

Systematic Teaching Design and Practice of PBL Combined with Virtual Simulation Technology in the Teaching of Magnetic Resonance Parameter Adjustment

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Abstract

The adjustment of magnetic resonance imaging parameters is a core difficulty in medical imaging technology education. Traditional teaching is constrained by limitations such as equipment availability, high risk, abstract theory, and disconnection from clinical practice. This paper systematically expounds on the teaching model that deeply integrates problem-based learning and virtual simulation technology, constructing a complete teaching path of “theoretical foundation-virtual exploration-practical verification-clinical transfer”. By designing three-level progressive PBL clinical cases and relying on a high-fidelity virtual simulation platform, the teaching goal of visualizing abstract concepts, ensuring the safety of high-risk operations, and systematizing clinical thinking in the teaching of MRI parameter adjustment is achieved. Teaching practice shows that this model significantly improves students’ parameter optimization ability, clinical decision-making ability, and self-learning ability, providing a replicable implementation framework for the transformation of medical imaging technology education paradigms.

Keywords

PBL, Virtual Simulation, Magnetic Resonance, Medical Imaging Technology, Teaching Design and Practice

1. Introduction

Magnetic resonance imaging (MRI) serves as the “scout” of modern medical di-

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agnosis, and the quality of its images directly affects the detection rate and diagnostic accuracy of diseases (Miao et al., 2022). The quality of the images is almost entirely determined by the precise adjustment of scanning parameters, such as repetition time (TR), echo time (TE), flip angle, field of view (FOV), matrix size, and dozens of other parameters, which are intercoupled and jointly affect the contrast, resolution, signal-to-noise ratio, and scanning time of the images. Understanding the physical principles behind these parameters (such as relaxation processes, Fourier transforms) and their clinical trade-offs is a core requirement for training qualified imaging technicians (Li et al., 2021).

Traditional MRI parameter adjustment teaching has long faced three structural challenges: first, the economic challenge of equipment, the purchase and maintenance costs of clinical-grade MRI equipment are high, and educational institutions struggle to provide sufficient teaching hours, leaving students with scarce practical opportunities, often limited to “window observation” (Gao et al., 2021); second, the safety challenge of teaching—misoperations in a strong magnetic field environment (such as bringing in metal objects) can trigger serious safety incidents like the “missile effect”, with a very low tolerance for errors in the teaching process (Tian et al., 2021); third, the cognitive construction challenge, parameter adjustment involves multi-dimensional abstract knowledge systems such as quantum physics, mathematical transformations, and anatomy and physiology. Relying solely on textbook formulas and two-dimensional image comparisons for explanation, students find it difficult to establish a dynamic and integrated mental model between parameter settings, image manifestations, and clinical pathology (Qi & Zhou, 2023). These three challenges collectively restrict students’ in-depth mastery of the core capabilities of MRI technology, highlighting the urgency of educational paradigm reform.

Against this backdrop, the educational paradigm urgently needs to shift from a “knowledge transmission type” to a “competency construction type”. Problem-Based Learning (PBL), which emerged in medical education in the 1960s, emphasizes starting with real and complex clinical problems and integrating knowledge and developing clinical thinking through group collaboration and self-directed exploration. International medical education research has confirmed through multiple systematic reviews that PBL has a medium to strong effect size in promoting clinical reasoning skills (Wei & Wang, 2025; Li et al., 2023; Trullàs et al., 2022). Recent meta-analyses on simulation training in health professional education have shown that virtual simulation-based teaching has significant advantages in improving operational skills (Shorey & Ng, 2021; Cook et al., 2023; Carless et al., 2023). The combination of the two is like providing a “smart brain” and “nimble hands” for the teaching of magnetic resonance parameters. This teaching plan aims to systematically elaborate the complete design, implementation, and evaluation system of this integrated model, and provide complete reproducible teaching resources and platform validation data.

2. Theoretical Foundation and Integration Framework

2.1. Common Orientation of Educational Theories: Constructivism and Situated Learning

Both PBL and virtual simulation are rooted in the constructivist learning theory. This theory posits that knowledge is not passively received but actively constructed by learners through interaction with the environment. In magnetic resonance teaching, students need to “discover” the intrinsic relationships among parameters by adjusting them, observing image changes, and analyzing the reasons for failures. The virtual simulation platform provides a free exploration environment, while PBL offers meaningful exploration goals and cognitive conflicts (for example: “Why does increasing TE make cerebrospinal fluid brighter but also increase noise at the same time?”).

