

# Integrating Basic Science Teachers and Clinicians in Problem-Based Learning: An Exploratory Study of a SMART Principle–Guided Co-Teaching Model

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## Research Article

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# **Abstract**

## **Background:**

Problem-based learning (PBL) integrates foundational biomedical knowledge with clinical application, fostering clinical reasoning. In many Chinese medical universities, preclinical PBL is mainly facilitated by basic medical science faculty, whose limited clinical experience may restrict discussions on real-world diagnosis and treatment. Co-teaching with clinicians offers complementary expertise, but without structured guidance it may create role ambiguity or undermine self-directed learning. The SMART framework (Specific, Measurable, Achievable, Relevant, Time-bound) provides a structured approach to clarify teaching objectives and enhance knowledge integration.

## **Objective:**

This study evaluated a SMART-guided co-teaching model combining basic science teachers and clinicians in a lung cancer PBL module, assessing its impact on learning efficiency, integration of basic and clinical knowledge, and students' intrinsic motivation.

## **Methods:**

In a single-center, parallel-group randomized trial, 72 preclinical medical students were assigned to an intervention group (co-taught PBL with SMART objectives) or a control group (traditional PBL). Both groups used identical materials and comparable clinical cases. The three-week module involved weekly 2-3-hour sessions. Post-intervention evaluation included multiple-choice questions, learning experience questionnaire, and semi-structured interviews. All other curricular conditions were standardized.

## **Results:**

Both groups achieved high foundational knowledge acquisition, but the intervention group demonstrated superior performance in complex integrative areas such as molecular pathology and targeted therapy. The intervention group also reported higher engagement, efficiency, and perceived clinical relevance. Pre-class preparation time decreased in both groups, but patterns of "expected versus actual preparation time" differed, suggesting an effect on self-directed learning. Qualitative feedback highlighted improved knowledge integration and more authentic clinical discussions.

## **Conclusions:**

SMART-guided co-teaching in PBL may enhance knowledge integration, optimize learning processes, and improve teaching acceptability. Structured co-teaching increases clinical relevance, supports integrated

biomedical and clinical reasoning skills, and offers a replicable framework for interdisciplinary medical education.

## **Trial registration:**

Chinese Clinical Trial Registry ChiCTR2600129565, registered August 6, 2026, retrospectively registered.

## **Introduction**

Problem-based learning (PBL) is widely recognized as a core pedagogical approach in contemporary medical education. Its student-centered orientation and use of clinically contextualized problems are intended to promote active learning, integration of foundational biomedical sciences with clinical application, and the development of clinical reasoning and lifelong learning skills (1-3). However, implementing PBL during the preclinical phase presents persistent challenges. In many Chinese medical universities, PBL groups are primarily facilitated by basic medical science faculty who, despite strong expertise in biomedical mechanisms, may have limited clinical involvement. This can restrict the clinical depth and authenticity of discussions on diagnosis and treatment decision-making for undergraduate student majoring in clinical medicine (4,5).

Co-teaching models involving both basic medical science teachers and clinicians have been proposed to address this limitation. Such collaboration allows complementary expertise to be leveraged: basic scientists provide mechanistic explanations, whereas clinicians contribute contextual insight, experiential knowledge, and modelling of clinical reasoning (6). However, co-teaching alone does not necessarily improve learning outcomes. Without explicit instructional design and clearly defined goals, co-teaching may result in role ambiguity, inconsistent pedagogical approaches, or excessive reliance on clinicians' authority, potentially undermining the self-directed learning ethos central to PBL (7). These challenges highlight the need for a structured framework to guide collaborative facilitation (8).

The SMART principle (Specific, Measurable, Achievable, Relevant and Time-bound) is a widely adopted framework for goal setting and performance management. It has been shown to enhance clarity, accountability and implementation effectiveness across educational contexts (9). Embedding SMART principles within a co-taught PBL model provides a structured framework that aligns objectives, clarifies facilitator roles, promotes meaningful knowledge integration through achievable, case-relevant tasks, and ensures focused, efficient discussion within defined time boundaries (10). This approach makes clinical integration an intentional and reproducible component of the learning design, rather than an outcome dependent on individual facilitator experience (11).

Despite its theoretical promise, empirical evidence on the application of SMART-guided frameworks within co-taught PBL in medical education remains limited (3,12). To address this gap, we developed a SMART principle-guided co-teaching model integrating basic medical science teachers and clinicians. A randomized controlled trial was conducted to compare this model with traditional PBL facilitated solely

by basic medical science faculty. The study aimed to evaluate whether the SMART-guided co-teaching model improves learning efficiency, enhances integration of basic and clinical knowledge and strengthens students' intrinsic learning motivation.

## METHODS

### *Study Design*

We conducted a single-center, parallel-group randomized controlled trial to evaluate the educational effectiveness of a SMART principle-based co-teaching model involving basic medical science teachers and clinicians within PBL modules (10,13).

Participants were randomly assigned to either an intervention group or a control group. The intervention group received co-taught PBL sessions facilitated jointly by basic medical science teachers and clinicians, with the instructional process explicitly structured according to SMART principles. The control group received conventional PBL facilitated solely by basic medical science teachers.

To minimize confounding, both groups used the same core teaching materials and comparable cases derived from authentic clinical scenarios and adapted for educational purposes. Assessment formats were identical across groups. Facilitators were selected from the same trained faculty pool to ensure consistency in teaching quality. Apart from the instructional model, all other curricular conditions were standardized.

The overall study design, including baseline assessment, student randomization, intervention implementation, and post-intervention evaluation, is summarized in Figure 1.

### **Figure 1 Flowchart of the study design**

This flowchart depicts the overall study procedure. Students were first assessed at baseline and provided with objectives and content specification. They were then randomly assigned to either the control group (traditional PBL,  $n=36$ ) or the intervention group (SMART-based PBL,  $n=36$ ). Both groups participated in 3-week PBL modules, with one session per week lasting 2-3 hours. Post-intervention evaluation included MCQ tests, questionnaire, and semi-structured interviews for both groups.

