read by another's system, necessitating costly duplication and limiting the potential for networked image distribution. In response, the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) jointly developed a standard for digital image communication, publishing initial versions in 1985 and 1988.[20,21]

The third version of the ACR-NEMA standard, released in 1993 and formally designated DICOM, represented a fundamental advance. DICOM introduced a comprehensive data model, standardized file format, and network communication protocols that enabled true device interoperability.[20] Over the subsequent three decades, DICOM achieved near-universal adoption in radiology, becoming the foundation upon which picture archiving and communication systems (PACS) and vendor-neutral archives (VNAs) were built.[23] As the standard matured, its use expanded well beyond radiology into cardiology, ophthalmology, dermatology, and other imaging-intensive specialties, ultimately establishing DICOM as the backbone of enterprise imaging across modern healthcare.

The extension of DICOM to pathology required substantial adaptation. Radiology images are typically measured in megabytes, rendered in grayscale, and stored at a single resolution. WSIs, by contrast, can exceed several gigabytes, require full RGB color fidelity, and must be stored in multi-resolution pyramidal formats to enable efficient navigation. The original DICOM specification lacked mechanisms for tiled storage, region-based retrieval, or multi-resolution representation—all of which are essential for microscopy workflows.

Supplement 145, ratified in 2010, addressed these limitations by defining the Visible Light (VL) Whole Slide Microscopy Image Information Object Definition (IOD), enabling DICOM to represent the large, tiled, multi-resolution images characteristic of digital pathology. Working Group 26 (WG-26), the DICOM committee responsible for pathology imaging, has continued to refine and extend the standard to better accommodate digital pathology. More recently, Supplement 222 introduced[24] a framework for microscopy bulk annotations, addressing the need to store and exchange the geometric markup and algorithmic outputs increasingly central to computational pathology workflows. A timeline of important events in the development of DICOM, leading to its application in DP, is provided in Fig. 1.

Technical architecture of DICOM whole slide images

Pyramidal image representation

WSIs pose unique challenges for digital storage, transmission, and interoperable viewing due to their size, resolution, and multi-resolution structure. A single slide scanned at 40× equivalent magnification may contain billions of pixels, far exceeding what can be practically loaded into memory or transmitted as a monolithic file for remote viewing. To address this, WSI formats—both proprietary and DICOM—employ a pyramidal, tiled architecture.

To meet these needs, the DICOM standard defines a dedicated image model, the VL Whole Slide Microscopy Image IOD. In this model, the full-resolution image is divided into a grid of tiles, typically 256 × 256 or 512 × 512 pixels each. Additional pyramid levels are generated by downsampling, with each successive level containing fewer tiles representing progressively larger regions of the slide at lower resolution (Fig. 2). This structure enables efficient random access: a viewer application only needs to retrieve the specific tiles required for the current field of view and zoom level, rather than loading the entire image. When present, focal-plane (z-stack) layers can also be incorporated within this framework, allowing multiple tiles to be stored for the same spatial location at different depths.

DICOM represents this structure using a multi-frame image object, where each tile corresponds to a single frame. Frame indexing and spatial coordinates are encoded in standardized attributes, enabling any compliant

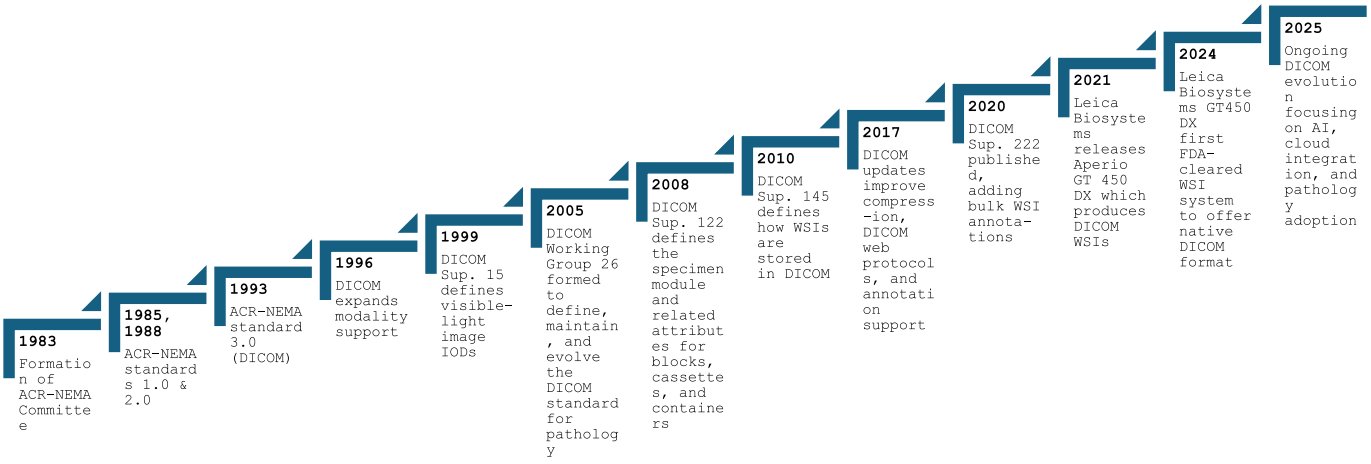

Fig. 1. Milestones in the development and use of DICOM in pathology.

