



Review Article

Preparing the Future Laboratory Workforce for Intelligent Diagnostics: The Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF)

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Abstract

Background: Artificial intelligence (AI) is rapidly transforming laboratory medicine by integrating it into diagnostic interpretation, digital pathology, molecular diagnostics, laboratory automation, quality management systems, and predictive analytics. While AI competency frameworks have emerged across health professions education, most existing models have been developed from physician-centered or general healthcare perspectives and provide limited guidance regarding the specific educational requirements of laboratory medicine professionals. As intelligent technologies become increasingly embedded within diagnostic workflows, the absence of a discipline-specific competency framework represents an important educational gap with implications for workforce preparedness, professional accountability, and responsible AI implementation.

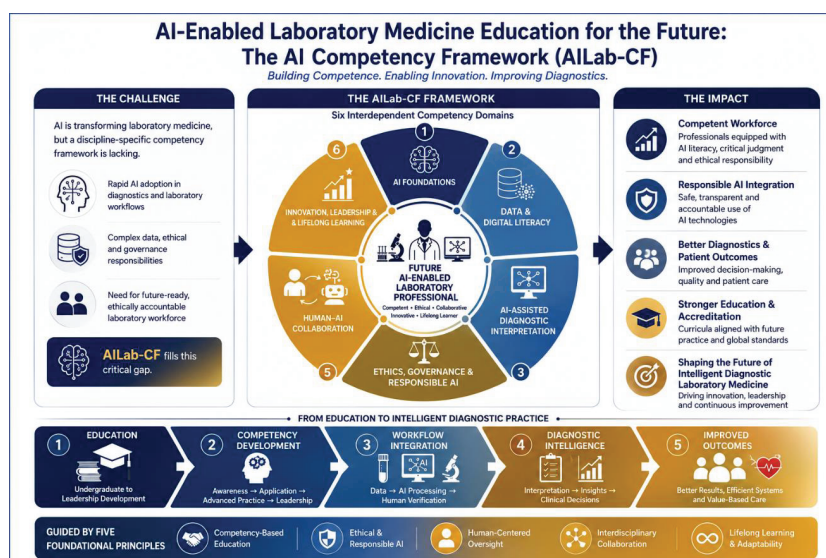
Objective: To develop a competency-based educational framework specifically designed to prepare current and future laboratory medicine professionals for safe, effective, ethical, and responsible practice within AI-enabled diagnostic environments.

Methods: A conceptual framework-development approach was used. The framework was constructed through an iterative critical synthesis of literature and established concepts in artificial intelligence, laboratory medicine, digital health, health professions education, competency-based education, data governance, and responsible AI. The work was not conducted as a systematic review, and no retrospective systematic-search procedure is claimed. Existing frameworks and guidance documents already identified during framework development were compared for scope, target population, competency emphasis, developmental structure, and relevance to laboratory practice; recurring concepts and laboratory-specific gaps were then translated into candidate principles, competency domains, developmental descriptors, and implementation elements, followed by iterative refinement for conceptual coherence and practical applicability.

Results: The Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF) was developed as a comprehensive competency architecture consisting of six interdependent domains: (1) AI Foundations, (2) Data and Digital Literacy, (3) AI-Assisted Diagnostic Interpretation, (4) Ethics, Governance, and Responsible AI, (5) Human-AI Collaboration, and (6) Innovation, Leadership and Lifelong Learning. The framework is supported by five foundational educational principles and incorporates a four-level developmental continuum comprising awareness, application, advanced practice, and leadership. In addition, a longitudinal implementation model was developed to facilitate integration across undergraduate education, internship training, postgraduate education, continuing professional development, and leadership pathways. Collectively, these components provide a structured approach to curriculum development, competency assessment, faculty development, workforce planning, and lifelong learning within AI-enabled laboratory medicine.

Discussion: AILab-CF addresses an important gap in health professions education by offering a laboratory medicine-specific competency architecture for AI-enabled diagnostic practice. In contrast to predominantly physician-oriented, healthcare-wide, or general digital-health frameworks, AILab-CF explicitly connects laboratory data stewardship, diagnostic validation and interpretation, human oversight, responsible governance, interdisciplinary collaboration, and lifelong professional adaptation. The framework is proposed as a conceptual model requiring future expert consensus and empirical validation.

Conclusions: The transition toward AI-enabled laboratory medicine requires professionals who can combine technical competence with critical judgment, ethical accountability, and continuous adaptation. AILab-CF provides a structured educational foundation to prepare the future laboratory workforce for intelligent diagnostics and may serve as a guide for curriculum reform, workforce development, and the responsible implementation of AI technologies across laboratory medicine.



Graphical Abstract

Abbreviations

AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education; AI/ML: Artificial Intelligence / Machine Learning; CPD: Continuing Professional Development; DL: Deep Learning; HPE: Health Professions Education; LIS: Laboratory Information System; ML: Machine Learning; MSc: Master of Science; NLP: Natural Language Processing; WHO: World Health Organization;

Introduction

The AI transformation of healthcare

Artificial intelligence (AI) has emerged as one of the most transformative technological developments in modern healthcare, fundamentally reshaping how clinical information is generated, analyzed, interpreted, and translated into patient care. Recent advances in machine learning, deep learning, natural language processing, computer vision, and generative AI have accelerated the evolution of healthcare from traditional data-driven models toward increasingly intelligent, predictive, and adaptive systems [1-10]. These developments are no longer confined to experimental settings and have become increasingly integrated into routine clinical practice across diverse specialties, including radiology, pathology, oncology, surgery, primary care, and population health management [6,8,10].

The growing influence of AI is largely attributable to its ability to process vast quantities of heterogeneous data, identify complex relationships that may not be readily apparent to human observers, and generate actionable insights to support clinical decision-making. Contemporary AI systems are increasingly applied to image interpretation, disease classification, prognostic modeling, clinical risk stratification, workflow optimization, and healthcare resource management. [6,8,10] Consequently, AI is increasingly viewed not simply as a technological tool but as a foundational infrastructure that influences virtually every stage of healthcare delivery [10-15].

The expansion of AI has simultaneously generated profound implications for health professions education. Historically, healthcare curricula evolved in environments where clinical expertise depended primarily on human knowledge, experience, and professional judgment. However, contemporary healthcare professionals are increasingly expected to interact with algorithmic systems, critically evaluate AI-generated outputs, understand principles of data-driven decision support, and maintain appropriate oversight of intelligent technologies [1,2,5,16-20]. These changing expectations have stimulated growing international interest in defining the competencies required for safe, effective, ethical, and responsible engagement with AI-enabled healthcare systems [1-5].

Recent educational scholarship reflects this shift. Multiple competency frameworks have emphasized AI literacy, digital health capabilities, data stewardship, ethical reasoning, and technology-enabled decision-making as emerging requirements for future healthcare practice [1-5]. Despite this growing consensus, substantial uncertainty remains regarding how such competencies should be structured, taught, assessed, and integrated into existing educational programs. Furthermore, most currently available frameworks have been developed from physician-centered or general healthcare perspectives, resulting in considerable variability in how AI education is conceptualized across healthcare disciplines [1-5].

Taken together, these developments suggest that AI represents not only a technological transformation but also an educational transformation. The challenge facing health professions education is no longer whether AI will influence healthcare practice. Still, the question is how educational systems can prepare future professionals to engage critically, ethically, and effectively with increasingly intelligent healthcare environments [1-5,21,22]. This challenge is particularly relevant in disciplines characterized by intensive data generation, extensive automation, and increasing reliance on computational decision-support systems. Among these

disciplines, laboratory medicine occupies a uniquely important position [6,7].

The transformation of laboratory medicine

Laboratory medicine has historically been among the most data-intensive disciplines in healthcare. Advances in automation, molecular diagnostics, genomics, flow cytometry, digital pathology, and laboratory information systems have dramatically expanded both the volume and complexity of laboratory-generated information [6,7]. Contemporary laboratories increasingly function as major generators of clinically actionable data that influence diagnosis, prognosis, therapeutic selection, disease monitoring, and population health management [6,8].

Unlike many clinical environments where AI is primarily used as a decision-support technology, laboratory medicine is witnessing the integration of AI directly into analytical and interpretive workflows. Machine learning algorithms are increasingly incorporated into hematology analyzers, digital morphology systems, molecular diagnostic pipelines, laboratory automation platforms, and quality management processes [6-9]. In hematology, AI-assisted technologies support blood cell classification, abnormality detection, digital smear interpretation, and predictive diagnostic modeling [7,9]. Similar developments are occurring within molecular diagnostics and digital pathology, where AI contributes to disease classification, biomarker discovery, and precision medicine initiatives [8,10].

The growing integration of intelligent technologies is transforming the role of laboratory professionals. While traditional competencies related to specimen processing, analytical quality control, and result verification remain essential, contemporary practice increasingly requires expertise in data interpretation, algorithm evaluation, validation of AI-generated outputs, ethical oversight, and human-AI collaboration [6,7,11]. Consequently, laboratory professionals are progressively transitioning from roles centered primarily on analytical execution toward responsibilities involving the interpretation, governance, and responsible application of diagnostic intelligence [6,8].

As AI becomes embedded throughout laboratory workflows, educational programs must prepare graduates not only to operate intelligent systems but also to understand their capabilities, recognize their limitations, critically evaluate their outputs, and maintain professional accountability [1,2,6,7]. However, the degree to which current educational models adequately address these emerging requirements remains uncertain [1-5].

Educational gaps in existing competency frameworks

The rapid expansion of AI within healthcare has stimulated substantial scholarly interest in defining the competencies required for future healthcare professionals. Numerous organizations, academic institutions, and professional societies have proposed frameworks emphasizing AI literacy, digital

health capabilities, data stewardship, ethical reasoning, and technology-enabled decision-making [1-5]. Collectively, these initiatives have helped establish AI as an educational priority across health professions education.

Despite these advances, important limitations remain. Most existing competency frameworks have been developed from physician-centered or general healthcare perspectives and provide limited guidance regarding the distinctive educational requirements of laboratory medicine [1-5]. Although laboratory professionals increasingly interact with AI-enabled systems throughout diagnostic workflows, relatively little attention has been devoted to defining the competencies specifically required for AI-enabled laboratory practice [6,7].

This gap is particularly important because laboratory medicine occupies a unique position at the intersection of biological data generation, analytical interpretation, diagnostic validation, quality management, and clinical decision support [6,7]. Consequently, laboratory professionals must understand how algorithms interact with analytical systems, how AI models are validated, how data quality influences algorithmic performance, and how AI-generated outputs should be interpreted within complex diagnostic environments [6,8,11].

Existing frameworks also tend to emphasize conceptual awareness while providing limited guidance regarding practical implementation, competency progression, assessment strategies, and professional leadership [1-5]. As a result, uncertainty persists regarding how AI-related competencies should be integrated into laboratory medicine curricula and how learners should progress from foundational awareness to independent professional practice [21,22].

