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# TEACHING MEDICAL BIOPHYSICS THROUGH GUIDED SIMULATION AND CLINICAL PROBLEM SOLVING

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**Abstract:** Medical biophysics requires students to connect mathematical relationships with physiological mechanisms and the operation of medical devices. This article develops an instructional approach that combines guided simulation, clinical problem solving and formative assessment. A focused narrative synthesis of eight publications on active learning, physics simulations, laboratory instruction and health professions education was used to identify principles relevant to undergraduate medical biophysics. The synthesis supports structured student participation, interpretable representations, explicit feedback and assessment beyond satisfaction; however, evidence from other disciplines cannot establish effectiveness in a local biophysics course. The proposed sequence requires learners to state assumptions, predict an outcome, vary a parameter, explain the observed relationship and apply the principle to an unfamiliar problem. An idealized fluid-flow example illustrates how numerical calculation can be connected to model limitations. A four-domain assessment framework addresses conceptual explanation, quantitative accuracy, interpretation of evidence and transfer. The article provides a practical basis for course design and prospective evaluation. No original classroom intervention or student outcome dataset is reported. Its principal contribution is an explicit connection between the learning task, the reasoning process and the evidence required to assess that reasoning.

**Keywords:** medical biophysics; guided simulation; active learning; clinical problem solving; quantitative reasoning; formative assessment.

## Introduction

Biophysics provides a quantitative language for understanding processes such as fluid transport, diffusion, membrane charging, sound propagation and optical measurement. In medical education, these topics become meaningful when students can explain how a physical relationship contributes to a physiological phenomenon or a measurement procedure. Successful instruction therefore requires more than recalling an equation: learners must select relevant variables, establish units, interpret the direction of change and identify the conditions under which a model is appropriate.

A student may reproduce a formula correctly while misunderstanding its application. For example, knowing that resistance depends on tube radius does not ensure that the student can predict the effect of a small radius change or explain why a model of a rigid tube cannot fully represent a living vessel. Teaching that separates calculation from interpretation makes such misunderstandings difficult to detect. A useful instructional task should reveal the learner's initial prediction and require an explanation after calculation or observation.

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Research in undergraduate science supports active learning as a broad instructional direction [1]. Nevertheless, students' perceptions of learning may differ from their performance on objective assessments [2]. Digital simulations can create opportunities to examine invisible processes and test relationships, but the educational value of a simulation depends on what learners are asked to investigate. The purpose of this article is to develop a practical approach to teaching medical biophysics that connects guided simulation with quantitative reasoning and clinically meaningful transfer. The central question is how a learning activity can make the reasoning between a physical model and a medical application observable and assessable.

## Methods

The article uses a focused narrative synthesis followed by instructional design. Targeted web searches were conducted on 15 October 2026 using combinations of "medical biophysics teaching," "interactive simulation," "active learning," "physics education," "gas exchange," and "retrieval practice." Publisher pages, research repositories and PubMed records were consulted to verify bibliographic details and the relevant study findings. Eight publications from 2005 to 2025 were selected purposively because they addressed conceptual learning, simulation design, physical and virtual laboratories, health professions instruction or retention. The evidence base includes primary educational studies and research syntheses; it does not represent an exhaustive systematic review.

For each source, the analysis considered the educational setting, instructional comparison, outcome assessed and limitation relevant to transferring the findings to medical biophysics. Reported findings were separated from the proposed teaching procedures. Principles were then mapped to observable student actions and possible assessment evidence. No new participants were recruited, no institutional teaching experiment was conducted and no local student scores were analyzed. Accordingly, the Results section presents the synthesis and its instructional outputs. The suggested lesson sequence and scoring criteria are proposals for future testing, not validated measures or demonstrated effects.

## Results

### Evidence relevant to instructional design

The reviewed literature supports several complementary design decisions. Freeman and colleagues found an overall advantage for active learning across undergraduate science, engineering and mathematics studies [1]. This finding supports opportunities for students to produce and discuss answers, while leaving the choice of a specific biophysics activity open to local evaluation. Deslauriers and colleagues demonstrated that students could learn more in active classes while feeling that they learned less [2]. Thus, favorable impressions of a lesson should be treated as information about the learning experience rather than as a direct measure of conceptual mastery.

