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Future prospects of learning in the clinical environment: exploring the technological revolution

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Future prospects of learning in the clinical environment: exploring the technological revolution

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Editorial: Future prospects of learning in the clinical environment: exploring the technological revolution

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Editorial on the Research Topic
Future prospects of learning in the clinical environment: exploring the technological revolution

The clinical learning environment is undergoing a significant transformation driven by an accelerating wave of technological innovation. The landscape of healthcare education is shifting from conventional, didactic approaches to more interactive, immersive, and personalized modalities. As emerging technologies such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), extended reality (XR), and metaverse-based environments gain traction, educators are reimagining how learning occurs, particularly in clinical contexts where practical skills, decision-making, and empathy are paramount (1).

This Research Topic, "*Future Prospects of Learning in the Clinical Environment: Exploring the Technological Revolution*," brings together 13 articles that exemplify the diverse and evolving roles of educational technology in shaping the future of clinical training. These 13 articles address five important key themes and technological modalities, as shown in Figure 1. The collective contributions present compelling evidence, insights, and innovations that inform how we design, implement, and evaluate learning in healthcare professions.

A prominent theme emerging from this Research Topic is the power of simulation-based learning. VR simulation has shown notable promise in nursing education. A systematic review and meta-analysis by Cho and Kim on enhancing nursing competency through virtual reality simulation among nursing students demonstrated its effectiveness in enhancing core competencies, engagement, and clinical confidence. Simulation-based

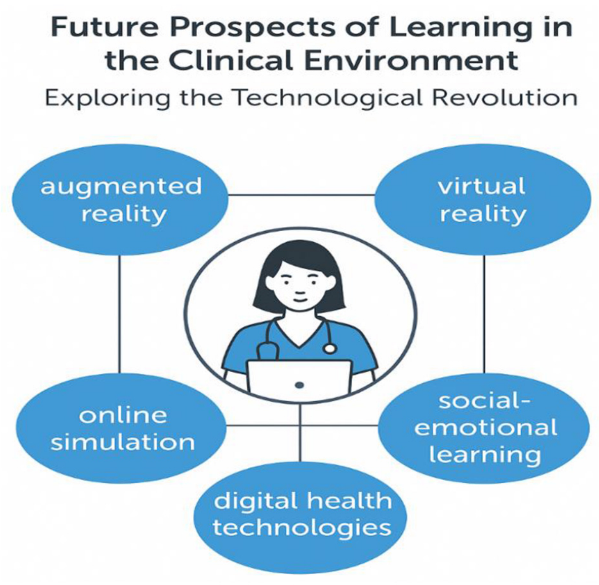

FIGURE 1
Identified key themes and technological modalities influencing the future of clinical education.

learning aligns with the broader literature on virtual patients and interactive learning tools (2).

Similarly, targeted simulations such as GASMAN software combined with case-based learning (Chen et al.) have proven superior to traditional lecture-based learning for inhalation anesthesia, indicating that interactivity significantly boosts knowledge retention and clinical reasoning.

Blended and hybrid models are also gaining momentum. The BOPPPS (Bridge-In, Objectives, Pretest, Participatory Learning, Post-test, and Summary) teaching model was rigorously evaluated in a meta-analysis by Li Y. et al., revealing its advantages in student satisfaction and academic performance. Other studies explored the merits of combining online and offline instruction. For example, an O2O (online-to-offline) teaching approach for non-anesthesiology residents in anesthesiology (Zhao et al.) and a blended model in clinical laboratory hematology (Li D. et al.) both underscored increased engagement, deeper learning, and practical skill acquisition (3).

Technological integration is not limited to hardware and platforms; it also challenges us to reimagine our pedagogical frameworks. A novel conceptual model of technology-enhanced practice competencies (Perle et al.) illustrates how competencies in digital literacy, ethics, and data management are becoming indispensable in clinical practice (4).

Beyond competencies, these technologies are reshaping fundamental educational theories. The shift from didactic delivery to immersive, interactive platforms aligns with constructivist and experiential learning paradigms, where knowledge is co-constructed through active engagement. Likewise, assessment practices are evolving to include performance-based tasks, real-time analytics, and AI-driven feedback, reflecting a broader redefinition of what constitutes competence in the clinical learning environment.

The metaverse, a once futuristic concept, is now being considered as a transformative tool in nursing practice and education. In their review, Li X. et al. present how immersive digital spaces can be leveraged for telemedicine, surgical assistance, chronic disease management, and psychological support. By merging physical and digital realities, the metaverse creates new spatial and relational dimensions for healthcare delivery and learning.

Meanwhile, extended reality (XR) technologies are making waves globally. A cross-sectional study in Pakistan by Khan et al. highlighted the enthusiasm among healthcare professionals and students toward XR technology, despite infrastructural and regulatory challenges. It emphasized the need for strategic planning to integrate XR into national healthcare education systems.

Simulation fidelity and realism continue to be central to clinical competence. An innovative Italian study by Neri et al. employed SimLife® to create hyper-realistic scenarios in medical training, providing students with a closer approximation to real-life patient interaction and physiological response.

Airway management, a critical component in clinical practice, was targeted in a scenario-based teaching intervention (Lin et al.). Results revealed enhanced procedural knowledge and confidence among anesthesia undergraduates, validating the potential of scenario-based online platforms in bridging theoretical and procedural gaps (5).

Notably, technology is also fostering new forms of reflective and emotional engagement. Social-emotional learning (SEL) is proposed as an essential complement to technological skills in medical training (Hsu et al.). SEL strengthens empathy, resilience, and professionalism—traits that are foundational for holistic medical care but are at risk of being overlooked in tech-centric models.

Even audio-based educational tools are under scrutiny. A critical analysis of cardiology podcasts by Kamalanathan et al. pointed out deficiencies in content transparency and referencing, urging the need for quality control standards in this increasingly popular modality.

Artificial intelligence is reshaping not just the delivery of care but also the way we teach and explain it—prompting educators to rethink sources of clinical knowledge.

While these studies provide promising evidence for the integration of simulation, blended models, XR, and metaverse-based learning, it is important to acknowledge their methodological limitations. Many rely on small samples, self-reported outcomes, or short-term assessments. In particular, research on VR and XR often carries inherent biases linked to novelty effects and limited generalizability across institutions and resource settings. A cautious interpretation is therefore essential, underscoring the need for more longitudinal, multicenter investigations.

Collectively, the studies articulate a vision of a technologically enhanced, learner-centered future where the clinical learning environment is deeply intertwined with technology. However, with opportunity comes responsibility. Equity in access, ethical deployment, standardization of content, and emotional intelligence must be cornerstones of this transformation.

Conclusion

The technological revolution is not merely altering educational tools—it is transforming how we think, teach, and learn. As we navigate this pivotal era, we must ensure that technology serves pedagogy, not the other way around. Future research and policy should not only document immediate learning gains but also measure the sustained impact of these technologies on graduate competence, patient outcomes, and healthcare system performance. Embedding evaluation frameworks that track long-term educational and clinical effects will be crucial in determining whether these innovations translate into tangible benefits for patients and societies. This Research Topic reflects a vibrant, multidisciplinary effort to imagine new possibilities for clinical education. Our challenge now is to move from innovation to integration, ensuring that digital advancements translate into meaningful, equitable, and human-centered learning experiences for all healthcare professionals.

Author contributions

HA: Resources, Writing – original draft, Investigation, Visualization, Project administration, Data curation, Conceptualization, Methodology, Writing – review & editing, Supervision. MS: Visualization, Project administration, Resources, Data curation, Methodology, Writing – review & editing, Writing – original draft, Conceptualization. AA: Resources, Writing – review & editing, Data curation, Methodology, Visualization. DK: Data curation, Resources, Writing – review & editing, Visualization. NW: Writing – review & editing, Visualization, Data curation, Methodology, Resources. KA: Data curation, Visualization, Resources, Methodology, Writing – review & editing. EA: Conceptualization, Writing – original draft, Investigation, Resources, Visualization, Writing – review & editing, Methodology, Project administration, Supervision, Data curation.

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Conflict of interest

The authors declare that the Research Topic was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tickling the heart: integrating social emotional learning into medical education to cultivate empathetic, resilient, and holistically developed physicians

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Objectives: Advancements in technology have improved healthcare quality but shifted the focus to efficiency, negatively impacting patient– doctor relationships. This study proposes integrating social-emotional learning (SEL) into medical education to address this issue.

Key arguments: Social-emotional learning (SEL) is based on social learning theory and has a focus on emotion management, stress management, empathy, and social skills. Through SEL, students can develop social and emotional skills by observing, interacting with, and imitating others. Incorporating SEL into medical education would ensure that physicians develop the social and emotional skills necessary to form positive relationships with patients and to cope with the emotional demands of medical work. SEL comprises six domains, namely, the cognitive, emotion, social, values, perspective, and identity domains. These six domains are closely related to the six core competencies the Accreditation Council for Graduate Medical Education (ACGME) indicated every doctor should possess, which indicates that the domains of SEL are highly relevant within the context of medical education. Furthermore, SEL can lead to the development of empathy, which can improve physicians' ability to understand patients' perspectives and emotions, and resilience, which can enable physicians to more effectively cope with the demands of their work, and it can lead to holistic development, with doctors gaining an understanding of both the technical and humanistic aspects of their work.

Conclusion: Incorporating SEL in medical education would enable doctors to develop key social and emotional skills that would improve their ability to provide holistic medical services and therefore would improve overall medical systems.

KEYWORDS

social-emotional learning (SEL), medical education, core competences, empathy, resilience

Background

Although developments in medical technology, including those involving the application of artificial intelligence, have improved the quality of healthcare, they may have led to physicians forming weaker interpersonal relationships with patients (1). When physicians focus too strongly on the technology-based aspects of their work, they may forget the value of humanity and the patients' sense of self-worth and may consequently overlook the emotional needs of their patients, compromising the quality of the doctor–patient relationship (2). Therefore, the pursuit of technological advancement in medicine without adequate consideration to educating and training physicians in ethics and the emotional aspects of their work may result in physicians who are unable to properly reflect on and consider patients' needs and values when engaged in ethical decision-making.

Emotions, emotion management, and emotional intelligence play crucial roles in the work of healthcare professionals (3). Healthcare professionals often face highly stressful and emotionally demanding situations at work, and frequent exposure to such situations can have negative effects on their mental health and work performance (4). Ensuring that healthcare professionals have experience with and are equipped with strategies for emotion management is crucial to improving their overall wellbeing and quality of healthcare. Mindfulness and emotional intelligence, which are closely related concepts, have protective effects on healthcare professionals. Therefore, cultivating mindfulness, emotional intelligence, and emotion management skills in healthcare workers can help them to more effectively cope with work-related stress, improve their emotion management skills, and improve their overall work quality (3, 4).

Healthcare is an interactive process, and focusing on technological advancements without considering the humanity and self-awareness of physicians can lead to ineffective patient-physician relationships and low healthcare quality. In addition to improving physicians' understanding of technological advancements, medical educators should cultivate physicians' awareness of the value of humanity and self-worth as well as their mindfulness, emotional intelligence, emotion management, and ability to self-reflect (1–4). Such an education would enable healthcare providers to strike a balance between applying their expertise and exercising their humanity, enabling the provision of comprehensive and compassionate medical care.

Social-emotional learning

Social-emotional learning (SEL) was proposed by the Collaborative for Academic, Social, and Emotional Learning (CASEL) in the United States. It is a form of emotional education that fosters understanding one's own and others' emotions, managing stress, exercising empathy, and developing social skills (5–7). SEL is based on social learning theory, which emphasizes that individuals learn behaviors and skills through observation, imitation, and social interaction. SEL focuses on the cultivation of social and emotional abilities among students, including those related to emotion management, interpersonal relationships, conflict resolution, and value development.

The development and implementation of SEL curricula typically draw upon the principles of social learning theory (8, 9). In educational programs based on SEL, students acquire knowledge through the observation and emulation of the social and emotional behaviors of peers and by actively participating in social interactions. This method of learning aligns with the core principles of social learning theory, which posits that learning is a social process, and that individuals acquire knowledge and skills through their interactions with others (8, 9). The development of SEL expanded the scope of application of social learning theory because in addition to focusing on how students learn social behaviors, it considers how educators can cultivate emotional intelligence and abilities among students. Such cultivation can help students recognize, understand, and effectively manage their own emotions, which can lead to their personal growth and wellbeing. In summary, SEL, with the principles of social learning theory at the core, can be used to develop social and emotional competencies among students. Structured curricula and activities based on SEL can cultivate crucial skills among students at all levels of education, including those related to emotion management, interpersonal relationships, and value development, which can improve the likelihood of growth and success.

Six domains of SEL

Social-emotional learning consists of primary core competencies in six domains: cognitive domain, emotion domain, social domain, value domain, perspective domain, and identity domain (5, 6). These competencies encompass several skills and abilities that are essential to students' social and emotional development.

The cognitive domain focuses on the fundamental cognitive skills required by students to achieve goals. Such skills include attention control, management of working memory and planning, inhibition control, cognitive flexibility, and critical thinking.

The emotion domain encompasses the skills that help individuals recognize, express, and regulate their emotions as well as understand and empathize with others. Developing the skills in this domain is crucial to managing one's own emotions and behaviors and engaging in positive interactions with others. These skills include emotional understanding and expression, emotional and behavioral regulation, empathy, and perspective taking.

The social domain involves skills that help an individual accurately interpret others' behavior, effectively navigate social situations, and effectively engage in positive interactions with others. Developing the skills in this domain is crucial to participating in collaborative work, solving social problems, building positive relationships, and living harmoniously with others, and such skills involve understanding social cues, implementing conflict resolution and social problem-solving, and employing prosocial and cooperative behaviors.

The value domain includes skills, character traits and virtues, and practices that enable individuals to become prosocial and productive members of their communities. This domain involves understanding, caring, and actions related to core moral values; a desire to achieve one's potential; and the habits required to live and work with friends, family members, and community members. The values encompassed in this domain include moral, performance, intellectual, and civic values.

The perspective domain involves a person's outlook on and approach to interacting with the world. It influences how individuals perceive themselves, others, and their circumstances, and it shapes how they interpret and respond to challenges in their daily lives. Having a positive perspective can prevent the development of and facilitate the management of negative emotions and can enable an individual to successfully complete tasks and interact harmoniously with others. A positive perspective involves being optimistic, grateful, open, or enthusiastic.

The identity domain encompasses an individual's understanding and perception of themselves and their capabilities, including their knowledge and beliefs about themselves and their ability to learn and grow. When individuals are satisfied with themselves; have a secure sense of their place in the world; and are confident in their ability to learn, grow, and overcome obstacles, they are better equipped to face challenges and build positive relationships. This domain includes self-awareness, goal-setting, self-efficacy and a growth mindset, and self-esteem.

Connections between the six domains of SEL and six core competencies of the Accreditation Council for Graduate Medical Education

The Accreditation Council for Graduate Medical Education (ACGME) recommended that physicians should have six core competencies (i.e., medical knowledge, professionalism, interpersonal and communication skills, systems-based practice, practice-based learning and improvement, and patient care), (10) which are closely aligned with the six domains of the SEL framework.

Cognitive domain versus medical knowledge

The cognitive domain of SEL, which focuses on attention control, management of working memory, critical thinking, and cognitive flexibility, is closely related to the ACGME core competency of medical knowledge. By developing strong cognitive skills, healthcare professionals can acquire, absorb, and apply medical knowledge, which can improve their diagnostic accuracy and evidence-based decision-making and ensure effective patient care.

Emotion domain versus professionalism

The emotion domain of SEL encompasses emotional knowledge and expression, emotion regulation, and empathy and therefore closely aligns with the ACGME core competency of professionalism. Emotional intelligence and empathy enable healthcare professionals to establish deeper connections with patients, demonstrate compassion and respect, and ensure the ethicality of their behavior. These skills help them build trust, develop positive physician–patient relationships, and provide patient-centered care.

Social domain versus interpersonal and communication skills

The social domain of SEL, which involves understanding social cues, conflict resolution, and normative behavior, aligns with the ACGME core competency of interpersonal and communication skills. Effective communication, collaboration, and teamwork are essential for interactions between healthcare professionals and patients, patients' families, and interdisciplinary teams. By developing social skills, physicians can navigate complex social dynamics, establish positive relationships, resolve conflicts, and promote a harmonious healthcare environment.

Value domain versus systems-based practice

The value domain of SEL, which encompasses moral values, performance values, intellectual values, and civic values, aligns with the ACGME core competency of systems-based practice. The strong values, ethics, and moral principles of healthcare professionals guide their practice and enable them to prioritize patient wellbeing and account for the effects of their healthcare decisions on individuals and communities. Strong values can lead physicians to engage in system thinking, advocate for patient rights, and participate in community health initiatives.

Perspective domain versus practice-based learning and improvement

The SEL perspective domain, which emphasizes optimism, gratitude, openness, and enthusiasm, aligns with the ACGME core competency of practice-based learning and improvement. Having a positive perspective can help physicians navigate challenges, manage stress, and engage in lifelong learning. In addition, such a perspective leads to a growth mindset, encourages reflection, and fosters resilience, all of which promote ongoing professional development and excellence in medical practice.

Identity domain versus patient care

The SEL identity domain, which involves self-awareness, goal-setting, self-efficacy, and self-esteem, is related to the ACGME core competency of personal and professional development. By establishing a strong professional identity, healthcare professionals can gain a deep understanding of their values, strengths, and motivations. This self-awareness supports personal growth, career planning, and the cultivation of self-efficacy. It also leads to confidence, resilience, and general wellbeing, which can help physicians navigate challenges and maintain their professional competence. The relationship between the six SEL domains and the six ACGME competences can be found in **Supplementary Table 1**.

Because of the relevance of the SEL domains to the ACGME core competencies, the SEL framework should be integrated into medical education and training programs for the development of the ACGME core competencies among healthcare professionals. By utilizing SEL, educators can cultivate well-rounded physicians who possess both technical expertise and strong social and emotional skills. This integration can lead to the development of compassionate, and resilient healthcare professionals who provide high-quality care, improving patient wellbeing and the overall healthcare system.

Implications of SEL in medical education

The abilities specified in SEL develop at different life stages. During early childhood, people generally develop emotion management and basic social skills, including the abilities to recognize and express emotions, share, and cooperate. In childhood and adolescence, more complex skills are developed, such as problem-solving, self-awareness, empathy, and coping abilities. In adulthood, self-planning skills, emotional intelligence, the ability to form interpersonal relationships, and skills related to career development are developed (11).

Empathy

Medical education focused on SEL principles can cultivate empathy in medical students through empathy training. Students can learn how to understand and empathize with patients' perspectives and emotions and how to respond appropriately to their needs. Furthermore, such education can help medical students establish trust and feel empathic resonance with patients, providing more personalized healthcare services with greater compassion.