At the same time, both perfectly align with the theory of situated learning. This theory emphasizes that learning is meaningful only in relevant cultural contexts (clinical diagnosis) and practical activities. A well-designed PBL case (such as “Rapid Screening of Acute Stroke Patients”) places students in urgent clinical decision-making scenarios. Virtual simulation, on the other hand, recreates the real working environment of an MRI operation console, making the learning activities highly consistent with future professional practice. This “cognitive apprenticeship” model enables students to think and operate like experts.

2.2. The Synergistic Enhancement Model of PBL and Virtual Simulation

The integration of the two is not a simple sequence but a deeply interwoven collaborative process, forming a closed-loop learning ecosystem (**Figure 1**).

2.2.1. PBL as the “Navigator”

It endows virtual simulation operations with clear clinical purposes and exploration directions, preventing students from getting lost in aimless “technical games”. For instance, in the case of “suspected meniscus tear of the knee joint”, the learning objective clearly points to how to optimize the proton density weighted image (PDWI) to achieve the best meniscus-joint fluid contrast.

2.2.2. Virtual Simulation as the “Validation Field”

It provides low-cost, risk-free immediate validation for the hypotheses and plans proposed by PBL. Students can boldly try extreme parameter combinations and witness firsthand how the images become undiagnosable. This kind of “failure learning” is impossible to achieve on real equipment.

2.2.3. Bidirectional Feedback and Iterative Deepening

The results of virtual operations (such as image quality scores, scan time) are immediately fed back to the learning group, prompting them to reflect on their original plans, consult literature, and start a new round of discussions and optimizations. This process simulates the real cycle of continuous improvement of scan-

ning protocols in clinical work.

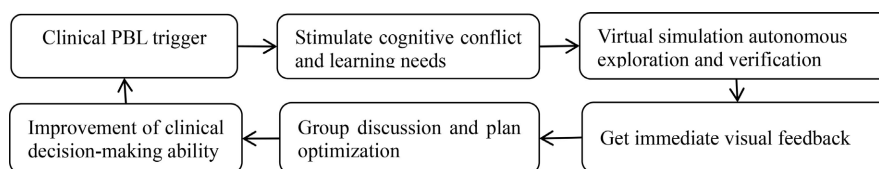


Figure 1. Closed-loop learning ecosystem integrating PBL and virtual simulation.

3. Systematic Teaching Design

This teaching design adopts the “Four-Stage Eight-Step” method to restructure the chapter on parameter adjustment in “Magnetic Resonance Imaging Technology” into a five-week integrated teaching module.

3.1. Theoretical Foundation and Context Anchoring (Week 1)

During the one-week theoretical foundation and context anchoring stage, the core teaching objective is to activate students’ existing knowledge, create a realistic clinical problem scenario, and initially form a collaborative inquiry learning community. First, through an online course platform, students independently study the basic physical concepts of magnetic resonance (such as relaxation processes, pulse sequences), and the teacher simultaneously releases a diagnostic pre-test to accurately assess students’ initial understanding level and common cognitive misunderstandings of key parameters such as TR, TE, and flip angle, providing personalized basis for subsequent teaching. Subsequently, the teacher releases a PBL start case, for example, a young woman with persistent headache needs to undergo a brain MRI plain scan, guiding students to focus on the core question: “To comprehensively screen for potential intracranial lesions (such as tumors, inflammation, ischemia), which basic contrast images should be obtained? What are the main parameter adjustment principles behind each image?” By providing fragmented clinical information of the patient, this stage combines abstract parameter theory with specific diagnostic tasks, focusing on helping students establish a fundamental connection between parameter settings and image contrast, thereby stimulating their exploration interest and laying a solid conceptual foundation for subsequent virtual simulation practice.