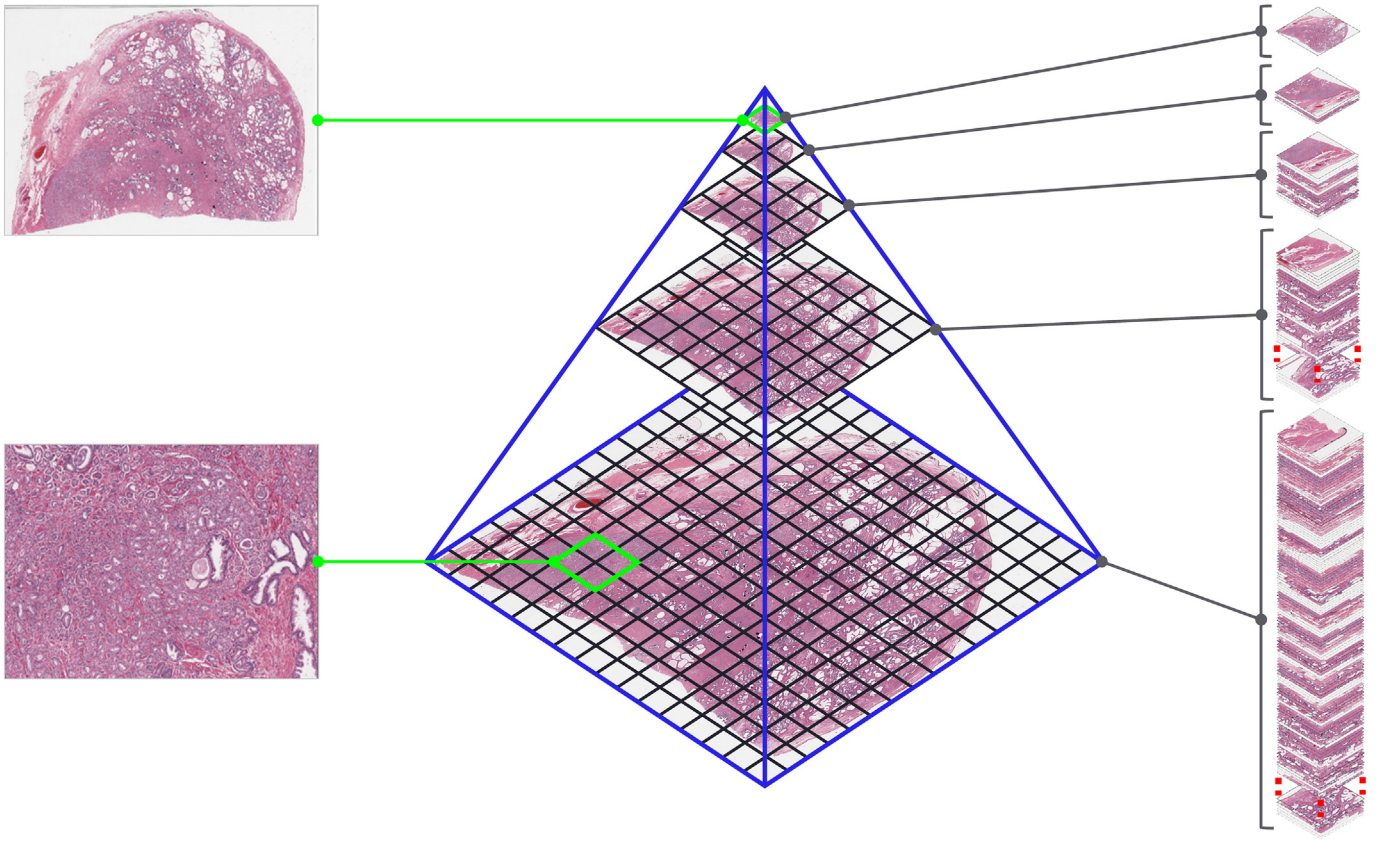

Fig. 2. The DICOM whole slide image structure. Center: A DICOM whole slide image is represented as a multi-resolution pyramid, with the base corresponding to the full-resolution image and progressively smaller, lower-resolution levels above it, culminating in an overview or thumbnail. Intermediate levels provide additional resolution steps. Each level is subdivided into small regions, or tiles. Right: Every tile is stored as a separate frame within the multi-frame DICOM object. Left: A DICOM viewer retrieves only the specific tiles needed to render the user's current field of view, enabling efficient navigation and zooming.

viewer to reconstruct the image geometry. The model also supports additional dimensions, such as focal depth (Z) or imaging channels (optical paths), through the Dimension Organization and Dimension Index sequences, allowing viewers to navigate z-stacks or multi-channel images using the same multi-frame structure. The relationships between pyramid levels are explicitly defined, ensuring consistent navigation behavior across implementations. A DICOM WSI object can be persisted to disk using the standard DICOM Part-10 File Format (.dcm), allowing for easy storage and exchange of WSIs.

Series organization and associated images

A complete DICOM representation of a scanned slide typically comprises multiple objects organized within a single series. The primary object contains the multi-resolution tissue image, whereas the label image and a macro image are stored as separate DICOM instances but linked by a common series identifier (Table 1). These companion images are stored as separate DICOM objects (and thus separate .dcm files) but are linked to the primary WSI within the same study and series. The inclusion of these associated images provides parity with proprietary file formats and mirrors the information pathologists rely upon when handling physical slides, facilitating quality assurance workflows in digital systems.

Metadata framework

A distinguishing feature of DICOM is its comprehensive metadata model. Each DICOM object contains structured header information encoded as standardized data elements, encompassing patient demographics, study and series identifiers, acquisition parameters, and specimen-specific attributes. For pathology, relevant metadata includes specimen type, anatomic site, staining protocol, and optical acquisition parameters such as objective magnification and focal plane position. This metadata is populated from the laboratory information system (LIS) or electronic health record (EHR) through HL7 messaging or DICOM worklist queries.

Mapping pathology's specimen identity hierarchy into DICOM requires alignment between laboratory and imaging data models. In the DICOM model for pathology, patient and case information are represented at the Patient and Study levels, respectively, with the accession number serving as the primary case-level identifier. The Specimen module, defined within the VL Whole Slide Microscopy Image IOD, describes the physical entities being imaged. The container, typically the glass slide, is described at the root dataset level by the Container Identifier and Container Type Code Sequence attributes. The tissue sections on the slide are described within the nested Specimen Description Sequence, which encodes each specimen's unique identifier, type, anatomic site, and laterality using coded

Table 1
Components of a DICOM whole-slide image series.