Resilience

Medical education based on SEL holds promise for fostering resilience among medical students. Firstly, SEL education aids students in gaining a deeper comprehension of emotions and their management, thereby enabling them to effectively confront stressors and challenges with reduced susceptibility to emotional fluctuations. Secondly, through SEL education, students acquire techniques and strategies for coping with stress, a pivotal skillset for addressing challenges within the demanding milieu of healthcare environments. Furthermore, SEL education promotes students' understanding of patients' needs and emotional states, concurrently fostering the development of peer support networks, which can provide invaluable psychological support during times of adversity. Most significantly, this form of education extends beyond the purview of medical knowledge and technical skills, emphasizing ethical, humanistic, and moral dimensions, thereby enabling students to adopt a more comprehensive approach when confronted with diverse situations. SEL education contributes significantly to the cultivation of resilience in medical students, equipping them with enhanced capabilities to effectively navigate the multifaceted challenges inherent to the medical profession.

Holistic development

The focus of SEL-based medical education is holistic development, and medical students are encouraged to practice comprehensive growth. In addition to learning medical knowledge and skills, students cultivate moral judgment, professional ethics, teamwork skills, and lifelong learning abilities. Such education equips medical students with various competencies because it focuses on both the technical and the ethical and humanistic aspects of medical services, enabling healthcare professionals to provide comprehensive healthcare services.

In conclusion, the integration of SEL principles into medical education carries three significant implications for the training and development of healthcare professionals. Firstly, by emphasizing SEL, medical educators can contribute to the cultivation of compassionate, empathetic, and resilient practitioners who provide high-quality care and positively influence the wellbeing of their patients. These educational initiatives equip prospective healthcare professionals with self-regulation skills, emotional intelligence, the ability to establish interpersonal relationships, and the essential competencies for professional growth. Secondly, the integration of SEL into medical education ensures that physicians possess both the necessary technical knowledge and social-emotional skills, thereby facilitating their professional advancement and enhancing the overall wellbeing and healthcare quality of their patients.

Thirdly, the infusion of SEL principles into medical education can foster the development of empathy and resilience among future physicians, thereby contributing to their holistic growth. In today's technological era, there has been a predominant focus on efficiency (1, 2). However, medical education enriched with SEL places a greater emphasis on humanistic care. Consequently, physicians educated in this manner provide more comprehensive and superior-quality healthcare services.

This study has explored the incorporation of SEL within medical education, with its primary objective being to provide medical educators and administrators with a foundational understanding of SEL principles. The development of SEL competencies among prospective physicians can ensure positive interpersonal relationships and proficiency in emotional management. Moreover, these individuals can serve as role models and inspire others within the organization to engage in SEL practices (12). This study represents an initial exploration of the application of SEL in medical education, paving the way for future researchers to delve deeper into the relationships between instructional approaches and the enhancement of SEL competencies among medical students.

Future medical educators can ensure the integration of SEL clinical courses into medical curricula and conduct appropriate qualitative course assessments through the following approaches:

1. Social-emotional learning (SEL) course design from basic to clinical learning: Medical educators should design courses based on SEL principles, covering topics such as emotional management, empathy cultivation, and conflict resolution. These courses should span the entire undergraduate medical curriculum, ensuring students receive comprehensive social and emotional learning throughout their medical training. The medical curriculum should be aligned with students' personal development and societal context, enabling students to integrate learned social and emotional skills across various learning contexts.
2. Incorporation of educational ecological perspectives: Both SEL course (13, 14) and medical education (15) designs emphasize the significance of educational ecology, as interactions between students and all stakeholders in the educational ecosystem influence students' learning outcomes and development. Educational ecological perspectives should be a crucial consideration in course design to ensure adaptation to the diverse needs and expectations of stakeholders. During course evaluation, the impact of educational ecology should be considered, and course content and teaching methods should be continually adjusted and improved based on feedback.
3. Appropriate qualitative course assessment: Medical educators need to develop effective qualitative assessment methods to evaluate the impact of SEL courses on students. These assessments may include qualitative surveys and observations of students' emotional intelligence levels, empathy skills, and emotional management abilities. Assessment results should comprehensively consider various factors in the educational environment, including course structure, teaching methods, and learning resources, to evaluate course effectiveness. Medical educators should collect and analyze evaluation data from SEL-based clinical courses to assess their impact on student empathy and holistic approaches. These data can guide further improvements and adjustments to the course. Data collection and analysis should consider students' individual differences, social backgrounds, and the impact of the course on students' personal development and societal systems.
4. Continuous development and enhancement of SEL course cycles: Medical educators can facilitate more research to explore the impact of SEL-based clinical courses on student-doctor relationships. Continuous research and development efforts can continually refine and enhance medical education, nurturing doctors with greater empathy and holistic approaches to promote the development of doctor-patient relationships. Additionally, attention should be paid to social-cultural factors and institutional environments to foster the overall development and transformation of medical education.

Author contributions

W-CH: Writing – original draft, Writing – review & editing, Conceptualization. L-JF: Writing – original draft, Writing – review & editing. S-CL: Writing – original draft, Conceptualization, Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Application of online to offline teaching mode in the training of non-anesthesiology residents in the department of anesthesiology: a randomized, controlled trial

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Objective: To explore the effect of applying the online to offline teaching mode in the training of non-anesthesiology residents in department of anesthesiology.

Trial design: The randomized controlled trial was performed on non-anesthesiology residents from Affiliated Jiangning Hospital of Nanjing Medical University.

Methods: All selected residents were randomly divided into the traditional teaching group (Group T) and the online to offline teaching group (Group O) by the random number table method. Traditional teaching mode was used in Group T, while the online to offline teaching mode was used in Group O. The training period lasted for two months. At the end of the training, theoretical and clinical skills were assessed for all residents, and students' satisfaction scores on teaching were investigated from the aspects of teaching mode, stimulating learning interest, improving learning process and teaching satisfaction. The teaching efficiency was compared and analyzed in the two groups.

Results: In total, 39 cases in Group O and 38 cases in Group T were included in the statistical analysis. Compared with Group T, theory test scores, clinical skills test scores, and overall scores improved significantly in Group O (82.2 ± 8.1 vs. 91.3 ± 7.6; 85.1 ± 4.7 vs. 93.3 ± 5.4 and 83.4 ± 6.4 vs. 92.1 ± 6.7, respectively, $p < 0.01$). Compared with Group T, scores on teaching mode, stimulating learning interest, improving learning process and teaching satisfaction were higher in Group O (81.1 ± 6.9 vs. 93.7 ± 5.2; 83.6 ± 5.8 vs. 91.6 ± 6.4; 82.4 ± 5.3 vs. 90.9 ± 4.8 and 82.1 ± 5.9 vs. 92.1 ± 5.5, respectively, $p < 0.01$).

Conclusion: The online to offline teaching mode can improve the level of professional theory and clinical skill operation, and teaching satisfaction of the non-anesthesiology residents in department of anesthesiology, thus improving the teaching effectiveness.

KEYWORDS

online to offline, teaching mode, residents, standardized training, anesthesiology

1 Introduction

Standardized training for residents is an important part of post-graduation education for medical students. With the increasingly refined division of clinical disciplines, although clinical specialists are familiar with the knowledge and skills of their major, they have some deficiencies in theoretical knowledge and clinical practice of related disciplines outside their major (1). Various monitoring theories and operation techniques, emergency treatment of various perioperative complications and pain treatment involved in clinical anesthesia work are the basic skills that clinicians should master (2). Therefore, it is necessary to explore the problems existing during the rotation of non-anesthesiology residents to anesthesiology department and propose corresponding solutions and countermeasures. These students' understanding of anesthesiology only was limited in the medical school of surgery introduction to anesthesiology part, and training time in department of anesthesiology was short in domestic hospitals (no more than two months). There were many problems in the process of teaching, such as students' lack of purpose, enthusiasm and initiative, also teachers' lack of enthusiasm and guidance, even strict training rules and evaluation plans (3, 4). Therefore, compared with the traditional teaching by PowerPoint (PPT) and auxiliary skills operation, it is particularly important to stimulate these students' interest and active their initiative in learning non-professional knowledge.

With the rapid development of information and network technology, and the continuous innovation of educational technology and means, the advantages of the mixed teaching mode combining online teaching with traditional offline teaching have become increasingly significant (5). The online to offline (O2O) mode first emerged in the field of e-commerce, which referred to the business model that used the online Internet as an offline trading platform to promote consumption and promotion (6). When the O2O mode was introduced into teaching, its connotation produced a qualitative change. "O2O Teaching Mode" was the integration of online and offline teaching, which used computer information, network technology and platform (7, 8). Studies have shown that using the O2O teaching mode in teaching of English (9), computer science (10) and medical students (11) have achieved good results such as the improvement of students' learning enthusiasm, interest and academic performance. Therefore, the aim of this study was to investigate the effect of the application of O2O teaching mode in the training of non-anesthesiology residents in the department of anesthesiology, so as to provide reference for improving the training quality of these residents.

2 Methods

2.1 Ethics statement

The Consolidated Standards of Reporting Trials (CONSORT) recommendations (12) were followed in this study for the design and implementation of randomized controlled trials. Ethical approval for this study (2021-02-028-K01) was provided by the Institutional Ethics Committee of the Affiliated Jiangning Hospital of Nanjing Medical University. All participants involved were informed of the proposal and gave their written, informed consent.

2.2 Participants

Eighty non-anesthesiology residents were enrolled in this study, who were trained from May 4th 2021 to May 5th 2023 in department of anesthesiology, the Affiliated Jiangning Hospital of Nanjing Medical University. All residents were randomly divided into two groups by the random number table method: the traditional teaching group (Group T) and the online to offline teaching group (Group O), with 40 cases in each group. The traditional teaching method was used in Group T, while the online to offline teaching mode was used in Group O. Inclusion criteria: (1) Non-anesthesiology postgraduate students; (2) The training time in department of anesthesiology was two months; (3) The students had physician qualification certificate. Exclusion criteria: Failure to complete the study according to the prescribed training program.

2.3 Sample size and randomization

According to previous relevant studies (7, 11) and results of preliminary test, it was estimated that the final score of residents in group O was about 9.5 points higher than that of Group T, α =0.05, 1- β =0.8, 36 cases were required in each group, assuming that the shedding rate was 10%, and the sample size included in the initial screening was 40 cases in each group. Residents were randomly assigned to one of the two groups. Random tables were generated by computer. Eighty sealed envelopes were prepared by a statistician who did not participate in the study.

2.4 Study design

2.4.1 Group O

① Online class: teachers published PPT, clinical operation videos and background materials related to the training course through the Chinese university Massive Open Online Courses (MOOC) platform before classes, and students were required to use flexible intelligent devices to complete independent learning before class. The online platform provided detailed information about the number of learners, the learning progress of the students and duration of study. After students ended their independent learning and examination, the platform provided evaluation and analysis of teachers' input, so that students could have a preliminary understanding of their knowledge mastery, and enter offline classes with thinking and problems about the course content. ② Offline class: residents were taught by PPT once a week, mainly face to face to discuss the theoretical and operational content of the platform that was difficult for students to understand. The operation of skills was from clinical operation videos by online class, observation, teacher-assisted practice to independent practice (Table 1).

2.4.2 Group T

Residents were taught by PPT twice a week, and followed the teacher in the daily clinical process. The operation of skills training was also followed with Table 1, but from learning by offline class, observation, teacher-assisted practice to independent practice. Additionally, to ensure the comparability with Group O, we converted the online study time of students in Group O into the offline self-study

TABLE 1 Standardized training program for non-anesthesia residents in the department of anesthesiology.

Time	Content	Requirements
First month		
First day	Training of entering the department	① Understanding the basic workflow and system of anesthesiology department. ② Preliminary understanding of the relevant knowledge of the anesthesiology department. ③ Exercising face mask ventilation, endotracheal intubation and other operations by the simulated person.
First week	Subprofessional observation (general surgery, urology, obstetrics and gynecology, vascular surgery)	① Further getting familiar with the daily work process of the anesthesiology department. ② Following the frontline teacher to observe and learn anesthesia management.
Second week	Subprofessional observation (orthopedics, oncology, E.N.T., cardiothoracic surgery, emergency)	① Preliminary understanding of the monitoring of complex anesthesia and management. ② Following the frontline teacher to learn pre-operative assessment related to anesthesia.
Third week	Sub-specialty practice (general surgery, urology)	① Practicing face mask ventilation, endotracheal intubation, and laryngeal mask placement etc. ② Learning to independently complete the anesthesia management of patients with simple conditions.
Fourth week	Sub-specialty practice (obstetrics and gynecology)	① Further skilled and independently complete mask ventilation, endotracheal intubation, laryngeal mask placement and other operations; Preliminary understanding of intraspinal anesthesia. ② Following the frontline teacher for preoperative visit; Mastering the special physiology of the puerpera.
Second month		
First week	Sub-specialty practice (orthopedics, vascular surgery)	① Completing the mask ventilation, endotracheal intubation and other operations independently. ② Performing anesthesaesthetic management of patients with simple conditions independently.
Second week	Sub-specialty practice (oncology, E.N.T.)	① Completing the mask ventilation, endotracheal intubation and other operations independently. ② Performing anesthesaesthetic management of patients with simple conditions independently. ③ Preliminary learning to master difficult airway management.
Third week	Sub-specialty practice (cardiothoracic surgery)	① Completing mask ventilation, endotracheal intubation, arteriovenous puncture, EEG monitoring and other operations independently. ② Participating in, formulating and implementing postoperative analgesic treatment plan, and independently conduct anesthesia management of patients with complicated conditions. ③ Participating in the study of anesthesia management of critically ill patients in cardiothoracic surgery.
Fourth week	Sub-specialty practice (emergency)	① Participating in the emergency duty, and further learn to master the emergency and difficult airway management of emergency surgery. ② Learning about anesthesia assessment, preparation, induction and management. ③ Learning anesthesia management for critically ill patients and complicated patients with emergency surgery.
Last day	Examination	Theory test, clinical skills test, and satisfaction survey.

time for students in Group T. We played the same PPT and clinical operation videos, distributed the same materials and test volumes in the classroom where there was a teacher who ensured the same duration of study as recorded by MOOC in Group O and provided evaluation and analysis of students' independent learning and examination.

2.5 Outcomes

2.5.1 Main outcomes

Residents' final examination scores. All students took offline theoretical and operational exams on the last day of training in the department of anesthesiology. The theoretical examination was based on the questions according to the Content and Standards of Standardized Training for Resident Doctors (Trial in China), including single choice, multiple choice, noun explanation and essay questions. The clinical skills assessment was carried out according to the Standard Scheme for The Clinical Practice Ability of Standardized Training of Residents (Department of Anesthesiology in China), including connection of conventional monitor, use of simple respirator, endotracheal intubation, single cardiopulmonary resuscitation and electrical defibrillation. The scores consisted of two parts: theory test score and clinical skills test score, accounting for 100 points, respectively. Final score = 60% theoretical score + 40% skill score.

2.5.2 Secondary outcomes

Satisfaction score for clinical teaching. The clinical teaching satisfaction questionnaire was used to evaluate residents' satisfaction with clinical teaching. The questionnaire score mainly included four items: teaching mode, stimulating learning interest, improving learning process and teaching satisfaction, each with a full score of 100 points. The satisfaction survey was conducted anonymously.

2.6 Statistical analysis

Data analysis was performed by the SPSS (version 25.0, SPSS Inc., Chicago, IL, United States). Continuous variables were presented as mean ± standard deviation (SD), and comparisons between groups were performed by an independent sample *t*-tests. Categorical variables were presented as frequency, and comparisons between groups were performed using the χ^2 test. A *p*-value <0.05 was considered to be statistically significant.

3 Results

3.1 Residents recruitment

In this study, 80 residents were initially screened, and 3 of them were excluded (One resident was excluded for personal leave in Group O, while one was excluded for sick leave and another for transferred to other departments in Group T). In total, 39 cases in Group O and 38 cases in Group T were included in the statistical analysis (Figure 1).

3.2 Baseline characteristics of the two groups

The non-anesthesiology residents referred in this study majored in general surgery, orthopedics, emergency, critical care medicine, E.N.T., urology, oncology, cardiothoracic surgery and obstetrics and gynecology, respectively. There was no significant difference in age, gender, major, and type of postgraduates between group O and group T ($p > 0.05$) (Table 2).

3.3 Test score of the two groups

Compared with Group T, theory test scores, clinical skills test scores, and overall scores improved significantly in Group O ($p < 0.01$) (Table 3).

3.4 Teaching score of the two groups

Compared with Group T, scores in teaching mode, stimulating learning interest, improving learning process and teaching satisfaction were higher in Group O ($p < 0.01$) (Table 4).

4 Discussion

With the development of medicine, the scale of hospitals is constantly expanding, and the division of clinical disciplines is becoming refined. Various specialties pay more and more attention to the cultivation of the theory and skill operation of their professional doctors, but the learning of other interdisciplinary theories and skills are still insufficient. The department of anesthesiology of our hospital also undertakes a large number of standardized training tasks for non-anesthesiology residents every year, including directed education and socialized recruitment of postgraduates. These students are mainly involved in a variety of surgery-related majors, such as general surgery, orthopedics, emergency department, intensive care medicine, E.N.T., obstetrics and gynecology, etc. As residents in anesthesiology, we used to use traditional teaching by PPT and "hand-in-hand" operation training for non-anesthesiology residents, which are difficult to stimulate their interest in learning and often lack active initiative because of insufficient understanding of anesthesiology related theories and operations (13). Most of them reflected that the knowledge in class was difficult to understand, and the actual operation was also very passive and difficult to accept. Therefore, this study adopted the O2O teaching model with preview, talking and interaction online outside the classroom. The results suggested that this teaching model improve the teaching effectiveness to non-anesthesiology residents in department of anesthesiology.