### *Participants*

A total of 72 third-year undergraduate students enrolled in a five-year clinical medicine program at a medical university in China participated in the study. All eligible students were invited to take part. Participants were randomly allocated in a 1:1 ratio to either the intervention group ( $n=36$ ) or the control group ( $n=36$ ) using a computer-generated randomization sequence.

All students had completed the core foundational medical science curriculum prior to enrolment. Baseline characteristics, including prior academic performance and learning-related psychological

measures, were comparable between groups, with no statistically significant differences observed ( $P>0.05$ ).

No formal sample size calculation was performed, as this study was designed as an exploratory investigation of a teaching model. The primary aim was to assess the feasibility and potential effects of the intervention. Random allocation of students to groups was used to evaluate the intervention, and no substantial systematic bias was anticipated (3).

### ***Educational Intervention***

#### **I. PBL procedures**

The study was conducted within the existing PBL curriculum, which is organized into disease-based modules (e.g., cardiovascular, respiratory, and neurodegenerative conditions). Each module spans three weeks and integrates content from physiology, pathology and pharmacology. Students participate in one small-group discussion per week, with each session lasting 2-3 hours (2,14). In the current study, the educational intervention was conducted specifically in the lung cancer module, comparing a co-teaching PBL model with a conventional model.

##### *Co-teaching PBL model*

The co-teaching model followed a structured four-stage process:

1. Faculty preparation: Before each session, the basic medical science teacher and clinician met to define their roles and agree on the core learning objectives, ensuring alignment and coherence in content delivery.
2. Student-led case analysis: Students conducted independent preparation followed by collaborative case analysis within their groups.
3. Facilitated discussion: facilitators guided learning through structured questioning and cognitive scaffolding rather than delivering didactic instruction, supporting progressive achievement of predefined learning objectives.
4. Evaluation and feedback: Learning outcomes were evaluated using quizzes, questionnaire and semi-structured interviews.

##### *Conventional PBL model*

In the control condition, PBL sessions were facilitated solely by a basic medical science teacher. All other elements, including curriculum structure, case materials, session frequency and duration, and evaluation methods, were identical to those used in the co-teaching model.

#### **II. Application of the SMART framework in the lung cancer module**

Learning objectives for the lung cancer module were developed using the SMART framework (Specific, Measurable, Achievable, Relevant and Time-bound) to ensure clarity, alignment and feasibility (9,11,15).

1. Specific: Objectives clearly defined the core knowledge, mechanisms, or competencies to be achieved, avoiding broad or ambiguous descriptions.
2. Measurable: Attainment was evaluated using case-based reasoning tests, key concept checklists, and formative assessment tools with predefined criteria.
3. Achievable: Objectives were tailored to students' stage of training, prior knowledge, and available instructional time.
4. Relevant: Objectives were aligned with program-level learning outcomes and clinical competency requirements, promoting integration of foundational sciences with clinical application.
5. Time-Bound: Objectives included clear timelines for achievement, enhancing the structure, focus, and accountability of the learning process.

Figure 2 illustrates the application of the SMART framework, showing how the learning objectives—Specific, Measurable, Achievable, Relevant, and Time-bound—are structured and facilitated collaboratively by basic medical science teachers and clinical physicians.

The lung cancer module included three to five sequential learning objectives distributed across three discussion sessions. Objectives progressed from foundational anatomical and physiological concepts to pathophysiological mechanisms and molecular classification, and ultimately to therapeutic strategies and drug resistance. These objectives guided facilitator preparation and evaluation but were not explicitly disclosed to students, in order to preserve the inquiry-driven nature of PBL.

The SMART-guided PBL syllabus for the lung cancer module is presented in Supplementary Table 1.

## **Figure 2 SMART application in the lung cancer module**

### ***Outcome Measures***

#### *Primary outcome*

The primary outcome was students' knowledge acquisition, assessed using a structured multiple-choice question (MCQ) test. The test included items of varying cognitive complexity to evaluate both foundational knowledge and higher-order integrative understanding. Overall performance was measured using total scores, and item-level response patterns were further explored through categorical heatmap visualization to examine differences across knowledge domains.

#### *Secondary outcomes*

Secondary outcomes encompassed three domains:

1. Learning Reaction: Students' learning approaches, perceived learning efficiency, learning attitude and enthusiasm, perceived achievement of learning objectives, and understanding of clinical scenarios.
2. Learning Process: Students' self-reported pre-class preparation time.
3. Teaching Model Evaluation: Perceived feasibility and sustainability of the co-teaching model.

### **Data Collection**

Data were collected immediately after completion of the lung cancer module.

Knowledge acquisition was assessed using the structured MCQ examination, which covered three domains: physiology, pathology and pharmacology related to lung cancer, including molecular mechanisms and targeted therapies. Each item was scored dichotomously (correct = 1, incorrect = 0), and total scores were calculated for each student. Domain-specific performance was extracted for subgroup analyses. Item-level response distributions were visualized using categorical heatmaps to explore patterns of correctness across knowledge domains.

Learning reaction variables were measured using structured questionnaire (provided as a supplementary file 1) employing a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Learning process was assessed using self-reported pre-class preparation time collected via Questionnaire. Internal consistency of the questionnaire was evaluated using Cronbach's alpha, yielding coefficients of 0.946 and 0.843, indicating good reliability.

Perceived feasibility and sustainability of the co-teaching model were explored through semi-structured interviews with faculty members. Interviews were audio-recorded and transcribed. Data were analyzed using NVivo software (QSR International). Thematic analysis was performed using an inductive approach, with open coding used to identify recurring themes related to implementation of SMART principles and perceptions of the co-teaching model.

The MCQ examination, questionnaire and semi-structured interview guides are provided in Supplementary Data.