3.2. Virtual Exploration and Initial Scheme Construction (Weeks 2 - 3)

During the 2 - 3 week virtual exploration and initial scheme construction stage, the teaching objective focuses on guiding students to conduct systematic parameter exploration in a high-fidelity virtual environment and initially form a scanning scheme based on clinical problems. This stage begins with basic operation training, where students familiarize themselves with the virtual operation interface of mainstream models and conduct “single parameter isolated change” core exercises, such as gradually adjusting TR under a fixed TE condition, visually ob-

servicing the continuous evolution process of brain phantom images from T1-weighted to proton-weighted to T2-weighted, and simultaneously using the signal intensity curve quantification tool provided by the platform to understand the correspondence between visual contrast and numerical changes. On this basis, each learning group conducts collaborative inquiry around the previously released PBL start case, determining the initial scanning sequence combination (such as T1WI, T2WI, and FLAIR) through literature review and group discussion, and configuring an initial set of parameters for each sequence, while recording the basis for parameter selection and predictions of image features. Subsequently, the group executes the self-designed scanning scheme on the digital standard brain phantom in the virtual platform, and the platform's built-in intelligent assessment system immediately generates quantitative scores and targeted suggestions from four dimensions: signal-to-noise ratio, contrast-to-noise ratio, artifact control, and scan time (for example: "The current T2WI image has a relatively low signal-to-noise ratio. It is recommended to consider increasing the average number or adjusting the receive bandwidth"). This immediate and objective feedback mechanism visualizes the gap between theoretical predictions and practical results for the first time, effectively triggering students' cognitive conflicts and promoting group-based in-depth reflection and scheme optimization discussions based on data, thus completing the critical leap from abstract cognition to initial practice.

3.3. Iterative Optimization and Principle Deepening (Week 4)

During the 1 - 2 week iterative optimization and principle deepening stage, the core teaching objective is to guide students to solve the complex problem of multi-parameter mutual constraints and deeply understand the art of balancing image quality and examination efficiency in clinical practice. This stage is driven by advanced PBL cases, for instance, after a suspicious lesion is found in a plain brain scan, the patient needs to undergo an enhanced scan to assess blood supply, but signs of restlessness require a shortened examination time. This introduces the core contradiction of "how to ensure the image quality required for diagnosis (especially lesion contrast) while minimizing the scan time as much as possible". Student groups conduct multiple rounds of "hypothesis-testing-analysis" iterative exploration on the virtual simulation platform, experiencing the coupling relationship between parameters firsthand: for example, reducing the average number or increasing the bandwidth to shorten the time will inevitably lead to a decrease in the signal-to-noise ratio. At this point, it is necessary to systematically explore how to compensate and optimize through strategies such as adjusting the matrix size, slice thickness, or enabling parallel acquisition techniques (such as SENSE). Based on practical exploration, teachers intervene in a timely manner to organize mini-lectures, focusing on explaining the deep physical principles behind parameter interactions (such as the inverse square root relationship between bandwidth and signal-to-noise ratio, the acceleration principle of parallel acquisition), thereby effectively elevating students' practical experience to the theoretical cognitive

level, and ultimately forming a systematic understanding of the “quality-efficiency” balance strategy in magnetic resonance parameter adjustment and clinical decision-making ability.

3.4. Comprehensive Application and Transfer Assessment (Week 5)

During the one-week comprehensive application and transfer assessment phase, the core teaching objective focuses on guiding students to integrate all the knowledge and skills they have learned previously to solve complex clinical problems and conduct multi-dimensional evaluations of their abilities. The ultimate challenge of this stage is a high-fidelity emergency case, for example, designing a magnetic resonance scanning protocol that can complete the anatomical display of the thoracic aorta and the assessment of the intimal flap within 20 minutes for a patient suspected of acute aortic dissection with severe chest pain and potentially poor breath-holding cooperation. This case deeply integrates multiple complex challenges such as image contrast optimization, spatial resolution guarantee, extreme compression of scanning speed, and control of physiological motion artifacts, requiring students to flexibly apply the knowledge they have learned and comprehensively consider advanced technical strategies such as ultra-fast gradient echo sequences, electrocardiogram gating synchronization, respiratory navigation or breath-holding prompts. The assessment adopts a multi-integrated approach: each group needs to submit a standardized scanning protocol document containing a complete parameter list and principle explanations, and execute the protocol in a virtual simulation platform; the final generated images will be blindly evaluated by a review panel composed of teachers and clinical imaging experts based on the core standard of “diagnostic usability”. At the same time, a closed-book theoretical examination and a time-limited virtual operation station assessment are conducted to form a comprehensive and three-dimensional evaluation of the mastery of the knowledge system, the proficiency of practical operations, and the ability of clinical decision-making thinking, ensuring the effective transfer of learning outcomes to real clinical scenarios.