4.1 Traditional teaching in department of anesthesiology

Traditional teaching methods are relatively simple in department of anesthesiology. The main body of teaching were teachers, who only regarded students as the container to accept knowledge, and to some extent ignored the existence of students as the subject of learning. Students only took the test for the purpose and mechanically memorized the knowledge points in the traditional teaching mode. In the study of Duan et al. (14), they compared the effects of an online teaching mode on WeChat platform with the traditional teaching model on learning outcomes of anesthesiology residents during the COVID-19 outbreak. The results showed that the examination performance, clinical thinking, communication skills, learning interest and self-learning ability of residents in the group of traditional teaching model were worse than those in the group of online teaching mode. However, online teaching alone cannot meet the needs of residents' practical skills and face-to-face communication with teachers and patients. Thus, online to offline teaching mode was designed in this study. Additionally, the integration of teaching and information technology was poor used in traditional teaching mode. At present, the use of information technology in the department of anesthesiology often stayed in PPT, after-class paper examination and questionnaire survey. Some hospitals or teachers were still in the stage of multimedia teaching and "face-to-face" teaching, and they could not flexibly use various online teaching platforms, WeChat public accounts and other media. In the study of Huang et al. (15), they used WeChat public platform for education in anesthesiology residents. The results suggested that residents in the WeChat group perform significantly better on assessments than those in the traditional group regarding theoretical knowledge scores, operational skill scores and overall scores, and the questionnaire results indicated that the degree of satisfaction of the residents and teachers in the WeChat group was significantly higher than that in the traditional group. In contrast, the MOOC platform was used in the present study which was more versatile and the most widely used platform for teaching in China

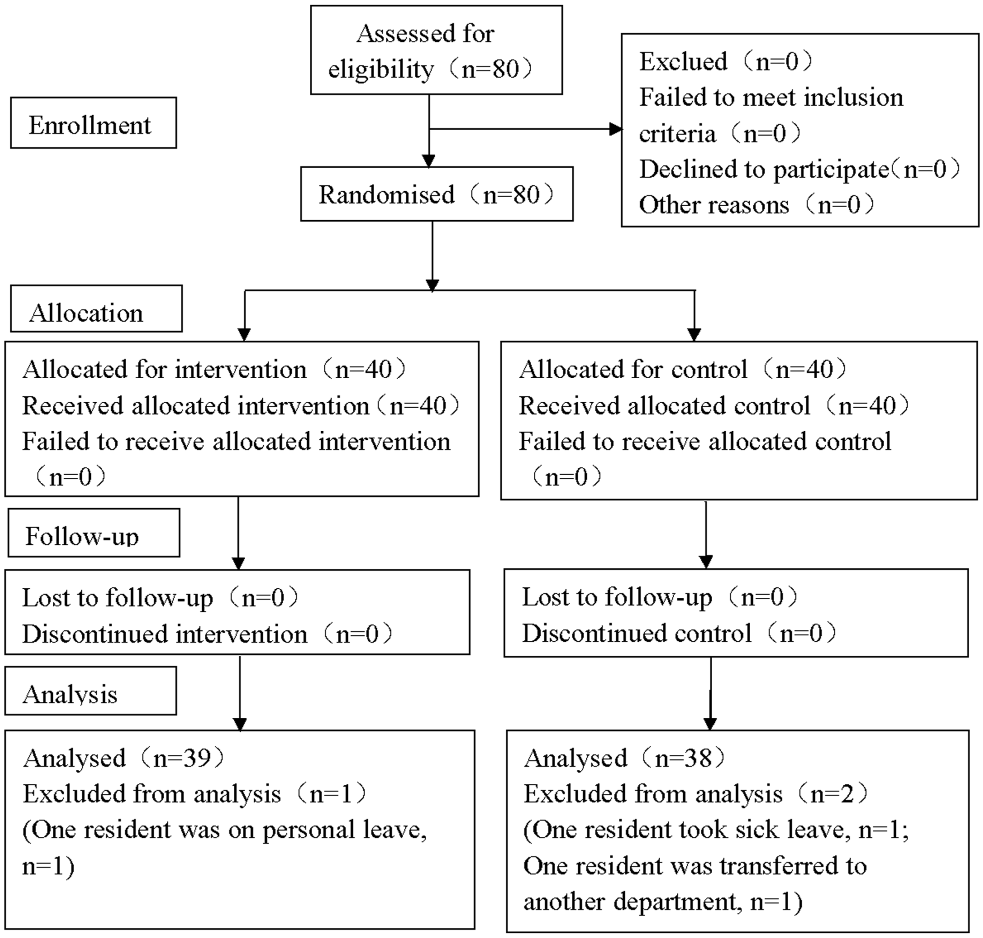

FIGURE 1
CONSORT flow diagram. In the study, a total of 80 participants were enrolled initially and three residents were excluded during the trial. Finally, there were 77 residents included in the statistical analysis (39 in Group O and 38 in Group C, respectively). CONSORT: the Consolidated Standards of Reporting Trials.

(16). Besides, residents' feedback to the class was not optimistic in the traditional teaching mode (17). Some residents had not prepared before class and knew nothing about the content of teaching. It was difficult to understand the professional knowledge points. Therefore, they can not pay attention in class and thought the course was boring.

4.2 Classification of O2O teaching mode

According to the differences of curriculum design idea, the current O2O teaching modes were as follows. (1) The O2O teaching mode based on the traditional classroom idea was reported by Daulatabad et al. (18). In this mode, online learning was only an auxiliary and supplement to the offline traditional classroom. Teachers can upload teaching content and expand knowledge online for students' preparation before class, consolidation and expansion after class. Offline classroom was still based on the students' preparation before class. This type of teaching mode can be used for courses with strong theory and difficult for students' self-study. (2) The O2O teaching mode based on the concept of flipped classroom reported by Zhang et al. (19). Students mainly chose courses and self-studied through online platform. They can also interact online through social network, participate in offline class regularly and conduct collaborative learning. This teaching mode can be used for easy self-study courses. (3) The O2O teaching mode based on the mixed teaching idea reported by Ding et al. (20). This mode divided the courses into easy and difficult content. Students studied easy content online by themselves, and made discussion and practice by offline face-to-face class. The difficult content was mainly learned by offline classroom lecture, while the online class was mainly for practice and consolidation. Considering the characteristics of anesthesiology and the correlation between different majors, the third O2O teaching mode was adopted in this study. Residents learned easy content online, and made discussion of difficult content in offline class. The results of this study showed that this mode improved the learning motivation of residents and the effect of teaching.

4.3 Advantages of the O2O teaching mode

Teaching resources were effectively utilized in the O2O teaching mode. In traditional teaching mode, many high-quality teaching resources on the internet, such as videos, animation and so on, were often unable to be used due to limitation of conditions. The study of

Shi et al. (21) showed that teachers could directly send these resources to students through links and other forms in the O2O teaching mode, and save time and effort, which improved teachers' work efficiency, so as to concentrate on polishing better course resources. Secondly, the time and space for students' study were greatly expanded. Students can only listen in the classroom during class time in traditional teaching mode. Most of the O2O teaching mode was online education. Students can learn at any time with only a computer or a mobile phone, which was conducive to students to make better use of the fragmented time (22). However, online teaching did not completely replace classroom teaching. Thus, in our study, residents in Group O were also taught by PPT in Offline class once a week, mainly face to face to discuss the theoretical and operational content of the platform that was difficult for students to understand, which can improve students' interest and efficiency in learning. The results of this study also showed that the theory test scores, clinical skills test scores, and overall scores improved significantly in Group O. In addition, the interaction between teachers and students was enhanced in the O2O teaching mode, which could improve the quality of teaching. According to the results of Asfhar et al. (23), teachers can learn students' preview, review, homework completion, participation in discussion, online examination and other conditions through background data in O2O teaching mode, and students can also see teaching resources and data on the platform and become teaching supervisors. Therefore, teachers and students can communicate and interact online, score each other, which will be conducive to the establishment of a harmonious teacher-student relationship. So that in the present study, students had significantly higher scores of teaching mode and teaching satisfaction in Group O.

TABLE 2 Comparison of baseline characteristics in the two groups ($n = 77$).

Characteristic	Group O (n = 39)	Group T (n = 38)	p-value
[a]Age (years), mean ± SD	25.3 ± 3.1	24.8 ± 3.6	0.826
[b]Gender (n)			
Male	22	20	0.318
Female	17	18	0.532
[b]Major (n)			
General surgery	6	5	0.916
Orthopedics	5	6	0.528
Emergency	6	5	0.916
Critical care medicine	3	4	0.428
E.N.T.	3	4	0.428
Urology	4	3	0.787
Oncology	5	3	0.624
Cardiothoracic surgery	3	3	0.998
Obstetrics and gynecology	4	5	0.722
[b]Type of postgraduates (n)			
Directed education	23	21	0.668
Socialized recruitment	16	17	0.325

SD, Standard deviation; E.N.T., ear, nose, and throat. [a]Comparison based on an independent sample t-tests. [b]Comparison based on χ^2 test.

TABLE 3 Test score of residents in the two groups (mean ± SD, score).

Group	Theory test	Skills test	Total scores
Group O (n = 39)	91.3 ± 7.6	93.3 ± 5.4	92.1 ± 6.7
Group T (n = 38)	82.2 ± 8.1	85.1 ± 4.7	83.4 ± 6.4
p-value[a]	**0.004**	**0.006**	**0.004**

SD, Standard deviation; p-value significant (i.e., <0.05) indicated in bold. [a]Comparison based on an independent sample t-tests.

4.4 Limitations of the O2O teaching mode and this study

Mobile phones were one of the important learning tools in O2O teaching mode. Some students played mobile games in class, which might have a negative impact on learning (24). In this study, we increased the frequency of answering questions online and offline in class. Students who played mobile phones could not answer questions in time, which might lead to low scores in class, thus promoting students to improve their learning concentration. In addition, the function construction of the course platform was also very important. If the mobile phone was locked after the students' scanning the code and entering the classroom, it could only be synchronized with the teacher's mobile phone or computer. Study of Zhao et al. (25) showed that the extensive use of O2O teaching mode also brought great pressure to students.

Due to the fact that subjects of this study were non-anesthesiology residents and different training methods of medical students in China were trained in different ways, the examination methods in this study were not based on the standardized training examination for anesthesiology residents in the United States. However, there was no unified international standard for the standardized training of non-anesthesiology residents in the department of anesthesiology. In our study, the training of non-anesthesiology residents followed the same domestic standards including basic theory, knowledge and skills according to anesthesiology residents, which did not affect the evaluation and promotion of online to offline teaching mode. In addition, due to the large number of course chapters and automatic evaluation scores on the MOOC platform, the scores of students'

TABLE 4 Score of teaching in the two groups (mean ± SD, score).

Group	Teaching mode	Stimulation of learning interest	Improvement of learning process	Teaching satisfaction
Group O (n = 39)	93.7 ± 5.2	91.6 ± 6.4	90.9 ± 4.8	92.1 ± 5.5
Group T (n = 38)	81.1 ± 6.9	83.6 ± 5.8	82.4 ± 5.3	82.1 ± 5.9
p-value[a]	**0.002**	**0.005**	**0.004**	**0.002**

SD, Standard deviation; p-value significant (i.e., <0.05) indicated in bold. [a]Comparison based on an independent sample t-tests.

online learning and evaluation were not counted in this study, but the final theoretical and operational examination scores on the last day of training in the department of anesthesiology were taken as the main outcomes. Finally, though it was difficult to achieve double blinding in this study, we ensured those who scored the test and the questionnaire did not know the grouping.

5 Conclusion

In conclusion, this randomized control trial shows that application of online to offline teaching mode in non-anesthesiology residents in department of anesthesiology can improve the level of anesthesia-related professional theory and clinical skill operation in these students, and their satisfaction with teaching mode, so as to improve the teaching effectiveness.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval for this study (2021-02-028-K01) was provided by the Institutional Ethics Committee of the Affiliated Jiangning Hospital of Nanjing Medical University. All participants involved were informed of the proposal and gave their written, informed consent.

Author contributions

Y-yZ: Data curation, Funding acquisition, Methodology, Writing – original draft. T-tZ: Methodology, Software, Writing – original draft. L-hL: Conceptualization, Investigation, Writing – original draft. QL: Investigation, Writing – original draft. L-jP: Investigation, Writing – original draft. QW: Conceptualization, Investigation, Writing – original draft. WW: Project administration, Supervision, Writing – review & editing. W-yY: Data curation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Enhancing nursing competency through virtual reality simulation among nursing students: a systematic review and meta-analysis

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Aim: Studies on the effectiveness of virtual reality (VR) in nursing education have explored its impact on learning outcomes, emotional immersion and engagement, learner self-confidence, and satisfaction, generally showing positive aspects. However, there is a need for a systematic review to examine the specific influence of VR-based education on nursing students' practical competency.

Method: According to the PRISMA 2020 guidelines, 22 studies were selected based on inclusion criteria from 579 articles, published from January 1, 2018, to March 31, 2024, across nine major databases including PubMed and EMbase. The target population comprised nursing students, and the intervention focused on VR-based simulations aimed at enhancing competency, compared to control groups receiving either no intervention or conventional non-virtual simulation. The primary outcome, nursing competency, was analyzed using MIX 2.0 Pro (Ver. 2.0.1.6, BiostatXL, 2017) to calculate pooled effect sizes.

Result: The pooled effect size for nursing competency was determined to be large, with Hedge's g = 0.88 (95% CI, 0.47 to 1.29). Meta-regression analysis identified several factors associated with an increase in nursing competency. These included studies published after 2022, approval of an IRB, absence of funding, randomized controlled trials (RCTs), interventions reported as shorter than 4 weeks or not reported, sessions fewer than 4 or not reported, session duration under 1 h or not reported, and observational measurement methods. Additional factors enhancing nursing competency were the inclusion of a pre-briefing before simulations, the absence of a debriefing afterward, and the exclusion of other activities during the simulation.

Conclusion: By combining the results of the included studies, the systematic review and meta-analysis accounted for variations in sample size, study methodology, and independent intervention effects, providing an overall evaluation of the effectiveness of simulation-based education in improving nursing students' competency.

Limitation: The selection criteria for the studies analyzed, which included only those published in English or Korean and reported precise means, standard deviations, and sample sizes, could lead to selection bias and limit the generalization of our study results.

Systematic review registration: PROSPERO International Prospective Register of Systematic Reviews: http://www.crd.york.ac.uk/PROSPERO/, identifier CRD42023446348.

KEYWORDS

virtual reality, simulation, nursing students, competency, meta-analysis

1 Introduction

Nursing education is an applied discipline in which theory and practical education are combined; prospective nurses prepare to become competent by applying the knowledge learned in theoretical education to the practical education process. The need for nursing education to train professionals who provide nursing and medical services to humans utilizing digital-based, non-face-to-face media such as artificial intelligence (AI) and big data has recently become more urgent (1). In nursing education, there has been an increasing interest in virtual-reality simulation (VRS) education as an alternative and complementary method to traditional simulation education, providing students with new learning experiences in a reproduced clinical environment and enhancing clinical adaptability (2). Virtual reality (VR) is defined as "the use of partial immersion through a digital learning environment (computer, tablet, phone, screen, etc.) to foster a perceived lived experience for an intended outcome (e.g., learning and entertainment)" (3). This study defines VRS to include VR and its derivatives, augmented reality (AR), and mixed reality (MR), using the terminology consistently. In VRS, learners can collaborate with other healthcare professionals to provide interventions, such as solving patients' problems or practicing simple skills (4, 5). Improved clinical performance skills, knowledge, and metacognition, as well as enhanced learning satisfaction, communication, self-efficacy, confidence, and teamwork have been reported as effects of these VR programs (4, 6). In addition, studies on the effectiveness of nursing education using VR have been conducted on learning effectiveness, emotional engagement and immersion, learner confidence, and satisfaction (7, 8). Reportedly, VRS programs for nursing skills are effective in improving skills (9) and have the advantage of enabling safe and repetitive training without time and space constraints (10). Thus, learning through VRS has demonstrated improvement in various factors related to clinical nursing competency, albeit often assessed in a fragmented manner. As various forms of VRS are being applied in nursing education, and diverse elements contributing to nursing competency are considered, there is a need to comprehend the holistic outcomes of these studies. Consequently, this study aims to comprehensively review the results, considering nursing competency in a broader sense that encompasses collaboration, interpersonal relationships, communication, professional development, and the nursing process, skills, and education (11).

Moreover, a systematic review and analysis of nursing students' outcomes are essential for determining specific factors that are deemed effective. Systematic reviews and meta-analyses can amalgamate the results of included studies, accounting for differences in sample size, variations in research approaches, and intervention effects among independent studies. We believe that the systematic review and meta-analysis in this study will enable an assessment of the overall effect of VRS-based education on nursing students' nursing competency. Consequently, this study aims to provide foundational data on VRS by conducting a systematic literature review and meta-analysis, investigating the improvement effect of VRS on nursing students' nursing competency as a primary outcome, and examining knowledge, self-efficacy, problem-solving skills, confidence, and satisfaction as secondary outcomes.

This study aims to acquire and analyze evidence regarding the enhancement of nursing students' nursing competency through VRS. The primary outcome focuses on nursing students' self-reported feelings and reactions, while the secondary outcome assesses nursing students' nursing competency following exposure to VRS.

2 Materials and methods

2.1 Search strategy and data sources

The search was jointly conducted by two researchers, Cho, M.-K. and Kim, M.Y., across nine electronic databases or e-journals: PubMed, Cochrane, EMBASE-OVID, CINAHL, World of Science, SCOPUS, PQDT, APA PsycArticles, and Research Information Sharing Service. The primary search, conducted from July 18, 2023, to August 20, 2023, targeted articles published in English and Korean from January 1, 2003, to April 30, 2023. A secondary search was carried out from April 6, 2024, to April 9, 2024, focusing on articles published from May 1, 2023, to March 31, 2024, also in English and Korean. The search strategy and formula, following the PICO-SD framework (population, intervention, comparison, outcome, study design), are detailed in Table 1. The keywords employed in search terms across the nine databases included combinations and variations of "nursing students," "virtual reality," "augmented reality," "extended reality," "metaverse," "competency-based education," "clinical competence," "competency," and "controlled clinical trial." These keywords were chosen to comprehensively capture studies relevant to the impact of virtual reality simulation on nursing competency.

2.2 Inclusion and exclusion criteria

The reporting of the results adhered to the PRISMA 2020 checklist. Inclusion criteria comprised nursing students aged 19 years or older (Population), interventions involving VRS (Intervention), with conventional learning methods or no intervention as the control (comparison). The primary outcome was nursing competency, and secondary outcomes included knowledge, self-efficacy,

TABLE 1 Search strategy according to PICO.

