DIDACTIC EFFECTIVENESS OF VIRTUAL LABORATORIES AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN TEACHING BIOPHYSICS AT MEDICAL HIGHER EDUCATION INSTITUTIONS

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ABSTRACT

Background: Medical biophysics requires students to connect mathematical and physical laws with complex physiological processes. Virtual laboratories can make invisible mechanisms observable, while artificial intelligence (AI) may support differentiated practice and timely formative feedback. Objective: To analyze the educational potential and limitations of virtual laboratories and AI-assisted learning in medical biophysics and to formulate an implementable blended-teaching framework. Methods: A focused narrative review of peer-reviewed reviews, randomized-trial syntheses, physics-education research and international guidance published mainly between 2023 and November 2026. Findings: Research in health-professions education supports the use of virtual laboratories to reinforce conceptual learning, although psychomotor gains are less consistent. A 2026 meta-analysis of 66 randomized trials in undergraduate health-professions education reported potentially beneficial outcomes for several AI interventions but low-to-very-low evidence certainty and substantial heterogeneity. Accordingly, these results cannot be treated as direct evidence of effectiveness in a specific biophysics course. This article proposes a five-stage learning cycle linking pre-class diagnosis, guided simulation, clinical interpretation, AI-supported feedback and instructor-verified assessment. Conclusion: The most defensible model is blended, clinically contextualized instruction in which simulation complements physical

experiments and AI provides monitored support rather than replacing academic judgement. The present article reports no original student experiment or newly measured outcomes.

Keywords: medical biophysics; virtual laboratory; artificial intelligence; adaptive learning; simulation; clinical interpretation; digital competence; formative assessment.

INTRODUCTION

Biophysics is a foundational discipline that translates physical principles into descriptions of living systems. Medical students need to understand membrane transport and electrical potentials, hemodynamics, optical and acoustic interactions, radiation, and the physics of diagnostic devices. However, learning may remain fragmented when formulas are presented without opportunities to vary parameters, visualize mechanisms, and connect calculated results with physiological or clinical meaning. A simulation-based approach offers a means of moving between a mathematical model, a visual representation and an experimentally testable hypothesis [1, 2].

Virtual laboratories permit repeated manipulation of parameters, immediate observation of outputs, and safe rehearsal of otherwise inaccessible or equipment-intensive experiments. Open educational environments such as PhET provide interactive simulations for core physical mechanisms, although they are not necessarily designed or validated for clinical use [8]. Artificial intelligence, including automated feedback systems and large language models, can generate questions, identify common misconceptions and suggest differentiated practice. The clinical and scientific correctness of such output remains dependent on instructor verification [3–7].

Evidence from adjacent disciplines is promising but not uniform. A 2025 systematized review of 21 studies of virtual or blended laboratories in healthcare students found educational benefits, especially for cognitive outcomes, while practical psychomotor skills were less consistently addressed [1]. A 2026 umbrella review of technology-enhanced physics education emphasized the potential of simulations, virtual reality and AI, but highlighted substantial between-study heterogeneity and methodological limitations

[2]. Thus, pedagogical effectiveness must be treated as a measurable local outcome rather than as a guaranteed consequence of adopting new software.

AIM AND REVIEW APPROACH

The aim is to synthesize contemporary evidence and develop a practically assessable framework for integrating virtual experiments and responsibly supervised AI into medical biophysics instruction. This work is a narrative, concept-oriented review, not a registered systematic review or original randomized study. Sources include published evidence syntheses on virtual laboratories and AI in healthcare education, a physics-education umbrella review, and UNESCO guidance on generative AI. Their conclusions were interpreted according to study population, outcome domain, implementation context and limitations [1–7, 9].

The proposed framework is the author's educational synthesis of these sources. It has not yet been experimentally validated at Andijan State Medical Institute. No fictional survey responses, control groups, effect sizes or statistical significance levels are introduced.

RESULTS OF THE EVIDENCE SYNTHESIS AND DISCUSSION

1. Why simulation is pedagogically relevant to medical biophysics

In membrane biophysics, for example, learners can vary a solute concentration gradient or membrane permeability in a simplified computational environment and then justify the direction and rate of net transport. In electrophysiology, they can compare changes in membrane voltage, resistance or waveform duration and relate the graphical output to excitable tissues. In hemodynamics, changing vessel radius under the assumptions of laminar flow makes the strong dependence of resistance on radius visually explicit. These activities are best designed as prediction–experiment–explanation sequences, not as passive screen demonstrations.

The distinction between simulation and wet-lab experience is fundamental. A virtual model can isolate variables and make calculations reproducible; a physical laboratory also trains calibration, manipulation, measurement uncertainty, safety and teamwork. Evidence in healthcare laboratory education suggests that cognitive improvement is more established than transfer to psychomotor performance [1]. A blended curriculum should therefore use virtual rehearsal to prepare students for physical equipment rather than presuming complete equivalence between the modalities.

2. Adaptive AI support: benefits and limits

AI tools can provide short diagnostic quizzes at the start of a lesson, rephrase explanations at different levels of mathematical complexity, present structured hints after an incorrect solution, and generate additional practice scenarios. In principle, such functions may reduce waiting time for feedback and support learners entering the course with different physics backgrounds. The instructor should establish an approved problem bank and a reference solution for each task before any automated feedback is enabled.