### **Statistical Analysis**

Data analysis was performed using R version 4.4.2. Continuous variables were expressed as mean  $\pm$  standard deviation (mean  $\pm$  SD), while categorical variables were expressed as frequencies and percentages. For continuous variables conforming to a normal distribution, independent-samples *t*-tests were used; for non-normally distributed data, the Mann–Whitney U test was applied. For the "learning reaction" dimension, scores were dichotomized into high-score ( $\geq 4$ ) and low-score ( $\leq 4$ ) groups, and Fisher's exact test was used to compare these categorical variables. All statistical analyses were two-sided, and a P value < 0.05 was considered statistically significant.

### **Ethics**

The study protocol was conducted in accordance with the Declaration of Helsinki (World Medical Association [WMA], 2013) and was approved by the Institutional Review Board of Peking University Health Science Center, the biomedical ethics committee affiliated with Peking University (Approval No. IRB00001052-22190). All participants provided written informed consent prior to study commencement (28 February 2025). Participation was voluntary, and students were assured that their decision to participate or withdraw would not affect their academic evaluation or standing within the program.

## Results

### Primary Outcome: Objective Knowledge Performance

At the conclusion of the lung cancer module, all students completed a structured MCQ test to assess knowledge acquisition. Overall, both groups achieved high scores, with the intervention group obtaining a mean score of 86.7, and the control group 86.4. No statistically significant difference was observed between the groups ( $P > 0.05$ ).

To further explore response patterns across different knowledge domains, MCQ items were categorized into three modules: Physiology, Pathology, and Pharmacology. Item-level responses were visualized descriptively using categorical heatmaps, as shown in Fig. 3.

In the Physiology domain, both groups demonstrated high rates of correct responses, with overall patterns largely consistent and minimal differences observed between groups.

In the Pathology domain, students in the intervention group displayed more consistent correct response patterns, particularly for items addressing molecular subtypes, including EGFR, ALK, KRAS, and ROS-1.

In the Pharmacology domain, especially items related to targeted therapies and mechanisms of drug resistance, differences between the groups were more pronounced. For example, in questions concerning EGFR-TKI resistance mutations (e.g., T790M and C797S), the control group had a higher proportion of incorrect responses, whereas the intervention group showed relatively higher correct response rates.

Overall, the heatmap visualization suggests that students in the intervention group performed better on integrative items related to molecular pathology and targeted therapies. However, these observations were primarily descriptive and based on item-level analyses.

**Figure 3. Standardized performance profiles for the control and intervention groups.** Individual MCQ item scores were normalized and visualized as a heatmap. Labels on the right indicate the specific topics assessed within the Physiology, Pathology, and Pharmacology domains. Color intensity reflects the normalized score (0–1), with purple representing higher proficiency and yellow representing lower proficiency. Differences in response patterns between the control and intervention groups are clearly observed, particularly for items related to molecular pathology and targeted therapies.

## Secondary Outcome One: Learning Reaction

As shown in Fig. 4a, across the learning reaction dimension (scored 0–5), the intervention group achieved higher mean scores than the control group across all evaluated domains. The radar plot demonstrates that the intervention group's curve extends consistently beyond that of the control group, indicating higher subjective ratings of the learning experience.

Among the domains, learning efficiency and learning attitude and enthusiasm scored relatively higher. The mean score for learning efficiency was  $4.50 \pm 0.61$  in the intervention group and  $4.25 \pm 0.68$  in the control group. For learning attitude and enthusiasm, the intervention group scored  $4.46 \pm 0.69$ , compared with  $4.41 \pm 0.64$  in the control group.

For perceived achievement of learning objectives, the intervention group had a mean of  $4.14 \pm 0.59$ , while the control group scored  $3.95 \pm 0.69$ . Both groups scored above 4, indicating generally positive evaluations of learning goal attainment, with the intervention group slightly higher.

In the learning approach domain, the intervention group scored  $4.61 \pm 0.50$ , compared with  $4.50 \pm 0.60$  in the control group. Item-level analysis indicated that the intervention group performed relatively better on the item “pre-class review of relevant literature and summarization of learning content.”

Regarding understanding of clinical scenarios (Fig. 4b), the intervention group scored higher on relevant items (e.g., “demonstrates in-depth understanding of the clinical context of the case”) than the control group ( $4.56 \pm 0.62$  vs  $4.26 \pm 0.64$ ), indicating greater self-assessed comprehension. In addition, a higher proportion of students in the intervention group (100%) reported that their clinical diagnostic doubts were resolved following the session, compared with 81.6% in the control group, further supporting the enhanced learning experience in clinical reasoning.

Item-level distribution plots (Fig. 4b) further show that, for items related to learning approach, clinical understanding, and learning efficiency, scores from the intervention group were generally positioned to the right of those from the control group, indicating consistent directional differences. However, according to Fisher's exact test, no statistically significant differences were observed between groups across any domain (all  $P > 0.05$ ).

Overall, although statistical significance was not reached, the intervention group consistently demonstrated higher mean scores across all indicators of learning reaction.

**Figure 4a. Radar chart of learning reaction scores across five pedagogical dimensions.** The chart illustrates the comparative performance of the control and intervention groups. Mean scores are plotted for Learning Approaches, Understanding of Clinical Scenarios, Perceived Learning Efficiency, Learning Attitude and Enthusiasm, and Perceived Achievement of Learning Objectives. Scores range from 0 to 5, where the expanded area in the intervention group indicating a broader positive shift in student feedback across all evaluated domains.

**Figure 4b. Distribution of student learning reaction scores across five dimensions.** The dumbbell plot compares mean scores of the control group (light blue) and the intervention group (dark blue) across five domains: Learning Approaches, Understanding of Clinical Scenarios, Perceived Learning Efficiency, Learning Attitude and Enthusiasm, and Perceived Achievement of Learning Objectives. Specific survey items are detailed on the right. Scores are based on a 5-point Likert scale (0–5), with horizontal displacement reflecting difference in students' subjective learning experiences following the PBL sessions.