PICO	Key terms	MeSH	PubMed Entry Terms	EMTREE (EMBASE)	Text words
P (Patient, Population, Participants, Problems)	Nursing student(s)	"Students, Nursing"[Mesh]	Pupil Nurses Student, Nursing Nurses, Pupil Nurse, Pupil Pupil Nurse Nursing Student Nursing Students	Nursing student/	[(student* OR pupil*) AND nurs*]
I (Intervention or Exposure or Index Test)	Virtual reality	"Virtual Reality"[Mesh]	Reality, Virtual Virtual Reality, Educational Educational Virtual Realities Educational Virtual Reality Reality, Educational Virtual Virtual Realities, Educational Virtual Reality, Instructional Instructional Virtual Realities Instructional Virtual Reality Realities, Instructional Virtual Reality, Instructional Virtual Virtual Realities, Instructional	Virtual reality/	[(educational OR instructional) AND virtual realit*]
	Augmented reality Mixed reality	"Augmented Reality"[Mesh]	Augmented Realities Realities, Augmented Reality, Augmented Mixed Reality Mixed Realities Realities, Mixed Reality, Mixed	Augmented reality/	(augmented OR mixed) AND realit*
	Extended reality	–		–	Extended realit*
	Metaverse	–		–	Metaverse OR meta-verse
C (Comparators, Comparisons, Controls)	None or usual				
O (Outcomes, Effects)	Competency	"Competency-Based Education" [Mesh]	Competency-based education education, competency-based competency-based educations education, competency-based educations, competency-based	–	

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TABLE 1 (Continued)

PICO	Key terms	MeSH	PubMed Entry Terms	EMTREE (EMBASE)	Text words
		"Clinical Competence"[Mesh]	competency, clinical competence, clinical clinical competency clinical competencies competencies, clinical clinical skill skill, clinical skills, clinical clinical skills	clinical competence/	Clinical compete*
Study Design	RCT, Quasi-experimental	"Controlled Clinical Trials as Topic"[Mesh]	Clinical Trials, Controlled as Topic	Controlled clinical trial (topic)/OR Controlled Clinical Trials as Topic. mp.	
Restrictions	English, Korean/Humans (Adult: 19+ years), (Young Adult 19–24 years) Male, Female/1900.01.01–2024.03.31				

problem-solving, confidence, satisfaction, and other variables, which were concurrently measured. If multiple measurements were conducted post-intervention, the first measurement was used to calculate the effect size. Only studies presenting subject numbers, means, and standard deviations in the results were selected for precise effect-size calculation. The study designs included randomized controlled trials (RCTs) and quasi-experimental studies. Exclusion criteria included studies encompassing students from majors other than nursing, interventions using conventional simulation-learning methods instead of VRS, the absence of nursing competency as an outcome variable, studies not reported in Korean or English, studies with inaccessible original texts, and single-group studies lacking a control group.

2.3 Data extraction

Two researchers, Cho, M.-K. and Kim, M.Y., independently conducted searches and selected studies for analysis based on the predefined inclusion and exclusion criteria. The selected studies were extracted, incorporating information such as author, year of publication, country, publication language, number of schools, institutional review board (IRB) approval, funding details, number of participants, study design, intervention characteristics (type, facilitator, duration, session, time/session, pre-briefing, debriefing, other activities, outcome measurement time, and measurement method), quality assessment score, and dependent variables. This information was meticulously recorded in a coding book created using the Microsoft Excel spreadsheet software. Any disparities in coding were addressed by revisiting the original text to ascertain and input the final coding values (Table 2).

2.4 Quality assessment

The quality assessment of selected articles was independently performed by Cho, M.-K. and Kim, M.Y. using the Joanna Briggs Institute (JBI) Checklist for RCTs and the Checklist for Quasi-Experimental Studies. Five RCTs were assessed using the 13-question JBI Checklist; the average score was 8.40, and all five studies lacked clear reporting on "Q2. Was allocation to treatment groups concealed?" and "Q4. Were participants blind to treatment assignment?" Quasi-experimental studies comprised eight articles, and on evaluation using the 9-item JBI Checklist for Quasi-Experimental Studies (32), the average score was 8.50, with generally well-reported items (Table 3).

2.5 Statistical analyses

MIX 2.0 Pro (Ver. 2.0.1.6, BiostatXL, 2017) was used to calculate and merge effect sizes for both the primary outcome of nursing competency and secondary outcomes. The overall effect was determined using a random-effects model, considering between-subject variability and heterogeneity between studies. Hedge's g was employed for effect-size calculation, and significance was assessed using 95% confidence intervals (CIs), Z tests, and p-values. The weight of each effect size was determined using the inverse of variance (33).

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TABLE 2 Descriptive summary of the included studies.

Study ID	Author (Year)	Country	Center	IRB	Fund	Research design	Participants	Intervention type	Program facilitator	Intervention duration	Intervention session	Intervention time/ session	Outcome measurement time	outcome variable	Pre-briefing	Debriefing	Non-simulation activities	Quality score
1	Lee (12)	Korea	1	Yes	Yes	Quasi	40 Senior nursing students from a nursing college (E: 20, C:20)	Virtual reality simulation (VRS)	Researcher	None reported	None reported	80 min	Delayed (3 days after interventions for each team)	-Knowledge -Performance confidence -Clinical practice competency	Yes	Yes	None	8
2	Ahn and Lee (13)	Korea	2	Yes	No	Quasi	84 Nursing students (E: 44, C: 40)	Virtual reality simulation (VRS)	Nursing faculty	1 day	1 session	35–50 min	Immediately	-Knowledge -Confidence -Self-efficacy -Clinical competency	Yes	Yes	None	8
3	Rossler et al. (14)	USA	1	Yes	Yes	RCT	20 Prelicensure baccalaureate nursing students (E: 5, C: 15)	Virtual reality simulation (VRS)	Investigator	None reported	None reported	None reported	Delayed (1 week)	-Knowledge of OR fire safety -Transfer of knowledge of OR fire safety skills	Yes	None	None	4
4	Aebersold et al. (15)	USA	1	Yes	Yes	RCT	69 Sophomore and junior nursing students (E: 35, C: 34)	Virtual reality simulation (VRS)	None reported	Over 4 weeks	None reported	None reported	Immediately	-Skill competency evaluation	Yes	Yes	None	8
5	An et al. (16)	Korea	2	Yes	No	RCT	62 First- and second-year nursing students (E: 31, C:31)	Virtual reality simulation (VRS)	Researcher	4 weeks	None reported	None reported	Immediately	- Self-regulated learning competency - Perceived learning competency - Knowledge - Learning flow - Academic stress	Yes	None	None	11

(Continued)

TABLE 2 (Continued)

Study ID	Author (Year)	Country	Center	IRB	Fund	Research design	Participants	Intervention type	Program facilitator	Intervention duration	Intervention session	Intervention time/ session	Outcome measurement time	outcome variable	Pre-briefing	Debriefing	Non-simulation activities	Quality score
6	Chang et al. (17)	Taiwan	1	No	Yes	Quasi	42 Two classes at a nursing university (E: 21, C:21)	Virtual reality simulation (VRS)	Nursing faculty	3 weeks	None reported	None reported	Immediately	- OSCE competency - Problem-solving skills - Learning engagement - Learning satisfaction	None	None	None	6
7	Ahn (11)	Korea	1	Yes	No	Quasi	72 second-year nursing students (E: 34, C:38)	Metaverse based simulation	Nursing faculty	None reported	1 session each	25–35 min	Immediately	- Knowledge of core nursing skills - Confidence in core nursing skill performance -Clinical competency	Yes	Yes	None	8
8	Kim and Jung (18)	Korea	1	Yes	No	RCT	73 First- and second-year nursing students (E: 37, C:36)	Virtual reality simulation (VRS)	Researcher	None reported	None reported	30 min	Immediately	-Clinical competency -Self-efficacy -Satisfaction	Yes	None	None	9
9	Ha et al. (19)	Korea	1	No	No	RCT	70 Third-year nursing students (E: 35, C: 35)	Virtual reality simulation (VRS)	Researcher	None reported	None reported	2 h	Immediately	-Clinical competency -Self-efficacy -Nursing skill competency -Satisfaction	None	None	None	10
10	Yoo and Yang (20)	Korea	1	Yes	No	Quasi	48 Second-year nursing students (E: 24, C: 24)	Virtual reality simulation (VRS)	Researcher	5 weeks	5 sessions	20–30 min/ once	Immediately	- Clinical competency - Problem-solving skills - Confidence in core nursing skill performance	Yes	Yes	None	7

(Continued)

TABLE 2 (Continued)

Study ID	Author (Year)	Country	Center	IRB	Fund	Research design	Participants	Intervention type	Program facilitator	Intervention duration	Intervention session	Intervention time/ session	Outcome measurement time	outcome variable	Pre-briefing	Debriefing	Non-simulation activities	Quality score
11	Bae and Shin (21)	Korea	1	Yes	No	Quasi	45 Fourth-year nursing student (E: 24, C: 21)	Virtual reality simulation (VRS)	Researcher	None reported	None reported	35 min	Immediately	- Clinical performance competency - Problem-solving skill - Confidence in performance	Yes	Yes	None	8
12	Song (22)	Korea	1	No	No	Quasi	117 Third-year nursing student (E: 58, C: 59)	Virtual reality simulation (VRS)	Nursing faculty	10 days	10 sessions	8 h/day	Immediately	-Competencies of socio-emotion - Psychiatric nursing competency - Learning self-efficacy - Transition synchronization -Social distance	None	None	Yes	7
13	Raman et al. (23)	Oman	1	Yes	Yes	Quasi	74 Fourth-year nursing student (E: 34, C: 40)	Virtual reality simulation (VRS)	Nursing faculty	34 h of HFS + 101 h of TCT	None reported	None reported	Immediately	-Clinical competencies -Knowledge levels among nursing students	Yes	Yes	None	8
14	Cho et al. (24)	Korea	1	Yes	Yes	Quasi	69 Senior nursing students (E: 36, C: 33)	Metaverse-based simulation	Researcher	1 day	None reported	1 h	Immediately	-Competency -Self-efficacy -Learning realism -Learning satisfaction	Yes	Yes	Yes	9
15	Lee and Baek (25)	Korea	1	Yes	No	Quasi	44 Third-year nursing students (E: 22, C: 22)	Virtual reality simulation (VRS)	Researcher	2 weeks	None reported	2 h of VRS + 4 h of HFS	Immediately	-Performance confidence -Clinical decision-making ability	Yes	Yes	None	9

(Continued)

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TABLE 2 (Continued)

Study ID	Author (Year)	Country	Center	IRB	Fund	Research design	Participants	Intervention type	Program facilitator	Intervention duration	Intervention session	Intervention time/ session	Outcome measurement time	outcome variable	Pre-briefing	Debriefing	Non-simulation activities	Quality score
16	Kim and Heo (26)	Korea	2	Yes	Yes	Quasi	63 Sophomore nursing students (E: 33, C: 30)	Augmented reality	Researcher	2 weeks	2 sessions	2 h	Immediately	-Learning satisfaction -Skill competency -Confidence in medication safety	Yes	None	None	8
17	Park and Yoon (27)	Korea	1	Yes	No	Quasi	44 Second-year students (E: 22, C: 22)	Virtual reality simulation (VRS)	Researcher	3 weeks	3 sessions	30 min	Immediately	-Nursing skills -Performance confidence -Learning satisfaction	Yes	None	None	9
18	Sahin Karaduman and Basak (28)	Turkey	1	Yes	No	RCT	126 Third-year nursing students (E1: 42, E2: 42, C: 42)	Virtual patient simulations	Researcher	None reported	2 sessions	15 min	Immediately	-Nursing anxiety -Self-confidence -Learning evaluation -Performance	Yes	Yes	None	10
19	Moon (29)	Korea	1	Yes	Yes	Quasi	72 Third-year nursing students (E: 34, C: 38)	Metaverse based program	Nursing faculty	1 day	1 session	3 h	Immediately	-Clinical competency -Problem solving efficacy -Learning satisfaction	Yes	No	Yes	8
20	Lee (30)	Korea	1	Yes	No	Quasi	48 Senior nursing students (E: 24, C: 24)	Virtual reality simulation (VRS)	Nursing faculty	None reported	None reported	3 h	Immediately	-Critical thinking disposition -Clinical competency -Self-efficacy	Yes	Yes	No	8

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TABLE 2 (Continued)

Study ID	Author (Year)	Country	Center	IRB	Fund	Research design	Participants	Intervention type	Program facilitator	Intervention duration	Intervention session	Intervention time/session	Outcome measurement time	outcome variable	Pre-briefing	Debriefing	Non-simulation activities	Quality score
21	Ahn (31)	Korea	1	Yes	No	Quasi	70 Nursing students (E: 34, C: 36)	Metaverse based training	Nursing faculty	1 day	1 session	10–15 min	Immediately	-Performance confidence -Performance ability	Yes	Yes	No	7

IRB, Institutional Review Board; USA, United States of America; E, experimental group; C, control group; RCT, randomized controlled trial; Quasi, quasi-experimental study; HFS, high fidelity simulation. TCT, traditional clinical training; OSCE, objective structured clinical examination; OR, operating room.

Heterogeneity was evaluated using Higgin's I^2 (34), with an I^2 of >50% indicating heterogeneity (35). Subgroup analysis, meta-regression, and exclusion-sensitivity analysis were conducted for nursing competency to identify factors contributing to heterogeneity. Publication bias was examined using funnel plots, trim-and-fill plots, Begg's test, Egger's regression, and the trim-and-fill method to correct for the overall effect (36).

3 Results

3.1 Characteristics of the included studies

A total of 579 articles were initially identified from 9 databases following the search strategy. After excluding duplicates, 373 articles were extracted. Following the application of the inclusion and exclusion criteria, 21 research articles were ultimately selected. The research by Sahin Karaduman and Basak (28) was designed using two experimental groups and was analyzed as two separate studies, resulting in 22 studies being analyzed (Figure 1). Of these, six studies were published before 2022; three were conducted in the United States (USA), twelve studies were published in English; nineteen were conducted at a single university; nineteen and nine studies had IRB approval and funding, respectively. The study designs included seven RCTs, fifteen quasi-experimental studies, and eight studies with fewer than 60 participants. Interventions comprised 18 VR/AR simulations and four metaverse. Eight studies had a professor as a facilitator, four had an intervention duration of more than 4 weeks, two had four or more intervention sessions, eight had an intervention time of more than 1 h per session, 19 had a pre-briefing, and nine had a debriefing. Dependent-variable measurements were taken immediately after the intervention in 20 studies, the measurement method was observational measurement in 12 studies, 19 studies had no additional activities, such as reflection, besides the simulation, and 14 studies had an above-average quality assessment score (Table 2).

3.2 Effect of VRS-based intervention on nursing competency

The overall effect of nursing competency, as the primary outcome for the 22 VRSs, was found to be Hedge's $g = 0.88$ (95% CI: 0.47 to 1.29). This was interpreted as a large effect based on the criteria provided by Brydges (37) for interpreting effect sizes (Figure 2). The high degree of heterogeneity among the studies, indicated by Higgins's I^2 of 91.8% in the heterogeneity test, prompted subgroup and meta-regression analyses to explore factors contributing to this heterogeneity.

In subgroup analyses, the characteristics of studies significantly associated with improvements in nursing competency IRB-approved studies (Hedge's $g = 1.02$, 95% CI: 0.57, 1.48); interventions with a duration not reported or those with a duration of less than 4 weeks (Hedge's $g = 1.05$, 95% CI: 0.56, 1.53); interventions with sessions not reported or those with less than 4 sessions (Hedge's $g = 0.95$, 95% CI: 0.50, 1.39); those with outcome measurement immediately after the intervention (Hedge's $g = 0.93$, 95% CI: 0.50, 1.37); those with pre-briefing before the simulation (Hedge's $g = 0.71$, 95% CI: 0.23, 1.20); those with debriefing after the simulation (Hedge's $g = 1.02$, 95%

TABLE 3 Quality assessment of the included studies.

Study ID	Joanna Briggs Institute of Critical Appraisal Tools Checklist for checklist for randomized controlled trials													Total score
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	
3	0	0	0	0	0	1	0	1	0	1	1	0	0	4
4	0	0	1	0	1	1	1	1	1	1	1	0	0	8
5	1	0	1	0	1	1	1	1	1	1	1	1	1	11
8	1	0	1	0	0	1	0	1	1	1	1	1	1	9
9	1	0	1	0	0	1	1	1	1	1	1	1	1	10
18	1	0	1	0	1	0	1	1	1	1	1	1	1	10
Total	4	0	5	0	3	5	4	6	5	6	6	4	4	8.67

Study ID	Joanna Briggs Institute of Critical Appraisal Tools Checklist for quasi-experimental study									Total score
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	
1	1	1	1	1	1	1	1	1	1	9
2	1	1	1	1	1	1	1	1	1	9
6	1	1	1	1	1	0	1	1	0	7
7	1	1	1	1	1	1	1	1	1	9
10	1	1	1	1	1	0	1	1	1	8
11	1	1	1	1	1	1	1	1	1	9
12	1	1	1	0	1	1	1	1	1	8
13	1	1	1	1	1	1	1	1	1	9
14	1	1	1	1	1	1	1	1	1	9
15	1	1	1	1	1	1	1	1	1	9
16	1	1	1	1	1	0	1	1	1	8
17	1	1	1	1	1	1	1	1	1	9
19	1	1	1	1	0	1	1	1	1	8
20	1	1	1	1	0	1	1	1	1	8
21	1	0	1	1	0	1	1	1	1	7
Total	15	14	15	14	12	12	15	15	14	8.40

CI: 0.57, 1.48); and those with no other activities besides the simulation, such as keeping a reflective journal (Hedge's $g = 1.03$, 95% CI: 0.55, 1.50). Publication year, Country, publication language, number of schools, funding status, research design, number of participants, intervention type, facilitator, intervention time per session, measurement method, debriefing, and quality assessment score also showed statistically significant effect sizes (Table 4).

Univariate meta-regression identified factors influencing the overall effect. Publication year after 2022 ($Z = 2.68$, $p = 0.007$); having an IRB ($Z = 5.17$, $p < 0.001$); having an fund ($Z = -2.61$, $p = 0.009$); RCT ($Z = 2.02$, $p = 0.044$); intervention duration over than 4 weeks ($Z = -3.33$, $p < 0.001$); intervention session over than 4 sessions ($Z = -3.01$, $p < 0.001$); intervention time/session over than 1 h ($Z = -5.20$, $p < 0.001$); observational measurement rather than self-reporting ($Z = 3.21$, $p = 0.001$); having a pre-briefing before the simulation ($Z = 3.76$, $p < 0.001$); having a debriefing after the simulation ($Z = -4.41$, $p < 0.001$); and having other activities besides the simulation ($Z = -4.41$, $p < 0.001$) had statistically significant effects on nursing competency (Table 5).

The exclusion-sensitivity test (38), excluding one study at a time, showed Hedge's g ranging from 0.67 to 0.94, indicating a moderate to large effect size. The 95% CI (0.36 ~ 0.53, 0.98 ~ 1.36) did not include 0, signifying statistical significance. The effect sizes from the exclusion-sensitivity test were not significantly different from Hedge's $g = 0.88$, which included all 22 studies (Table 6).