Rationale and objectives of the present framework

The present work was developed in response to the growing disconnect between the accelerating integration of artificial intelligence into laboratory medicine and the relative absence of educational frameworks specifically designed to prepare laboratory professionals for AI-enabled practice [1,2,6]. While intelligent technologies continue to transform diagnostic workflows, educational systems have evolved more slowly, creating a situation in which technological capabilities increasingly outpace competency development [1-5].

To address this challenge, I propose the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF). The overall conceptual architecture of the framework is illustrated in Figure 1, which conceptualizes AI-enabled laboratory professionalism as the integration of six interdependent competency domains informed by contemporary scholarship in AI literacy, digital health, responsible AI, and competency-based education [1-5,21,22].

The operational structure of these domains is summarized in Table 1, while detailed competency descriptions, expected learning outcomes, and professional capabilities are presented in Table 2 [1-5]. Together, these components provide a structured foundation for curriculum development, competency-based



Figure 1: The AILab-CF Conceptual Framework.

Description: The Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF) proposes six interdependent competency domains required for future AI-enabled laboratory professionals. The framework positions the learner at the center of competency development and emphasizes the integration of AI foundations, data and digital literacy, AI-assisted diagnostic interpretation, ethics and governance, human-AI collaboration, and innovation-oriented lifelong learning. Together, these domains provide a comprehensive foundation for competency-based curriculum development and workforce preparation in AI-integrated laboratory medicine. Created by the author.

Abbreviations: AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education.

Table 1: The AILab-CF Competency Matrix: This table presents the core competency matrix underpinning the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF). The matrix defines six interrelated competency domains required for preparing future laboratory professionals for AI-enabled diagnostic environments. Each domain is linked to representative competencies, learning outcomes, and assessment approaches that can support curriculum design, competency mapping, accreditation, and workforce development.

Domain	Sub-Competencies	Expected Learning Outcomes	Assessment Methods	Educational Activities
AI Foundations	AI fundamentals; ML; DL; model evaluation; algorithm interpretation	Explain AI principles and evaluate model performance	MCQs; oral exams; case discussions	AI seminars; technology demonstrations
Data & Digital Literacy	Data quality; governance; privacy; security; interoperability	Manage and interpret laboratory data responsibly	Data audits; practical exercises	Dataset review workshops
AI-Assisted Diagnostic Interpretation	Validation; decision support; error recognition	Critically evaluate AI-assisted findings	Case-based assessments	Digital morphology exercises
Ethics & Responsible AI	Bias; fairness; transparency; accountability; regulation	Apply ethical principles in AI-enabled practice	Reflective assignments	Ethics debates
Human-AI Collaboration	Oversight; communication; teamwork; escalation	Collaborate effectively with AI systems	Simulation exercises	Interdisciplinary simulations
Innovation & Leadership	Innovation; change management; implementation science; leadership	Lead AI-enabled improvement initiatives	Portfolio assessment	Innovation projects

Interpretive Note: The information presented in this table is intended to guide curriculum development, competency assessment, and workforce preparation. Institutions may adapt the content according to educational level, local priorities, accreditation standards, and available resources.

Abbreviations: AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education; ML; Machine Learning; DL; Deep Learning; CPD: Continuing Professional Development; MSc: Master of Science.

assessment, faculty development, workforce planning, and lifelong professional learning [1–5,21,22].

The specific objectives of this article are fourfold. First, I examine the educational implications of AI-driven transformation within laboratory medicine. Second, I identify the limitations of existing competency frameworks when applied to laboratory medicine education. Third, I propose a comprehensive competency framework tailored specifically to AI-enabled laboratory practice (Figure 1; Tables 1,2). Finally, I discuss how this framework may be implemented across

the laboratory medicine educational continuum to support future workforce development, competency progression, and professional leadership (Figure 2; Tables 3–5) [21–24].

By establishing a discipline-specific competency architecture grounded in contemporary educational theory and emerging AI scholarship, this work seeks to contribute to the ongoing evolution of health professions education and provide practical guidance for educators, institutions, accreditation bodies, and policymakers. Ultimately, the proposed framework aims to support the development of future

Table 2: Detailed Competency Domains: This table operationalizes each competency domain through knowledge, skills, professional behaviors, competency indicators, and learning activities. It translates the conceptual framework into observable educational expectations that can be directly integrated into curricula.

Domain	Knowledge	Skills	Professional Behaviors	Competency Indicators	Learning Activities
AI Foundations	AI terminology; ML; DL	Interpret outputs	Scientific curiosity	Explains model limitations	AI seminars
Data & Digital Literacy	Data governance	Data analysis	Responsible stewardship	Evaluates dataset quality	Dataset audits
AI-Assisted Interpretation	Diagnostic algorithms	Critical evaluation	Evidence-based judgment	Validates AI recommendations	Case review workshops
Ethics, Governance, and Responsible AI	Ethical frameworks	Risk assessment	Accountability	Identifies bias and governance risks	Ethics debates
Human-AI Collaboration	Human factors	Communication	Appropriate oversight	Escalates discrepancies appropriately	Simulation training
Innovation & Leadership	Change management	Leadership	Lifelong learning	Leads improvement initiatives	Innovation projects

Interpretive Note: The information presented in this table is intended to guide curriculum development, competency assessment, and workforce preparation. Institutions may adapt the content according to educational level, local priorities, accreditation standards, and available resources within AI-enabled laboratory medicine.

Abbreviations: AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education; ML: Machine Learning; DL: Deep Learning; CPD: Continuing Professional Development; MSc: Master of Science.



Figure 2: Competency Development Continuum.

Description: This figure illustrates the progressive development of AI-related competencies across four levels of professional maturation: Awareness, Application, Advanced Practice, and Leadership. The model demonstrates how learners evolve from foundational understanding of AI concepts to independent implementation, critical evaluation, and ultimately leadership of AI-enabled innovation within laboratory medicine. The continuum emphasizes the parallel growth of knowledge, technical skills, professional judgment, and leadership capacity. Created by the author.

Abbreviations: AI, Artificial Intelligence.

laboratory professionals who are not only technologically competent but also capable of exercising critical judgment, ethical responsibility, and adaptive leadership in increasingly intelligent diagnostic ecosystems [1–5,21–24].

Framework development approach

The AILab-CF was developed as a conceptual educational framework rather than as the product of a systematic review, Delphi study, or formal consensus exercise. The development process reflected the procedure actually undertaken and comprised four iterative activities. First, contemporary literature and established guidance already identified during manuscript development were critically synthesized across AI education, laboratory medicine, digital health, competency-based education, data governance, responsible AI, and workforce development. Second, existing healthcare and medical AI

competency frameworks were compared conceptually with the requirements of laboratory practice, focusing on target users, scope, data responsibilities, diagnostic interpretation, governance, human oversight, assessment, and longitudinal professional development. Third, recurring concepts were organized into two deliberately distinct layers: cross-cutting foundational design principles and observable competency domains. Candidate domains and descriptors were refined to minimize conceptual overlap and to retain laboratory-specific relevance. Fourth, the domains were mapped to developmental descriptors and educational stages to create an implementation-oriented architecture, with internal checks for consistency across the narrative, tables, and figures. This was an interpretive and iterative synthesis; no exhaustive database search, formal study-selection flow, quantitative evidence grading, or external stakeholder consensus was

Table 3: Competency Milestones Across Development Levels: This table outlines the progression of competency acquisition from awareness to leadership. It supports competency-based education and longitudinal learner assessment.

Domain	Awareness	Application	Advanced Practice	Leadership / Systems Responsibility
AI Foundations	Recognizes concepts	Applies concepts	Evaluates models	Leads AI strategy and policy
Data Literacy	Understands quality	Manages datasets	Evaluates governance	Develops governance policy
Diagnostic Interpretation	Recognizes outputs	Uses AI-supported interpretation	Validates recommendations	Establishes interpretation standards
Ethics & Governance	Understands issues	Applies principles	Evaluates risks	Leads governance frameworks
Human-AI Collaboration	Recognizes oversight role	Collaborates with AI	Manages workflows	Leads interdisciplinary teams
Innovation & Leadership	Appreciates innovation	Participates in improvement	Leads initiatives	Shapes future practice

Interpretive Note: The information presented in this table is intended to guide curriculum development, competency assessment, and workforce preparation. Institutions may adapt the content according to educational level, local priorities, accreditation standards, and available resources.

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Table 4: Educational Implementation Strategy: This table links competencies to educational stages, teaching methods, assessments, educational activities, and expected deliverables.

Educational Stage	Competencies	Teaching Methods	Assessment Methods	Educational Activities	Example Deliverables
Undergraduate	Foundations and literacy	Lectures; workshops	Exams	Introductory AI modules	Reflection report
Internship	Application skills	Supervised practice	Workplace assessment	Digital morphology exercises	Case portfolio
Residency/MSc	Advanced interpretation	Case-based learning	OSCEs; projects	Algorithm critique workshops	Validation report
CPD	Specialized competencies	Continuing education	Portfolios	Advanced AI certification	CPD portfolio
Leadership	Strategic competencies	Leadership programs	Impact evaluation	Institutional AI initiatives	Implementation roadmap

Interpretive Note: This table supports curriculum design, competency assessment, implementation planning, and workforce development within AI-enabled laboratory medicine education. Institutions may adapt the content according to educational level, local priorities, accreditation standards, and available resources.

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Table 5: Challenges and Mitigation Strategies for AI-Enabled Laboratory Medicine Education: This table summarizes implementation barriers, stakeholders, mitigation strategies, and implementation priorities.

Challenge	Educational Risk	Stakeholder	Mitigation Strategy	Priority Level
Rapid technological change	Curriculum obsolescence	Institutions	Continuous curriculum review	High
Limited faculty expertise	Variable teaching quality	Faculty	Faculty development programs	High
Ethical concerns	Unsafe AI use	Students & Faculty	Ethics-focused training	High
Data governance challenges	Misinterpretation	Institutions	Data literacy training	High
Resource limitations	Unequal implementation	Institutions	Scalable models	Moderate
Resistance to change	Poor adoption	All stakeholders	Change-management strategies	Moderate

Interpretive Note: This table supports curriculum design, competency assessment, implementation planning, and workforce development within AI-enabled laboratory medicine education. Institutions may adapt the content according to educational level, local priorities, accreditation standards, and available resources.

Abbreviations: AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education; ML: Machine Learning; DL: Deep Learning; CPD: Continuing Professional Development; MSc: Master of Science.

undertaken. Accordingly, AILab-CF should be regarded as a theory-informed proposal that now requires structured expert validation and empirical testing.

Why laboratory medicine requires a distinct ai competency framework

The growing body of literature addressing artificial intelligence competencies in healthcare reflects a broad recognition that future healthcare professionals must be prepared to function within increasingly digital, data-rich, and technology-enabled environments. Across medicine, nursing, public health, and allied health professions, multiple competency frameworks have emphasized the importance of AI literacy, digital health capabilities, data-informed decision-

making, ethical awareness, and technology-enabled practice [1-5]. These developments represent important progress toward preparing the healthcare workforce for the digital era. However, they also reveal a persistent assumption that a single competency framework can adequately address the educational requirements of highly diverse healthcare disciplines [1-5].