Research on introductory physics provides a more specific rationale for simulations. In a circuit-learning study, Finkelstein and colleagues reported that students using simulated equipment performed better on selected conceptual and subsequent real-circuit tasks than students using physical equipment [3]. The result concerns the tested circuit activity and cannot be generalized to every laboratory skill. Podolefsky and colleagues identified simulation features that supported exploratory reasoning,

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including interactive feedback and connections among representations [4]. The review by de Jong and colleagues supports deliberate combinations of physical and virtual investigation [5]. These studies inform the present recommendation to connect a model-based activity with a relevant measurement task when equipment and time permit.

Evidence from medical education also requires careful interpretation. Broderick and colleagues evaluated an interactive gas-exchange program using successive student cohorts. Examination performance improved, but the additional improvement on gas-exchange questions compared with other questions did not reach statistical significance [6]. The study demonstrates a usable instructional approach without establishing an isolated causal effect of the simulation. Kononowicz and colleagues reported heterogeneous and generally low-quality evidence for virtual patients in health professions education [7]. Finally, a randomized study by Larsen and colleagues supported repeated retrieval with feedback for longer-term retention among medical residents [8]. These findings justify evaluating learning, retention and implementation separately.

A sequence for learning from a biophysical model

The proposed sequence begins with a focused problem that students can address using one principal relationship. The teacher supplies sufficient context to identify the physical mechanism without introducing unrelated diagnostic complexity. Students first write the model assumptions and distinguish the variable to be changed from the quantities held constant. They then predict the direction and, where feasible, magnitude of the result before opening the simulator. A written prediction provides evidence of the initial conception and prevents an observed animation from being mistaken for an independently reasoned answer.

During investigation, students change one parameter at a time and record the input and output in a small table. They compare the observed result with the prediction, explain any discrepancy and revise the explanation where necessary. Peer discussion is followed by an individual response so that group agreement does not conceal incomplete understanding. The final step presents a different context or representation. A learner who can transfer the relationship and state a relevant limitation provides stronger evidence of understanding than a learner who can repeat the original calculation.

**Table 1. Proposed links between biophysics tasks and assessment evidence**

| Topic | Student task | Evidence of understanding |
|---|---|---|
| Fluid flow | Predict and test the effect of changing radius at a fixed pressure difference. | Correct proportional reasoning and a stated limitation of the tube model. |
| Diffusion | Vary membrane thickness while other model parameters remain constant. | Explanation of the inverse relationship between thickness and diffusive flux. |
| Membrane charging | Change resistance or capacitance in a passive equivalent circuit. | Interpretation of the time constant and recognition of the model's limited scope. |

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| Topic | Student task | Evidence of understanding |
|---|---|---|
| Optical measurement | Compare a reference signal with measurements at different concentrations. | Identification of calibration, assumptions and possible measurement error. |

Illustrative calculation and interpretation

Consider steady laminar flow of an incompressible Newtonian fluid through a straight, rigid circular tube. The Hagen–Poiseuille model relates volumetric flow rate Q to the pressure difference ΔP, radius r, dynamic viscosity η and tube length L:

$$Q = \frac{\pi \Delta P r^4}{8 \eta L}$$

With pressure difference, viscosity and length held constant, reducing the radius to 80% of its original value gives a flow ratio of $0.8^4 = 0.4096$. The calculated reduction is therefore 59.04%. This is an illustrative mathematical result, not an observed change in patients or a classroom outcome. A teaching prompt asks why a 20% decrease in radius does not produce a 20% decrease in flow. A second prompt asks what happens to the prediction when pressure difference is also allowed to change.