3.3 Effect of intervention program on secondary outcomes

The secondary outcomes in this study included knowledge, self-efficacy, problem-solving, confidence, and satisfaction. Among these, knowledge, self-efficacy, confidence, and satisfaction exhibited statistically significant changes. After VRS, knowledge and self-efficacy showed significant increases, with moderate effect sizes of Hedge's $g = 0.60$ (95% CI: 0.07, 1.14) and Hedge's $g = 0.53$ (95% CI: 0.09, 0.97), respectively. Confidence and satisfaction exhibited substantial increases, with large effect sizes of Hedge's g = 1.02 (95%

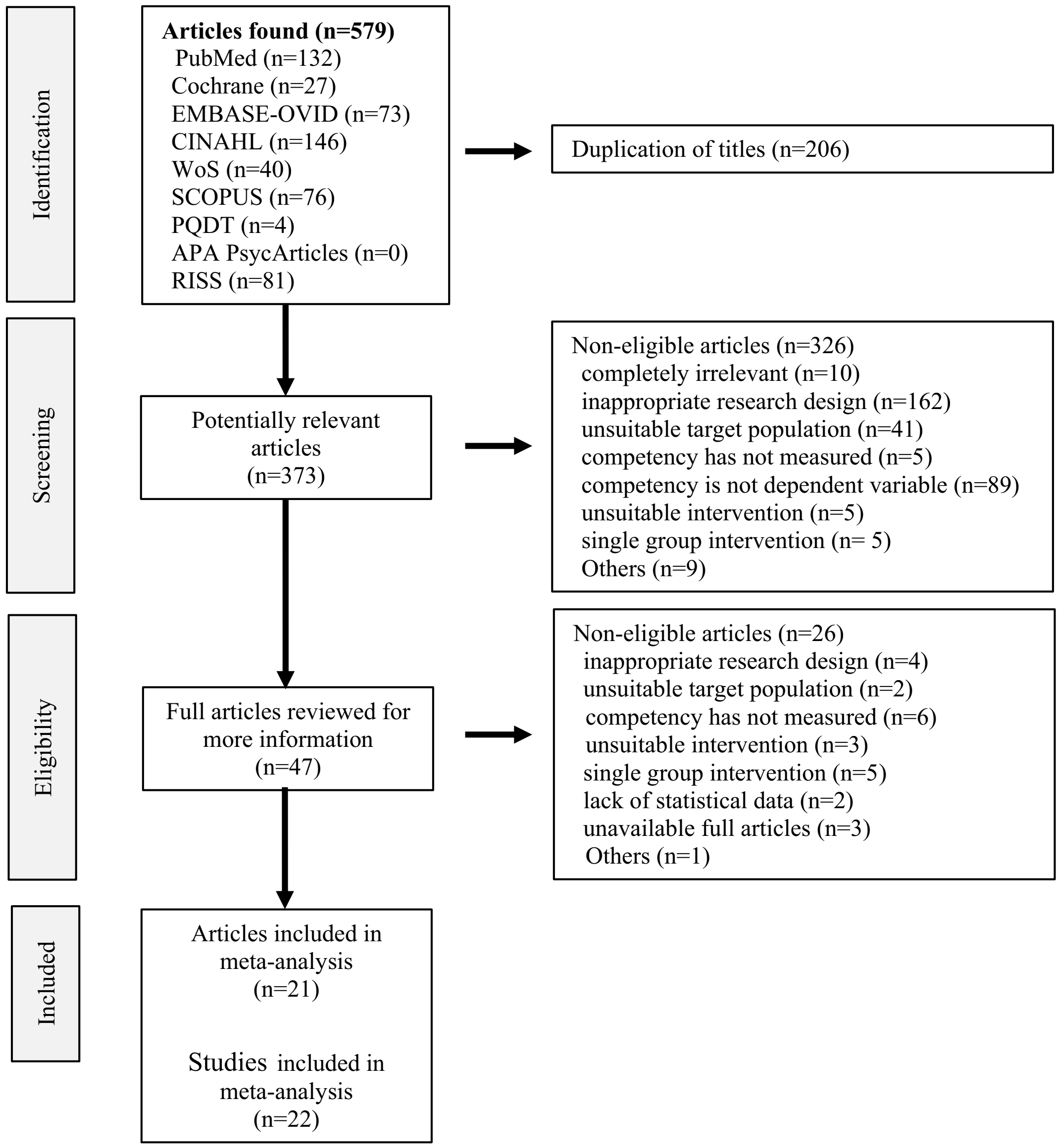


FIGURE 1
PRISMA flow diagram. An article by Sahin Karaduman and Basak (28), designed using two experimental groups, was divided into two studies.

CI: 0.48, 1.57) and Hedge's $g = 1.35$ (95% CI: 0.43, 2.28), respectively (Table 7).

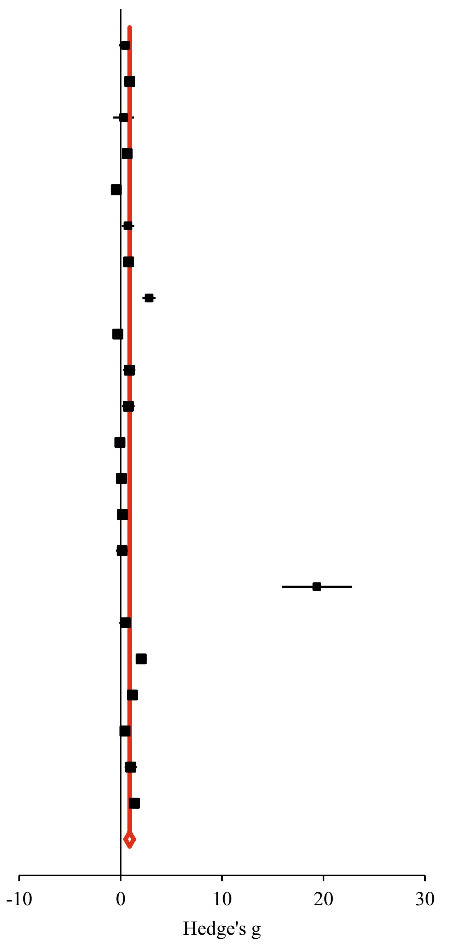
3.4 Publication bias

To evaluate publication bias, funnel-plot and trim-and-fill plot analyses were conducted. Represented by the black circle, the individual effect sizes of the 22 studies included in the study were asymmetrical— slightly skewed to the right—indicating some potential publication bias (Figure 3). The trim-and-fill plot suggested the addition of one study, represented by the white circle, skewing to the left (Figure 4). Further analysis, The coefficient of the bias was 8.58, indicating the initial value (intercept) and the p-value was 0.001. Thus, the null hypothesis was rejected, and the existence of a publication bias could be confirmed. Unlike Egger's regression test result, Begg's test for rank correlation (Tau $b = 0.27$, ties = 0; $Z = 1.75$, $p = 0.080$) confirmed the absence of publication bias. Moreover, the trim-and-fill method suggested adding one article; the effect size of the 23 corrected articles was 0.60 (95% CI: 0.49, 0.72). Although the effect size of nursing competency was somewhat smaller after correction than before, it remained statistically significant. In conclusion, this study was deemed free of publication bias (Table 8).

4 Discussion

In this study, the impact of simulation-based programs on nursing competency demonstrated a significant effect size of 0.88. It's notable that this simulation-based program yielded encouraging results by positively enhancing nursing competency. This is consistent with similar improvements observed in self-efficacy, a factor linked to nursing competency (19), enhanced knowledge, educational

Id	N	ES	95% CI Lower limit	95% CI Upper limit	Z	p	w
1	40	0.48	-0.15	1.11	1.49	0.136	4.6%
2	84	0.90	0.45	1.35	3.91	<0.001	4.9%
3	20	0.29	-0.73	1.30	0.55	0.582	3.9%
4	69	0.64	0.16	1.13	2.60	0.009	4.8%
5	62	-0.44	-0.95	0.06	-1.72	0.086	4.8%
6	42	0.72	0.10	1.35	2.26	0.024	4.6%
7	72	0.79	0.31	1.27	3.22	0.001	4.8%
8	73	2.79	2.15	3.44	8.43	<0.001	4.6%
9	70	-0.28	-0.75	0.19	-1.16	0.248	4.8%
10	48	0.86	0.27	1.45	2.85	0.004	4.7%
11	45	0.76	0.15	1.37	2.46	0.014	4.6%
12	117	-0.07	-0.44	0.29	-0.40	0.692	5.0%
13	74	0.08	-0.38	0.54	0.34	0.737	4.9%
14	69	0.18	-0.29	0.65	0.75	0.454	4.8%
15	44	0.15	-0.44	0.74	0.49	0.626	4.7%
16	63	19.35	15.88	22.82	10.93	<0.001	1.1%
17	44	0.47	-0.13	1.07	1.55	0.122	4.7%
18[a]	84	2.02	1.49	2.55	7.50	<0.001	4.8%
18[b]	84	1.16	0.70	1.63	4.93	<0.001	4.8%
19	72	0.43	-0.04	0.90	1.80	0.072	4.8%
20	48	0.99	0.39	1.59	3.23	0.001	4.7%
21	70	1.36	0.84	1.88	5.10	<0.001	4.8%
Total	1352*	0.88	0.47	1.29	4.23	<0.001	100%



Heterogeneity: Q = 257.11, Q-df = 234.11 ($p < 0.001$);
I^2 = 91.8% (95% CI: 89.0~94.0%)
Overall effect: Z = 4.23 (p <0.001)

FIGURE 2
The effect of virtual reality simulation-based intervention on nursing competency. ES, effect size; CI, confidence interval. An article by Sahin Karaduman and Basak (29), designed using two experimental groups, was divided into two studies (18[a] and 18[b]). *Removal of the number of duplicate subjects in the 18th study.

satisfaction, and academic achievement through VR in a hospital environment (39); and improved nursing-process performance (40), heightened critical thinking, clinical performance, and practice satisfaction through vSim for Nursing (41). Additionally, these results partially correlate with those in a study indicating that hands-on training utilizing scenario-based admission management in VR increased learning immersion, learner confidence, and learning satisfaction (7).

In the meta-regression analysis evaluating nursing competency, several factors emerged as influential. First, in cases where the publication year was 2022 or later, nursing competency was found to be significantly improved compared to studies that received IRB approval, compared to studies published before then. In the evolving landscape of clinical practice, recent emphasis on patient safety and rights has shifted the focus toward observing nursing behavior rather than direct patient care (42). This shift underscores the active implementation of simulation-based education, suggesting a more systematic adaptation of teaching methods and educational systems to enhance nursing competency compared to previous approaches. Moreover, studies with an intervention duration not reported or one of less than 4 weeks demonstrated a significant effect on nursing competency compared to those lasting more than 4 weeks. In cases of intervention with fewer than four sessions, competency was significantly improved compared to intervention sessions with four or more sessions. Similarly, interventions with time per session not reported or those lasting less than 1 h were associated with a significant improvement in nursing competency compared to those lasting more than 1 h. These findings suggest that shorter, more intensive

TABLE 4 Subgroup analysis of nursing competency according to study characteristics.

Variables	Category	*K*	Study ID	*N*	ES	95% CI		*Z*	*p*-value
						Lower limit	Upper limit		
Year	2018 ~ 2021	6	2, 3, 4, 10, 12, 13	412	0.44	0.06	0.82	2.29	0.022
	≥2022	16	1, 5, 6, 7, 8, 9, 11, 14, 15, 16, 17, 18[a], 18[b], 19, 20, 21	940	1.12	0.56	1.68	3.93	<0.001
Country	Beyond the USA	19	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18[a],18[b], 19, 20, 21	1,219	0.96	0.50	1.43	4.08	<0.001
	USA	3	3, 4, 17	133	0.54	0.19	0.89	3.00	0.003
Language	Korean	10	2, 7, 8, 9, 10, 11, 12, 16, 19, 21	714	1.49	0.70	2.28	3.68	<0.001
	English	12	1, 3, 4, 5, 6, 13, 14, 15, 17, 18[a], 18[b], 20	638	0.57	0.18	0.95	2.91	0.004
School	1	19	1, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18[a], 18[b], 19, 20, 21	1,143	0.72	0.40	1.05	4.36	<0.001
	2	3	2, 5, 16	209	5.23	1.98	8.48	3.15	0.002
IRB	No	3	6, 9, 12	229	0.08	−0.42	0.58	0.30	0.764
	Yes	19	1, 2, 3, 4, 5, 7, 8, 10, 11, 13, 14, 15, 16, 17, 18[a], 18[b], 19, 20, 21	1,123	1.02	0.57	1.48	4.39	<0.001
Fund	No	13	2, 5, 7, 8, 9, 10, 11, 12, 17, 18[a], 18[b], 20, 21	859	0.86	0.39	1.32	3.61	<0.001
	Yes	9	1, 3, 4, 6, 13, 14, 15, 16, 19	493	1.07	0.28	1.87	2.66	0.008
Research design	Quasi-E	15	1, 2, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 19, 20, 21	932	0.85	0.38	1.31	3.59	<0.001
	RCT	7	3, 4, 5, 8, 9, 18[a],18[b]	420	0.89	0.03	1.75	2.02	0.044
Participants	< 60	8	1, 3, 6, 10, 11, 15, 17, 20	331	0.62	0.39	0.84	5.40	<0.001
	≥ 60	14	2, 4, 5, 7, 8, 9, 12, 13, 14, 16, 18[a], 18[b], 19, 21	1,021	1.13	0.53	1.72	3.71	<0.001
Intervention type	Metaverse	4	7, 14 19, 21	283	0.68	0.20	1.17	2.75	0.006
	AR/VR	18	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 15, 16, 17, 18[a], 18[b], 20	1,069	0.97	0.47	1.47	3.78	<0.001
Facilitator	Researcher	14	1, 3, 4, 5, 8, 9, 10, 11, 14, 15, 16, 17, 18[a], 18[b]	773	1.16	0.50	1.82	3.46	0.001
	Nursing faculty	8	2, 6, 7, 12, 13, 19, 20, 21	579	0.63	0.27	0.98	3.45	0.001
Intervention duration	Not reported or < 4 weeks	18	1, 2, 3, 6, 7, 8, 9, 11, 12, 14, 15, 16, 17, 18[a],18[b], 19, 20, 21	1,099	1.05	0.56	1.53	4.24	<0.001
	≥ 4 weeks	4	4, 5, 10, 13	253	0.27	−0.28	0.83	0.97	0.333
Intervention session	Not reported or < 4sessions	20	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 16, 17, 18[a],18[b], 19, 20, 21	1,187	0.95	0.50	1.39	4.17	<0.001
	≥ 4sessions	2	10, 12	165	0.36	−0.55	1.28	0.78	0.436
Intervention time/session	Not reported or < 1 h	14	2, 3, 4, 5, 6, 7, 8, 10, 11, 13, 17, 18[a], 18[b], 21	829	0.89	0.49	1.29	4.34	<0.001
	≥ 1 h	8	1, 9, 12, 14, 15, 16, 19, 20	523	1.08	0.22	1.93	2.47	0.013
Outcome measurement time	Immediately	20	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18[a], 18[b], 19, 20, 21	1,292	0.93	0.50	1.37	4.19	<0.001
	Delayed	2	1, 3	60	0.43	−0.11	0.96	1.56	0.119
Measurement method	Self-report	10	2, 5, 7, 10, 12, 14, 15, 19, 20, 21	686	0.50	0.16	0.85	2.84	0.005

(Continued)

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TABLE 4 (Continued)

Variables	Category	*K*	Study ID	*N*	ES	95% CI Lower limit	95% CI Upper limit	*Z*	*p*-value
	Observation	12	1, 3, 4, 6, 8, 9, 11, 13, 16, 17, 18[a], 18[b]	666	1.41	0.66	2.15	3.69	<0.001
Pre-briefing	No	3	6, 9, 12	229	0.08	−0.42	0.58	0.30	0.764
	Yes	19	1, 2, 3, 4, 5, 7, 8, 10, 11, 13, 14, 15, 16, 17, 18[a], 18[b], 19, 20, 21	1,123	1.02	0.57	1.48	4.39	<0.001
Debriefing	No	9	3, 5, 6, 8, 9, 12, 16, 17, 19	563	1.39	0.42	2.35	2.81	0.005
	Yes	13	1, 2, 4, 7, 10, 11, 13, 14, 15, 18[a], 18[b], 20, 21	789	0.80	0.50	1.09	5.29	<0.001
Other activities	No	19	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15, 16, 17, 18[a], 18[b], 20, 21	1,094	1.03	0.55	1.50	4.25	<0.001
	Yes	3	12, 14, 19	258	0.15	−0.15	0.44	0.98	0.326
Quality score	< Mean	8	3, 6, 10, 12, 16, 19, 20, 21	480	1.58	0.63	2.54	3.25	0.001
	≥ Mean	14	1, 2, 4, 5, 7, 8, 9, 11, 13, 14, 15, 17, 18[a], 18[b]	872	0.68	0.26	1.11	3.19	0.001

K, number of analysis sets; N, number of participants; ES, effect size; CI, confidence interval; IRB, institutional review board; Quasi-E, quasi-experimental study; RCT, randomized controlled trial; AR/VR, augmented reality/virtual reality.

interventions may be more effective in enhancing nursing competency through VRS. Establishing short-term intensive courses could thus be a meaningful approach. Even in the case of pre-briefings, which are recognized for their utility, the introduction and assignment of roles and expectations during pre-briefings may not be optimal. This is because simulation anxiety is linked to higher levels of extraneous cognitive load (43). Further investigation into the timing and temporal aspects of these activities is warranted to optimize their effectiveness. Therefore, further research specifically focusing on the temporal aspect is deemed necessary to comprehensively understand its implications.

Furthermore, pre-briefing before simulation emerged as a significant factor contributing to the improvement of nursing competency compared to that in the control group. This is consistent with the recognized importance of pre-briefing in face-to-face simulations, in which it influences simulation readiness (44). Given that most included studies conducted virtual pre-briefing activities individually, such as pre-briefing lessons and quizzes, the findings imply that virtual pre-briefing can be actively utilized with comparable effectiveness in face-to-face simulations. Various pre-briefing methods, including role rubrics, are currently under development (45). Further research will be necessary to ascertain the effectiveness of these diverse pre-briefing approaches.

Moreover, this study identified that post-simulation debriefing had a more significant effect of improving nursing competency compared to non-simulation debriefing. This could be attributed to the characteristic of VRS that enables repeated and reflective learning through debriefing with immediate feedback, thus providing learner-customized learning (46). The ability to facilitate individual improvement in nursing competency through immediate feedback is consistent with previous studies emphasizing the effectiveness and importance of debriefing in simulation (47). While debriefing in a virtual setting may differ from team interaction, reflection, and discussion in a face-to-face simulation, the results underscore the crucial role of debriefing in VRS situations.