## Secondary Outcome Two: Learning Process

For the learning process, students' pre-class preparation time was compared across the three PBL sessions, including both estimated and actual preparation durations. Overall, pre-class preparation time decreased as the course progressed in both groups; however, the timing and pattern of these changes differed between groups (Fig. 5).

During PBL1, the control group showed a statistically significant difference between estimated and actual preparation time ( $P < 0.05$ ), whereas no significant difference was observed in the intervention group ( $P > 0.05$ ).

In PBL2, the intervention group demonstrated a significant difference between estimated and actual preparation time ( $P < 0.05$ ), while no significant difference was observed in the control group ( $P > 0.05$ ).

By PBL3, both groups showed reduced estimated and actual preparation times compared with the previous sessions. Within-group comparisons revealed no significant differences in either group (all  $P > 0.05$ ).

**Figure 5. Comparison of pre-class preparation time between the control and intervention groups.** The bar charts represent the mean estimated (left) and actual (right) pre-preparation time (hours) across three consecutive PBL sessions. Individual data points are superimposed on the bars to illustrate the distribution of responses. Error bars indicate standard deviation (SD). Significant differences in preparation time were observed between the first and second PBL sessions within each group (Mann–Whitney  $U$  test;  $*P < 0.05$ ,  $**P < 0.005$ ).

## Secondary Outcome Three: Feasibility and Sustainability of the Teaching Model

At the student level, most students expressed positive attitudes toward clinician participation in PBL sessions. Specifically, 86.6% of students considered clinician involvement valuable; 20% suggested that clinicians participate throughout the course; and 73.3% preferred increased clinician guidance during the knowledge integration phase. Student feedback indicated that clinician involvement helped link foundational theory to real clinical scenarios, particularly during complex case discussions, and facilitated a deeper understanding of disease mechanisms and clinical decision-making.

At the faculty level, all interviewed teachers acknowledged the educational value of the co-teaching model in bridging theory and practice. Teachers noted that clinicians could provide authentic case materials, imaging data, and current treatment updates, enhancing the real-world relevance of teaching content. One faculty member commented:

Clinicians provided real imaging data and contemporary treatment perspectives, enriching students' holistic understanding of the disease.

Some faculty also highlighted the importance of defining “guidance boundaries” during implementation to prevent clinicians from providing direct answers, which could undermine students' self-directed inquiry.

## Discussion

### Key Findings

This study evaluated a SMART principle-guided co-teaching model involving basic science teachers and clinicians in a lung cancer PBL module. Overall, MCQ scores were high in both groups, with no significant differences. However, item-level analysis revealed that students in the intervention group performed more consistently on integrative questions related to molecular pathology mechanisms and targeted therapy. Secondary outcomes showed higher mean scores across all dimensions of learning reactions in the intervention group, suggesting a more positive perception of the teaching model. Regarding the learning process, pre-class preparation time decreased over the PBL phases for both groups, but patterns of “expected versus actual preparation time” differed. Both students and teachers reported that co-teaching enhanced the clinical relevance of the course and promoted integration of basic and clinical knowledge, highlighting potential benefits for knowledge integration, learning experience, and teaching acceptability.

### Objective Knowledge Performance

The lack of significant differences in overall MCQ scores may reflect the generally strong baseline knowledge of both groups, as traditional teaching remains effective in conveying foundational content. Moreover, MCQs primarily assess knowledge acquisition, whereas higher-order cognitive skills, such as knowledge integration, clinical reasoning, and mechanistic understanding, may not be fully captured in total scores. Item-level analyses suggested that the intervention group's improved performance on integrative questions reflected better structuring and application of knowledge through co-teaching (4).

Clinicians' involvement in high-complexity integrative modules may further enhance students' clinical reasoning skills and professional identity. By analyzing cases such as how molecular marker testing informs targeted therapy selection, abstract molecular mechanisms are translated into applied clinical reasoning. This helps students develop a “pathology mechanism → precision treatment” cognitive pathway, deepening their understanding of indications and resistance mechanisms, and enhancing their ability to address complex clinical problems (16). Clinicians also serve as role models, demonstrating

individualized decision-making and professionalism, which may subtly reinforce students' recognition of the physician role (7). Although long-term impacts could not be fully assessed, item-level results suggest that co-teaching begins to foster clinical thinking and professional awareness during the knowledge integration phase.

## **Learning Reactions: Positive Changes in Learning Experience**

The intervention group reported higher mean scores in learning efficiency, motivation, goal achievement, learning strategies, and clinical scenario understanding. Radar chart analysis indicated that their performance consistently exceeded that of the control group, demonstrating improvements across multiple dimensions. Higher scores in efficiency and motivation suggest that co-teaching enhances engagement and perceived learning effectiveness, while improved clinical scenario understanding indicates better integration of basic knowledge into real clinical contexts (5,10,15). Although differences were not statistically significant - likely due to sample size, ceiling effects, and the subjectivity of measures - the trends point to a positive influence of co-teaching on learning experience

## **Learning Process: Dynamic Development of Learning Strategies**

Pre-class preparation time decreased across the PBL phases for both groups, reflecting increasing familiarity with the PBL process and the development of more effective strategies (17). Differences emerged in the "expected versus actual preparation time" patterns: in traditional PBL led solely by a basic science teacher, students may misjudge task complexity early in the course, resulting in discrepancies between expected and actual preparation time. In contrast, the co-teaching model, guided by SMART objectives and integrated clinical cases, allowed students to more accurately assess learning demands. During phase 2, the intervention group's discrepancy increased, reflecting proactive adjustments such as systematic literature review and deeper case analysis, leading to higher engagement. By phase 3, students had stabilized their strategies and improved time management, reducing discrepancies and illustrating the learning curve effect and enhanced self-regulated learning (18).