4. Core Element Design of High-Fidelity Virtual Simulation Teaching Platform

The virtual simulation platform is the technical cornerstone for the implementation of this teaching mode. Its design must go beyond simple interface simulation and possess the following core teaching functions:

4.1. Multi-Modal Digital Twin: The Three Pillars of High-Fidelity Virtual Simulation

The core of the virtual simulation teaching platform lies in the construction of a multi-modal digital twin system, which accurately replicates the real world through three pillars. The first is equipment twin, which precisely reproduces the control

console operation logic, physical interface, and workflow of mainstream MRI equipment such as GE and Siemens at a 1:1 scale, ensuring seamless integration between virtual operation and clinical practice. The second is patient/manikin twin, which builds a digital three-dimensional model library based on real MRI data, including different anatomical parts and pathological states (such as tumors, edema, hemorrhage), and each model is assigned simulated biological tissue parameters such as T1, T2, and proton density, providing a foundation for the simulation of diverse clinical scenarios. The third is physical process twin, which incorporates a signal generation model that is reasonably simplified but maintains physical correctness. When students adjust parameters, the platform does not call pre-set images but calculates the changes in simulated signals in real time based on core principles such as the Bloch equation and generates corresponding images, fundamentally ensuring the scientific nature and educational value of the parameter-image feedback relationship. These three twins support each other, jointly forming a virtual laboratory environment that is both realistic and reliable and suitable for teaching exploration.

4.2. Intelligent Teaching Assistant System: The Technological Core for Personalized Guidance and Deep Understanding

The intelligent teaching assistant system of the virtual simulation platform is the core engine for achieving efficient and in-depth learning. The system first provides dynamic prompts and guidance, intelligently suggesting the reasonable range of parameter settings for beginners and promptly popping up a “principle conflict warning” when students attempt parameter combinations that clearly violate physical principles (such as extremely short TR combined with extremely long TE), thereby establishing correct conceptual boundaries during exploration. Secondly, the platform has the ability to perform real-time multi-dimensional image quality analysis, synchronously displaying quantitative curves of signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) next to the images, and supporting side-by-side comparison of images under different parameter combinations and marking key differences, transforming the abstract evaluation of image quality into intuitive and measurable visual feedback. More importantly, the system integrates a “principle insight” function, allowing students to click a button to watch a dynamic demonstration of the pulse sequence diagram and animation simulation of the K-space filling process of the current sequence. This function transforms the most abstract physics and mathematics principles hidden behind the images into visual dynamic processes, fundamentally promoting students’ deep conceptual understanding of how parameters affect images.

4.3. Learning Behavior Data Analysis Backend

It records each student’s operation trajectory, parameter selection preferences, number of incorrect attempts, and time spent on a certain problem. The teacher’s backend can generate learning analysis reports, accurately identifying common class difficulties (such as general misunderstanding of bandwidth adjustment) or

individual students' knowledge weaknesses, enabling data-driven precise teaching intervention.

4.4. Platform Feedback Generation Mechanism and Physical Reasonableness Verification

To ensure that the teaching feedback of the virtual simulation platform is scientific and clinically relevant, this study systematically designed and verified the core scoring algorithm and physical simulation engine of the platform.

4.4.1. Multi-Dimensional Image Quality Scoring Algorithm

The intelligent evaluation system built into the platform uses a weighted comprehensive scoring model to quantitatively evaluate the scanning protocol from four dimensions: Signal-to-Noise Ratio (SNR) is calculated based on the ratio of the mean signal in the uniform area of the image to the background standard deviation, with a weight of 30%; Contrast-to-Noise Ratio (CNR) is calculated based on the ratio of the signal difference between the target tissue and the background tissue to the noise standard deviation, with a weight of 35%; Artifact control is quantified based on the severity of artifacts using edge energy spectrum analysis (0 - 100 points), with a weight of 20%; Scan time efficiency is the ratio of the actual scan time to the clinical benchmark time (based on the RSNA recommended protocol), with a weight of 15%.