Such an assumption is increasingly difficult to justify. Healthcare professionals operate within substantially different technological environments, professional responsibilities, decision-making structures, and data ecosystems. Consequently, competencies developed for one professional context may not fully address the educational needs of another. This issue is particularly relevant in laboratory medicine, where interactions with intelligent technologies differ fundamentally

from those observed in many patient-facing healthcare disciplines [6,7].

Unlike physicians, who frequently encounter AI as a clinical decision-support tool, laboratory professionals increasingly interact with AI throughout the entire diagnostic pathway. Intelligent technologies may participate in specimen prioritization, image analysis, morphological classification, molecular interpretation, quality assurance, workflow optimization, predictive analytics, and result verification [6–9]. Consequently, AI frequently operates at the analytical core of laboratory medicine rather than at its periphery. Laboratory professionals, therefore, require competencies extending beyond general awareness of AI technologies and encompassing the ability to evaluate, validate, supervise, and govern AI-assisted diagnostic processes [6,7,11].

This distinction becomes particularly important because laboratory medicine occupies a unique position within contemporary healthcare systems. Modern laboratories generate enormous quantities of structured and unstructured data derived from hematology analyzers, molecular diagnostic platforms, flow cytometers, digital pathology systems, laboratory information systems, and increasingly complex multi-omics technologies [6–9]. These data streams constitute the informational foundation upon which many AI systems depend. Consequently, laboratory professionals frequently function not only as users of AI technologies but also as custodians of the data that drives algorithmic performance. This role introduces educational requirements in data stewardship, data quality assessment, interoperability, governance, and algorithmic accountability that are not consistently emphasized in existing healthcare competency frameworks [5,6,19].

A second distinguishing feature relates to diagnostic accountability. Although AI systems may assist with classification, prediction, interpretation, and prioritization, responsibility for diagnostic quality ultimately remains a professional obligation [11,13,17]. The increasing integration of AI into laboratory workflows, therefore, creates an educational imperative to ensure that practitioners possess sufficient expertise to critically evaluate algorithmic outputs rather than accepting them uncritically. Laboratory professionals must be capable of recognizing potential sources of error, understanding model limitations, identifying situations requiring additional human review, and maintaining appropriate oversight throughout diagnostic processes [11–17]. These responsibilities demand competencies that extend beyond technological familiarity and require the development of professional judgment, critical appraisal, ethical reasoning, and governance awareness.

Developments in precision medicine further reinforce the need for a dedicated educational framework. Advances in genomics, molecular diagnostics, digital pathology, and computational biology have transformed laboratory medicine into one of the most information-intensive disciplines within healthcare [6–10]. As AI technologies increasingly integrate diverse biological and clinical data sources, laboratory professionals must develop competencies enabling them to

interpret complex diagnostic information within broader clinical contexts. This requires a combination of analytical expertise, digital literacy, interdisciplinary communication, systems thinking, and evidence-based interpretation that is not adequately represented in many existing competency models [5,6,8].

Importantly, the educational implications of AI extend beyond knowledge acquisition. Effective engagement with intelligent technologies requires developing professional attitudes and behaviors that support responsible implementation. Transparency, accountability, ethical awareness, adaptability, lifelong learning, and human oversight have emerged as recurring themes across contemporary discussions of AI-enabled healthcare [11–17]. However, translating these principles into discipline-specific educational outcomes remains underdeveloped within laboratory medicine. Educational institutions, therefore, face the challenge of preparing learners not only to understand intelligent technologies but also to function responsibly within environments increasingly shaped by algorithmic decision-making [11,13,16].

The absence of a dedicated competency framework also creates practical challenges for curriculum design and educational governance. Without clearly defined competencies, educational programs may struggle to determine which AI-related topics to teach, how to assess learning outcomes, and how to evaluate competency progression across different stages of professional development. Similarly, faculty members may encounter uncertainty regarding educational priorities, instructional strategies, and assessment approaches. These challenges are compounded by the rapid pace of technological change, which further increases the need for structured and adaptable educational guidance [21–22].

For these reasons, laboratory medicine requires a distinct competency framework specifically tailored to AI-enabled professional practice. Such a framework should reflect the unique characteristics of laboratory diagnostics, address emerging responsibilities related to intelligent technologies, and provide educators with a practical structure for curriculum design, learner assessment, and workforce development. The proposed AILab-CF framework seeks to address these needs by integrating technological literacy, data stewardship, diagnostic interpretation, ethical governance, human oversight, interdisciplinary collaboration, and leadership development within a unified educational architecture (Figure 1; Tables 1–2) [1–5,6,11,21,22].

Rather than viewing AI as an additional technical subject appended to existing curricula, the present framework recognizes AI as a transformative force reshaping the nature of professional competence itself. Consequently, educational preparation must evolve accordingly. The future laboratory professional will require not only technical expertise but also the ability to work intelligently, critically, ethically, and collaboratively within increasingly AI-enabled diagnostic ecosystems. The foundational principles that underpin this educational vision are summarized conceptually in Figure

1, while the relationships among competency domains are operationalized in Tables 1,2 and further developed throughout the remainder of this framework [1-5,21,22].

Comparative positioning and novelty of AILab-CF

AILab-CF is intended to complement, not displace, existing AI and digital-health competency frameworks. Contemporary frameworks have made important contributions by defining broad AI literacy, digital-health capability, ethical awareness, and professional-development expectations across medicine and the wider health workforce. Their principal strength is generalizability across professions; however, this breadth can limit specification of competencies arising from the laboratory's distinctive position as both a generator of high-volume diagnostic data and a site of analytical validation, quality assurance, result verification, and downstream clinical interpretation. The novelty claimed for AILab-CF is therefore contextual and architectural rather than a claim that its individual competency concepts are unprecedented. It integrates established cross-professional themes with laboratory-specific responsibilities - including data provenance and quality, analytical and diagnostic validation of AI outputs, algorithm-related quality assurance, escalation of discrepant results, governance within laboratory workflows, and longitudinal adaptation to evolving diagnostic technologies. It also explicitly links these competencies to a set of cross-cutting design principles, developmental descriptors, assessment approaches, and implementation stages. This combination is proposed as a laboratory medicine-specific educational architecture that requires external consensus and empirical evaluation before it can be regarded as a validated standard.

Foundational principles of AI-enabled laboratory medicine education

Competency frameworks derive their educational value not only from the competencies they define but also from the principles that guide their design, implementation, interpretation, and long-term application. In the context of artificial intelligence, this distinction is particularly important because technological innovation often outpaces educational adaptation. Consequently, competency development cannot be reduced to the acquisition of technical knowledge alone. Rather, it must be grounded in an educational philosophy that balances technological capability with professional responsibility, patient welfare, scientific rigor, and ethical accountability [1-5,11-17].

The need for such a principled approach is especially evident within laboratory medicine. As intelligent technologies become increasingly embedded within analytical workflows, diagnostic interpretation, quality management systems, and decision-support processes, laboratory professionals must navigate increasingly complex relationships between human expertise and algorithmic assistance [6-10]. The educational challenge, therefore, extends beyond teaching learners how AI systems function. It also involves preparing them to determine when such systems should be trusted, how their outputs should be interpreted, what limitations may influence performance, and

how professional accountability should be maintained when intelligent technologies contribute to diagnostic decision-making [11-17].

To address these challenges, AILab-CF is guided by five foundational principles derived through conceptual synthesis of literature in artificial intelligence, laboratory medicine, digital health, competency-based education, healthcare governance, and responsible AI. These principles are not additional competencies, developmental stages, or derivation criteria. They function as cross-cutting design and interpretive principles that shape how every competency domain should be taught, assessed, and enacted. Patient-centered intelligence provides the overarching purpose; human oversight and professional accountability constrain the use of AI-assisted interpretation and collaboration; data stewardship informs data literacy and governance; ethical and regulatory responsibility applies across all domains; and continuous adaptation provides the temporal orientation for innovation and lifelong learning. The six competency domains, by contrast, specify the capabilities that learners and professionals are expected to develop. Thus, the principles answer how and why AI competence should be enacted, whereas the domains specify what capabilities should be developed. This two-layer relationship is reflected in Figure 1 and operationalized in Tables 1 and 2.

Patient-centered intelligence

The first principle recognizes that the ultimate purpose of laboratory medicine is to improve patient care. Consequently, AI education should not be organized around technology itself but rather around how intelligent systems contribute to diagnostic quality, clinical decision-making, patient safety, and healthcare outcomes. Although discussions surrounding AI frequently emphasize computational performance, algorithmic sophistication, and technological innovation, these characteristics possess limited value unless they ultimately support patient-centered healthcare [6,10,15].

Within laboratory medicine, this principle is particularly important because many AI applications operate at a considerable distance from direct patient interaction. Professionals working with laboratory information systems, digital pathology platforms, molecular diagnostic algorithms, or predictive analytical tools may become increasingly focused on technical performance metrics. However, educational frameworks must ensure that learners consistently recognize the clinical implications of laboratory-generated information and understand how AI-supported outputs influence diagnosis, treatment decisions, monitoring strategies, and patient outcomes [6-10].

Accordingly, the proposed framework conceptualizes AI not as an autonomous decision-maker but as an enabling technology that supports human-centered diagnostic intelligence. As illustrated in Figure 4, intelligent systems may contribute to multiple stages of the diagnostic pathway; however, their value ultimately depends upon their ability to enhance the quality, safety, efficiency, and clinical relevance of laboratory services [6-10].

Human oversight and professional accountability

The second principle acknowledges that responsibility for healthcare decisions remains fundamentally human, regardless of the sophistication of AI technologies. Although contemporary AI systems may assist with classification, prediction, interpretation, workflow optimization, and risk stratification, professional accountability cannot be delegated to algorithms [11–17]. Consequently, educational programs must cultivate competencies that enable learners to maintain meaningful oversight of AI-supported processes.

This principle reflects growing international concern regarding algorithmic opacity, automation bias, excessive reliance on intelligent technologies, and the potential erosion of professional judgment [11–17]. Studies across healthcare settings have demonstrated that users may overestimate algorithmic accuracy, underestimate uncertainty, or fail to recognize situations in which AI-generated outputs require additional scrutiny [12,13,24]. Such risks are particularly relevant within laboratory medicine, where errors in interpretation may directly influence downstream clinical decision-making [6,7,11].

Within AILab-CF, human oversight is therefore viewed as a professional competency rather than an administrative obligation. Learners must be prepared to evaluate algorithmic outputs critically, recognize discrepancies, understand model limitations, and intervene when necessary. These capabilities are reflected within the domains of AI-assisted diagnostic interpretation and Human–AI collaboration, summarized in Figure 1 and operationalized through Tables 1 and 2 [11–17,21,22].

Data stewardship and digital responsibility

The third principle recognizes that AI systems are fundamentally dependent upon data. Model performance, reliability, fairness, transparency, and clinical utility are all influenced by the quality, integrity, representativeness, and governance of underlying datasets [5,18,19]. Consequently, effective AI education requires substantially more than algorithmic literacy; it also requires the development of competencies related to data stewardship and digital responsibility.