Competency improved significantly when observation was measured rather than self-report. Role assignment in nursing simulation often elicits significant anxiety stemming from uncertainty, performing in front of faculty and peers, and social evaluation (45). Moreover, many individuals perceive themselves as lacking proficiency, particularly in terms of nursing competency. Consequently, self-reported improvements in nursing competency may underestimate actual progress observed through objective evaluation. Hence, effective communication and encouragement regarding the significance of simulation are vital when implementing simulation programs.

Nursing competency was statistically significantly improved when compared to those who did not engage in any other activities other than simulation. Other activities take as much time, which suggests that core simulation activities are important for improving nursing competency. Non-simulation activities, denoting the absence of activities other than simulation, exhibited a significant effect on nursing competency. While non-simulation activities may improve competencies such as team cooperation, communication, or empathy, they were not associated with improvements in nursing competency. This suggests that clear simulation content, along with pre-briefing and debriefing activities tailored to enhance nursing competency, directly influence this competency.

TABLE 5 Meta-regression analysis to evaluate competency.

Covariates (Ref.)	Estimate	SE	95% CI		Z	p-value
			Lower limit	Upper limit		
Year (Ref.: 2018 ~ 2021)	0.10	0.04	0.03	0.18	2.68	0.007
Country (Ref.: Beyond USA)	−0.09	0.19	−0.46	0.28	−0.48	0.631
Language (Ref.: Korean)	−0.12	0.12	−0.35	0.11	−1.03	0.303
School (Ref.: 1)	−0.16	0.18	−0.52	0.19	−0.89	0.376
IRB (Ref.: No)	0.76	0.15	0.47	1.05	5.17	< 0.001
Fund (Ref.: No)	−0.32	0.12	−0.56	−0.08	−2.61	0.009
Research design (Ref.: Quasi-E)	0.25	0.12	0.01	0. 50	2.02	0.044
Participants (Ref.: < 60)	0.01	0.13	−0.25	0.27	0.07	0.945
Intervention type (Ref.: Metaverse)	−0.04	0.14	−0.32	0.23	−0.31	0.756
Facilitator (Ref.: Researcher)	−0.14	0.12	−0.37	0.09	−1.21	0.225
Intervention duration (Ref.: Not reported or <4 weeks)	−0.48	0.14	−0.76	−0.20	−3.33	< 0.001
Intervention session (Ref.: Not reported or <4sessions)	−0.51	0.17	−0.84	−0.18	−3.01	< 0.001
Intervention time/session (Ref.: Not reported or <1 h)	−0.62	0.12	−0.85	−0.39	−5.20	< 0.001
Outcome measurement time (Ref.: Immediately)	−0.21	0.28	−0.75	0.34	−0.74	0.460
Measurement method (Ref.: Self-report)	0.37	0.12	0.15	0.60	3.21	0.001
Pre-briefing (Ref.: No)	0.76	0.15	0.47	1.05	5.17	< 0.001
Debriefing (Ref.: No)	0.45	0.12	0.21	0.68	3.76	< 0.001
Other activities (Ref.: No)	−0.62	0.14	−0.90	−0.35	−4.41	< 0.001
Quality score (Ref.: < Mean)	0.02	0.12	−0.23	0.26	0.14	0.890

Ref, reference; SE, standard error; CI, confidence interval; IRB: institutional review board; Quasi-E, quasi-experimental study.

TABLE 6 Exclusion-sensitivity test of the virtual-reality simulation-based intervention.

Study ID	K	ES	95% CI		Z	p-value
			Lower limit	Upper limit		
1	21	0.91	0.48	1.33	4.18	<0.001
2	21	0.89	0.46	1.32	4.05	<0.001
3	21	0.91	0.49	1.32	4.25	<0.001
4	21	0.90	0.47	1.33	4.11	<0.001
5	21	0.94	0.53	1.36	4.47	<0.001
6	21	0.89	0.47	1.32	4.13	<0.001
7	21	0.89	0.46	1.32	4.08	<0.001
8	21	0.76	0.38	1.15	3.88	<0.001
9	21	0.94	0.52	1.36	4.40	<0.001
10	21	0.89	0.46	1.31	4.09	<0.001
11	21	0.89	0.47	1.32	4.11	<0.001
12	21	0.94	0.51	1.36	4.31	<0.001
13	21	0.93	0.50	1.35	4.27	<0.001
14	21	0.92	0.50	1.35	4.23	<0.001
15	21	0.92	0.50	1.34	4.26	<0.001
16	21	0.67	0.36	0.98	4.27	<0.001
17	21	0.91	0.48	1.33	4.18	<0.001
18	21	0.81	0.41	1.22	3.94	<0.001
19	21	0.87	0.45	1.30	4.01	<0.001
20	21	0.91	0.48	1.34	4.16	<0.001
21	21	0.88	0.46	1.30	4.07	<0.001
22	21	0.86	0.44	1.28	4.00	<0.001

K, number of analysis sets; ES, effect size; CI, confidence interval.

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TABLE 7 Effects of virtual reality simulation-based intervention on other variables.

Variables	*K*	Study ID	*N*	ES	95% CI		*Z*	*p*-value
					Lower limit	Upper limit		
Knowledge	6	1, 2, 5, 6, 7, 13	374	0.60	0.07	1.14	2.22	0.027
Self-efficacy	7	2, 8, 9, 12, 14,19, 20	533	0.53	0.09	0.97	2.34	0.019
Problem-solving	3	6, 10, 11	135	0.99	0.00	1.98	1.95	0.051
Confidence	13	1, 2, 5, 7, 9, 10, 11, 15, 16, 17, 18[a], 18[b], 21	768	1.02	0.48	1.57	3.66	<0.001
Satisfaction	7	6, 8, 9, 14, 16, 17, 19	433	1.35	0.43	2.28	2.86	0.004

K, number of analysis sets; N, number of participants; ES, effect size; CI, confidence interval.

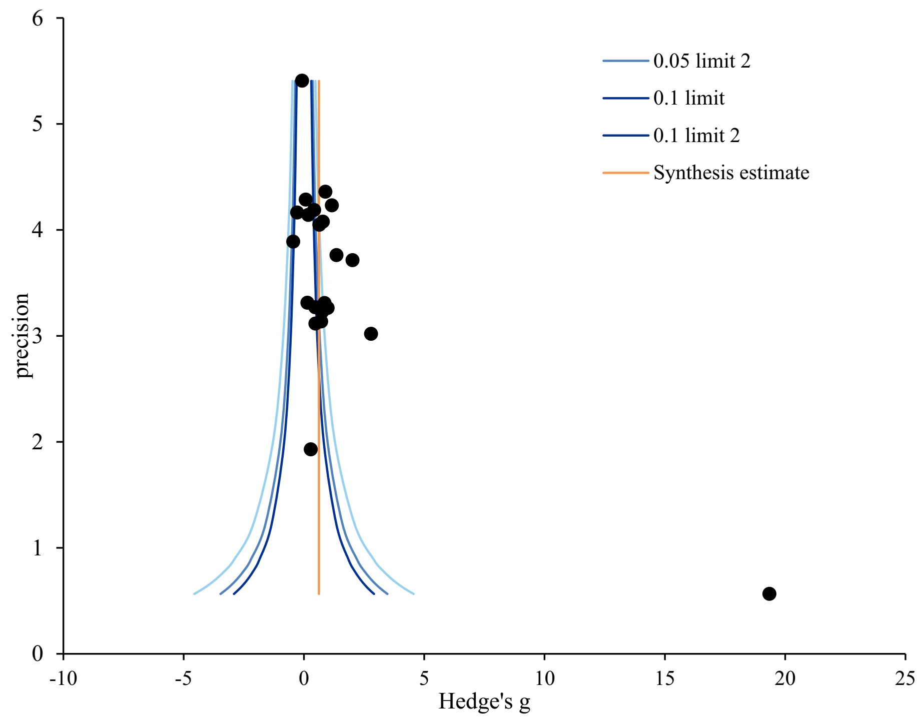

FIGURE 3
Funnel plot of virtual reality simulation-based intervention on nursing competency. Precision = 1/standard error; 0.05; limit line = 95% confidence limit.

Meanwhile, several variables did not demonstrate a statistically significant effect of improving nursing competency. The country, number of centers, funding status, research design, and all the variables related to the operation of the intervention program (participants, intervention type, facilitator, intervention session, and outcome-measurement time), as well as the quality score, did not show significant differences in improving nursing competency. The inconsistency in trends observed across these variables can be attributed to the diverse definitions and measurements of nursing competency utilized in the included studies. This variability in research outcomes underscores the absence of a standardized measurement tool for nursing competency, potentially leading to increased heterogeneity in results.

Furthermore, the secondary outcomes measured alongside nursing competency in this study included knowledge, self-efficacy, problem-solving, confidence, and satisfaction. Among these, knowledge and confidence demonstrated statistically significant improvement. These variables, particularly knowledge and confidence, are closely related to nursing competency and can concurrently improve with it in VRS. Conversely, self-efficacy, problem-solving, and satisfaction did not show significant improvement. This is consistent with previous research indicating that VR nursing education improves knowledge (48) and increases learning satisfaction (49) but does not enhance technical skills (48) or significantly impact self-efficacy (49). This suggests that while VRS is effective in improving knowledge-related competencies, consistent improvements in self-efficacy, problem-solving, and satisfaction may depend on its design and utilization.

Given that learning immersion through simulation has been demonstrated to impact the development of clinical-nursing competence (50), and VR-based programs have been effective in improving cognitive performance, such as theoretical knowledge, through realism (51), VRS holds promise in nursing education. However, the results of this study underscore the need to carefully consider elements that are more challenging to implement in virtual situations than in face-to-face scenarios. Therefore, further research,

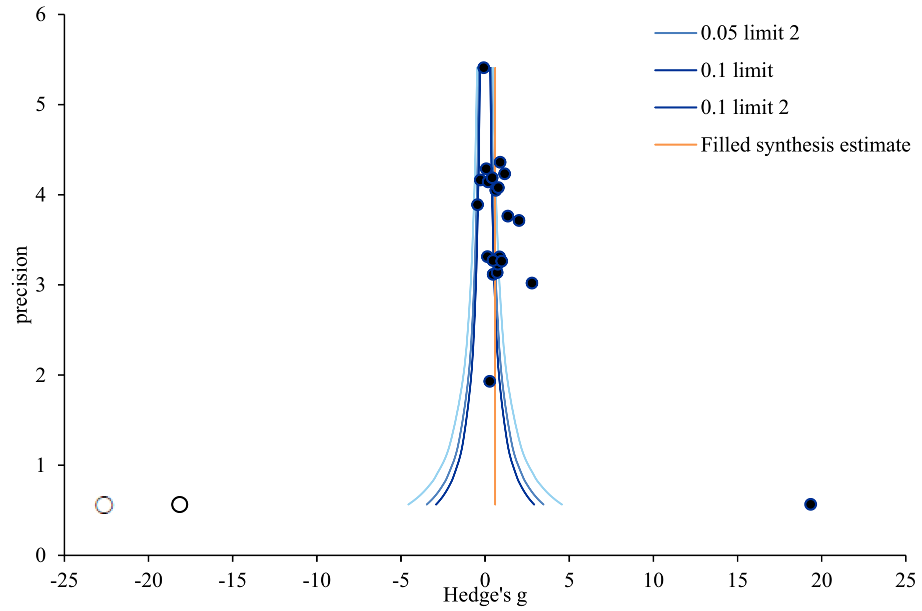

FIGURE 4
Trim and fill plot of virtual reality simulation-based intervention on nursing competency. Precision = 1/standard error; 0.05; limit line = 95% confidence limit.

TABLE 8 Publication bias test of virtual reality simulation-based intervention on competency.

Begg's test	Tau *b*	*K*	S (P-Q)	Ties	*Z*	*p*-value
Standard	0.27	22	63	0	1.78	0.076
Corrected	0.27	22	63	0	1.75	0.080
Egger's regression test	Coefficient	SE	95% CI		*Z*	*P*-value
			Lower limit	Upper limit		
Intercept	8.58	2.30	4.08	13.08	3.74	0.001
Slope	−1.63	0.62	−2.85	−0.41	−2.62	0.009
Trim and fill method	*K*	ES	95% CI		*Z*	*P*-value
			Lower limit	Upper limit		
Original	22	0.88	0.47	1.29	4.23	<0.001
Corrected	23	0.60	0.49	0.72	10.28	<0.001

Begg's test for rank correlation; Egger's regression test for zero intercepts; SE, standard error; CI, confidence interval; K, number of analysis sets; ES, effect size.

such as systematic reviews and meta-analyses exploring other variables in VRS, is recommended for a more comprehensive understanding of its impact on nursing education.

VR-based nursing education represents an innovative field that has not been previously explored. These simulators offer a range of environments that transcend physical constraints, enabling participants to immerse themselves within the virtual space (52). It's crucial for educators responsible for program development to grasp the distinctions between virtual reality and reality to facilitate effective education.

This study underscores the significance of pre-briefing and debriefing elements in VR-based simulation, highlighting the importance of their organization. Rather than focusing solely on operational time or the duration of the simulation itself, the key lies in how these elements are implemented for optimal educational outcomes. Additionally, when assessing effectiveness, we advocate for a combined approach utilizing both self-reported evaluations and objective evaluations through observation or assessment.

4.1 Limitations of the study

This study acknowledges several limitations. First, there is variability in reporting randomization methods among the included studies, with some providing comprehensive discussions on the topic while others lack detailed information on the methods employed. Second, the diverse interpretations and definitions of nursing competency across the included studies may introduce variability in the study outcomes. Third, the absence of a standardized measurement tool for nursing competency could contribute to increased heterogeneity. Fourth, the selection criteria for the studies analyzed, which included only those published in English or Korean and reported precise means, standard deviations, and sample sizes, could lead to selection bias and limit the generalization of our study results. Additionally, the studies encompass sample sizes from different countries, further contributing to overall heterogeneity. To enhance the robustness of future research and validate the effectiveness of interventions for nursing students, larger sample sizes and higher-quality studies are recommended.

5 Conclusion

The meta-analysis of nursing competency in VRS revealed the latter's effectiveness in enhancing nursing competency. Notably, the incorporation of key elements from face-to-face simulation, such as pre-briefing and debriefing, significantly improved nursing competency compared to scenarios in which these elements were absent. This study suggests the importance of reflecting core simulation elements in virtual simulations and underscores the need to enhance the quality of pre-briefing and debriefing in virtual contexts. Moreover, the findings suggest that intensively operating VRS over a short period could be more effective in improving nursing competency. This implies the significance of considering the effectiveness of short-term intensive courses for nursing-competency improvement within virtual spaces. The study findings provide valuable insights for the design of VRS aimed at enhancing nursing competency.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

M-KC: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. MK: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Application effect of BOPPPS teaching model on fundamentals of nursing education: a meta-analysis of randomized controlled studies

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Background: BOPPPS (bridge-in, learning objective, pretest, participatory learning, posttest, and summary) is a student-centered, closed-loop teaching model that emphasizes real-time communication and feedback.

Objectives: The purpose of this study was to review and evaluate the effect of BOPPPS teaching model in "Fundamentals of Nursing" teaching.

Methods: We conducted a meta-analysis of randomized controlled trials (RCTs) based on the BOPPPS teaching model in "Fundamentals of Nursing" teaching. To review domestic and foreign databases for the period 2010 to September 2023. Finally, 13 RCTs were included and the teaching outcomes were measured and analyzed. Two researchers independently identified, selected, and extracted data from the study and examined the risk of bias. The primary outcomes were students' examination scores (theoretical scores: scores obtained in the nursing fundamentals course, reflecting students' understanding and mastery of the course content; practical scores: assessment results based on practical application or experimental skills, evaluating students' practical skill level). The secondary outcomes were self-learning ability score: indicators assessing students' self-directed learning ability, reflecting their competence in independent learning and autonomous exploration; and satisfaction rate of teaching effect: the overall satisfaction rate of students with the teaching effects experienced during teaching process reflects the proportion of students' acceptance and satisfaction with the teaching program. The results were evaluated using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) profiler software. The GRADE profiler software is used to assess and grade the recommendations according to the GRADE (Grading of Recommendations Assessment, Development, and Assessment) criteria.

Results: A total of 13 studies were included, consisting of 2,991 nursing students. Among them, 1,465 students were in the BOPPPS teaching group, while 1,526 students were in the traditional teaching group. The summary analysis of the main outcomes showed that the BOPPPS teaching model had significantly higher scores in theoretical score (MD = 3.35, 95% CI: 2.35–4.35, $Z = 6.56$, $p < 0.00001$), practice score (MD = 4.50, 95% CI: 1.95–7.05, $Z = 3.45$, $p = 0.0006$), and self-learning ability score (MD = 6.76, 95% CI: 5.38–8.14, $Z = 9.60$, $p < 0.00001$) compared to the traditional teaching group. The satisfaction rate of students in the BOPPPS teaching group regarding teaching effectiveness was 89% (95% CI = 0.84–0.93). The differences were statistically significant ($p < 0.05$). The GRADE evidence level for theoretical score and satisfaction rate of teaching effect is low. The evidence level for practice score is very low, and for self-learning ability score is moderate.

Conclusion: The BOPPPS teaching mode is helpful to improve the theoretical score, practice score, and self-learning ability score of "Fundamentals of Nursing," and improve the satisfaction rate of students to the teaching effect. The teaching effect is better than the traditional teaching method.

KEYWORDS

BOPPPS (bridge-in), teaching model, "Fundamentals of Nursing" education, meta-analysis, GRADE quality evaluation

Introduction

The goal of nursing education is to cultivate comprehensive and applied talents with diversified abilities (1). With the development of societal disciplines, there is an increasing demand for higher-quality nursing professionals. Therefore, it is particularly important to focus on how to cultivate high-quality nursing professionals. "Fundamentals of Nursing" is one of the most basic and important core courses in the curriculum system of nursing, and it is the basis of all professional courses (2). This course aims to not only develop students' basic nursing knowledge and skills but also emphasize the cultivation of their abilities in problem-solving, critical thinking, and judgment (3). The goal is to enable students to apply fundamental theories and skills flexibly in clinical nursing, playing a crucial role in nursing education and teaching. The course "Fundamentals of Nursing" covers a wide range of content and requires students to have a high level of theoretical learning and practical skills. However, compared to other disciplines, the content of this course is more abstract and the knowledge points are more complex, making it challenging for students to learn (4).