## **Feasibility and Sustainability of the Teaching Model**

Both students and teachers rated the co-teaching model highly. Students reported that clinician involvement enhanced course value, particularly during case discussions and knowledge integration. Most preferred clinician guidance during knowledge integration rather than full-course participation, suggesting clinicians are most effective as scenario guides and experience providers rather than traditional lecturers. Teachers agreed, noting that clinicians provide real cases, imaging data, and treatment updates, supporting comprehensive disease understanding and aligning with the integration of basic and clinical sciences (6). Some teachers emphasized the need to define boundaries for clinician

guidance to preserve student autonomy, underscoring the importance of balancing clinical support with independent learning (8).

## Limitations and Future Directions

The intervention was confined to the lung cancer module, limiting generalizability to other modules and long-term outcomes. Limitations also include a relatively small sample size, assessment primarily via MCQs and questionnaire, and limited evaluation of higher-order skills such as clinical reasoning. Future research should incorporate contextualized assessments, clinical reasoning tests, and longitudinal knowledge retention to systematically evaluate the co-teaching model across the full PBL curriculum. Additionally, exploring adaptability across modules, phases, and student backgrounds will help assess its impact on knowledge integration, learning strategies, and clinical competence.

## Educational Significance

The SMART-guided co-teaching PBL model shows potential for enhancing knowledge integration, optimizing learning processes, and improving teaching acceptability. The model not only increases clinical relevance but also offers a framework for advancing interdisciplinary teaching and supporting the development of future physicians with stronger integration of foundational knowledge and clinical application.

## Conclusion

This study develops and evaluates a SMART-guided co-teaching model integrating basic science teachers and clinicians within a PBL module. Although overall knowledge scores does not differ, the intervention enhances integrative knowledge, learning experience, and self-regulated learning strategies. Students and teachers report improved clinical relevance and knowledge integration. These findings suggest that the SMART-guided co-teaching model is a feasible and effective approach for bridging foundational and clinical sciences, with potential to optimize learning processes and support interdisciplinary medical education.

## Declarations

### ***Ethics approval and consent to participate***

The study protocol was reviewed and approved by the Institutional Review Board of Peking University Health Science Center, the biomedical ethics committee affiliated with Peking University (Approval No. IRB00001052-22190). This study adhered to the Declaration of Helsinki. All participants provided written informed consent prior to study commencement (28 February 2025).

### ***Consent for publication***

Not Applicable.

### ***Availability of data and materials***

The datasets generated and/or analyzed during the current study are not publicly available due to participant confidentiality and institutional restrictions but are available from the corresponding author on reasonable request.

### ***Competing interests***

The authors declare no competing interests.

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Figures

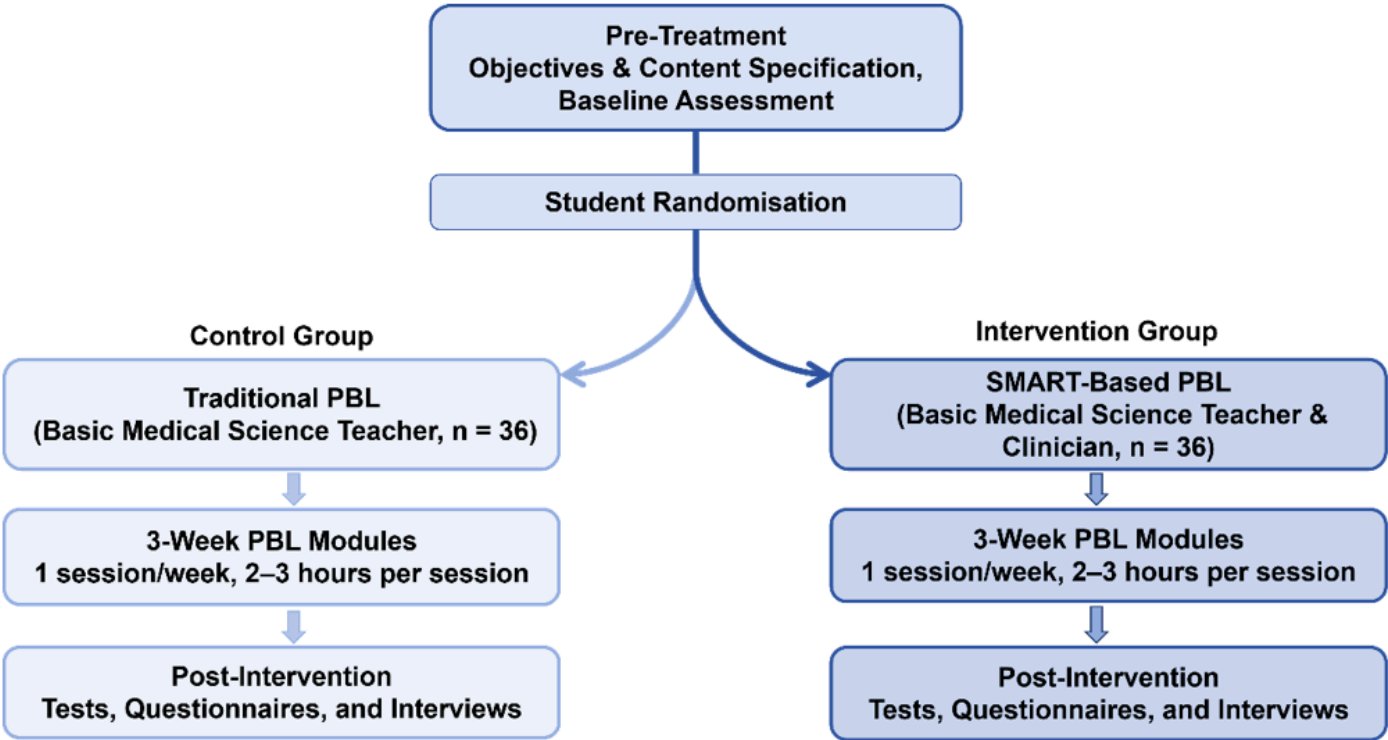


Figure 1

Flowchart of the study design

This flowchart depicts the overall study procedure. Students were first assessed at baseline and provided with objectives and content specification. They were then randomly assigned to either the control group (traditional PBL,  $n=36$ ) or the intervention group (SMART-based PBL,  $n=36$ ). Both groups participated in 3-week PBL modules, with one session per week lasting 2-3 hours. Post-intervention evaluation included MCQ tests, questionnaire, and semi-structured interviews for both groups.