Laboratories occupy a unique position within this discussion because they generate many of the datasets that underpin contemporary AI applications. Hematology analyzers, molecular diagnostic platforms, digital pathology systems, laboratory information systems, and emerging multi-omics technologies collectively generate enormous amounts of structured and unstructured data [6–10]. As illustrated conceptually in Figure 4, these data streams form the foundation upon which intelligent diagnostic systems depend.

Educational preparation must therefore include competencies related to data quality, interoperability, governance, privacy protection, cybersecurity, stewardship, and responsible data use [5,18,19]. These competencies are reflected in Domain 2 (Data and Digital Literacy) within Figure

1 and further operationalized through the knowledge, skills, and professional behaviors summarized in Tables 1 and 2 [1–5].

Ethical and regulatory responsibility

The fourth principle emphasizes that AI implementation must remain aligned with ethical standards, professional values, regulatory expectations, and societal trust. Contemporary international guidance consistently identifies fairness, transparency, accountability, explainability, privacy protection, equity, and human oversight as essential components of responsible AI deployment [11–17].

Within healthcare, ethical challenges associated with AI frequently extend beyond technical performance. Algorithmic bias may contribute to inequitable outcomes, insufficient transparency may undermine trust, and poorly governed systems may introduce risks that are difficult to identify or mitigate [12–16]. These concerns are particularly important in laboratory medicine because diagnostic information generated within laboratories often influences subsequent clinical pathways and therapeutic decisions [6,7,11].

Accordingly, ethical competence should not be viewed as a supplementary component of AI education. Rather, it should function as a foundational element of professional preparation. Learners must understand not only how intelligent systems operate but also how they should be governed, evaluated, regulated, and implemented within ethically responsible healthcare environments. This principle provides the conceptual basis for Domain 4 (Ethics, Governance, and Responsible AI) illustrated in Figure 1 and detailed in Tables 1 and 2 [11–17].

Continuous adaptation and lifelong learning

The final principle recognizes that AI-related competence is not a static achievement. Unlike many traditional laboratory technologies, AI systems evolve continuously through algorithmic refinement, technological innovation, regulatory developments, and expanding clinical applications [1,4,20]. Consequently, educational programs cannot simply prepare learners for currently available technologies; they must also prepare them to adapt to technologies that do not yet exist.

This challenge has profound implications for curriculum design. Educational success should be measured not only by immediate knowledge acquisition but also by the development of adaptive capabilities that support lifelong professional learning. Recent work on AI-enhanced lifelong learning similarly emphasizes continuous reskilling, adaptive learning environments, and the need to align technological change with sustained professional development. Learners must therefore become comfortable with uncertainty, continuous technological change, interdisciplinary collaboration, and ongoing professional development [4,20,23,25].

For this reason, the proposed framework incorporates Innovation, Leadership, and lifelong learning as a distinct competency domain rather than treating adaptation as an implicit educational outcome. As illustrated in Figure 5, competency acquisition, educational progression, and

professional practice interact continuously throughout the professional lifespan. Furthermore, Tables 1 and 2 identify specific competencies related to innovation assessment, leadership development, change management, and lifelong learning that support sustained professional growth [4,20,23].

Collectively, these five principles establish the philosophical and educational foundations of AILab-CF. They emphasize that AI competency should be understood as the integration of technological literacy, professional judgment, ethical responsibility, data stewardship, human oversight, and adaptive leadership rather than the acquisition of isolated technical skills. As summarized in Figure 1, elaborated in Figure 4 and Figure 5, and operationalized through Tables 1 and 2, these principles provide the conceptual bridge between the educational gap identified in the preceding section and the competency architecture presented in the following section [1-5,6-10,11-17,21-25].

The proposed ailab-cf competency framework

Building upon the educational gap identified in Section 2 and the foundational principles established in Section 3, the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF) proposes a structured competency architecture specifically designed for AI-enabled laboratory practice. Unlike existing competency frameworks that primarily address general healthcare or physician-focused educational contexts, AILab-CF was developed to reflect the distinctive characteristics of laboratory medicine, including its dependence on complex diagnostic technologies, extensive data generation, advanced analytical systems, and increasingly intelligent workflows [1-10].

The overall architecture of the framework is illustrated in Figure 1, which conceptualizes AI-enabled laboratory professionalism as the integration of six interdependent competency domains. These domains are operationalized through the competency matrix presented in Table 1 and further elaborated through the detailed knowledge, skills, professional behaviors, and educational activities summarized in Table 2. Together, these components provide a practical structure supporting curriculum development, learner assessment, faculty development, workforce planning, and lifelong professional learning [1-5,21,22].

Importantly, these domains should not be interpreted as isolated educational units. Rather, they function as an integrated competency ecosystem in which technical expertise, ethical reasoning, communication skills, professional judgment, and leadership capabilities develop concurrently throughout professional training. As illustrated in Figure 5, competency acquisition, educational progression, and professional practice continuously interact to support the development of future-ready laboratory professionals [21,22].

The six domains comprising AILab-CF are organized according to their primary educational functions. AI Foundations provides conceptual understanding of intelligent technologies.

Data and digital literacy focus on data stewardship and digital competence. AI-assisted diagnostic interpretation addresses the practical application of AI within diagnostic workflows. Ethics, governance, and responsible AI ensure alignment with professional and societal expectations. Human-AI Collaboration emphasizes communication, oversight, and accountability. Finally, Innovation, Leadership, and lifelong learning prepare professionals to adapt to future technological developments and contribute to ongoing transformation within laboratory medicine (Figure 1; Tables 1-2) [1-10,21,22].

Domain 1: AI Foundations

Among the six domains comprising AILab-CF, AI Foundations occupies a uniquely enabling role because it provides the conceptual infrastructure upon which all subsequent competencies depend. Across health professions education, contemporary scholarship consistently identifies foundational AI literacy as a prerequisite for meaningful engagement with intelligent technologies. However, the knowledge required within laboratory medicine extends beyond general awareness of AI and must encompass an understanding of analytical systems, diagnostic algorithms, computational workflows, model evaluation, and technology-enabled laboratory practice [6-10].

The educational rationale for this domain stems from the growing integration of AI throughout laboratory medicine. Machine learning algorithms are increasingly incorporated into digital pathology platforms, hematology analyzers, laboratory automation systems, molecular diagnostic workflows, image analysis technologies, and predictive diagnostic models [6-10]. Consequently, laboratory professionals require sufficient conceptual understanding to interpret AI outputs appropriately, evaluate algorithmic limitations, and participate meaningfully in technology-enabled diagnostic decision-making [6-8].

As summarized in Table 1, the core competencies associated with this domain include understanding fundamental AI concepts, differentiating between machine learning and deep learning approaches, recognizing major categories of intelligent technologies, interpreting model performance metrics, and understanding the principles underlying algorithm development and validation. Corresponding knowledge, skills, and professional behaviors are detailed in Table 2 [1-5].

Particular emphasis should be placed on understanding model performance and uncertainty. Metrics such as sensitivity, specificity, precision, recall, predictive value, and area under the receiver operating characteristic curve increasingly influence decisions regarding the adoption and evaluation of AI-enabled diagnostic systems [6,8,10]. Consequently, laboratory professionals must possess sufficient analytical literacy to interpret such measures critically rather than accepting them uncritically.

Educational implementation may involve introductory coursework, seminars, technology demonstrations, case-based discussions, interdisciplinary workshops, and digital learning modules. As illustrated conceptually in Figure 5, competency development within this domain progresses from foundational

awareness toward increasingly sophisticated critical appraisal and professional application [21,22].

Domain 2: Data and digital literacy

If AI foundations provide the conceptual basis of AI-enabled practice, data and digital literacy provides its operational foundation. AI systems are fundamentally dependent upon data, and the quality, integrity, representativeness, interoperability, and governance of that data directly influence algorithmic performance [5,18,19]. Consequently, professionals who lack competence in data stewardship may struggle to evaluate the reliability, fairness, and clinical utility of AI-enabled technologies.

This domain reflects the reality that laboratory medicine is among the most data-intensive disciplines within healthcare. Modern laboratories generate large volumes of structured and unstructured information originating from hematology analyzers, flow cytometers, molecular diagnostic platforms, digital pathology systems, laboratory information systems, and increasingly complex multi-omics technologies [6–10]. As illustrated in Figure 4, these data streams form the foundation of the AI-enabled diagnostic pathway and directly influence the performance of intelligent systems.

As outlined in Table 1, competencies within this domain include data quality assessment, interoperability, privacy protection, cybersecurity, governance, stewardship, and responsible data use. Table 2 further details how these competencies translate into educational outcomes involving knowledge, technical skills, and professional behaviors [1–5].

Poor-quality datasets may introduce bias, reduce model performance, compromise diagnostic accuracy, and generate inequitable outcomes [13,14,18]. Consequently, learners must understand principles of data validation, completeness, representativeness, standardization, and quality assurance. Such competencies are increasingly important as laboratories contribute data to large-scale AI development initiatives and precision medicine programs [6–10].

Domain 3: AI-Assisted diagnostic interpretation

Among the six competency domains comprising AILab-CF, AI-Assisted Diagnostic Interpretation most directly reflects the changing nature of diagnostic practice within contemporary laboratory medicine. While AI Foundations provides conceptual literacy and Data and Digital Literacy establishes competence in managing diagnostic information, this domain addresses the practical application of AI within real-world laboratory workflows [6–10].

As illustrated in Figure 4, AI increasingly participates in multiple stages of the diagnostic pathway, influencing processes such as morphological classification, abnormality detection, molecular variant interpretation, risk prediction, quality monitoring, and result verification. In hematology, AI-assisted digital morphology platforms support blood cell recognition and classification, while predictive models may assist in identifying clinically significant abnormalities requiring further review [7,9]. Similar developments are

occurring across molecular diagnostics, digital pathology, and precision medicine [8,10].

These developments create new educational requirements. Laboratory professionals must be capable not only of understanding AI-generated outputs but also of evaluating their validity, interpreting their clinical significance, recognizing potential limitations, and determining when additional review is required. Consequently, competency within this domain extends beyond technical operation and includes critical appraisal, diagnostic reasoning, contextual interpretation, and professional judgment [6,7,11].

The competencies associated with this domain are summarized in Table 1, while detailed knowledge, skills, and professional behaviors are presented in Table 2. Together, these competencies provide the practical bridge between technological capability and clinically meaningful diagnostic intelligence.

Domain 4: Ethics, Governance, and Responsible AI

The growing integration of AI into healthcare has led to widespread recognition that appropriate ethical oversight and governance structures must accompany technological innovation. International organizations, regulatory authorities, professional societies, and educational institutions have consistently emphasized that responsible AI implementation requires substantially more than technical excellence alone [11–17]. Issues related to fairness, transparency, accountability, explainability, privacy protection, human oversight, and regulatory compliance have emerged as central considerations within contemporary discussions of AI-enabled healthcare [11–17]. Consequently, ethical and governance competencies represent a foundational component of the proposed AILab-CF framework rather than a supplementary educational topic.