Traditional nursing education often relies on a teacher-centered approach, where students passively receive knowledge, resulting in a lack of teacher-student interaction (5). This teaching method hinders students' ability to think critically and fails to stimulate their independent learning capabilities. Most students lack critical thinking skills during their learning process and fail to integrate theoretical knowledge with practical knowledge through real-world clinical case studies. As a result, when they enter the clinical practicum, they often realize that they have not truly understood many of the procedures taught in the classroom and struggle to adapt to the demands of clinical nursing work (6). In recent years, although medical schools have gradually adopted diversified teaching methods (7, 8), there are still some problems, such as the large amount of information in classroom lectures and the lack of interaction between teachers and students, which cannot effectively solve the problem of the disconnect between theory and clinical practice in teaching (9, 10). As nursing is a practice-oriented field within medicine, it requires a combination of theoretical knowledge and clinical skills. In nursing education, deficiencies in the teaching and learning process, lack of perceived professional support, and disparities between simulated and real clinical practice can hinder students from effectively applying theoretical knowledge in clinical settings (11). Nursing educators have recognized the gap between theory and practice and actively seek solutions. For instance, telemedicine education (12), virtual reality technology education (13), gamified education (14), and simulation-based teaching (15) have shown promising teaching outcomes to some extent. However, implementing these teaching models still faces challenges. Firstly, substantial investment in equipment and technological support is required. Secondly, adequate space and facilities are needed for simulation teaching. Additionally, a competent faculty is essential, with instructors possessing relevant skills and knowledge to effectively utilize teaching technologies and tools. Due to these constraints, the comprehensive implementation of these teaching models becomes challenging.

BOPPPS teaching mode also known as guided learning interactive additive education (16), was initially developed for teacher skill training to enhance teaching effectiveness and instructors' teaching skills. It is a closed-loop instructional design model based on constructivism theory (17). The BOPPPS teaching model divides classroom instruction into six modules: Bridge-in, Objective, Pre-assessment, Participatory Learning, Post-assessment, and Summary. B (Bridge-in) is the introductory phase of classroom teaching where students' attention is captivated through problem-based introduction, aiming to stimulate students' interest in learning. O (Objective) refers to the achievable and assessable learning objectives set for students at different levels. P (Pre-assessment) is a diagnostic assessment conducted before the lesson to help teachers understand students' current learning status and make necessary adjustments to the teaching content and pace. P (Participatory Learning) involves interactive and collaborative learning activities between teachers and students to achieve the learning objectives. P (Post-assessment) refers to the testing or evaluation of students at the end of the lesson to assess the effectiveness of teaching. S (Summary) involves summarizing the key points and concepts covered in the lesson (18).

In the past decade, there has been an increasing amount of research on BOPPPS in nursing education, including areas such as medical nursing (19), surgical nursing (20), health assessment (21), and nursing management (22). These studies indicate that the BOPPS teaching model has a positive impact on student's academic performance, self-directed learning abilities, and satisfaction with their learning, compared to control groups receiving traditional teaching methods. In the application of the BOPPPS teaching model in nursing education, most of the studies have small sample sizes and lack RCTs. There is no high-level evidence comparing the instructional effectiveness of the BOPPPS teaching model to other teaching methods in nursing education. To understand the practical significance of this model in the foundational nursing courses, this systematic review aims to evaluate the impact of the BOPPPS teaching model on the effectiveness of teaching in "Fundamentals of Nursing" courses, including the theoretical score, practice score, self-learning ability score, and satisfaction rate of teaching effect.

Methods

This systematic review and meta-analysis are conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) tool proposed by Page et al. (23). PRISMA is a set of evidence-based minimum items for reporting in systematic reviews and meta-analyses. The completed PRISMA checklist is provided as Supplementary material. Additionally, this review is conducted following the guidelines of the Cochrane Systematic Review and Intervention Manual but is not registered in a protocol (24).

Search strategy

The literature search was conducted from January 2012 to September 14, 2023, using the following databases: PubMed, Web of Science, Embase, and the Cochrane Library. English keywords used for the search included BOPPPS (bridge-in, learning objective, pretest, participatory learning, posttest, and summary) and "Fundamentals of Nursing" education. Additionally, Chinese databases including CNKI, WanFang Data, and VIP were searched. Chinese keywords used for the search included BOPPPS, interactive additive education, and "Fundamentals of Nursing." MeSH terms or titles or abstracts were used for the English database search, while subjects or titles or abstracts were used for the Chinese database search. The search strategies for different databases are provided as Supplementary material.

Inclusion and exclusion criteria

Inclusion criteria

This study developed search strategies based on the PICOS criteria (Population, Intervention, Comparison, Outcome, and Study Design) (Table 1).

Exclusion criteria

(1) Observational studies or non-randomized controlled studies.
(2) Not in the field of "Fundamentals of Nursing" education.
(3) No reporting of quantitative outcomes.
(4) Conference papers.
(5) Non-Chinese articles, English articles.

TABLE 1 Inclusion criteria based on PICO in this systematic review and meta-analysis.

Population	Students receiving "Fundamentals of Nursing" education in medical school
Intervention	BOPPPS teaching model
Comparison	Conventional Teaching Group
Outcomes	Primary: Theoretical score; Practice score
	Secondary: Self-learning ability score; Satisfaction rate of teaching effect
Study design	Randomized Clinical Trial (RCT)

Data extraction

We extracted data from the studies based on the Cochrane Handbook for Systematic Reviews of Interventions (25). Two reviewers (YuL and YaL) independently screened the titles and abstracts of the included studies. Disagreements were resolved by discussion with a third researcher (YaL). The following information was extracted from each study: first author name, publication year, sample size, intervention measures, final scores, measurement time point, and learning outcomes.

Risk of bias assessment

Two researchers independently assessed the quality of the included studies using the Cochrane Risk of Bias Tool (24). The evaluation criteria included the randomization process, deviation from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. When there were disagreements, a third researcher was consulted for discussion. Each item was assessed in three categories: low risk, high risk, and unclear. If all the included literature items met the criteria for low risk (Grade A), some items met the criteria for low risk (Grade B), and each item failed to meet the criteria for low risk (Grade C), they were excluded. A funnel plot was employed to assess publication bias.

Study quality

The included studies in this article are all RCTs. The quality of evidence for the outcome measures studied was further graded using the GRADE criteria (26). RCTs are considered the highest level of evidence, and the grading takes into account five factors: risk of bias in the studies, directness of the evidence, inconsistency of effect estimates (heterogeneity), precision of the effect estimates, and risk of publication bias. These factors are assessed to determine any downgrading or upgrading of the evidence quality.

Statistical analysis

Meta-analysis was performed using Rev. Man 5.4 and Stata 17.0 software. For continuous data, such as theoretical score, practice score, and self-learning ability score, the standardized mean difference (MD) and corresponding 95% confidence interval (CI) were used to estimate the effect size. For categorical variables, such as the satisfaction rate of teaching effect, the relative risk (RR) and 95% CI were used for statistical evaluation. Heterogeneity tests were conducted for each study result. If $I^2 < 25\%$, it suggests low heterogeneity; if $I^2 = 25–75\%$, it suggests moderate heterogeneity; if $I^2 > 75\%$, it suggests high heterogeneity (27). If $I^2 < 50\%$, a fixed-effects model was used for analysis, indicating low to moderate heterogeneity or no statistical heterogeneity in the studies. If $I^2 \geq 50\%$, a random-effects model was used for analysis.

Results

Search results

A systematic search was conducted for both Chinese and English articles from January 2012 to September 14, 2023. The initial search yielded 44 relevant articles, and after removing 23 duplicate articles using Endnote software, 21 articles remained. Upon reviewing the titles and abstracts, 7 articles were excluded, leaving 14 articles. Through a snowballing technique, 2 additional articles were identified and included. A comprehensive review was conducted on the resulting 16 articles, leading to the exclusion of 3 articles due to insufficient data for extraction ($n = 1$), lack of controlled trials ($n = 1$), and being a review article ($n = 1$). Finally, based on inclusion and exclusion criteria, a total of 13 RCTs were included in this meta-analysis (Figure 1).

General characteristics of the included studies

Table 2 presents the general characteristics of the included studies. All 13 included RCTs involved in the education of the "Fundamentals of Nursing" course, with a total of 2,991 nursing students participating in the experiments. Among them, 1,465 subjects received BOPPPS teaching in the experimental group, while 1,526 subjects received traditional teaching in the control group. All 13 articles included in the analysis were published in Chinese.

In the experimental group of the included studies, different learning platforms were used in combination with the BOPPPS teaching model. Among them, two studies used BOPPPS teaching approach combined with Presentation-Assimilation-Discussion (PAD) class teaching methods (29, 33), while five studies were based on the BOPPPS teaching model using information technology platforms (31, 32, 36, 37, 40). One study used a flipped classroom-based BOPPPS teaching model (39), and the remaining five studies used the BOPPPS teaching method without any additional intervention measures (28, 30, 34, 35, 38). The control group in all studies adopted traditional classroom teaching methods.

The meaning of the Learning outcomes column number is: ①course assessment results, students' satisfaction with the teaching mode, ③self-learning ability, ④critical thinking ability, ⑤humanistic care ability, ⑥learning attitude, ⑦learning initiative, ⑧learning engagement level, ⑨learning adaptation level, ⑩Self-directed learning ability.

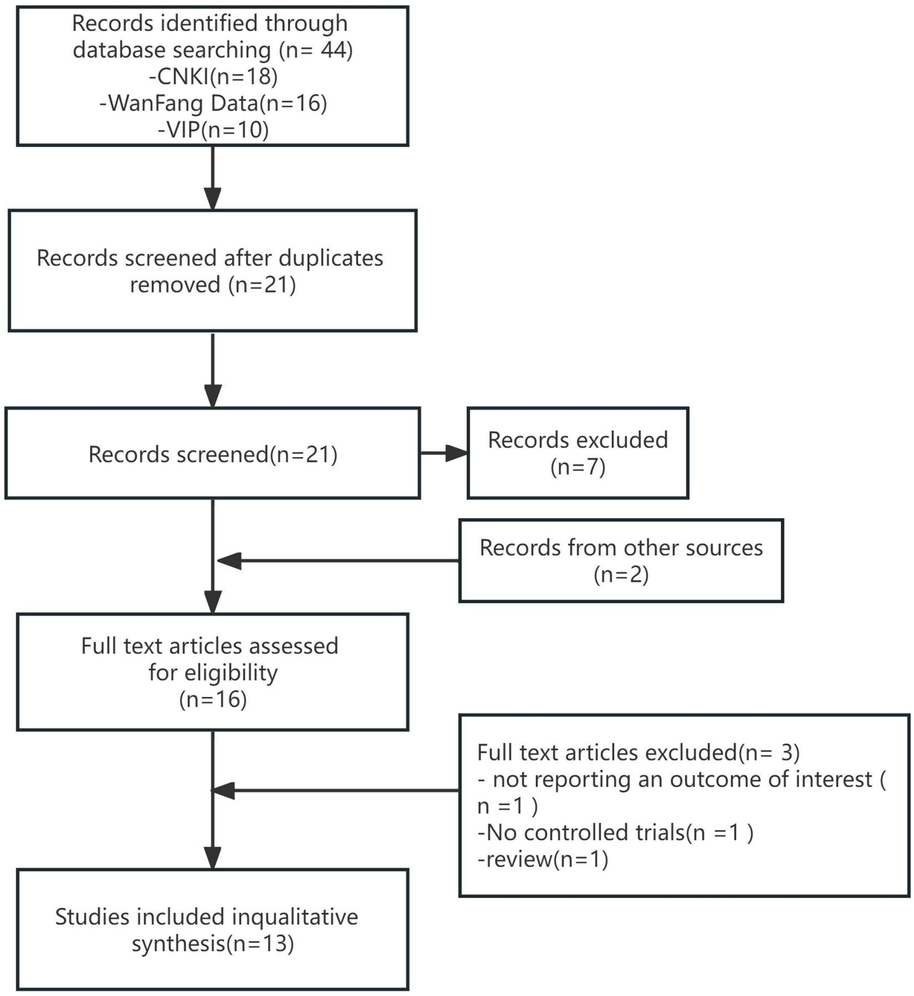

FIGURE 1
Flowchart of the search strategy.

TABLE 2 General characteristics of the included studies ($n = 10$).

Author (year)	Sample size		Mode of teaching		Final test results		Measurement time point	Learning outcomes
	Intervention group	Control group	Intervention group	Control group	Intervention group	Control group		
Zhang et al. (28)	80	80	BOPPPS teaching mode	Traditional teaching method	78.99 ± 9.3	77.23 ± 8.78	Only after intervention	①②
Ni (29)	86	95	The teaching method of BOPPPS combined with PAD class	Routine teaching method	91.37 ± 5.56	86.90 ± 12.74	Baseline and after intervention	①②③④⑤
Bi (30)	67	67	BOPPPS teaching mode	Traditional teaching method	78.34	75.29	Only after intervention	①②
Hao et al. (31)	50	55	BOPPPS teaching based on 'Xuexitong 'platform	Traditional teaching method	86.83 ± 2.98	83.22 ± 1.39	Only after intervention	①③
Zhang et al. (32)	114	112	Based on 'Rain Classroom 'and BOPPPS model	Traditional teaching method	80.22 ± 7.88	77.39 ± 8.65	Baseline and after intervention	①②③
Liu et al. (33)	48	48	The teaching mode based on BOPPPS and PAD class	Routine teaching method	NA	NA	Baseline and after intervention	②③⑥
Wang (34)	106	109	BOPPPS teaching mode	Traditional teaching method	81.66 ± 6.35	79.61 ± 7.64	Baseline and after intervention	①②③④⑦
Xia et al. (35)	233	238	BOPPPS teaching mode	Traditional teaching method	87.67 ± 6.10	83.62 ± 8.97	Only after intervention	①⑧⑨
Liu et al. (36)	111	110	On the basis of conventional teaching, BOPPPS mold is carried out. Type of rain classroom teaching	Traditional teaching method	80.36 ± 7.77	77.96 ± 9.45	Only after intervention	①③
Zhou et al. (37)	57	60	BOPPPS teaching model based on Superstar Learning Platform	Traditional teaching method	78.67 ± 8.14	72.67 ± 12.07	Only after intervention	①③⑧
Li et al. (38)	261	259	BOPPPS teaching mode	Traditional teaching method	77.15 ± 7.03	75.40 ± 6.94	Only after intervention	①
Xu et al. (39)	143	187	BOPPPS teaching mode based on flipped classroom	Traditional teaching method	87.41 ± 4.58	85.37 ± 4.92	Only after intervention	①③⑩
Cui et al. (40)	109	106	BOPPPS teaching mode, with the help of the campus 'real 'teaching platform	Traditional teaching method	71.11 ± 0.75	62.64 ± 10.72	Only after intervention	①③

Risk of bias in the included studies

The results of the quality assessment for the included studies indicated that the overall risk of bias for each included study was considered "low risk of bias." All included studies reported their outcome data, but 4 studies (30.7%) (31, 32, 37, 40) did not report the method of randomization, resulting in an assessment of "unclear." Due to the possibility of participants and educators being aware of the assigned interventions during the study, 12 studies (92.3%) (28, 30–40) were deemed to have allocation bias, assessed as "unclear." Given the nature of the interventions, blinding of students and teachers during the study was deemed impractical, resulting in a high-risk evaluation for participants and personnel blinding. Five studies (38.4%) (32, 35, 36, 38, 40) did not report attrition rates, resulting in an assessment of "unclear." The quality assessment for the included studies (Figure 2).

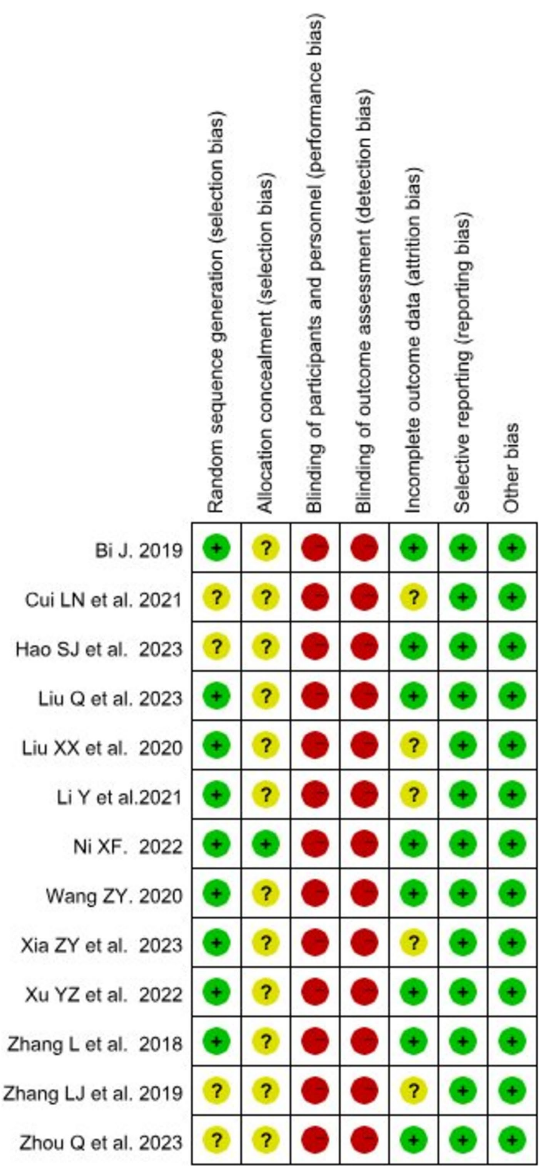

FIGURE 2
Risk of bias of included RCTs with the Cochrane RoB2 tool.

Data analysis

Theoretical score

A total of 12 studies (28–32, 34–40) with data related to Theoretical score were included, involving 1,417 and 1,478 students in the BOPPPS group and traditional teaching group, respectively. Compared with traditional teaching, the overall effect size of the 12 studies (MD = 3.35, 95% CI: 2.35–4.35, $Z = 6.56$, $p < 0.00001$) indicated a significant improvement in theoretical score in the BOPPPS teaching group. Due to significant statistical heterogeneity among the studies ($p < 0.00001$, $I^2 = 83\% > 50\%$), a random-effects model was used for the meta-analysis (Figure 3).

Practice score

A total of 7 studies (28, 29, 31, 34, 35, 38, 40) with data related to practice score were included, involving 925 and 942 students in the BOPPPS group and traditional teaching group, respectively. Compared with traditional teaching, the overall effect size of the 7 studies (MD = 4.50, 95% CI: 1.95–7.05, $Z = 3.45$, $p = 0.0006$) indicated a significant improvement in practice score in the BOPPPS teaching group. Due to significant statistical heterogeneity among the studies ($p < 0.00001$, $I^2 = 98\% > 50\%$), a random-effects model was used for the meta-analysis (Figure 4).