4.4.2. Physical Reasonableness Verification Process

The platform adopts a three-level verification strategy to ensure the authenticity of the simulation: Firstly, through benchmark protocol reproduction verification, 10 sets of standard clinical scanning protocols released by RSNA/AAPM are input into the platform, and the output images are compared with those obtained from a 3.0TM scanner on the same volunteer using the Structural Similarity Index (SSIM). The results show that the SSIM of 9 protocols is greater than 0.85, and for 1 protocol (abdominal breath-hold), the SSIM is 0.79 (affected by the simplification of respiratory motion simulation), with an overall average SSIM of 0.89. Secondly, an expert content validity review is conducted, inviting 3 chief technicians with over 10 years of MRI clinical experience and 2 medical physics experts to evaluate the "parameter-image response accuracy", "artifact morphology realism", and "interface operation smoothness" of the platform using a 5-point Likert scale. The average scores for each dimension are 4.8, 4.6, and 4.9, respectively. Finally, a sensitivity analysis is performed to verify whether the changes in image SNR/CNR caused by variations in key parameters ($TR \pm 10\%$, $TE \pm 2$ ms, bandwidth ± 50 Hz) are consistent with the expectations of classical signal theory. The verification shows that the response directions of all tested parameters are completely consistent with the theory.

5. Teaching Effect Evaluation and Reflection

5.1. Diversified Evaluation System

A combined evaluation matrix of "process evaluation + terminal evaluation" and

“ability evaluation + knowledge evaluation” is constructed (**Table 1**).

Table 1. Diversified evaluation system.

Evaluation Dimension	Evaluation Method	Proportion
Knowledge and Principle Mastery	Individual theoretical closed-book examination (focusing on parameter principles and sequence characteristics)	30%
Virtual Operation Skills	Examination at virtual operation station (given clinical tasks, complete scheme design and image acquisition within a time limit)	25%
Clinical Thinking and Collaboration	PBL group performance (discussion contribution, scheme logic, report quality), final challenge scheme review	30%
Self-directed Learning and Reflection	Learning portfolio (including learning logs, virtual experiment reports, self-reflection summaries)	15%

5.2. Research Design and Ethical Statement

5.2.1. Research Design and Sample

This study adopted an equivalent group quasi-experimental design. One natural class of the 2021 grade of the Medical Imaging Technology major in our school was selected, and the experimental group (15 students) and the control group (15 students) were randomly determined by drawing lots. There were no statistically significant differences between the two groups in terms of age, gender composition, previous “Medical Physics” course grades, and pre-test scores for MRI parameter adjustment ($P > 0.05$), indicating comparable baselines. The course was taught by the same instructor, with a total of 12 class hours (4 theoretical hours + 8 practical hours). The experimental group adopted the PBL combined with virtual simulation mode, while the control group adopted the traditional “theoretical lecture + equipment observation + video analysis” mode. The average operation/observation time per person in the practical session was 90 minutes for both groups.

5.2.2. Ethics and Informed Consent

This study was exempted from approval by the Medical Ethics Committee of Wannan Medical College. After review, it was determined that this teaching reform research was a routine educational practice, did not involve additional intervention or potential risks, and met the conditions for exemption from informed consent. During the research process, the learning behavior logs collected (including virtual platform operation trajectories, parameter selection, number of incorrect attempts, and dwell time) were all de-identified. The data were stored on an encrypted server within the school, accessible only to the research team members, and no personal identification information was included in the published paper.

5.2.3. Assessment Tools and Implementation Procedures

This study used multi-dimensional assessment tools to measure the effect: knowledge and principle mastery was assessed using a self-compiled “MRI Parameter Adjust-

ment Theory Test” (closed-book), which included multiple-choice, multiple-answer, short-answer, and case analysis questions, and the content validity was reviewed and approved by three experts; virtual operation skills were assessed using the OSCE model, with a clinical task of “Knee Joint Trauma-Proton Density Weighted Image Optimization” set, requiring completion of the scheme design and image acquisition within 20 minutes, and the score was a weighted combination of automatic platform scoring and independent scoring by two examiners; clinical problem-solving ability was assessed using a transfer test, presenting a new case of “MRI Parameter Optimization for Neonatal Hypoxic-Ischemic Encephalopathy”, requiring students to write a scanning plan, and scored by two clinical experts based on the standard answer in a blind manner; learning attitude and confidence were assessed using a 5-point Likert scale questionnaire, including six items such as “This mode has enhanced my confidence in operating real equipment”.

5.2.4. Statistical Processing Method

Data were analyzed using SPSS 26.0. Measurement data were expressed as ($\bar{x} \pm s$), and independent sample t-tests were used for inter-group comparisons; count data were expressed as frequency (%), and χ^2 tests or Fisher’s exact probability method were used. Effect sizes were calculated using Cohen’s *d* (t-test) or ϕ coefficient (χ^2 test), and 95% confidence intervals were calculated.