The rationale for including a dedicated Ethics, Governance, and Responsible AI domain is particularly strong within laboratory medicine. Diagnostic information generated within laboratories frequently influences subsequent clinical decisions, therapeutic interventions, and patient outcomes. As AI systems increasingly participate in these processes, laboratory professionals must be equipped to recognize ethical risks, evaluate governance requirements, and ensure that intelligent technologies are implemented responsibly. Failure to address these issues may compromise trust, introduce inequities, reduce transparency, or undermine patient safety [11–17].

One of the most widely discussed challenges involves algorithmic bias. AI systems learn from historical datasets, and the quality and representativeness of those datasets directly influence model behavior [13,14]. Consequently, poorly representative datasets may generate biased outputs that disproportionately affect specific populations or clinical groups. Educational preparation should therefore include competencies related to bias recognition, fairness evaluation, dataset representativeness, and mitigation strategies. These competencies are summarized within Table 1 and further operationalized through the educational outcomes described in Table 2 [11–17].

Transparency and explainability represent additional educational priorities. Although many contemporary AI systems demonstrate impressive predictive performance, some operate as highly complex models whose internal decision-making processes may be difficult to interpret [12]. Such complexity creates challenges for healthcare professionals responsible for explaining diagnostic decisions, evaluating model behavior, and maintaining professional accountability. Learners must therefore understand concepts related to interpretability, explainability, transparency, and trustworthy AI [11,12,16].

Regulatory competence is equally important. The rapid expansion of AI technologies has stimulated the development of evolving governance and regulatory frameworks intended to ensure safety, effectiveness, accountability, and ethical compliance [11,16]. Consequently, educational programs should provide learners with a foundational understanding of governance structures, regulatory pathways, quality management systems, and institutional oversight mechanisms. These relationships are incorporated into the overall framework architecture shown in Figure 1 and detailed in Tables 1 and 2 [11-17].

Educational implementation may include ethics workshops, governance simulations, policy analyses, structured debates, and interdisciplinary learning activities. Assessment approaches may involve ethical reasoning exercises, policy critiques, scenario-based evaluations, and reflective assignments that encourage learners to apply ethical principles within authentic professional contexts [11-17,21,22].

As illustrated in Figure 1, ethics, governance, and responsible AI function as a cross-cutting domain influencing every aspect of AI-enabled laboratory practice. This domain therefore serves as a critical safeguard within the framework, ensuring that technological advancement remains aligned with professional values, patient welfare, and societal expectations [11-17].

Domain 5: Human-AI Collaboration

Although discussions surrounding artificial intelligence frequently emphasize algorithmic performance, computational capability, and technological innovation, healthcare remains fundamentally a human enterprise. Consequently, the successful implementation of AI within laboratory medicine depends not only upon the capabilities of intelligent systems but also upon the quality of interaction between human professionals and those systems. This reality underpins the fifth competency domain of AILab-CF: Human-AI Collaboration.

The educational rationale for this domain derives from the recognition that AI systems do not function independently of human users. Rather, they operate within complex sociotechnical environments in which algorithmic outputs, professional judgment, organizational processes, and clinical decision-making continuously interact [11-17,24]. As a result, human factors influence implementation success as much as technological performance. Even highly accurate systems may produce suboptimal outcomes if users misunderstand

outputs, fail to recognize limitations, communicate findings inadequately, or rely excessively upon automated recommendations [12,17,24].

Within laboratory medicine, these challenges are particularly relevant because AI-supported systems increasingly participate in diagnostic workflows that influence patient care [6-10]. Laboratory professionals must therefore develop competencies enabling them to engage critically with intelligent technologies while maintaining appropriate professional oversight. This requires moving beyond the view of AI as either a replacement for human expertise or a passive technological tool. Instead, AI should be understood as a collaborative partner whose outputs require contextual interpretation, professional judgment, and continuous evaluation [11-17].

A central competency within this domain involves maintaining meaningful human oversight. International guidance consistently emphasizes that accountability for healthcare decisions remains a human responsibility regardless of algorithmic sophistication [11,16]. Accordingly, laboratory professionals must understand when AI recommendations can be accepted, when additional review is required, and when algorithmic outputs should be challenged or overridden. These competencies are summarized in Table 1 and operationalized through the professional behaviors outlined in Table 2.

Communication constitutes a second major component of the domain. As AI-generated insights become increasingly integrated into laboratory reports, multidisciplinary discussions, and clinical consultations, laboratory professionals must be able to communicate algorithm-supported findings effectively to clinicians, administrators, policymakers, and other stakeholders. This includes discussing uncertainty, explaining limitations, and facilitating appropriate interpretation of AI-supported outputs [12,17,24].

The domain also emphasizes interdisciplinary collaboration. AI implementation frequently involves interactions among laboratory professionals, clinicians, data scientists, software developers, informaticians, quality specialists, and regulatory personnel. Effective participation in such environments requires communication skills, collaborative decision-making, systems thinking, and conflict-resolution capabilities [21-23].

As illustrated in Figure 4, human verification is a critical component that links AI processing to clinically actionable diagnostic intelligence. Furthermore, Figure 5 demonstrates how collaborative competencies intersect with educational progression and professional development throughout the learner continuum. Together, these relationships reinforce the principle that successful AI implementation depends not merely upon algorithmic performance but upon the quality of interaction between intelligent systems and the professionals responsible for their use [11-17,21-24].

Domain 6: Innovation, Leadership, and Lifelong Learning

The final domain of the AILab-CF framework recognizes that competency development must extend beyond currently available technologies. Artificial intelligence continues to evolve

rapidly, introducing new analytical capabilities, diagnostic applications, governance challenges, and professional responsibilities. Consequently, future laboratory professionals must not only engage effectively with existing technologies but also adapt to innovations that have yet to emerge [1,4,20].

The educational significance of this domain derives from the dynamic nature of AI-enabled healthcare. Unlike many traditional laboratory technologies, intelligent systems are characterized by continuous refinement, frequent updates, evolving regulatory frameworks, and expanding clinical applications [1,4,20]. Competencies acquired during formal education may therefore become insufficient if learners lack the capacity for ongoing adaptation. Educational programs must consequently cultivate habits of continuous learning, reflective practice, innovation awareness, and professional development [4,20,23].

Innovation represents the first major component of this domain. Laboratory professionals increasingly encounter emerging technologies capable of transforming diagnostic workflows, enhancing quality, improving efficiency, and generating new forms of diagnostic intelligence [6–10]. Learners should therefore develop competencies related to technology evaluation, innovation assessment, implementation science, and evidence-based adoption of emerging tools. These competencies are summarized in Table 1 and elaborated within Table 2.

Leadership constitutes a second critical component. Successful implementation of AI within healthcare organizations requires professionals capable of guiding change, managing uncertainty, supporting innovation, and facilitating interdisciplinary collaboration [4,23]. As AI becomes increasingly integrated into laboratory medicine, professionals may be called upon to contribute to technology selection, policy development, quality oversight, governance initiatives, workforce transformation, and strategic planning. Educational preparation should therefore include opportunities to develop leadership capabilities alongside technical expertise [4,23].

The domain also emphasizes lifelong learning. Contemporary healthcare professionals are expected to engage in continuing professional development throughout their careers. This expectation becomes even more important within AI-enabled environments where technological change occurs continuously [20]. Consequently, learners should develop self-directed learning skills, adaptive mindsets, reflective practice habits, and resilience that support sustained professional growth.

As illustrated in Figure 5, competency acquisition within this domain spans the entire educational continuum, extending from undergraduate education through advanced professional leadership roles. Furthermore, Tables 1 and 2 position Innovation, Leadership, and lifelong learning as the domain most closely associated with the long-term sustainability of AI-enabled laboratory professionalism. Without continuous adaptation, competencies acquired within other domains may gradually lose relevance as technologies evolve [1,4,20,23].

Collectively, the six domains comprising AILab-CF establish a comprehensive educational architecture for AI-enabled laboratory medicine. As summarized in Figure 1 and operationalized through Tables 1 and 2, the framework integrates technological literacy, data stewardship, diagnostic interpretation, ethical governance, collaborative practice, and adaptive leadership within a unified competency model. Together, these domains provide the educational foundation necessary to prepare future laboratory professionals for increasingly intelligent diagnostic ecosystems and establish the basis for the developmental progression model described in the following section.

Competency development continuum

The successful implementation of competency-based education requires more than the identification of competency domains alone. Educational frameworks must also define how competencies develop over time, how progression should be assessed, and how learners advance from foundational understanding to independent professional practice and leadership. Contemporary competency-based educational theory increasingly emphasizes developmental progression, authentic assessment, workplace relevance, and lifelong learning as essential components of professional formation [21,22]. Consequently, competency frameworks are increasingly expected to describe not only what learners should know and be able to do, but also how those capabilities evolve across different stages of professional development.

Within AILab-CF, competency development is represented by four practical descriptors – Awareness, Application, Advanced Practice, and Leadership/Systems Responsibility – informed by general principles of competency-based education, authentic assessment, increasing autonomy, and professional responsibility [21,22]. These descriptors are proposed as curriculum-mapping heuristics rather than empirically established universal developmental stages. They should not be assumed to progress identically across all six domains, and the framework has not yet established, through consensus or longitudinal evidence, that every learner must traverse the four descriptors in a fixed sequence.

Importantly, the continuum should not be interpreted as a rigid, time-dependent, or seniority-based ladder. Competence is domain-specific: an individual may demonstrate advanced diagnostic interpretation while remaining at an application level in governance or implementation science. The fourth descriptor, Leadership/Systems Responsibility, is especially important to distinguish from simple mastery. It denotes an expansion of role, accountability, organizational influence, and responsibility for policy or system design; it may accompany advanced expertise but is not inherently a higher level of the same technical competency. Accordingly, progression from evaluating governance to developing governance policy reflects both deeper capability and a change in professional responsibility. The continuum is therefore a proposed educational scaffold for curriculum design and assessment, not a validated hierarchy of professional rank.

Furthermore, as illustrated in Figure 5, competency progression occurs through continuous interaction among educational experiences, workplace practice, reflective learning, and professional development. Consequently, competency acquisition should be viewed as a dynamic and lifelong process rather than a finite educational achievement [4,20,21].

Level 1: Awareness

Awareness represents the foundational stage of competency development and serves as the entry point for all six domains of the AILab-CF framework (Figure 2; Table 3). At this level, learners acquire introductory knowledge regarding artificial intelligence, digital health technologies, data stewardship, ethical principles, human oversight, and innovation within laboratory medicine. The primary objective is not independent performance but rather the development of conceptual understanding and professional awareness [1-5].

Within the AI Foundations domain, learners should be able to recognize key AI concepts, understand common terminology, and identify examples of AI-enabled technologies used within laboratory medicine. Similarly, within data and digital literacy, learners should understand fundamental principles related to data quality, governance, privacy, interoperability, and stewardship. Ethical awareness should include familiarity with concepts such as fairness, transparency, accountability, explainability, and responsible AI implementation [11-17].