Object	Content	Purpose	Image type
Primary WSI	Multi-resolution pyramidal tissue image (one or more VOLUME instances per level)	Diagnostic review and analysis	VOLUME
Label image	Photograph of slide label	Specimen and stain identification/verification	LABEL
Macroimage	Low-magnification slide overview	Navigation, tissue localization	OVERVIEW

terminology. Critically, the Specimen Preparation Sequence records the chain of processing steps (fixation, embedding, sectioning, and staining), linking each imaged section back to its parent block and originating specimen.[19] This hierarchical model enables traceability from the scanned image back through the block, specimen part, and case, ensuring that identity is preserved as images move from scanner to archive to viewer. However, populating these attributes completely and consistently requires tight integration between the LIS and the scanning system, typically through HL7 messaging or DICOM Modality Worklist queries. This integration remains inconsistently implemented across vendor platforms.

DICOM also provides standardized mechanisms for protecting patient privacy when images are used outside the clinical environment. Part 15 of the DICOM standard defines a set of de-identification profiles that specify how individual attributes should be handled, including removal, replacement with dummy values, or retention. The Basic Application Level Confidentiality Profile provides a baseline set of rules, whereas supplementary options (such as Retain Patient Characteristics, Retain Longitudinal Temporal Information, and Retain Safe Private Option) allow institutions to balance privacy protection with the preservation of attributes needed for specific research or clinical purposes. For WSIs, de-identification requires additional considerations beyond metadata, because protected health information (PHI) may also be present in label and macro images that are captured as part of the scanning process. Approaches to addressing this include removing or redacting label and macro image objects, pixel-level scrubbing of burned-in text, or replacing them with de-identified surrogate images. Secure transmission of DICOM objects is supported through Transport Layer Security encryption for both DIMSE and DICOMweb connections, and access control can be enforced at the archive level through standard authentication and authorization mechanisms.

As in radiology, the DICOM object attributes should reference standardized terminologies such as SNOMED CT,[25] which is utilized by DICOM authorities for coding specimen and tissue concepts.[25] Likewise, to ensure color consistency across WSIs, the use of a common color profile, such as those defined by the International Color Consortium (ICC), is strongly encouraged. These steps help ensure that digital pathology images are reproducible and maintain consistent visual quality across devices and vendors.

Difference between DICOM use in radiology and digital pathology

The application of DICOM to pathology differs substantially from its radiology origins, reflecting fundamental differences in image characteristics and clinical workflows (Table 2). Radiology DICOM adoption benefited from immediate economic drivers—elimination of film costs and physical storage—that do not directly translate to pathology, where glass slide archives must often be maintained regardless of digital adoption. The infrastructure investments required for pathology are correspondingly higher: greater storage capacity, faster network connectivity, and specialized viewing applications capable of efficiently navigating gigapixel images.

Table 2
A comparison of DICOM for digital pathology and radiology.

Parameter	Radiology	Digital pathology
Typical image size	5–200 MB (per study)	500 MB–5 GB (per slide)
Color model	Grayscale (predominantly)	RGB color
Storage structure	Single-frame, row-based	Multi-frame, tiled pyramid
Format adoption	Universal adoption of DICOM	Proprietary formats dominant; DICOM emerging
Vendor support	Native DICOM output standard across vendors	Limited; one FDA-cleared DICOM-native scanner to date (Leica GT450 with Sectra)
Worklist implementation	Standard practice	Inconsistent and partial implementation
Workflow maturity	Established streamlined workflow	Need to standardize workflow, including both viewing and storage of WSI file in DICOM format
Metadata source	Radiology information system (RIS)	Laboratory information system (LIS)
Primary economic driver	Film elimination and elimination of redundant information systems	Workflow efficiency, remote access, and implementation of computational pathology
DICOM maturity	>30 years, universal	~15 years, emerging

Interoperability using DICOM

One of the primary purposes of using DICOM is to achieve interoperability, enabling WSIs to be viewed and managed by any DICOM-compliant system. To support seamless information exchange, vendors must correctly implement the DICOM protocols, services, and data structures. In practice, some systems may include private attributes or optional features that other vendors do not interpret in the same way. All such identifiers must be documented in the vendor's DICOM conformance statement, which describes exactly how the device implements the standard, including supported SOP Classes, services, roles, transfer syntaxes, and any private extensions.[13,26] The DICOM Conformance Process, defined in Part 2 of the DICOM standard, provides the formal framework for vendors to declare the specific capabilities and behaviors of their implementations. A conformance statement is not merely a product specification; it is a structured, standardized document that enables institutions to systematically compare implementations and identify potential interoperability gaps before deployment. For digital pathology, where the ecosystem of scanners, archives, and viewers is still maturing, careful evaluation of conformance statements is particularly important. Institutions should verify that a vendor's conformance statement covers the VL Whole Slide Microscopy Image SOP Classes, the transfer syntaxes used for image compression, support for the Specimen module, and whether DICOMweb services are offered alongside or in place of traditional DIMSE. Discrepancies in supported optional attributes or private extensions between systems are a common source of interoperability failures that conformance review can help anticipate. As more vendors adopt DICOM for whole slide imaging, routine conformance evaluation should become a standard component of procurement and systems integration.[27]

To advance interoperability, leading digital pathology vendors coordinate with stakeholders to test DICOM-based information exchange. Much of this validation occurs through regular Connectathons and similar interoperability events organized by groups such as Integrating the Healthcare Enterprise (IHE) and DICOM WG-26.[8] These events provide a structured environment in which vendors can verify that their systems correctly implement the DICOM standard and interoperate with other DICOM-compliant tools. Beyond protocol-level interoperability, comprehensive validation of a digital pathology deployment should also address image-level concerns such as rendering fidelity, tile correctness, pyramidal navigation, *Z*-stack behavior, gross image linking, and annotation alignment.