5.3. Practical Effects

The experimental group significantly outperformed the control group in all dimensions ($P < 0.001$), with effect sizes reaching a large effect level ($d = 1.62 - 2.58$, $\phi = 0.36 - 0.50$). Among them, the virtual operation skill score difference between the groups was 20.23 points ($d = 2.58$), showing the most significant improvement; the correct rate of parameter interaction understanding (84.8% vs 52.4%), the rate of complex scheme proposal (78.3% vs 35.7%), and the confidence in operating the equipment (91.3% vs 45.2%) were all significantly higher than those of the control group. The significant difference in confidence enhancement suggests that the risk-free trial-and-error experience in virtual simulation may effectively reduce students’ technical anxiety.

6. Discussion

During the implementation of the PBL combined with virtual simulation teaching model, we also need to confront the challenges that come with it. Firstly, the role of teachers undergoes a profound transformation, requiring them to shift from traditional knowledge lecturers to course designers, learning facilitators, and resource providers. This places higher demands on teachers’ abilities to develop high-quality PBL cases, guide in-depth discussions, and integrate technological resources. Secondly, it is essential to recognize that virtual simulation cannot fully replace real operations. Teaching modules need to be connected through “integrated practical operation classes” to bridge the gap between virtual and real, al-

lowing students to verify virtual solutions in practice and experience real equipment feedback and patient interaction, thus completing the “last mile” of ability transformation. Additionally, this model relies on stable networks and high-performance computers. Schools need to ensure resource fairness by building public computer rooms and other measures to avoid creating new educational divides due to differences in technical conditions.

The effect size of this study (Cohen’s d for operational skills = 2.58) was significantly higher than the average effect level of virtual simulation teaching reported in the international systematic review (SMD = 0.71) (Shorey & Ng, 2021). This “excess effect” is not simply an additive effect but may stem from the synergistic amplification of PBL and virtual simulation. This result is highly consistent with the conclusion of Cook et al. (Cook et al., 2023) that “the effect of simulation teaching depends on the degree of integration of teaching design”, and also responds to the hypothesis of Carless et al. (Carless et al., 2023) that “the density of formative feedback is positively correlated with skill automation”. In this study, the immediate quantitative feedback from the platform and the peer discussions in the PBL groups interwove to form a high-frequency, multi-source formative feedback ecosystem, which might be the key mechanism for the significant increase in the effect size.

Looking ahead, technological development offers broad space for the evolution of this model. Artificial intelligence can analyze learning behavior data to achieve personalized case recommendations and adaptive difficulty adjustments, playing the role of an “intelligent mentor” and enhancing learning accuracy. Extended reality (XR) technology, especially mixed reality (MR), can overlay virtual operation interfaces onto real equipment models, creating a more immersive learning environment with a sense of presence. The construction of a national medical imaging virtual simulation teaching cloud platform can promote the aggregation and sharing of high-quality case resources, forming an open and collaborative teaching ecosystem and driving the overall improvement of educational standards.

This study has the following limitations: First, due to the natural constraints of medical education class organization, complete randomization of groups could not be achieved, which may have led to potential selection bias. Second, the intervention period was only five weeks, and the long-term retention effect of knowledge (retention tests after six months or one year) was not examined. Third, although the virtual platform was strictly physically verified, there is still a lack of large-sample evidence of effectiveness from multi-center and cross-institutional studies. Fourth, although the control group tried to keep the class hours consistent, the “Hawthorne effect” may partially explain the increased enthusiasm of the experimental group. Subsequent studies will conduct multi-center randomized controlled trials and include delayed post-tests.

Overall, the PBL combined with virtual simulation technology provides a systematic, operational, and highly efficient solution for teaching magnetic resonance parameter adjustment. By “anchoring learning significance in problems

and empowering exploration and practice through simulation”, it successfully transforms high-risk, high-cost, and highly abstract teaching content into safe, accessible, and in-depth learning experiences. This is not only an innovation in teaching tools but also a profound shift in educational philosophy from “teaching” to “learning”, representing the inevitable direction of medical engineering technology education development. The implementation experience and framework of this model have significant reference and promotion value for professional education and training in similar fields such as CT, interventional radiology, and radiotherapy planning design.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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