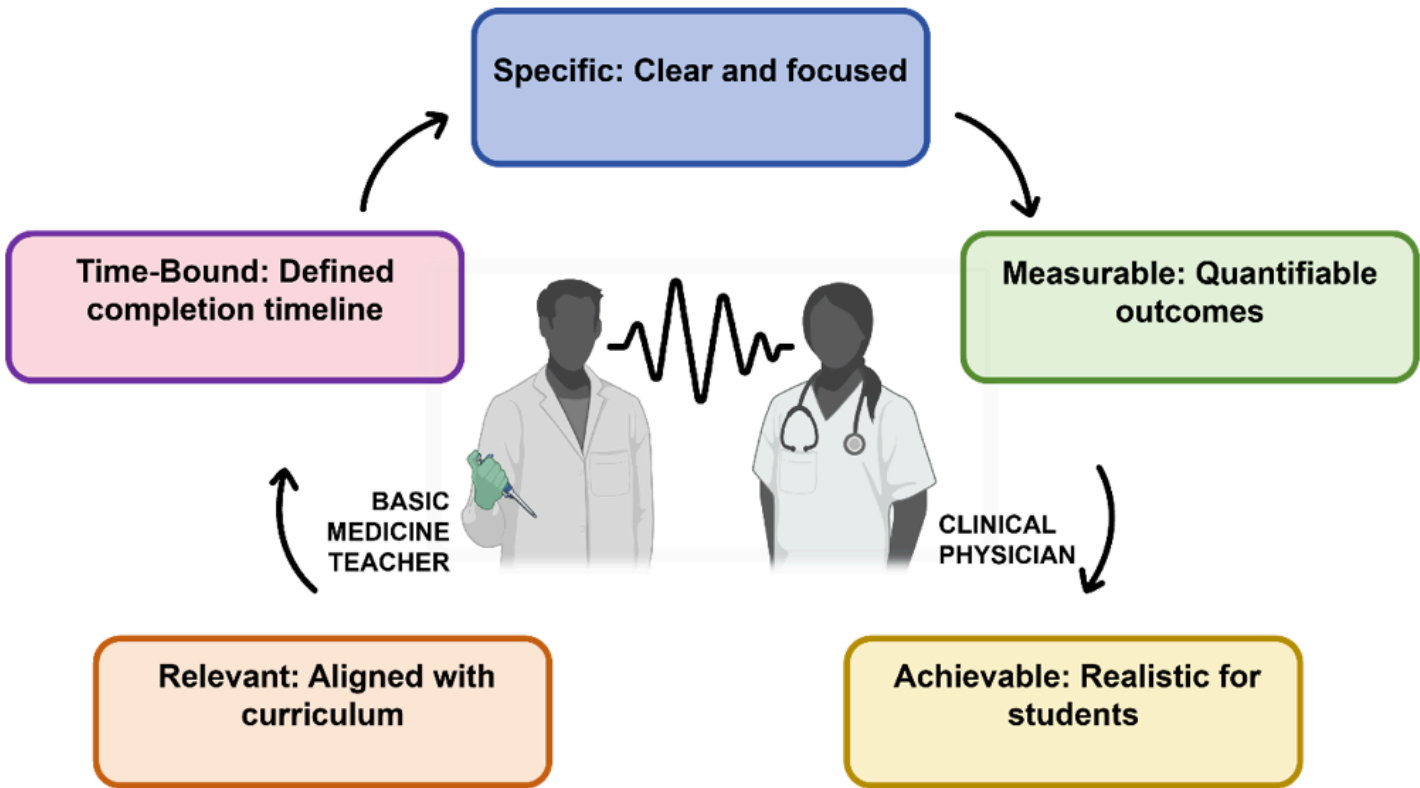


Figure 2

SMART application in the lung cancer module

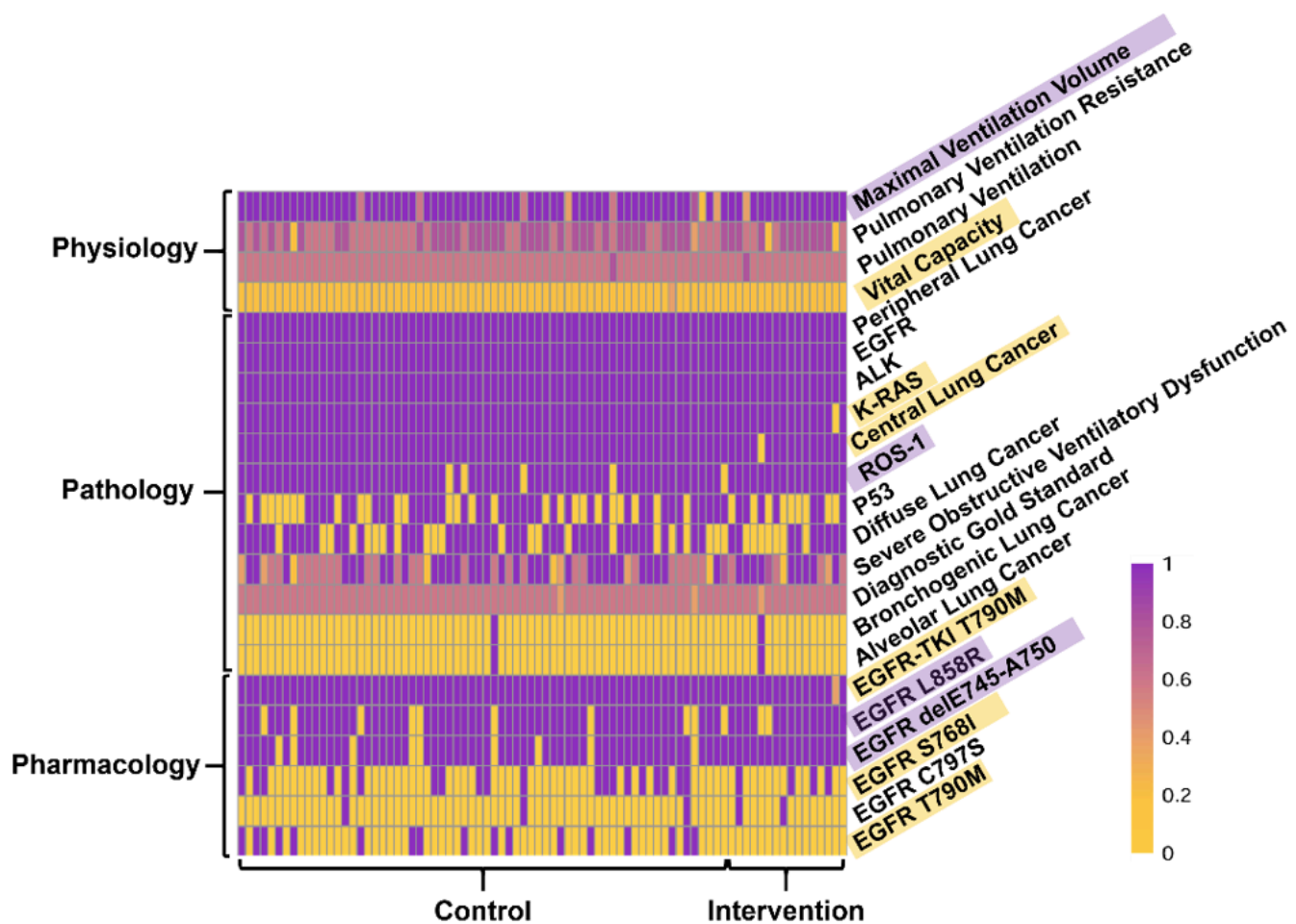


**Figure 3**

**Standardized performance profiles for the control and intervention groups.**

Individual MCQ item scores were normalized and visualized as a heatmap. Labels on the right indicate the specific topics assessed within the Physiology, Pathology, and Pharmacology domains. Color intensity reflects the normalized score (0–1), with purple representing higher proficiency and yellow representing lower proficiency. Differences in response patterns between the control and intervention groups are clearly observed, particularly for items related to molecular pathology and targeted therapies.