Educational activities appropriate for this level may include introductory lectures, seminars, guided discussions, foundational workshops, technology demonstrations, and self-directed learning modules. Assessment approaches typically focus on knowledge acquisition and conceptual understanding through written examinations, quizzes, structured discussions, and reflective exercises [21,22]. As summarized in Table 3, awareness provides the educational foundation upon which all subsequent competency development depends.

Level 2: Application

Application represents the transition from conceptual understanding to practical implementation. At this stage, learners begin to utilize AI-related knowledge within authentic or simulated professional environments and develop the ability to apply theoretical concepts to real-world laboratory scenarios (Figure 2; Table 3). The educational emphasis therefore shifts from learning about AI toward using AI-enabled systems appropriately, critically, and responsibly [1-5].

Within AI Foundations, learners begin interpreting model outputs, understanding performance indicators, and utilizing AI-supported technologies under supervision. Within Data and Digital Literacy, learners should be capable of evaluating data quality, recognizing governance considerations, and participating in data-informed decision-making. Similarly, within AI-Assisted Diagnostic Interpretation, learners begin applying algorithm-supported recommendations within structured diagnostic contexts while maintaining awareness of uncertainty and human oversight requirements [6-17].

Educational strategies supporting this stage frequently include case-based learning, simulation exercises, laboratory practicums, digital morphology activities, workplace-based learning opportunities, and interdisciplinary problem-solving activities. Assessment approaches may include objective structured practical examinations, scenario-based evaluations, competency demonstrations, workplace-based assessments, and applied problem-solving exercises [21,22].

As shown in Table 3, successful progression through the application stage requires demonstration of both technical competence and professional judgment. Learners must begin integrating competencies across multiple domains rather than applying isolated skills independently.

Level 3: Advanced practice

Advanced Practice reflects a stage of increasing independence, professional judgment, and critical evaluation. Learners operating at this level are expected not only to apply AI-related competencies but also to critically evaluate technologies, identify limitations, manage uncertainty, and contribute meaningfully to implementation and quality improvement activities. As illustrated in Figure 2, this stage represents the transition from supervised application toward increasingly autonomous professional practice [21,22].

Within AI-Assisted Diagnostic Interpretation, advanced practitioners should be capable of critically evaluating algorithmic recommendations, validating outputs, identifying discrepancies, recognizing limitations, and determining when additional review is required. Within Data and Digital Literacy, learners should demonstrate competence in evaluating governance frameworks, assessing data integrity, identifying data-quality risks, and contributing to quality-assurance initiatives [5,18,19].

Similarly, competencies within ethics, governance, and responsible AI require the ability to identify ethical challenges, evaluate fairness, recognize algorithmic bias, assess transparency concerns, and apply governance principles within complex professional environments [11-17]. At this stage, learners are expected to integrate technical expertise with professional judgment and ethical reasoning.

Educational experiences supporting advanced practice may include quality improvement projects, advanced case reviews, scholarly activities, implementation initiatives, interdisciplinary collaborations, and supervised leadership experiences. Assessment approaches increasingly emphasize authentic workplace performance and may include portfolio reviews, project evaluations, workplace-based assessments, scholarly outputs, and evidence of professional contribution [21,22].

As summarized in Table 3, Advanced Practice reflects the emergence of independent professional competence across all domains of the framework. Furthermore, Figure 5 demonstrates how this stage represents an important intersection between educational achievement and professional identity formation.

Level 4: Leadership/Systems Responsibility

Leadership/Systems Responsibility represents the systems-facing descriptor within AILab-CF. It should not be interpreted as a universally higher level of technical mastery or as a stage that every practitioner must attain. Rather, it captures the additional responsibilities assumed by professionals who contribute to the development, implementation, governance, evaluation, and strategic direction of AI-enabled laboratory medicine. As illustrated in Figure 2, this descriptor combines advanced competence with broader organizational influence, innovation management, systems leadership, and stewardship of technological change.

Within AI Foundations, leaders contribute to institutional decision-making regarding technology evaluation, procurement, implementation, and oversight. Within Data and Digital Literacy, they may participate in governance initiatives, policy development, digital transformation strategies, and organizational leadership. Ethical and governance competencies extend to institutional accountability, regulatory engagement, responsible implementation, and promotion of trustworthy AI [11–17].

Human–AI Collaboration at this level involves leading multidisciplinary teams, facilitating communication among stakeholders, supporting organizational transformation, and fostering cultures of responsible innovation. Similarly, Innovation, Leadership, and lifelong learning become dominant competency domains emphasizing strategic leadership, change management, continuous improvement, workforce development, and future-oriented thinking [4,20,23].

Educational preparation for leadership frequently extends beyond formal degree programs and may include executive education, advanced professional development, mentorship programs, scholarly leadership activities, institutional service, strategic planning initiatives, and participation in national or international professional organizations [4,23].

Assessment approaches are correspondingly broader and may include evidence of organizational impact, leadership achievements, innovation activities, policy contributions, workforce development initiatives, and sustained professional influence. As detailed in Table 3, leadership competencies extend beyond technical proficiency and emphasize the ability to shape future directions of professional practice.

Collectively, the four descriptors provide a pragmatic structure for mapping increasing autonomy, complexity, and professional responsibility from awareness through application and advanced practice to leadership/systems responsibility. As operationalized in Table 3 and illustrated in Figure 2, they can help educators align learning objectives, educational activities, assessment strategies, and role expectations. However, they remain proposed descriptors rather than empirically validated stages, and progression may be nonlinear and domain-specific. Future Delphi and implementation studies should test whether the four-part structure is educationally meaningful across different laboratory professions, settings, and career pathways.

Educational implementation of the AILab-CF Framework

The successful development of competency frameworks depends not only upon conceptual rigor but also upon practical applicability. Educational models that fail to provide implementation pathways often face challenges in curriculum integration, learner assessment, faculty engagement, sustainability, and institutional adoption [21,22]. Consequently, the value of AILab-CF should be evaluated not only according to the competencies it defines but also according to its ability to guide educational practice across diverse learning environments and stages of professional development.

As illustrated in Figure 3 and operationalized through Table 4, the proposed implementation model adopts a longitudinal approach in which competencies are progressively introduced, reinforced, expanded, and assessed across multiple phases of professional education. This approach is consistent with contemporary competency-based educational theory, which emphasizes developmental progression, authentic assessment, workplace relevance, and lifelong learning rather than isolated educational experiences [21,22].

Importantly, implementation should not be interpreted as the addition of a single AI-related course to existing curricula. Such approaches risk fragmenting competency development and may reinforce the misconception that AI represents a discrete technological topic rather than a transformative influence on professional practice. Instead, the framework advocates both vertical and horizontal integration of competencies throughout educational programs, ensuring that AI-related learning remains contextualized within laboratory medicine rather than taught in isolation [1–5,21,22].

Furthermore, as illustrated in Figure 5, educational implementation should be viewed as part of a broader competency ecosystem in which educational experiences, workplace practice, professional development, and organizational readiness continuously interact to support competency acquisition throughout the professional lifespan [21,22].

Undergraduate education

Undergraduate education represents the foundational stage of competency development and corresponds primarily to the awareness level described in Figure 2 and Table 3. At this stage, educational priorities focus on establishing conceptual literacy, introducing AI-related terminology, and developing a foundational understanding of data-driven healthcare systems [1–5].

Within laboratory medicine programs, undergraduate learners should be introduced to fundamental concepts related to artificial intelligence, machine learning, digital diagnostics, laboratory information systems, healthcare data governance, and responsible AI. The objective is not to develop advanced technical expertise but rather to establish sufficient conceptual understanding to support future learning and professional adaptation [1–5].

As outlined in Table 4, educational activities at this stage may include introductory lectures, technology demonstrations, guided discussions, digital learning modules, and case-based exploration of contemporary AI applications within laboratory medicine. Contextualization is particularly important because learners are more likely to engage meaningfully with AI concepts when educational content is directly linked to laboratory workflows, diagnostic interpretation, quality management, and patient care [6-10].

Assessment strategies at the undergraduate level may include written examinations, structured discussions, reflective assignments, quizzes, and introductory case analyses. The primary goal is to evaluate conceptual understanding and emerging professional awareness rather than independent technical performance [21,22].

Internship and early professional training

Internship training provides the first substantial opportunity for learners to apply AI-related competencies within authentic professional environments. Corresponding primarily to the application level of the competency continuum (Figure 2; Table 3), this stage emphasizes supervised engagement with AI-enabled systems and translation of theoretical knowledge into workplace practice [21,22].

Interns should encounter opportunities to interact with laboratory information systems, digital morphology platforms, automated analytical technologies, quality management systems, and AI-assisted diagnostic workflows [6-10]. Educational activities may include supervised interpretation exercises, quality-assurance projects, simulation-based learning, case reviews, and workplace discussions that focus on both the strengths and limitations of intelligent technologies.

An important objective at this stage is the development of critical thinking. Learners should be encouraged not merely to use AI-supported tools but also to critically evaluate outputs, recognize uncertainty, identify discrepancies, and appreciate the importance of human oversight [11-17]. These experiences provide the practical foundation necessary for progression toward more advanced levels of competency.

As summarized in Table 4, assessment approaches may include workplace-based assessment, structured feedback, competency portfolios, direct observation, and performance evaluations linked to authentic laboratory activities. Such methods align educational evaluation with real-world professional practice and support competency-based progression [21,22].

Postgraduate education and advanced professional training

Postgraduate education, specialist training pathways, residency programs, and advanced professional qualifications provide opportunities for learners to develop competencies corresponding to the Advanced Practice level of the framework (Figure 2; Table 3). At this stage, educational activities move beyond application toward critical evaluation, implementation,

quality improvement, leadership development, and scholarly engagement [21,22].

Advanced learners should be expected to evaluate AI technologies critically, assess evidence supporting implementation, participate in validation activities, analyze governance challenges, and contribute to quality improvement initiatives. Educational experiences may include advanced case reviews, implementation science projects, interdisciplinary collaborations, research activities, and structured evaluation of AI-enabled diagnostic systems [6-17].

This stage also provides an opportunity to strengthen competencies related to ethics, governance, responsible AI, algorithmic bias, explainability, transparency, accountability, and institutional oversight [11-17]. Such competencies become increasingly important as AI technologies move from experimental environments into routine clinical practice.

Assessment approaches may include project-based evaluation, portfolio review, scholarly output, workplace performance measures, leadership activities, and evidence of independent professional judgment. As summarized in Table 4, educational objectives at this stage focus on preparing professionals capable of functioning independently within increasingly complex AI-enabled environments [21,22].

Continuing professional development

The rapid pace of technological innovation means that competency development cannot conclude upon graduation or completion of specialist training. Rather, AI-related competence must be continuously maintained, refined, and updated throughout the professional lifespan [1,4,20]. Consequently, the implementation model places particular emphasis on Continuing Professional Development (CPD), as illustrated in Figure 3 and summarized in Table 4.