DICOM working group 26 (WG-26)

WG-26 is the DICOM committee responsible for developing and maintaining the standards that support whole slide imaging and related digital pathology workflows. The group includes pathologists, imaging informaticians, academic organizations, and industry partners, who contribute domain expertise and technical guidance. WG-26 collaborates with external groups, the DPA, IHE, the National Cancer Institute, and others, to harmonize standards and promote interoperability across modalities. Updates to the digital pathology components of the DICOM standard are informed by vendor feedback, lessons learned from Connectathons, and emerging requirements arising from professional conferences, published literature, and technical advancements.

DICOM workflow

A standard WSI can be converted into a DICOM file set by a WSI management system (IMS), which then stores the resulting DICOM objects in a DICOM-compliant storage modality such as an IMS, PACS, or VNA. These objects can later be retrieved and reviewed using DICOM-capable

viewing software that supports WSIs (Fig. 3). When proprietary file formats are used, each stage of this process becomes more complicated due to vendor-specific restrictions, incompatible data structures, and inconsistent metadata. As demonstrated through Connectathons, however, DICOM enables vendors to interoperate around a standard communication and file specification, ensuring that image viewing, archiving, and retrieval functions perform consistently without the overhead of translating between multiple proprietary formats.[26] Studies have shown that this standards-based approach not only matches the capabilities of proprietary WSI formats but also facilitates metadata exchange.[26]

Communication services: DIMSE and DICOMweb

Two complementary communication paradigms exist for exchanging DICOM WSIs. The traditional DIMSE services—C-STORE, C-FIND, and C-MOVE—operate over dedicated network connections and have been widely deployed in radiology for decades, offering mature tooling and broad vendor support. However, DIMSE requires point-to-point connections between known peers and can be difficult to deploy across firewalls, cloud environments, and wide-area networks. DICOMweb addresses these limitations by providing a RESTful, HTTP-based interface through three core services: STOW-RS (storage), QIDO-RS (query), and WADO-RS (retrieval). For whole slide imaging, WADO-RS is particularly useful because it supports frame-level retrieval, allowing viewers to request individual tiles on demand rather than downloading an entire multi-gigabyte image. In practice, many deployments use both approaches: DIMSE for scanner-to-archive communication within local networks and DICOMweb for viewer access, remote consultation, and cloud-based workflows.

Integrating the healthcare enterprise (IHE)

To further advance interoperability, IHE[27] plays a central coordinating role across the medical imaging and laboratory domains. IHE develops integration profiles—implementation guides that specify how existing standards such as DICOM and HL7 should be used together to support consistent, interoperable clinical workflows (key DICOM terms are defined in Table 3).[28] These profiles reduce ambiguity in how systems exchange imaging, laboratory, and patient data, ensuring that vendors implement standards in compatible ways.

Within IHE, the Pathology and Laboratory Medicine (PaLM) domain focuses on workflows for anatomic pathology, clinical pathology, and LISs.[29] Several integration profiles are directly relevant to digital pathology. The

Table 3
Key terms related to DICOM.

Term	Definition
PACS	A picture archiving and communication system (PACS) is an image management and storage platform originally developed for radiology to handle modalities such as CT, MRI, and X-ray. With the adoption of the DICOM standard, PACS evolved into an enterprise-wide, interoperable system capable of storing and distributing images across multiple specialties. In digital pathology, PACS is increasingly used to manage DICOM whole slide images, providing centralized storage, retrieval, and viewing.
Conformance statement	A document that describes how a device implements the DICOM standard, detailing its supported services, SOP classes, roles, options, and communication behaviors to ensure interoperability.
IOD	An information object definition (IOD) is a DICOM specification that defines the required attributes, structure, and semantics for a particular type of imaging object, ensuring it can be interpreted consistently across systems.
DICOM WSI Object	A DICOM imaging object that represents a whole slide image using the VL Whole Slide Microscopy Image IOD, encoding tiled, multi-resolution pixel data along with slide, specimen, and optical-path metadata for interoperable viewing.
.dcm	The DICOM Part-10 File Format is the on-disk file format used to store a single DICOM instance. Any DICOM object, including WSI, can be written as a .dcm file; however, whereas DICOM objects are required for workflows, the file format is not required when objects are transmitted directly over the network or using web-based workflows.
HL7	A standardized messaging framework for developing interfaces that exchange clinical information between systems, such as EHRs, LISes, and PACS, enabling interoperable communication across healthcare applications.
IHE	Integrating the Healthcare Enterprise (IHE) is a collaborative initiative that developed profiles and standards to improve the interoperability of healthcare information systems, enabling consistent data exchange across diverse clinical applications and modalities.
VNA	A vendor-neutral archive (VNA) is a centralized storage system that manages both DICOM and non-DICOM imaging data and serves as a neutral platform between imaging sources and viewing systems, enabling consistent access across departments and vendors. VNAs are especially useful in large institutes that require unified storage of diverse imaging formats.
WG-26	Working Group 26 (WG-26) is the DICOM committee focused on digital pathology. It develops and maintains the standards needed to support whole slide imaging and related workflows. Its members include pathologists, academic experts, and industry representatives collaborating to advance DICOM adoption in pathology.

