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Digital Intelligence Teaching in PBL/Flipped PBL: A Tiered Undergraduate-to-Graduate Approach for Clinically Driven Pathophysiological Education

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Abstract: Problem-Based Learning (PBL) in pathophysiology education is a student-centered teaching approach that enhances students' understanding and application of pathophysiological knowledge by solving clinical pathophysiology problems. The key challenges include how to integrate pathophysiology PBL teaching into a knowledge graph and implement an undergraduate-to-graduate tiered curriculum system, achieving a "research-teaching-practice" trinity framework that synergistically enhances students' scientific literacy and clinical competencies. This study developed a digital intelligence-augmented pathophysiology education framework at Tongji University, integrating knowledge graphs (210 core concepts from 5 textbooks with 383 relationships) with tiered PBL approaches for 150 undergraduates and 140 graduates. The model combines an AI-linked PBL Case Engine (5 four-act clinical cases), Smart Tree Platform (AI-driven Q&A), and Tongxuetang Advanced Course (virtual labs with 1000+ digital slides), implementing flipped PBL where undergraduates analyze AI-assisted cases through structured discussions while graduates create case modules incorporating latest research via medical databases. The framework achieved 95% graduate satisfaction and 60% undergraduate preference for AI-learning, with top exam scores >85/100, effectively bridging basic-clinical medicine through adaptive knowledge mapping—particularly benefiting the 50% non-medical graduates. By having graduates lead flipped PBL development and using competency graphs, it enables clinically-driven mechanism exploration while enhancing scientific literacy and diagnostic competence across all levels.

Keywords: pathophysiology; PBL; knowledge graph; flipped PBL; education

1. Introduction

Pathophysiology is the study of functional, metabolic, and morphological changes in the body during the onset, progression and outcomes of diseases. It serves as a bridging discipline between basic and clinical medicine, with its core focus on uncovering the nature and mechanisms of diseases to provide theoretical foundations for prevention, diagnosis and treatment. As a pivotal bridge connecting basic and clinical medicine, its research advancements directly reflect the forefront of medical education and practice. Research-driven reforms in teaching systems have led to competency-oriented and clinically integrated innovations in undergraduate and graduate education globally [1,2]. Outcome-Based Education (OBE) combined with Problem-Based Learning (PBL), where teaching scenarios are designed around clinical and research questions, supplemented by digital platforms such as MOOCs and virtual teaching communities to enable cross-

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institutional resource sharing [3,4]. This enhances undergraduates' mastery of pathophysiology-related foundational medical knowledge and facilitates their transition to clinical training [5,6].

As artificial intelligence (AI) becomes an integral part of modern education, it is crucial for students to develop the skills to use AI effectively and ethically, particularly in the context of research-based assignments and takehome assessments [7–9]. In this report, we detail the teaching reform of clinically problem-driven exploration of pathophysiological mechanisms—undergraduate-to-graduate tiered PBL/flipped PBL digital intelligence teaching adopted in Tongji university school of medicine. Advances in pathophysiology research in China are profoundly reshaping medical education paradigms. By establishing a tripartite training system of “research leadership—teaching innovation—practical reinforcement”, students' scientific literacy and clinical competency are effectively enhanced. Moving forward, multidimensional collaborative innovation must be strengthened to cultivate a new generation of medical talent aligned with the Healthy China strategy.

2. Methodology

2.1. Resource System

(1) Intelligent Knowledge Graph System: Multi-tier architecture with 5 Chinese/English textbooks (undergraduate/graduate) divided into 210 core knowledge points containing 383 logical relationships. (2) PBL Case Engine: 5 clinical cases decomposed into four acts per case linked to the knowledge graph (including problem maps). (3) Dynamic Assessment System: Chapter quizzes (30 questions/chapter) with real-time knowledge network analysis. (4) Blended Teaching Platform: Smart Tree (<https://www.zhihuishu.com/>) dual courses—Knowledge Graph Course (ID: 1862684893285322752), Flipped Classroom (K8141821), Tongxuetang advanced online course (<https://tongxuetang.tongji.edu.cn>) and Morphology Virtual Laboratory (mednew.tongji.edu.cn/mengoo/Course) with 45 Micro-lectures videos, 1K pathological digital slides, 1,200+ virtual microscope, 20+ Doctor-patient communication cases.