The available research requires caution. In a 2025 scoping review of 310 publications on AI in undergraduate medical education, applications included tutoring, learning assistance, assessment and simulation, yet the authors highlighted a lack of standardized implementation and gaps concerning higher-order reasoning [4]. A 2026 meta-analysis of 66 randomized controlled trials (4,911 participants) across undergraduate health-professions education found some positive average effects for AI-assisted interventions, but the certainty of evidence was low or very low and no studies measured higher Kirkpatrick-level practice or patient outcomes [5]. Those numbers describe a broad educational evidence base—not measured outcomes of a medical biophysics program.

Generative systems may also produce mathematically plausible but scientifically incorrect responses, incorrect units, invented references or oversimplified physiological explanations. Therefore, AI use should be disclosed when required by institutional rules, clinical information should be excluded from public prompts, and students should

demonstrate independent reasoning without AI assistance during selected assessments. Human oversight, equitable access and privacy safeguards are consistent with UNESCO recommendations [7].

3. A structured blended-learning model

The proposed five-stage cycle begins with a brief pre-class diagnostic assessment (5–10 minutes) to identify prerequisite gaps. In the second stage, learners predict the effect of changing one variable and state a physical rationale before running a guided virtual experiment. The third stage requires interpretation of the resulting graph or calculation in a defined physiological case. Next, an approved AI assistant can offer graduated feedback and additional practice while recording the specific misconceptions addressed. The final stage is an instructor-verified transfer task, preferably involving new parameters or a real instrument, followed by a short reflection on model assumptions and uncertainty.

For example, in a module on ultrasound physics, students first explain the relationship between frequency, wavelength and sound speed, then vary frequency in an appropriate educational model and distinguish spatial resolution from penetration depth. They subsequently analyze why image quality and depth involve clinical trade-offs. Automated hints may point to an omitted unit conversion, but an instructor evaluates whether the proposed physical interpretation is consistent with the chosen model and real-world limitations.

4. Comparison of instructional components

Table 1. Proposed uses, assessment targets and limitations of digital tools in medical biophysics

Instructional component	Biophysics example	Evidence-oriented target	Principal limitation
Guided virtual experiment	Diffusion and membrane transport	Hypothesis, variable control and graph interpretation	Idealized models may hide experimental error
Interactive physical simulation	Hemodynamic resistance; electrical circuits	Conceptual transfer and correct calculation	Not a substitute for equipment handling
AI-supported formative feedback	Ultrasound frequency–resolution questions	Error diagnosis and targeted revision	May produce inaccurate or fabricated explanations
Instructor-led physical laboratory	Sensors, ECG signals and calibration	Measurement, safety, precision and teamwork	Equipment and time requirements
Integrated clinical case	Apply transport or wave principles to diagnosis	Mechanistic explanation and transfer	Requires carefully validated scenarios

Note: The table is a proposed teaching design, not a report of observed student outcomes. AI = artificial intelligence; ECG = electrocardiogram.

5. Suggested assessment and research protocol

Educational effectiveness should be assessed through predefined learning outcomes rather than satisfaction alone. A feasible institutional study would compare a blended virtual-laboratory-plus-AI pathway with a curriculum-matched conventional or simulation-only pathway. Groups should be comparable in prior physics achievement; students should complete equivalent baseline and final knowledge tests, an unseen clinical-interpretation task, and a practical skill checklist. A delayed assessment after several weeks would distinguish immediate performance from retention.

A suggested analytical rubric scores four domains separately: physical-model accuracy, quantitative reasoning with units, interpretation of physiological implications, and recognition of assumptions/measurement uncertainty. Each domain can be rated on a 0–4 scale using agreed descriptors, with two independent assessors and a prespecified approach to adjudicating discrepancies. A research report should present group sizes, missing observations, baseline differences, confidence intervals and effect sizes. Where appropriate, adjusted between-group comparisons can account for baseline achievement and instructor or cohort effects. The proposed indicators are a protocol outline; no data have been collected in this article.

Implementation feasibility should also be evaluated: proportion completing tasks, instructor preparation time, accessibility on common student devices, network stability, data minimization and student perceptions. These process outcomes matter because a resource-intensive tool may show favorable short-term results under ideal supervision yet be difficult to scale. Equally, students with weak connectivity should have access to offline or low-bandwidth equivalents, and grades must not depend on purchasing a commercial AI subscription.

6. Implications for curriculum quality and responsible use

A biophysics course can prioritize a limited number of high-value modules before extending digital approaches throughout the syllabus. The selection criterion should be a demonstrable conceptual bottleneck: an invisible mechanism, a multivariable relationship or a difficulty transferring an equation to a clinical interpretation. Each digital exercise must identify the physical law represented, assumptions, validity range and a method for checking predictions against observed or reference results.

Faculty development is essential. Instructors need to audit simulation settings, examine AI outputs for unit consistency, verify references and identify where automated feedback cannot distinguish multiple valid solution pathways. Periodic review of accessibility, software version changes and academic-integrity requirements is also

necessary. International evidence supports cautious adoption, but context-specific evaluation is required before claiming measurable improvement in students of a particular institution [2–7].

CONCLUSION

Virtual laboratories and AI-assisted instruction can create a more interactive, feedback-rich environment for teaching the quantitative foundations of medicine. The most educationally defensible application links prediction, controlled simulation, clinical explanation and independently assessed practical performance. Existing reviews support the potential of virtual laboratories and selected AI functions, but heterogeneous study designs, limited psychomotor evidence and uncertain transfer prevent an unconditional assertion of superiority. For medical biophysics, a staged blended model with validated content, teacher oversight, equitable access and transparent outcome assessment offers a practical research direction. This paper presents an evidence-informed instructional framework; its effectiveness remains to be tested in a prospective educational study.

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