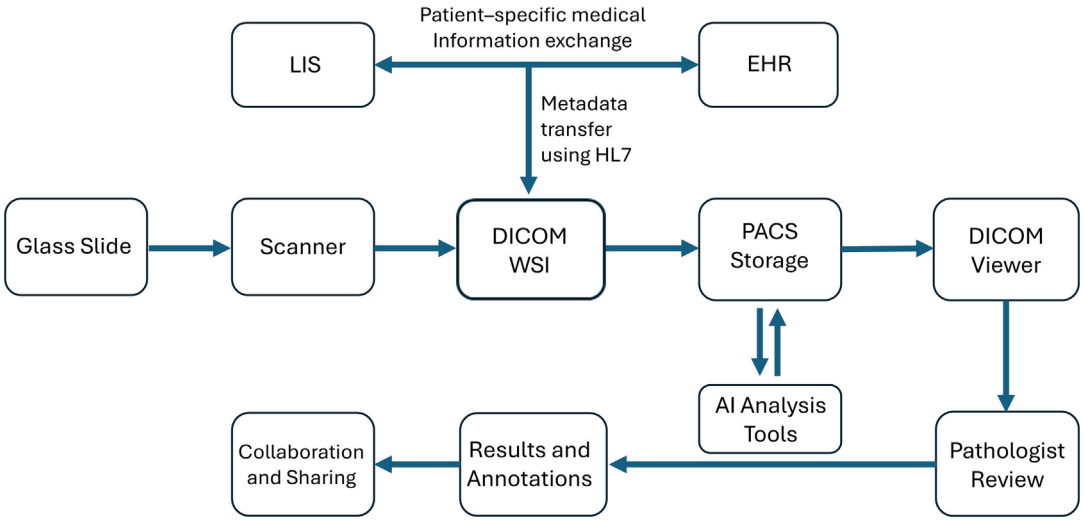

Fig. 3. DICOM workflow in Digital Pathology. LIS, laboratory information system; EHR, electronic health record; PACS, picture archiving and communication system; AI, artificial intelligence.

original Anatomic Pathology Workflow profile defined transactions for ordering, imaging, and reporting across surgical pathology, cytopathology, and clinical autopsy. More recently, the Digital Pathology Workflow Image Acquisition profile specifies how the LIS communicates work orders to slide scanners via HL7 v2 messaging, how scanners store DICOM WSI objects in an archive via C-STORE, and how viewers retrieve images for display via DICOMweb. The Anatomic Pathology Structured Report content profile complements these workflow profiles by defining a machine-readable format for encoding diagnostic observations using standardized terminology. Additional profiles addressing digital pathology ordering and reporting, image ordering, and evidence creation (e.g., AI-generated analytical results) have been outlined for future development.[30] Each profile defines specific actors and transactions within the PaLM Technical Framework; readers considering local implementation are directed to the current framework documentation for detailed specifications.[30] As these profiles mature and vendors adopt them, they will play a central role in enabling reliable, end-to-end interoperability for whole slide imaging, building on lessons learned from radiology, where IHE integration profiles have been widely adopted.

Annotation standards and DICOM supplement 222

Image annotations—geometric markup delineating regions of interest, diagnostic findings, or algorithmic outputs—are increasingly central to digital pathology workflows. They serve many purposes: documenting the pathologist's diagnostic reasoning, highlighting features for tumor board discussion, providing ground truth for ML training, and encoding the outputs of computational analysis algorithms. Historically, however, each vendor has implemented its own annotation format, using XML, JSON, or binary data written to proprietary annotation files alongside the native WSI file or stored in a proprietary database. The lack of standards for encoding and storing WSI annotations has made them difficult to share, compare, or reuse across platforms. This fragmentation impedes collaboration, complicates AI results in restricted interoperability, which complicates ingesting and output by AI tools and hinders archiving within enterprise imaging systems.

To address these challenges, DICOM WG-26 introduced Supplement 222, defining a standardized, scalable model for storing bulk microscopy annotations that supports both human-generated markup and the large, complex outputs produced by modern computational pathology algorithms.[24] The supplement supports multiple annotation types: point sets, polylines, polygons, ellipses, and segmentation masks. Critically, it accommodates the scale of modern computational pathology, where algorithms may generate millions of annotations per slide, far exceeding what earlier DICOM annotation mechanisms could efficiently support. Another useful annotation tool is the parametric map, which can be used to encode heat maps for visualizing the output of AI algorithms.

A related DICOM technology that complements geometric annotations is structured reporting (SR). SR objects complement geometric annotations by encoding quantitative measurements, classification results, and other algorithmic outputs in machine-readable form. When combined with standardized terminology codes, these reports enable automated downstream processing, for example, extracting biomarker scores for clinical decision-support or populating synoptic reports.

Benefits of the DICOM format in healthcare and specifically pathology

The DICOM standard is foundational in modern healthcare, addressing the complex requirements of medical imaging data management and exchange. It provides a uniform framework that ensures interoperability between imaging devices and information systems, enabling efficient and accurate handling of both images and associated patient data. Acting as a common language, DICOM allows devices from different manufacturers to communicate seamlessly, ensuring that images generated by one system—whether WSI, MRI, CT, ultrasound, or others—can be displayed and interpreted by DICOM-compliant systems across an institution or between facilities. By eliminating data silos, DICOM improves access to imaging information for pathologists, radiologists, cardiologists, and other clinicians, regardless of location.

DICOM also enhances clinical collaboration. By enabling whole slide imaging and other modalities to be shared between providers, DICOM supports rapid consultations, second opinions, multi-disciplinary case reviews, and access to specialized expertise. This capability is particularly valuable in rural or resource-limited settings where subspecialists may not be locally available.

Standardization of image storage, transmission, and retrieval further streamlines diagnostic workflows. DICOM supports interoperable network communication protocols (e.g., C-STORE, C-FIND, C-MOVE, and DICOMweb), allowing scanners to send images directly to a PACS or to cloud-based storage, making them available for immediate access. In an integrated environment, the LIS can communicate order information to a scanner using HL7 or IHE profiles, after which the resulting DICOM images can be automatically archived and associated with the correct case in the EHR. These capabilities reduce delays, support quality control, promote patient safety, and enhance the accuracy of diagnostic workflows.

DICOM also supports scalability across large hospital networks or regional healthcare systems and facilitates integration of digital pathology into the broader enterprise imaging ecosystem. Scanners at multiple sites can transmit DICOM-compliant WSIs to a shared enterprise PACS or VAN, providing consistent access to digital slides across laboratories and campuses. This is particularly useful for hospitals with satellite labs or those collaborating in research or referral networks, as DICOM ensures that images are universally accessible without requiring custom integrations for each site. Furthermore, integration into enterprise imaging solutions allows digital pathology to benefit from economies of scale and network effects.