CPD activities may include workshops, professional courses, certification programs, online learning platforms, conferences, journal clubs, technology updates, and structured self-directed learning. AI-enhanced lifelong-learning approaches may additionally support adaptive and personalized professional retraining, although their educational effectiveness and governance requirements should be evaluated in context [25]. Importantly, CPD should address not only emerging technologies but also evolving governance requirements, regulatory expectations, and professional standards [11-17,20].

Educational institutions, professional societies, accreditation bodies, healthcare organizations, and employers all possess important roles in supporting lifelong learning. Collaborative approaches help ensure alignment between educational opportunities, workforce needs, and technological developments [20,23].

As demonstrated in Figure 5, lifelong learning serves as a continuous mechanism that supports competency maintenance and adaptation throughout professional practice. Without ongoing development, competencies acquired during formal education may gradually lose relevance as technologies evolve [4,20,23].



Figure 3.: AI Integration Across the Laboratory Medicine Educational Continuum.

Description: This figure maps the integration of AI-related competencies across the educational continuum of laboratory medicine, spanning undergraduate education, internship training, postgraduate specialization, continuing professional development, and leadership stages. The model demonstrates how competency domains are progressively introduced, reinforced, and expanded throughout professional development to support lifelong learning and workforce readiness.

Created by the author.

Abbreviations: AI: Artificial Intelligence; CPD: Continuing Professional Development; MSc: Master of Science.

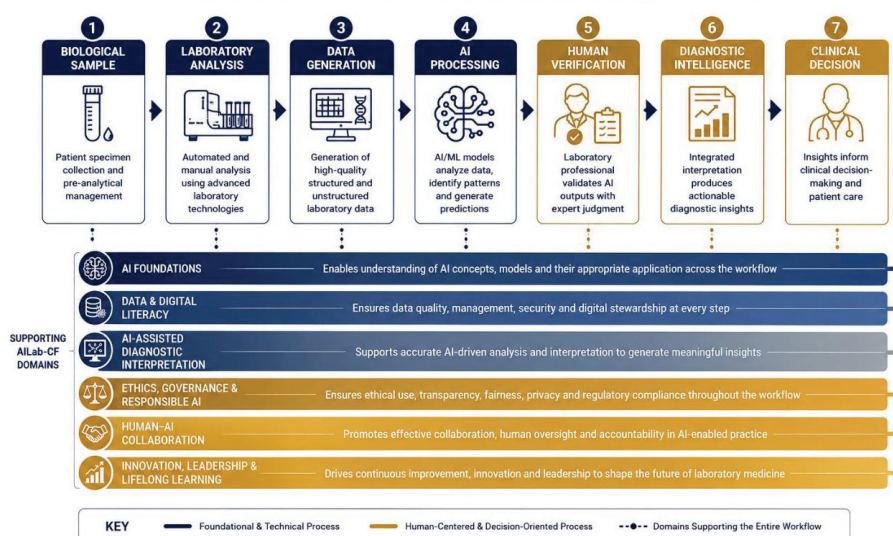


Figure 4: From Data to Diagnostic Intelligence: The Future Workflow of AI-Enabled Laboratory Medicine.

Description: This figure illustrates the future diagnostic workflow within AI-enabled laboratory medicine. The process begins with biological sample acquisition and laboratory analysis, progresses through data generation and AI-assisted processing, and culminates in human verification, diagnostic intelligence generation, and clinical decision-making. The framework highlights how the competency domains of AILab-CF support each stage of the diagnostic pathway and reinforce responsible integration of AI into laboratory practice. Created by the author.

Abbreviations: AI: Artificial Intelligence; AI/ML: Artificial Intelligence/Machine Learning.

Faculty development and institutional readiness

Successful implementation of AI-related competencies depends not only upon learner preparation but also upon faculty readiness and institutional capacity. Across health professions education, limited faculty expertise has emerged as one of the most frequently cited barriers to the successful implementation of AI curricula [1,4,5]. Consequently, faculty

development should be regarded as a strategic priority rather than a secondary consideration.

Faculty members may require support in areas such as AI literacy, competency-based assessment, curriculum design, digital health education, ethical governance, educational scholarship, and implementation science. Development initiatives may include faculty workshops, mentoring

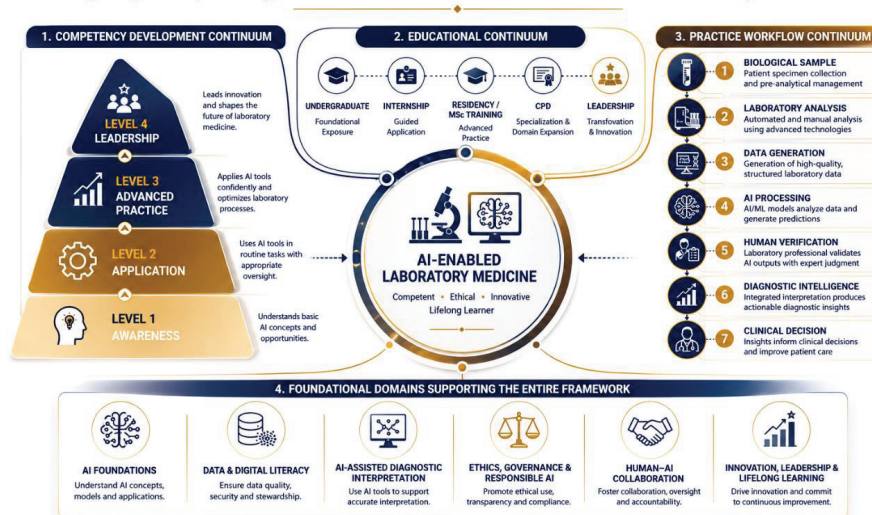


Figure 5: The AILab-CF Integrated Intelligence Model: Aligning Competency, Education, and Practice in AI-Enabled Laboratory Medicine.

Description: This integrative model synthesizes the three major dimensions of the AILab-CF framework: competency development, educational progression, and AI-enabled laboratory practice. The figure demonstrates how competency acquisition, educational experiences, and real-world diagnostic workflows interact to create a future-ready laboratory workforce capable of utilizing AI technologies safely, effectively, and responsibly. The six foundational competency domains function as cross-cutting elements that support all dimensions of the framework.

Created by the author.

Abbreviations: AI: Artificial Intelligence; AILab-CF: Artificial Intelligence Competency Framework for Laboratory Medicine Education; CPD: Continuing Professional Development; MSc: Master of Science.

programs, collaborative teaching models, communities of practice, and interdisciplinary partnerships involving laboratory professionals, educators, informaticians, and data scientists [1,4,5].

Institutional readiness is equally important. Sustainable implementation requires alignment among curricula, assessment systems, accreditation requirements, technological infrastructure, governance structures, faculty expertise, and organizational priorities. Many of these challenges are summarized in Table 5, which outlines key implementation barriers and potential mitigation strategies [11-17,23].

Toward an integrated educational ecosystem

The implementation model proposed in this article views competency development as a continuous process extending across the entire professional lifespan. As illustrated in Figure 3, educational progression begins with foundational exposure during undergraduate education and continues through internship, postgraduate training, continuing professional development, and leadership roles. Simultaneously, Figure 5 demonstrates how educational experiences, competency acquisition, professional practice, leadership development, and lifelong learning interact to create an integrated ecosystem of AI-enabled laboratory professionalism [21,22].

This perspective is important because AI competency cannot be achieved through isolated educational interventions alone. Rather, it emerges through sustained engagement with technology, workplace experience, ethical reflection, interdisciplinary collaboration, competency-based assessment, and continuous learning. Consequently, the educational continuum functions not merely as a training pathway but as

a developmental structure supporting adaptation to evolving diagnostic ecosystems.

Collectively, the implementation strategies summarized in Figure 3, Figure 5, and Tables 4–5 provide a practical roadmap for translating the conceptual architecture of AILab-CF into educational practice. By aligning competencies, developmental milestones, educational activities, assessment strategies, faculty development initiatives, and organizational readiness, the framework seeks to support the preparation of future laboratory professionals who can function safely, effectively, ethically, and responsibly within increasingly AI-enabled healthcare environments [1–5,11–17,21–23].

Practical implications

The proposed AILab-CF framework has several practical implications for educators, academic institutions, professional societies, accreditation bodies, healthcare organizations, and policymakers seeking to prepare the laboratory workforce for the era of intelligent diagnostics. As summarized in Figure 3, Figure 5, and Tables 1–5, the framework provides a structured educational architecture that extends beyond technological literacy to encompass governance, data stewardship, diagnostic interpretation, professional accountability, and adaptive leadership [1–5,21,22].

First, the framework provides a practical foundation for curriculum development. By identifying six competency domains and defining developmental milestones across the educational continuum, AILab-CF enables educational institutions to map existing curricula, identify competency gaps, and integrate AI-related learning outcomes into undergraduate, postgraduate, and continuing professional

development programs [1-5,21,22]. The curriculum integration pathway proposed in Figure 3 and detailed in Table 4 provides a practical roadmap for educational implementation.

Second, AILab-CF offers a structured approach to competency-based assessment. The developmental continuum spanning awareness, application, advanced practice, and leadership (Figure 2; Table 3) provides educators with a mechanism for defining learning milestones, selecting assessment strategies, and evaluating learner progression across different stages of professional development [21,22]. Such alignment may facilitate greater consistency between educational objectives, assessment approaches, and workforce expectations.

Third, the framework may support faculty development initiatives. Many institutions currently face challenges related to limited faculty expertise in artificial intelligence, digital health, and data-driven healthcare [1,4,5]. By defining competency domains, implementation pathways, and expected educational outcomes (Tables 1-4), AILab-CF may help guide faculty development programs and strengthen institutional educational capacity.

Fourth, the framework may contribute to accreditation and workforce planning. As AI technologies become increasingly integrated into laboratory diagnostics, professional organizations and accreditation bodies may require clearer guidance regarding competency expectations and educational standards. The framework, therefore, provides a potential foundation for future discussions concerning certification requirements, educational benchmarks, and workforce readiness within AI-enabled laboratory medicine [21,22].

Finally, AILab-CF emphasizes that successful use of AI relies not just on adopting technology but also on training professionals who can think critically, act ethically, oversee effectively, and lead adaptively. By integrating technological competence with governance, collaboration, stewardship, and innovation, the framework supports the development of a future-ready laboratory workforce that can maximize the benefits of intelligent diagnostics while maintaining patient-centered, professionally accountable practice [11-17,23].

Limitations and future directions

Although the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF) provides a structured and theoretically grounded approach to AI-enabled laboratory medicine education, several limitations should be acknowledged. Recognition of these limitations is important because competency frameworks must evolve alongside advances in technology, educational theory, healthcare systems, and workforce requirements [1-5,21,22].