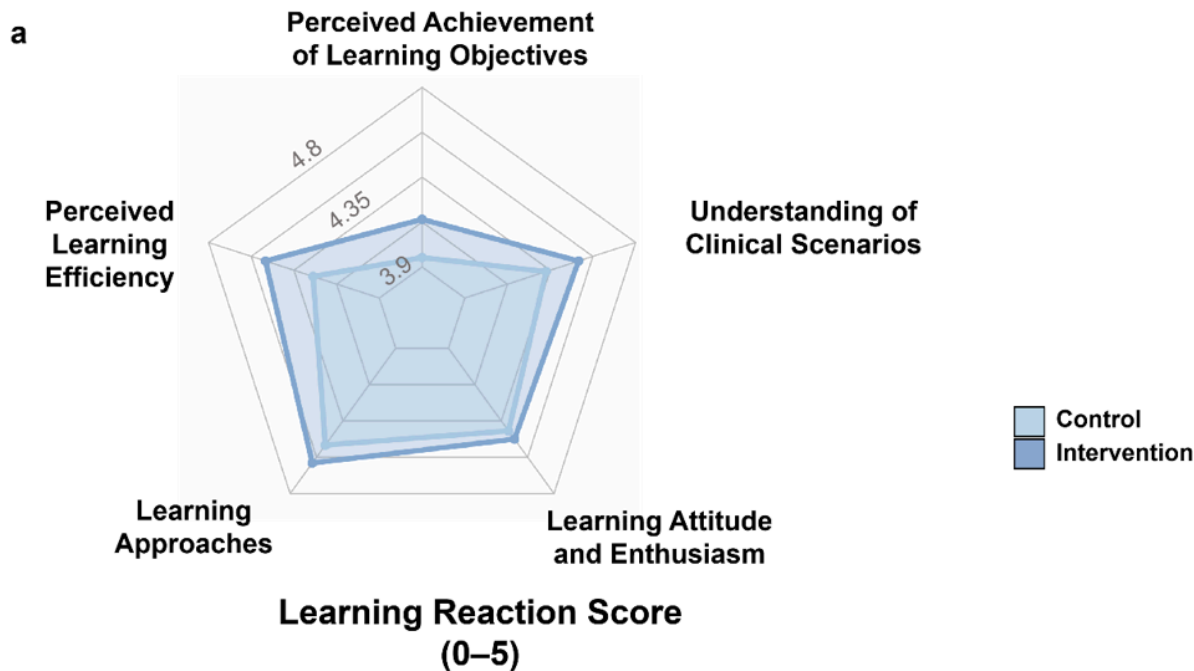


**Figure 4a.**

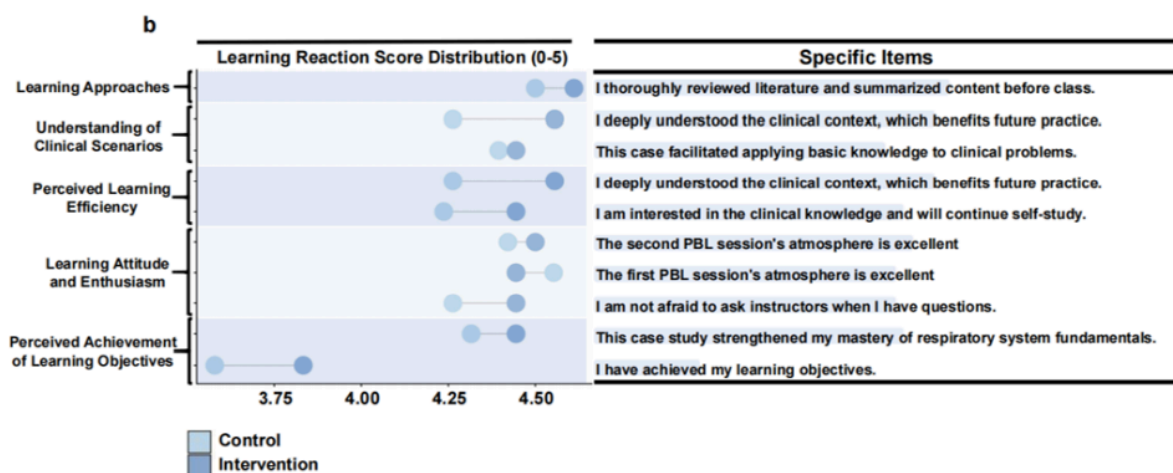


**Figure 4b.**

**Figure 4**

**a. Radar chart of learning reaction scores across five pedagogical dimensions.** The chart illustrates the comparative performance of the control and intervention groups. Mean scores are plotted for Learning Approaches, Understanding of Clinical Scenarios, Perceived Learning Efficiency, Learning Attitude and Enthusiasm, and Perceived Achievement of Learning Objectives. Scores range from 0 to 5, where the

expanded area in the intervention group indicating a broader positive shift in student feedback across all evaluated domains.

**b. Distribution of student learning reaction scores across five dimensions.** The dumbbell plot compares mean scores of the control group (light blue) and the intervention group (dark blue) across five domains: Learning Approaches, Understanding of Clinical Scenarios, Perceived Learning Efficiency, Learning Attitude and