Finally, the DICOM file format is better suited for long-term retention of WSIs. Unlike proprietary formats that rely on continued vendor support, DICOM format will remain standardized and openly documented, qualities that promote long-term readability and accessibility. This is particularly important given regulatory retention requirements in anatomic pathology. The College of American Pathologists requires that WSIs be retained for at least 10 years when the original glass slides are unavailable, and local, state, or institutional policies may mandate even longer retention periods, particularly for pediatric specimens. Beyond clinical and regulatory needs, WSIs are increasingly retained for research, education, quality assurance, and AI development, often for durations that exceed mandated retention periods. DICOM's standardized structure and rich metadata support reliable archiving, retrieval, and traceability over extended timeframes, helping institutions meet both regulatory obligations and long-term research and innovation goals within the digital pathology workflow.

Table 4 summarizes these and other benefits of DICOM compared to proprietary file formats.

DICOM fosters innovation

DICOM provides a strong foundation for advanced technologies like computational pathology, AI, and ML. By standardizing how images and metadata are stored and exchanged, DICOM facilitates the aggregation of large, diverse, multi-institutional datasets that are essential for training and validating AI models. Its structured metadata—including patient demographics, specimen details, acquisition parameters, and annotations—supports that algorithms can use to sort, access, and interpret images quickly. Metadata with image data during training significantly boosts ML performance.

Beyond standardization, DICOM incorporates mechanisms for de-identifying PHI, ensuring compliance with ethical and legal frameworks while safeguarding patient privacy during research and AI development.

Within clinical workflows, DICOM's structured metadata can also drive automation. For example, urgency indicators or specimen attributes can support intelligent case prioritization via worklists, trigger computational workflows, or support quality control mechanisms. This standardized framework not only supports advanced image analysis and predictive

Table 4
DICOM whole-slide images offer advantages relative to proprietary formats.

Category	Advantages of DICOM for WSI	Limitations of proprietary formats
Interoperability	Vendor-neutral standard enabling images to be viewed and processed across scanners, viewers, archives, and AI tools.	Vendor-specific formats limit cross-platform compatibility and often require conversion.
Workflow integration	Readily integrates with PACS/VNA, DICOM Modality Worklist, LIS/EHR systems within enterprise imaging.	Often isolated within proprietary ecosystems and requires custom interfaces for LIS/EHR/PACS linkage.
Scalability and longevity	Supports enterprise storage and long-term stability due to a mature, widely adopted, and enduring standard.	Format longevity depends on vendor support; risk of obsolescence.
Metadata standardization	Structured metadata model for specimen, optical path, and acquisition parameters.	Metadata content varies across vendors and may be incomplete or proprietary.
Tile retrieval and web access	Enables DICOMweb-based tile retrieval (WADO-RS, QIDO-RS, and STOW-RS) for modern web and cloud workflows.	Tile access often depends on proprietary APIs or SDKs.
Ecosystem compatibility	Compatible with enterprise and universal viewers, PACS/VNAs, and multi-modality imaging workflows.	Often restricted to vendor-specific viewing tools and infrastructure.
Artificial intelligence support	Standardized structure facilitates AI model ingestion; supports DICOM annotation objects.	AI workflows must accommodate multiple incompatible formats; annotations remain vendor-specific.
Governance and compliance	Supports de-identification, access control metadata, and standardized audit capabilities.	Compliance features vary and may require custom solutions.
Data exchange and collaboration	Standard format simplifies cross-institutional data sharing and research collaboration.	Sharing requires conversion that may result in lost or incomplete metadata.

modeling but also lays the foundation for enhanced diagnostic accuracy, streamlined processes, and more personalized patient care.

As healthcare technology evolves, DICOM continues to adapt innovations such as cloud-based imaging and the Internet of Medical Things. These advancements further improve data accessibility, interoperability, and scalability, allowing laboratories to expand their digital infrastructure without being constrained by proprietary systems. In short, DICOM's adaptability and robust design make it indispensable for the future of AI-enabled healthcare.

Challenges to DICOM adoption

Despite its advantages, questions remain about the clinical application of DICOM in digital pathology. Much of this uncertainty stems from the relative newness of DICOM WSI support and its limited adoption. One challenge is ensuring reproducible image display across digital pathology systems. Although DICOM enables interoperability, the consistency of WSI rendering across different viewers has not been extensively tested.[31] Hence, image display consistency is an important parameter that should be tested. NEMA recommends that, to ensure consistent DICOM image display across systems, images should be calibrated and encoded in accordance with the standards established by the DICOM Committee.[32]

Whereas radiology images are typically required to conform to the Grayscale Standard Display Function (GSDF), no equivalent standard for color display currently exists within the DICOM framework for digital pathology. This absence has potential clinical implications. GSDF ensures that differences in tissue density are rendered with perceptually uniform contrast across compliant radiology displays regardless of vendor or hardware generation. In pathology, however, diagnostic interpretation depends on accurate rendering of histochemical stain colors. Without a standardized color display function, variations in display calibration may influence the perception of stain intensity, nuclear detail, and color contrast between tissue components. Studies have shown that uncalibrated displays can introduce measurable color variation that affects diagnostic confidence and contributes to inconsistent image presentation across viewing stations.[33,34] These issues are particularly relevant for telepathology and multi-site deployments, where diagnostic reproducibility depends on consistent image rendering across geographically distributed systems.

The display represents the final stage of the imaging chain at which DICOM data are interpreted by the pathologist, yet minimum technical specifications for diagnostic pathology monitors remain incompletely defined. Key parameters that influence image fidelity include luminance, contrast ratio, color bit depth, spatial resolution, and display calibration. For example, luminance levels near 300 cd/m^2 have been suggested to approximate the visual experience of a conventional microscope, contrast ratios of at least 1000:1 support differentiation of dark and bright image regions, and higher color bit depth (e.g., 10-bit panels) improves rendering of subtle chromatic gradients in stained tissue.[35–37] Maintaining display performance over time also requires hardware-level calibration and color management, typically implemented using ICC color profiles and periodic quality assurance testing.[33,38] The development of a consensus color display standard—analogous to GSDF but tailored for color microscopy images—remains an important area for future work and could improve cross-system reproducibility in digital pathology.