2.2. Students

Each year of Tongji University School of Medicine, around 150 clinical undergraduate students study the Pathophysiology course in their second year. 100 master's students completed optional subjects of an online course in Advanced Pathophysiology Theory and Experimental Techniques. 40 PhD students complete optional course for Basic and Advanced Topics in Pathophysiology. Among the graduate students, 5% are from non-medical schools, and almost 50% are without clinical undergraduate background.

2.3. Teaching Plan

2.3.1. Smart Tree Intelligent Course Platform

(1) Knowledge Graph Learning

The platform links textbook chapters to a structured knowledge graph, integrating four distinct four-act PBL (Problem-Based Learning) clinical cases into the Smart Tree knowledge mapping system. This achieves comprehensive coverage of all key concepts, enabling systematic, dynamic, and holistic learning. By constructing discipline-specific knowledge graphs, it enhances students' mastery of the curriculum framework and cultivates their ability to: Dynamically analyze disease etiology and progression from an integrated human perspective. physiology perspective. Interpret clinical problems through pathological/pathophysiological lenses. Decipher the essence of symptoms/signs and laboratory diagnostic variations. Thereby establishing a solid foundation for clinical decision-making.

(2) Question Graph Learning

Deconstructs PBL cases act-by-act (symptoms, examinations, treatments) into granular Q&A pairs with annotated knowledge point linkages, facilitating clinical problem-driven pathophysiology exploration. Correlates test bank items with knowledge nodes for reinforced comprehension. Features a comprehensive exercise repository covering all course objectives, supplemented by AI-powered adaptive drills for personalized

remediation. Provides 24/7 AI+ teacher assistant support through AI-driven course Q&A, DeepSeek Answer Engine and Real-time virtual tutoring.

2.3.2. PBL Learning for Undergraduates

Due to the reduction of in-class hours and large class sizes of approximately 50–70 students per class, it is challenging to conduct PBL discussions in the classroom. Moving forward, we shift to more online interactions and implement the following improvements:

(1) Pre-Class (Online: Smart Tree Platform of Flipped Classroom)

The instructor releases PBL case materials on the Smart Tree platform one week in advance, including the first two acts of each case. Students review the materials. Students research the case questions, engage in free discussions in the forum, and preliminarily propose diagnostic hypotheses and supporting evidence based on Acts 1–2 with the assistance of AI on the platform.

(2) In-Class (Group Discussion & Presentation)

- I. Warm-up: Each group presents their diagnosis and supporting evidence in a PPT, citing relevant textbook chapters.
- II. Guided Analysis: The instructor walks through the case, selects the best group analysis, and explains the learning objectives. Common misconceptions are addressed, with emphasis on easily overlooked details or ambiguous points.
- III. Group Discussion: Acts 3–4 are distributed. Students discuss in groups, assign subtopics, conduct research, evaluate AI-generated information and prepare PPTs. The instructor circulates to guide discussions.
- IV. Presentations: Groups present their assigned subtopics, analyzing pathophysiological clues, causal relationships, and mechanisms via PPT.
- V. Summary: The instructor answers questions, reviews learning objectives, and provides feedback—highlighting strengths and areas for improvement. Students are encouraged to use AI critically in academic research.

(3) Post-Class (Online: Smart Tree)

Each group submits a case analysis diagram and a written report.

Grading breakdown: Instructor evaluation (50%) + inter-group peer review (20%) + intra-group peer review (20%) + self-evaluation (10%).

2.3.3. Flipped PBL Learning for graduates

Online Course (Tongxuetang advanced online course)

This online course of Advanced Pathophysiology Theory and Experimental Techniques is grounded in the theoretical framework of pathophysiology and encompasses the development, diseases, and research advancements of the heart, brain, liver, and breast. It also includes Problem-Based Learning (PBL) modules closely tied to pathophysiological principles. Through theoretical lectures, literature analysis, and video demonstrations of experimental techniques, the course integrates foundational theories of common clinical diseases with cutting-edge research developments.