The explanation should identify the fourth-power dependence and the assumptions that produced it. Transfer to circulation requires acknowledging features omitted by the simple model, including vessel compliance, pulsatility, branching and context-dependent blood rheology. The educational objective is to use the model to reason about a relationship while recognizing its limits. A simulator should therefore expose its governing relationship and assumptions, rather than present an output as an unexplained answer.

Assessment of reasoning and transfer

Assessment is organized into four domains: conceptual explanation, quantitative accuracy, interpretation of evidence and transfer with recognition of limitations. Each domain may be scored provisionally from 0 to 3, yielding a total of 12 points. For conceptual explanation, 0 indicates an absent or incorrect explanation; 1 identifies a relevant variable; 2 explains the relationship correctly; and 3 also justifies the conditions under which it applies. Parallel descriptors should be developed for the other domains. These scores are suggested for formative use and require piloting before decisions about achievement thresholds are made.

An entry question establishes prior understanding, an exit task examines the immediate learning objective, and a later task evaluates retention and transfer. The later task should use new numerical values or a changed representation. A brief explanation is scored alongside the answer. Interface fluency, satisfaction and time on task can inform lesson design, but they are recorded separately from learning outcomes. Repeated low-stakes retrieval with feedback provides a reasonable design principle [8]; its effectiveness and appropriate spacing within this course still require investigation.

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## Discussion

The proposed approach makes the connection between calculation and interpretation explicit. Its contribution lies in specifying the evidence that a teacher should collect at each stage: an initial prediction, a controlled comparison, an explanatory revision and an independent transfer response. A simulation can make the consequences of a parameter change visible, but the written explanation reveals whether the learner understands why the change occurs. This distinction is particularly useful in medical biophysics, where attractive visualizations may coexist with weak quantitative reasoning.

Implementation should be matched to students' preparation. Learners with limited mathematical fluency may first need a worked example with units and a graph, followed by a partially completed problem. More experienced students can compare competing assumptions or design their own parameter changes. Guidance can be reduced as students demonstrate independence. A short glossary in English and the teaching language can help separate difficulties with scientific terminology from difficulties with the physical concept. The teacher should assess the explanation before attributing an incorrect response solely to a language problem.

An 80-minute session could allocate 10 minutes to prerequisite questions and predictions, 15 minutes to explanation of the model, 25 minutes to guided investigation, 20 minutes to interpretation and transfer, and 10 minutes to individual assessment. This schedule is a proposed implementation example. Students working in pairs can alternate between operating the software and checking assumptions and units. Where computers are limited, a teacher-controlled simulation can support predictions and discussion, while each student still submits an individual reasoning task. Software availability alone should not determine the learning objective.

Evaluation of the approach should compare it with a clearly described alternative that covers the same content for the same duration. A prospective study could assign intact teaching groups to different instructional approaches, measure baseline knowledge and predefine a delayed transfer outcome. Analysis would need to account for the assignment unit and any clustering of students within groups. Teacher effects, prior mathematical preparation, attendance and unequal access to practice should be considered. Blinded scoring of written responses, a common scoring guide and checks of agreement between raters would strengthen the interpretation of the findings.

Several limitations constrain the present synthesis. The literature was selected purposively, and some evidence comes from general physics or postgraduate medical education rather than undergraduate medical biophysics. The sources differ in instructional content, comparison groups and outcomes; no pooled effect estimate was calculated for the proposed approach. The fluid-flow example demonstrates mathematical reasoning under stated assumptions, not the effectiveness of a lesson. Furthermore, the assessment framework has not been validated, and no claims can be made about improvement in clinical performance. These limitations define priorities for local empirical evaluation.

## Conclusion

Teaching medical biophysics can be organized around a sequence in which students state assumptions, predict a result, investigate a controlled change, explain the evidence and transfer the principle to a new problem. Guided simulation provides a setting for this sequence when the model is transparent

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and the task requires reasoning. Assessment should examine conceptual explanation, calculation, evidence interpretation and the limits of application. The proposed approach offers a practical instructional design supported by relevant literature, while its effects on undergraduate medical students' learning and retention remain to be established through prospective study.

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