A related technical barrier is the limited availability of open libraries capable of reading and writing the full DICOM pyramidal image structure file format,[13] thereby inhibiting adaptability of source code across vendors. Converting legacy images, which are most often stored in TIFF-based formats, into DICOM also presents challenges. To ease this transition, DICOM provides a “dual-personality” capability that allows TIFF data to be embedded within a DICOM file, enabling the same file to function both as a valid TIFF and a valid DICOM object.[39,40] This approach offers a pragmatic migration path: existing TIFF-based software can continue to read the file using conventional TIFF libraries, whereas DICOM-aware systems can access the standardized metadata and services provided by DICOM. However, the dual-personality approach is not a durable long-term solution. The TIFF layer does not enforce the DICOM-defined structured metadata model, and metadata written via the DICOM interface may not be visible or interpretable via the TIFF pathway. This creates the potential for inconsistencies between the two representations of the same image. In addition, maintaining compatibility with both formats may increase file size and complexity while reducing incentives for vendors to adopt fully native DICOM workflows. For these reasons, dual-personality files are best viewed as a transitional migration mechanism that supports backward compatibility with legacy TIFF-based software. Over time, transitioning to native DICOM workflows remains the preferred strategy, allowing laboratories to fully leverage standardized metadata, interoperability, and network-based services within the DICOM ecosystem.

Fully converting native file formats into DICOM is a challenge that still requires significant financial and engineering resources. In addition to image data, legacy files frequently lack standardized or complete metadata for tissue, specimen, staining, and acquisition parameters. As a result, metadata must be reconstructed, inferred, or manually mapped during conversion, increasing the risk of inconsistencies and making it difficult to achieve fully compliant DICOM objects. These issues highlight the need for better tools and clearer metadata-mapping strategies to enable reliable, accurate conversion workflows. Switching workflows to native DICOM images as soon as feasible prevents the accumulation of technical debt incurred by legacy file formats.

Another challenge in implementing DICOM standards is ensuring that the system architecture used for PACS integration is modern and equipped with the necessary tools to prevent security breaches that may compromise patient data. Some argue that aspects of the file format itself need modernization to eliminate legacy constraints and better support future digital pathology workflows,[33,41] whereas others suggest that any potential concerns with the DICOM format are far outweighed by the gains in interoperability —even if further harmonization and improvements are required.[31,35] In all cases, regular engagement among stakeholders will be essential to

optimizing DICOM's capabilities and establishing a trusted, interoperable foundation for improved patient care and efficient enterprise imaging.

Current adoption landscape

Despite compelling advantages, DICOM adoption in digital pathology remains limited compared to radiology. A 2024 survey of predominantly European pathologists found that non-DICOM formats remain dominant, with proprietary formats like SVS (58.5% of respondents) and MRXS (40% of respondents). Only 11% of participants reported routine use of DICOM-format images, similar to NDPI.[42] Additionally, all the participating pathologists pointed out that interoperability and common file sharing, regardless of the imaging system, will substantially enhance medical diagnosis efficiency in digital pathology.[42]

Regulatory and commercial developments signal accelerating progress. In 2024, the Aperio GT 450 DX, became the first—and to date, only—whole slide imaging system to receive FDA clearance[37] for native DICOM output in addition to the Leica SVS format (Table 5).[37] The FDA clearance specifically uses the Aperio GT 450 DX scanner with Sectra's digital pathology module (3.3) viewing software to generate, manage, and view the DICOM-compliant WSIs.[38] In 2025, Philips announced that its upcoming Pathology Scanner SGi will also support native DICOM, although this scanner is not yet available for purchase nor is it FDA cleared or CE marked.[39] The current generation of Philips scanners and Intellisite software, which use the iSyntax format, are capable of exporting a DICOM file. Other vendors, including 3DHISTECH, Hamamatsu, Roche, and Pramana are also able to produce a DICOM file using conversion software, add-on modules, or middleware solutions. The hope is that, in the years to come, more manufacturers will adopt native DICOM in their digital pathology workflows.

Future direction

The trajectory toward widespread adoption of DICOM in digital pathology is closely aligned with the broader digital transformation of pathology workflows. As laboratories expand their use of whole-slide imaging, enterprise imaging platforms, and computational tools, the need for a standardized, interoperable format becomes increasingly urgent. DICOM provides this foundation, and recent developments indicate growing momentum. WG-26's ongoing work, including the establishment of the WSI Annotation Ad-Hoc Group (AHG), reflects recognition that modern pathology workflows will increasingly depend on sophisticated, AI-driven processes. Standardized representation of annotations, metadata, and acquisition parameters will be essential for reproducibility, algorithm validation, and multi-institutional research.[25] The AHG is a great start that should be followed by workgroups that expand the standard to support additional aspects of pathology workflows.

Table 5
Almost all FDA-cleared or approved systems still produce a proprietary image file format.

Vendor	Scanner	File format(s)	FDA 510 k/De Novo
Leica Biosystems	Aperio GT 450 DX	SVS and DICOM	K232202[43]
Leica Biosystems	Aperio AT2 DX	SVS	K190332[44]
Hamamatsu	NanoZoomer S360MD	NDPI	K213883[45]
Roche	VENTANA DP 600	BIF	K242783[46]
Roche	VENTANA DP 200	BIF	K232879[47]
Epredia	E1000 DxDigital Pathology Scanner	MRXS	K241717[48]
Philips	Ultra Fast Scanner (UFS)	iSyntax	DEN160056[49]
Philips	Pathology Scanner SG20	iSyntax	K233204[50]
Philips	Pathology Scanner SG60	iSyntax	K233204[50]
Philips	Pathology Scanner SG300	iSyntax	K233204[50]