Aligned with the course structure, a theoretical knowledge graph is constructed to facilitate both scientific research and clinical-theoretical practice. By extracting and refining this knowledge graph, students engage in experimental module design and PBL case writing, enabling the application of competency mapping.

Course Implementation Framework:

(1) Theoretical Knowledge Graph Development

Construct a pathophysiology knowledge graph for graduate education by integrating core disciplinary concepts with contemporary research breakthroughs. Extract experimentally relevant theoretical nodes and cross-link them with corresponding textbook chapters to finalize the course knowledge architecture.

(2) Competency Enhancement Phase

Curate literature-derived knowledge units and map them to relevant curricular modules. Design theory-based experimental templates to guide students in drafting project-specific research modules, laying the groundwork for study design (targeted for biomedical/bioengineering learners).

(3) Clinical Application via Flipped PBL

Post-PBL training, clinical graduate students synthesize multi-chapter core concepts from the knowledge graph to compose four-act PBL cases aligned with scientific advances in disease pathophysiological mechanisms, diagnosis, and therapy under the guidance of AI and further intelligent depth-aware disambiguation from professional medical websites such as Academic Medical Portal, Clinical Medicine Web Platform, Medical Information Hub, and Curated Medical Database, thereby solidifying clinical diagnostic foundations.

I. Presentations: Groups present their assigned subtopics, analyzing pathophysiological clues, causal relationships, mechanisms, advances in research, and clinical treatment via PPT.

II. Discussion: Based on the case, students discuss possible diagnoses and supporting evidence, analyze pathophysiological differences among different diseases, and explore potential treatment strategies (e. g., medications, surgery, supportive care) based on pathophysiological mechanisms, and analyze how treatments intervene in disease progression (e.g., anti-inflammatory, metabolic correction, hypoxia relief).

III. Summary & Reflection: The instructor or a student representative summarizes the core pathophysiological mechanisms, reflects on learning gaps, and proposes further research questions, and discusses potential molecular, cellular, and organ-system-level changes (e. g.), signaling pathways, gene expression, organ dysfunction).

3. Results

Enhanced Learning Outcomes

Student feedback: Case-guided mechanism discussions helped in understanding complex pathological processes. Leveraging knowledge graph exercises and connections with textbook concepts enables more efficient comprehension of key knowledge points. A survey of 155 undergraduate students showed that 60% of the students expressed their preference for the online course, 36% remained undecided, and only 2% indicated they did not like it (Figure 1A). The online course provides multifaceted assistance for learning pathophysiology, including visualized knowledge mapping, intelligent recommendation of personalized learning content, automated generation of study summaries, and interactive Q&A integrated with clinical cases and question bank practice (Figure 1B).

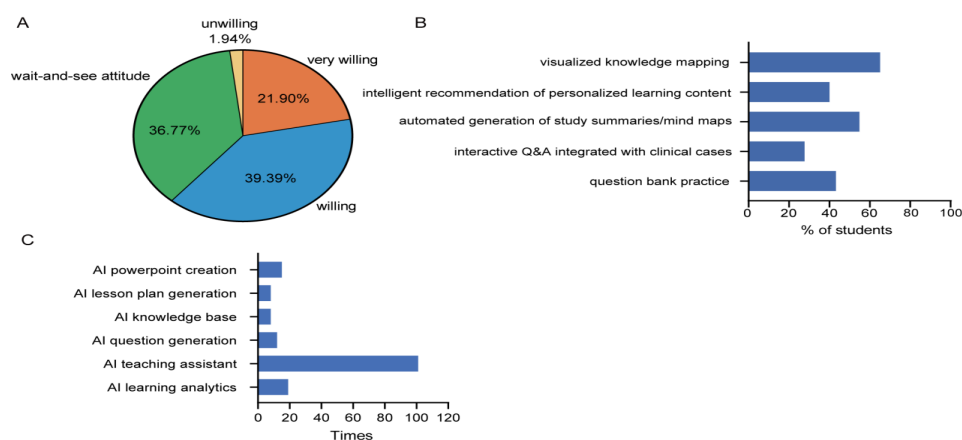


Figure 1. Evaluation of innovative teaching methods in pathophysiology education. (A) Student preferences for the online course format (n = 155). (B) Key features of the online course enhancing pathophysiology learning, including visualized knowledge mapping, AI-driven content recommendations, automated summaries, and interactive case-based Q&A. (C) Utilization frequency of AI-assisted teaching tools (DeepSeek-R1 model with RAG integration), ranked as the most widely adopted resource among students.