First, the framework represents a conceptual model developed through an interpretive and iterative synthesis of contemporary literature rather than through a systematic review, formal consensus-building methodology, or prospective framework-development protocol. The source literature was used to inform conceptual construction and

comparison, but no exhaustive search, duplicate screening, formal quality appraisal, or PRISMA-style selection process was undertaken. This limits reproducibility and introduces the possibility of selection and interpretation bias. Future work should therefore subject the proposed architecture to systematic evidence mapping and structured Delphi-based expert validation involving laboratory professionals, educators, healthcare leaders, informaticians, accreditation specialists, and AI experts.

Second, the framework has not yet been evaluated through empirical implementation studies. The educational value of competency frameworks ultimately depends upon their ability to influence curriculum design, learner outcomes, faculty development, and workforce preparedness. Although AILab-CF was intentionally designed to support practical implementation across the educational continuum (Figure 3; Table 4), its effectiveness remains to be tested within real-world educational environments. Future pilot implementation studies will therefore be necessary to evaluate feasibility, acceptability, educational impact, and long-term sustainability [21,22].

Third, stakeholder engagement has not yet been formally incorporated into the framework development process. Educational frameworks are most effective when they reflect the perspectives of diverse stakeholder groups, including students, trainees, practicing laboratory professionals, educators, healthcare organizations, employers, professional societies, accreditation bodies, and policymakers. Future development efforts should therefore include structured stakeholder consultation to ensure continued alignment with evolving workforce needs and educational priorities [21,22].

Fourth, the rapidly evolving nature of artificial intelligence presents an inherent challenge for any competency framework. AI technologies, governance models, regulatory expectations, healthcare applications, and educational priorities continue to evolve at a pace that frequently exceeds traditional curriculum revision cycles [11-17,20]. Consequently, AILab-CF should not be regarded as a static competency inventory but rather as a dynamic educational framework requiring periodic review and revision.

Fifth, the four developmental descriptors have not been empirically validated as universal stages across all six competency domains. In particular, Leadership/Systems Responsibility combines advanced capability with expanded professional role and organizational accountability. Future longitudinal and consensus studies should determine whether progression is best represented by a single continuum, domain-specific milestones, entrustment-based descriptors, or role-dependent pathways.

Despite these limitations, the framework provides an important starting point for advancing AI education within laboratory medicine. By integrating technological literacy, diagnostic interpretation, ethical governance, data stewardship, human oversight, interdisciplinary collaboration, and adaptive leadership into a unified competency architecture

(Figure 1; Tables 1–2), AILab-CF establishes a foundation for future validation and implementation efforts.

Several future directions emerge from the present work. First, international Delphi consensus studies could be undertaken to refine competency definitions and establish broader agreement regarding educational priorities. Second, curriculum mapping studies may evaluate the extent to which existing laboratory medicine programs already address the proposed competencies and identify areas requiring further development. Third, pilot implementation projects across undergraduate, postgraduate, and continuing professional development settings may evaluate educational feasibility and learner outcomes. Fourth, outcome-based educational studies should examine whether the framework's implementation improves AI literacy, diagnostic reasoning, ethical decision-making, workforce readiness, and professional confidence. Finally, collaboration with accreditation organizations, certification bodies, and professional societies may facilitate the incorporation of AI-related competencies into future educational standards and workforce development initiatives [1–5,21–23].

Collectively, these future directions provide a roadmap for transforming AILab-CF from a conceptual framework into a validated educational model that supports the long-term evolution of laboratory medicine education in the era of intelligent diagnostics (Figure 5; Tables 3–5).

Discussion

The rapid integration of artificial intelligence into healthcare has generated growing recognition that future healthcare professionals require competencies extending beyond traditional disciplinary knowledge and technical proficiency. Although substantial progress has been made in defining AI-related competencies across health professions education, most existing frameworks have been developed from physician-centered, digital health, or general healthcare perspectives [1–5]. Consequently, the educational implications of AI for laboratory medicine have remained comparatively underexplored despite the increasingly central role that intelligent technologies play within contemporary diagnostic systems [6–10].

The present work addresses this gap by proposing the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF), a discipline-specific competency architecture designed to support the preparation of future laboratory professionals for AI-enabled practice. As illustrated in Figure 1 and operationalized in Tables 1 and 2, the framework conceptualizes AI competency as the integration of six interdependent domains, including technological literacy, data stewardship, diagnostic interpretation, ethical governance, human oversight, collaboration, innovation, and adaptive leadership [1–5,21,22]. This multidimensional perspective differs from approaches that focus primarily on technical knowledge and instead recognizes that professional competence emerges through interaction among knowledge, skills, professional judgment, ethical responsibility, and organizational context.

A central contribution of the framework lies in its explicit contextualization of established AI-education concepts for laboratory medicine. Existing healthcare-wide and physician-oriented frameworks appropriately emphasize AI literacy, digital competence, ethics, and professional development; AILab-CF does not claim these constructs as novel in themselves. Its proposed contribution is to reorganize them around laboratory-specific responsibilities in data generation and stewardship, analytical and diagnostic validation, algorithm-related quality assurance, result verification, governance, and escalation within AI-enabled workflows. The framework therefore advances a discipline-specific architecture rather than a wholly new competency vocabulary.

The framework also contributes to ongoing discussions regarding competency-based education by separating two conceptual layers. The five foundational principles are cross-cutting design commitments that govern how competence should be enacted, whereas the six domains define the capabilities to be developed. AILab-CF then uses four developmental descriptors to support curriculum mapping and assessment. These descriptors are intentionally heuristic: they reflect increasing autonomy, complexity, and responsibility but have not yet been validated as universal stages. Leadership/Systems Responsibility, in particular, represents expansion of professional role and organizational accountability as well as advanced capability. This distinction avoids equating seniority with competence and allows domain-specific, nonlinear progression.

Another important strength of the framework is its integration of ethical and governance considerations into the core competency architecture. Ethical discussions surrounding AI are frequently treated as supplementary topics existing alongside technological education. The present framework adopts a different position. By incorporating ethics, governance, and responsible AI as a dedicated competency domain (Figure 1; Tables 1–2), AILab-CF recognizes that responsible implementation is inseparable from technical competence. This position aligns with international guidance emphasizing fairness, transparency, accountability, explainability, privacy protection, and human oversight as essential components of trustworthy AI-enabled healthcare [11–17].

Similarly, the inclusion of Human-AI Collaboration as a distinct competency domain reflects growing recognition that healthcare remains fundamentally a sociotechnical enterprise. Successful implementation depends not merely upon algorithmic performance but also upon communication, teamwork, professional judgment, organizational culture, and effective interaction between intelligent systems and human professionals [11–17,24]. As illustrated in Figure 4, human oversight functions as a critical component of the AI-enabled diagnostic pathway, while Figure 5 demonstrates how collaborative competencies influence progression across the educational continuum.

The framework further contributes to workforce development discussions by emphasizing leadership, innovation, and lifelong learning. The rapid pace of

technological change means that competencies acquired during formal education may become insufficient if professionals lack the ability to adapt continuously [1,4,20]. Consequently, AILab-CF incorporates Innovation, Leadership, and Lifelong Learning as a dedicated competency domain and positions continuous adaptation as a central characteristic of future-ready laboratory professionalism (Figure 5; Tables 1–4). This perspective aligns with broader healthcare workforce reports emphasizing the importance of adaptability, digital capability, leadership capacity, and continuous professional development within technology-enabled healthcare environments [4,20,23].

From a practical perspective, the framework provides educators, institutions, professional societies, accreditation bodies, and policymakers with a structured model for curriculum development, assessment design, workforce planning, and faculty development. The educational implementation pathway summarized in Figure 3 and detailed in Table 4 demonstrates how competency development may be integrated across undergraduate education, internship training, postgraduate programs, continuing professional development, and leadership pathways. Furthermore, Table 5 highlights key implementation challenges and mitigation strategies to facilitate successful adoption across diverse educational contexts.

Importantly, AILab-CF should not be interpreted as a fixed curriculum or prescriptive educational standard. Rather, it should be viewed as a flexible competency architecture adaptable to local educational needs, professional requirements, technological developments, and regulatory environments. This flexibility is particularly important given the rapid evolution of AI technologies and the diversity of laboratory medicine education globally [11–17,20].

Taken together, the framework advances the emerging conversation surrounding AI-enabled laboratory medicine education by providing a coherent educational structure that integrates technological competence with ethical responsibility, professional accountability, diagnostic expertise, data stewardship, collaboration, leadership, and lifelong learning. As summarized in Figures 1–5 and Tables 1–5, AILab-CF provides a practical foundation for preparing future laboratory professionals to operate safely, effectively, ethically, and responsibly in increasingly intelligent diagnostic ecosystems. Ultimately, the framework seeks not merely to prepare professionals to use AI but to prepare them to lead, govern, evaluate, and continuously improve AI-enabled laboratory practice in ways that advance patient care and strengthen healthcare systems [1–17,21,24].

Conclusion

The integration of artificial intelligence into laboratory medicine is reshaping diagnostic practice, workforce expectations, and educational priorities. As intelligent technologies become increasingly embedded in laboratory workflows, future professionals will require competencies that extend beyond traditional technical expertise to include AI literacy, data stewardship, ethical governance,

diagnostic interpretation, human oversight, interdisciplinary collaboration, and adaptive leadership [6–17].

Despite growing international interest in AI-related competencies in health professions education, existing frameworks offer limited guidance on the distinctive educational requirements of laboratory medicine [1–5]. The present work addresses this gap through the development of the Artificial Intelligence Competency Framework for Laboratory Medicine Education (AILab-CF), a discipline-specific competency architecture that integrates six interdependent domains within a unified educational model (Figure 1; Tables 1–2). By combining foundational principles (Figures 1, 4, and 5), a structured developmental continuum (Figure 2; Table 3), and a longitudinal implementation strategy (Figure 3; Tables 4–5), the framework provides a practical roadmap for preparing laboratory professionals for AI-enabled diagnostic environments [1–5,21,22].

Importantly, AILab-CF conceptualizes AI competency not as the acquisition of isolated technical skills but as the integration of technological understanding, professional judgment, ethical responsibility, human-centered practice, and lifelong learning. As healthcare systems continue to evolve toward increasingly intelligent diagnostic ecosystems, educational preparation must evolve accordingly [11–17,20].

Although expert consensus, empirical implementation, and validation studies remain necessary, the proposed framework provides an initial, theory-informed foundation for curriculum development, competency-based assessment, faculty development, workforce planning, and professional standard-setting within laboratory medicine. Its foundational principles, competency domains, and developmental descriptors should therefore be treated as a testable educational architecture rather than a validated standard. Ultimately, AILab-CF seeks to support laboratory professionals who can use, evaluate, govern, and continuously improve AI-enabled diagnostic practice while maintaining patient-centered accountability.

Author contributions

Ahmed M. Hjazi solely conceived the study concept, performed the literature synthesis, developed the framework, designed all figures and tables, interpreted the findings, wrote the manuscript, critically revised the content, and approved the final version for submission.

Ethics statement

Ethical approval was not required because this study did not involve human participants, animals, patient data, or identifiable personal information.

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