Among the areas warranting attention from future workgroups, two stand out. First, the development of a color display standard for pathology—analogous to radiology's GSDF—would define requirements for consistent, reproducible color rendering across viewing stations, addressing a gap that currently limits diagnostic reproducibility in multi-site and multi-institution telepathology environments. Second, the standardization of semantic annotations and SR for pathology workflows represents an important opportunity. Whereas Supplement 222 enables standardized storage of geometric annotations and parametric maps can encode algorithm outputs, DICOM currently offers limited support for semantically rich annotations linking morphological findings to standardized terminology (such as SNOMED CT) or for structured pathology reports containing diagnostic conclusions, biomarker results, and synoptic data. Extending the standard in this direction would improve data reuse, research interoperability, and integration of computational pathology results into clinical systems. Whereas the adoption of the DICOM standard in digital pathology has been gradual, clear indicators point to accelerating progress. Industry leaders actively participate in regular Connectathons, fostering collaboration and technical refinement. Regulatory milestones, such as FDA approval of DICOM-compliant whole slide imaging scanners, underscore growing confidence in the standard. Coupled with the broader trend toward healthcare digitization and enterprise imaging, these developments signal that DICOM standardization is poised for significant growth.

As acceptance deepens within the scientific and clinical communities, the availability of DICOM datasets will expand, enabling more rigorous testing and iterative improvements through collaborative events and educational forums. Leading organizations are championing openness to drive adoption. For example, Leica Biosystems, following FDA clearance of its GT 450 DX scanner with native DICOM output, has chosen not to enforce licensing restrictions on its patented imaging module, an approach that encourages interoperability and innovation across the ecosystem.

The trajectory is clear: DICOM is evolving from a technical standard into a cornerstone of digital pathology, paving the way for scalable, interoperable solutions that enhance diagnostic accuracy, streamline workflows, and support AI-driven advancements in patient care.[51,52]

Conclusion

DICOM provides a unified, interoperable framework for storing, transmitting, and integrating WSIs across clinical systems. Adoption of the DICOM file format is the essential on-ramp to leveraging the broader DICOM ecosystem and embracing the promise of enterprise imaging in pathology. Although adoption in digital pathology is still emerging, the healthcare community increasingly recognizes its potential to transform diagnostic workflows. To fully realize these benefits, coordinated action by all interested parties is required (see Fig. 4).

- Vendors must incorporate DICOM specifications across scanning, archiving, and viewing systems while ensuring secure handling of PHI. Adoption of DICOM as a native output format reduces long-term integration costs for customers, broadens market access by enabling compatibility with enterprise imaging infrastructure, and positions products favorably for institutional procurement processes that increasingly require compliance with standards.
- Pathologists should advocate for DICOM-compliant systems and ensure that DICOM capabilities are reflected in technical requirements. Because scanner purchases represent long-term infrastructure commitments, a requirement for native DICOM output, conformance statements covering the VL Whole Slide Microscopy Image SOP Classes, and DICOMweb support creates a durable incentive for vendors to prioritize standards compliance. Prioritizing interoperability helps guarantee that WSIs integrate cleanly with PACS, VNA, LIS, and AI tools. Pathologists should also promote the use of interoperable metadata in research and AI development to support scalable, reproducible workflows.
- Regulators and Standards Organizations should collaborate with industry and clinical stakeholders to promote consistent use of DICOM and related

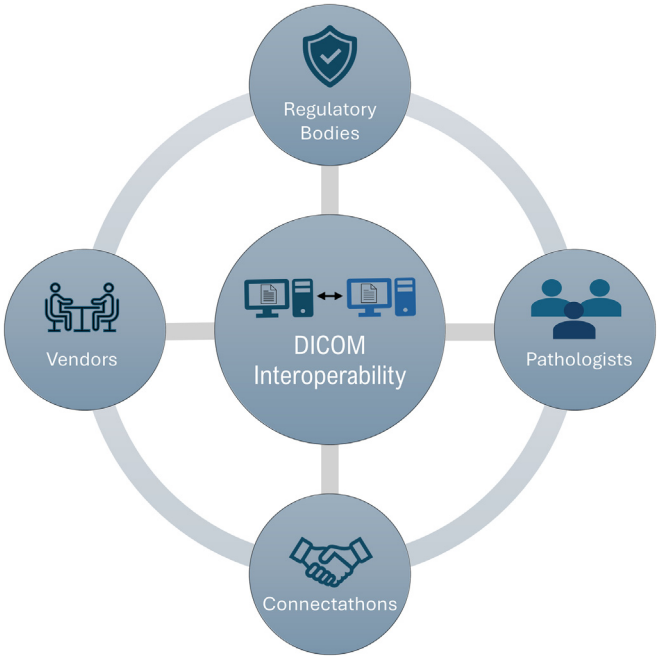

Fig. 4. Collaboration among regulatory bodies, vendors, and pathologists, along with open testing in Connectathons and discussion at conferences, will accelerate DICOM standardization in digital pathology.

interoperability standards in device design, validation, and documentation. Aligning products with established standards reduces ambiguity in submissions, facilitates more predictable and efficient regulatory review, and supports the safe, scalable integration of digital pathology and AI technologies into clinical practice.

- Stakeholders must participate in Connectathons and establish educational efforts to validate interoperability, accelerate improvement of the standard, and support and encourage broader adoption by vendors and laboratories.

Through shared commitment and collaboration, DICOM can evolve from a technical specification into a cornerstone of digital pathology—enabling interoperable, scalable, AI-ready solutions that enhance diagnostic accuracy, streamline workflows, and ultimately improve patient care.

Declaration of competing interest

TC is a member of the Leica Biosystems Scientific Advisory Board, a member of the Roche Diagnostics Steering Committee for Digital Pathology, and Co-chair of the Publications Committee for the Association for Pathology Informatics, the sponsoring society of the *Journal of Pathology Informatics*. This role did not influence the editorial review or decision-making process for this manuscript. SD, DF, JC, and RM are full-time employees of Leica Biosystems.

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