Effectiveness of AI Study: AI Study Companion, built on the DeepSeek-R1 large model, deeply integrates course knowledge bases through RAG technology to provide real-time professional Q&A. This AI companion acts like a knowledgeable tutor, offering students expert guidance whenever needed. According to backend statistics, AI-assisted teaching is the most widely used tool by each student (Figure 1C).

Instructor observations: Students more actively connected clinical scenarios with foundational mechanisms, and showed improvement in students' proficiency in creating mechanism-based mind maps using intelligent systems. The average final exam score of the undergraduates was 75, while all of the top 60 students in knowledge mastery scored above 85.

Knowledge continuity: Among the 162 graduate students surveyed, 43% were supervised by basic medicine faculty, with three-quarters of these advisors engaged in basic research. 50% had advisors from clinical medicine, with approximately half focused on basic research and the other half on clinical research. The remaining 7% were mentored by faculty from non-medical schools, all of whom conducted basic research. Additionally, nearly half ($\approx 50\%$) of the 162 students lacked a prior medical undergraduate degree (Figure 2A). The organic integration of knowledge graphs with textbook-based key concepts and clinical PBL cases provides a streamlined pathway for non-medical-background students to master pathophysiology knowledge points through self-directed personalized learning. Non-medical-background graduate students collaborate with clinical students in teams to collect, systematize, discuss, and prepare reports on pathophysiology PBL cases, enabling in-depth analysis of mechanism exploration. Over 95% of students expressed satisfaction with our graduate pathophysiology course (Figure 2B). According to the survey, they listed that the course could facilitate better integration of course content, enhance collaboration among classmates, increase interaction between teachers and students, and boost everyone's motivation (Figure 2C).

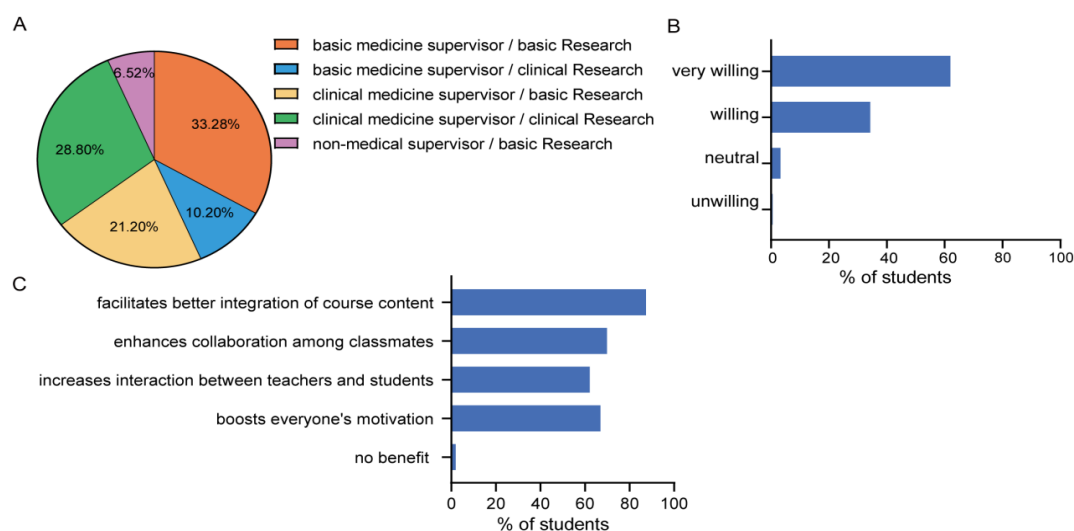


Figure 2. Knowledge continuity and interdisciplinary integration in graduate pathophysiology education. **(A)** Background distribution of 162 graduate students, including advisor affiliations (basic/clinical/non-medical faculty) and student prior medical training status. **(B)** Student satisfaction rates with the pathophysiology course, highlighting collaborative PBL case discussions between medical and non-medical-background students. **(C)** Perceived benefits of the course, including content integration, peer collaboration, teacher-student interaction, and learning motivation.