Enthusiasm, and Perceived Achievement of Learning Objectives. Specific survey items are detailed on the right. Scores are based on a 5-point Likert scale (0–5), with horizontal displacement reflecting difference in students’ subjective learning experiences following the PBL sessions.

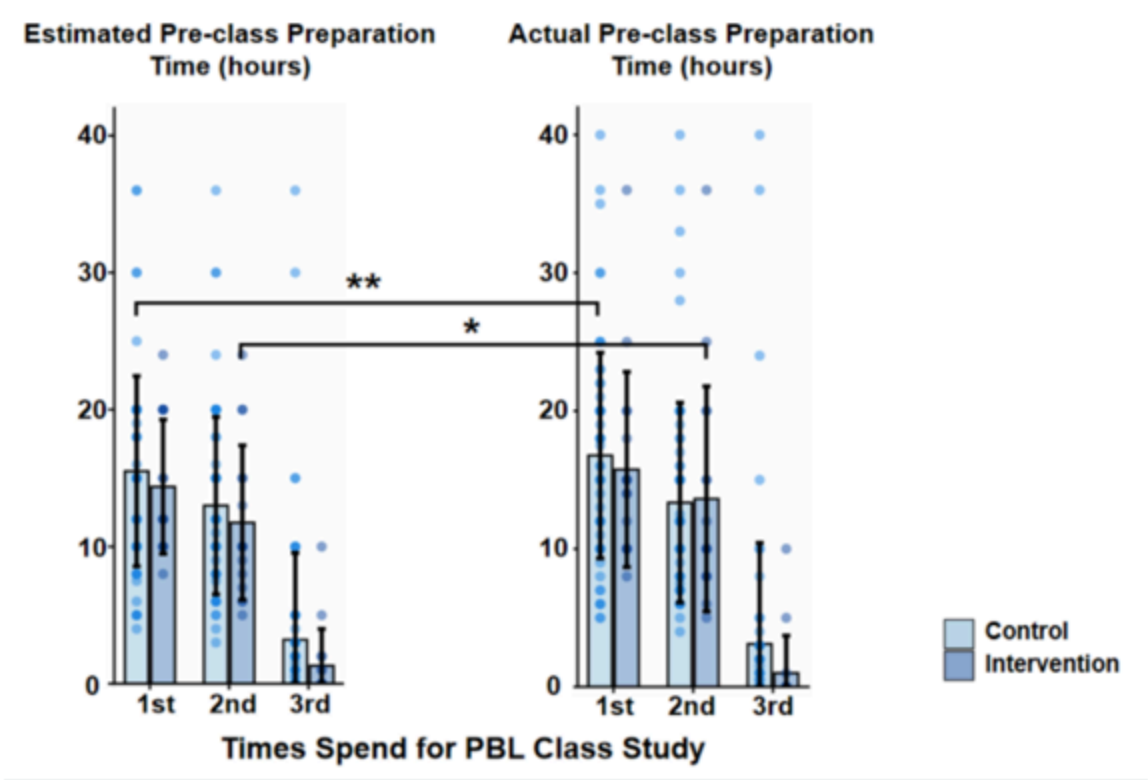


Figure 5

**Comparison of pre-class preparation time between the control and intervention groups.** The bar charts represent the mean estimated (left) and actual (right) pre-preparation time (hours) across three consecutive PBL sessions. Individual data points are superimposed on the bars to illustrate the distribution of responses. Error bars indicate standard deviation (SD). Significant differences in preparation time were observed between the first and second PBL sessions within each group (Mann–Whitney  $U$  test  $\ast P < 0.05$ ,  $\ast\ast P < 0.005$ ).

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarytable1.docx](#)
- [questionnaire.docx](#)