4. Discussion

For medical undergraduate students, after completing foundational courses such as anatomy, histology and embryology, physiology, and biochemistry, they begin studying pathophysiology in the second semester of their second year, alongside immunology, microbiology, and pathology—before taking any clinical courses. However, pathophysiology primarily focuses on the mechanistic analysis of clinical pathological processes, so greater emphasis should be placed on balancing “clinical problems” and “mechanistic depth,” avoiding superficial discussions among undergraduates due to knowledge gaps. Thus, PBL requires tiered case design.

Postgraduate pathophysiology education requires in-depth analysis of clinical cases, including diagnosis, differential diagnosis, treatment, the latest research advances, and pathophysiological mechanisms spanning organ, tissue, cellular, and even molecular changes—thereby enhancing students’ research and clinical skills.

Since students come from different departments with varying research focuses, their learning interests may differ significantly. Therefore, problem-based learning (PBL) centered on pathophysiological changes in different organ systems can facilitate interdisciplinary exchange and improvement. However, the depth of expertise and accuracy of such learning approaches still warrant critical evaluation. Among students’ surveys, most students were concerned about the authority of AI data sources, the usability of interactive design, multi-modal presentation, and real-time updates on the latest research progress (Figure 3). Therefore, more in-depth mechanistic research and advances in clinical treatment require professional guidance from postgraduate supervisors.

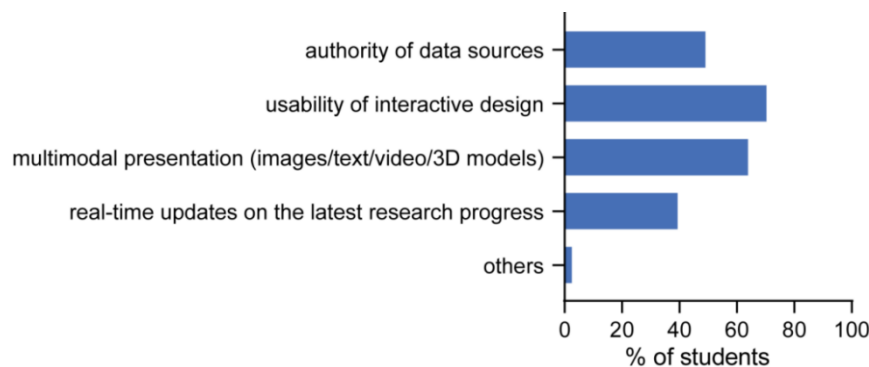


Figure 3. Student perspectives on AI-enhanced pathophysiology learning. Survey responses highlight key concerns regarding AI-assisted PBL approaches, including: reliability of data sources, usability of interactive interfaces, effectiveness of multi-modal content presentation, and timeliness of research updates.

5. Conclusions

Clinically driven problems significantly enhance the depth of mechanism exploration [10,11]. Digital intelligent tools, such as theoretical knowledge graph-based cases as well as AI-based pathological analysis, address the limitations of traditional PBL resources [12–14]. The Flipped PBL Model of graduate courses enhances the pre-class self-study of foundational knowledge via digital platforms, allowing in-class time to focus on high-level mechanism discussions. To mitigate increased reliance on AI-assisted diagnosis while preventing the decline of independent critical thinking skills, graduate students were organized into PBL groups to collaboratively develop case analyses and engage in structured classroom discussions.

The year-long pedagogical innovations showed high learner satisfaction, with undergraduates showing significantly improved engagement when utilizing graduate-developed PBL materials. Long-term effects require further validation, including tracking graduates’ research capabilities. Subsequent phases will involve granular micro-module development to optimize knowledge point mastery.

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Author Contributions

L.L. and J.X. conceived and designed research; L.L., J.X., J.H. and L.Y. performed experiments; L.L., L.Y., and J.H. analyzed data; L.L., L.Y., and J.H. interpreted results of experiments; L.L. and L.Y. prepared figures; L.L. drafted the manuscript; L.L. edited and revised the manuscript; L.L. and L.Y. approved the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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