Self-learning ability score

A total of 8 studies (29, 31–34, 37, 39, 40) with data related to self-learning ability score were included, involving 824 and 882 students in the BOPPPS group and traditional teaching group, respectively. In this meta-analysis, the overall effect size of the 8 studies (MD = 6.76, 95% CI: 5.38–8.14, $Z = 9.60$, $p < 0.00001$) indicated a significantly higher self-learning ability score in the BOPPPS teaching group compared to the traditional teaching group. Due to moderate statistical heterogeneity among the studies ($p = 0.0006$, $I^2 = 73 > 50\%$), a random-effects model was used for the meta-analysis (Figure 5).

Satisfaction rate of teaching effect

A total of 7 studies (28, 30–34, 38) related to the Satisfaction rate of teaching effect were included. Since only data on teaching satisfaction from the BOPPPS group were available in the included studies, a single proportion analysis was conducted using Stata 17.0 software. The results showed that the satisfaction rate of teaching among students in the BOPPPS group was 89% (95% CI = 0.84–0.93). Due to significant statistical heterogeneity among the studies ($p = 0.000$, $I^2 = 89\% > 50\%$), a random-effects model was used for the meta-analysis (Figure 6).

Publication bias

According to the Cochrane Handbook standards, fewer than 10 studies were included in the literature review on self-learning ability score, practice score, and satisfaction rate of teaching effect, making it impossible to conduct a funnel plot test for publication bias. Therefore, a funnel plot was created to assess publication bias for the theoretical score, which is a major objective evaluation indicator. The results showed that the funnel plot was generally symmetrical, with evenly distributed scatter points, indicating the credibility and reliability of the conclusions drawn from this study (Figure 7).

Rating the quality of evidence

The included studies were RCTs, which represent the highest level of evidence. The GRADE evidence level for theoretical score and satisfaction rate of teaching effect was low. The evidence level for practice score was very low, and the evidence level for self-learning

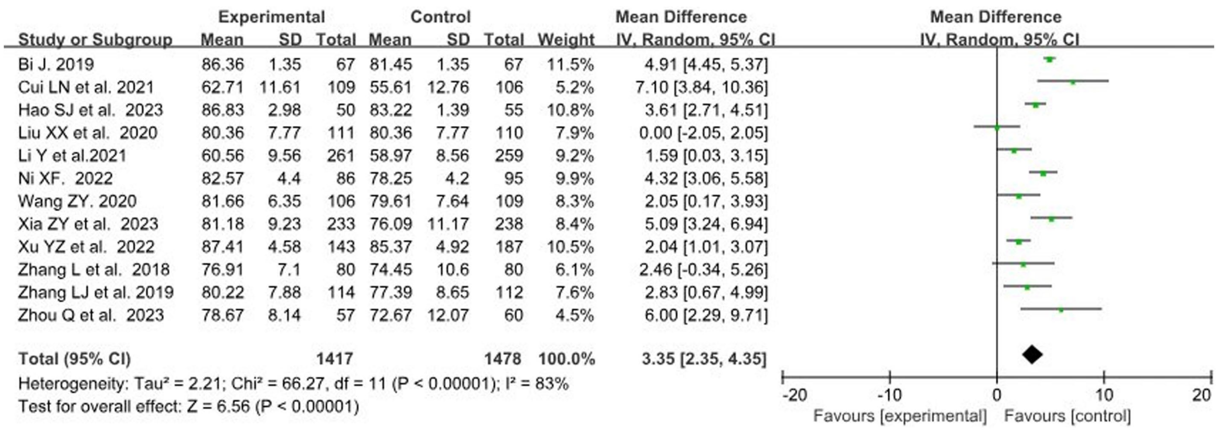

FIGURE 3
Forest plot of theoretical score for BOPPPS compared with the traditional teaching group.

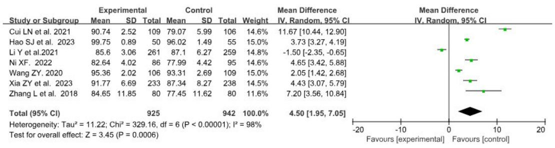

FIGURE 4
Forest plot of practice score for BOPPPS compared with the traditional teaching group.

ability score was moderate. All studies reported outcome measures directly. The reasons for downgrading the evidence are as follows (Table 3).

Discussion

Although the evidence level in the GRADE assessment may be relatively low, it still provides some evidence regarding the effectiveness and feasibility of the BOPPPS teaching method. Among these, randomized controlled trials represent the highest level of evidence, demonstrating that the included studies support the effectiveness of the BOPPPS method. This finding is crucial because randomized controlled trials are the most reliable and trustworthy method in research design.

Furthermore, evidence of moderate levels suggests that the Self-learning ability score provides some degree of support for the effectiveness of the BOPPPS teaching method. Despite the lower evidence levels for Theoretical score and Satisfaction rate of teaching effect, intervention studies show that BOPPPS can significantly improve these scores, with the BOPPPS group's scores significantly higher than those of the control group. This indicates that BOPPPS may have certain benefits in terms of theoretical knowledge acquisition and teaching effectiveness, despite the exact evidence level being relatively low. Although the evidence level for practical scores is extremely low, intervention studies show that the scores of the BOPPPS group are significantly higher than those of the control group, suggesting that BOPPPS may have favorable effects in practical environments, although more research is needed to confirm this.

Although the issue of "inconsistency" exists in the GRADE assessment, it is necessary to consider factors such as the sample size involved in the study, the level of teachers in the research methods, curriculum construction, difficulty of assessment, and students' learning abilities, which may influence the results.

In conclusion, despite the weak evidence level in the GRADE assessment, it can still be concluded based on the included studies, moderate evidence levels, and intervention effects that the BOPPPS teaching method has positive implications for nursing students' Fundamentals of Nursing courses to some extent. However, more high-quality research is still needed to provide more compelling evidence to further support the effectiveness and feasibility of the BOPPPS method.

The BOPPPS teaching model facilitates students' comprehension of theoretical knowledge

The BOPPPS teaching model, through its comprehensive and organized structure, greatly facilitates students' mastery of theoretical knowledge in nursing. This theoretical knowledge encompasses nursing science, technology, and theoretical frameworks in practice, such as understanding human anatomy and physiology, theories related to diseases and health, various models, and principles of nursing techniques (41). These form the cornerstone of professional growth for nursing students or nurses. The BOPPPS model emphasizes a student-centered teaching philosophy (42). By effectively connecting three stages: pre-class preview, in-class interactive participation, and post-class review, it provides students with a planned and systematic learning process (43). In the pre-class phase, through previewing, students can better prepare for and understand the upcoming content. During class, various teaching methods such as group discussions and scenario demonstrations not only stimulate students' interest in learning but also deepen their understanding and mastery of knowledge. Additionally, classroom discussions and evaluation sessions enhance students' learning motivation. Through questioning,

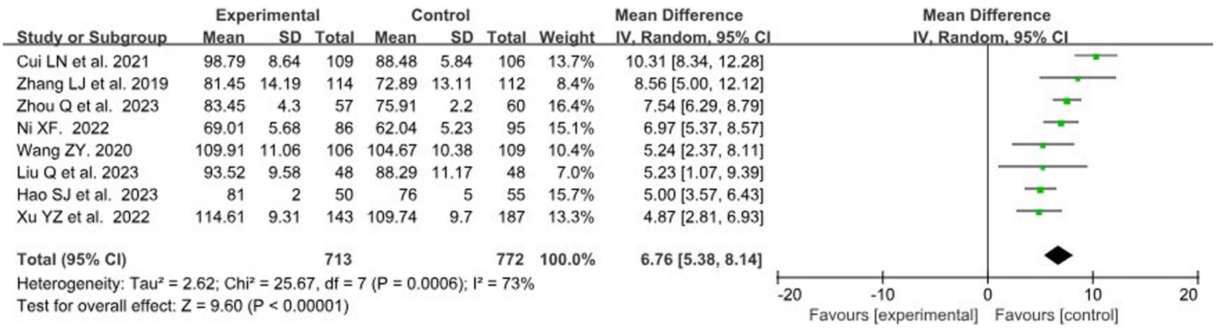

FIGURE 5
Forest plot of self-learning ability score for BOPPPS compared with the traditional teaching group.

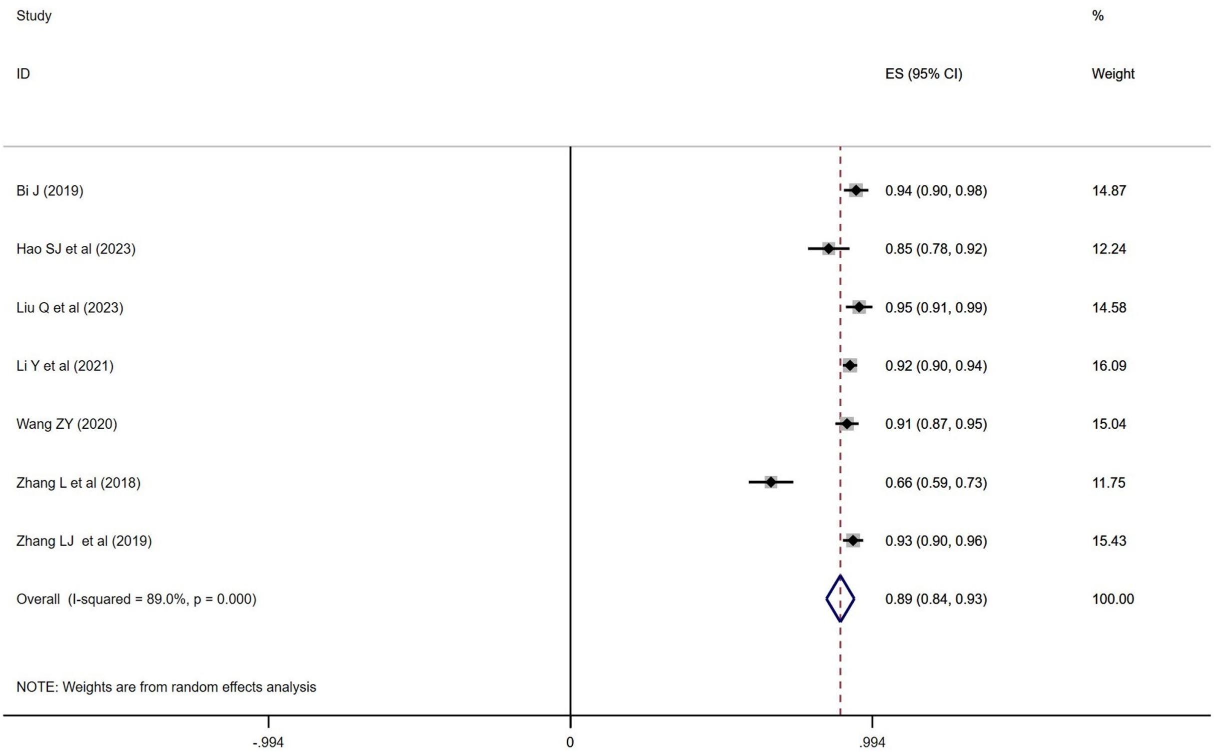

FIGURE 6
Meta-analysis of the satisfaction rate of teaching effect in BOPPPS group.

problem-solving, and immediate feedback from teachers, students' abilities and confidence in autonomous learning are enhanced. After class, by completing assignments and quizzes, students can self-assess their learning outcomes, and identify and fill in knowledge gaps, thus forming an effective learning cycle.

The BOPPPS teaching model is advantageous in strengthening students' proficiency in practical skills

The level of practical skills refers to the skill level and ability demonstrated by nursing students in nursing practice operations or actual clinical work (44). This includes but is not limited to, abilities in patient care procedures, correct usage of medical equipment, emergency treatment, patient observation, and evaluation of conditions (45). The level of practical skills directly impacts the quality of work for nursing professionals and the effectiveness of patient care (46). The BOPPPS teaching model is advantageous in facilitating the mastery of theoretical knowledge and enhancing skill levels. The pre-test and post-test of this teaching model serve to develop students' independent thinking abilities while also enabling them to address any knowledge gaps they may have missed, thereby enhancing their comprehension and mastery of the subject (17). In class, students learn through discussions and actively engage in discussions as part of their learning process. The integration of these two aspects

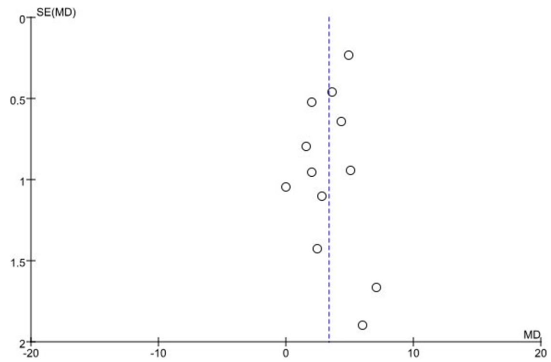

FIGURE 7
Funnel plot of theoretical score for BOPPPS compared with the traditional teaching group.

promotes a thorough understanding and solidification of knowledge for students (47). Building upon a solid theoretical framework, students delve into the intricacies of practical implementation through activities such as group discussions, presentations, and comprehensive evaluations. Moreover, having thoroughly examined the operational aspects and laid out initial procedures beforehand, students develop a high level of proficiency and the adaptability required to apply this knowledge across diverse clinical settings. Consequently, there is a seamless transition from theory to practice (48) yielding substantial improvements in their hands-on capabilities and analytical problem-solving aptitude. Ultimately, this translates into an elevated mastery of practical skills.

The BOPPPS teaching model is advantageous in strengthening students' ability for independent learning

The ability for self-directed learning refers to an individual's capacity during the learning process to autonomously and actively engage in learning activities, including setting goals, developing study plans, acquiring information, problem-solving, reflection, and evaluation (49). This ability enables individuals to efficiently acquire the necessary knowledge and skills and to adapt and develop within constantly changing learning environments (50). Conventional teaching methods are limited in their ability to cultivate students' self-directed learning skills, manifesting primarily in insufficient motivation levels (19). Typically, students rely on educational management from their schools and teachers, thereby lacking a sense of accountability and exhibiting poor self-control and self-management strategies (51). By comparison, control groups tend to adopt a passive approach to learning and often struggle with boredom, leading to low motivation and minimal levels of initiative during the learning process. The BOPPPS teaching model is rooted in promoting students' independence (52). It places great emphasis on students autonomously obtaining pertinent learning information through various means, including pre-class readings, in-class group discussions, and post-class reinforcement activities (53). As students engage in this process, their capabilities in information acquisition and processing steadily improve, leading to enhanced self-management skills and a growing aptitude for self-directed learning.

The BOPPPS teaching model is advantageous in enhancing students' satisfaction with the effectiveness of teaching

Student satisfaction rate with teaching refers to the ratio or percentage of the overall satisfaction level of students with the teaching process. This data is typically obtained through surveys or evaluations of students. The level of student satisfaction with teaching reflects the proportion of their approval and satisfaction with the teaching program (54). The BOPPPS teaching model emphasizes equality between teachers and students, with the latter serving as the main agents of learning (55). It promotes self-directed learning, thereby enabling students to transform from passive learners to active ones. Through class activities that encourage student-to-student and teacher-to-student interactions, the traditional teaching approaches have been disrupted, creating a stimulating and energetic classroom environment (56). Such an atmosphere enhances students' participation in educational activities, facilitating the development of their overall skills, and elevating their interest and productivity levels. Students value classes filled with interactive and engaging content, showing a willingness to actively participate in educational endeavors, thereby elevating their satisfaction with the quality of teaching.

Limitations of BOPPPS teaching mode in fundamentals of nursing education

The BOPPPS model has the following limitations: (1) Despite its widespread application in the field of education, there is relatively little specific research on its effectiveness in Fundamentals of Nursing education, and a lack of sufficient empirical studies may restrict understanding of its actual impact in nursing curricula. (2) The inclusion of studies with short implementation periods and small sample sizes may affect understanding of whether this teaching model is suitable for widespread adoption in nursing education. (3) The heterogeneous nature of the BOPPPS intervention measures used in studies may make comparative results difficult. (4) Effective implementation of the BOPPPS method may require teachers to undergo appropriate training. However, the methods and levels of nursing teacher training included in the studies vary, which may affect the results and lead to heterogeneity. (5) The BOPPPS method may consume more resources than traditional teaching methods, as it requires additional planning, preparation, and teacher support.

Limitations of research and analysis

The analysis presented in this article has some limitations. (1) The studies ultimately included in the analysis were all conducted in China, with participants consisting solely of Chinese students. This may reduce the representativeness and generalizability of the results.

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TABLE 3 GRADE evidence summary table.

Outcomes	Quality assessment						Effect (95%CI)	No. of Participants (Studies)	Quality of the evidence (GRADE)
	Design	Risk of bias	Inconsistency	Indirectness	Imprecision	Other considerations			
Theoretical score	RCT	No serious risk of bias	Very serious[a]	No serious indirectness	No serious imprecision	None	SMD = 3.35,95%CI(2.35 ~ 4.35)	2,895 (12 studies)	ÅÅOO LOW
Practice score	RCT	No serious risk of bias	Very serious[a]	No serious indirectness	Serious[b]	None	SMD = 4.50,95%CI(1.95 ~ 7.05)	1867 (7 studies)	⊕OOO VERY LOW
Self-learning ability score	RCT	No serious risk of bias	Serious[c]	No serious indirectness	No serious imprecision	None	SMD = 6.76,95%CI(5.38 ~ 8.14)	1,485 (8 studies)	⊕⊕⊕O MODERATE
Satisfaction rate of teaching effect	RCT	No serious risk of bias	Very serious[a]	No serious indirectness	No serious imprecision	None	RR = 0.89,95%CI(0.84 ~ 0.93)	1,456 (7 studies)	ÅÅOO LOW

CI, confidence interval; RCT, randomized trials. GRADE Working Group grades of evidence. High quality: Further research is very unlikely to change our confidence in the estimate of effect. Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate. Low quality: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate. Very low quality: We are very uncertain about the estimate. [a]I^2 >75%.

[b]The overlap is not good.

[c]I^2 > 50%.

(2) Based on the scientific nature of the study, researchers should strive to minimize implementation bias in quasi-experimental research to accurately determine the impact of teaching models on student learning outcomes. However, implementing blinding procedures for research participants during the teaching process is impractical because the instructional mode employed cannot be concealed from the students. Therefore, blinding the students presents significant challenges. (3) There is significant heterogeneity among the studies included in this analysis, which may be attributed to factors such as differences in teaching qualifications, course design, assessment difficulty, and variation in learning abilities. This poses a challenge to conducting a systematic meta-analysis. (4) The quality of a meta-analysis relies on the quality of the data from included studies. As the quality of the included literature is relatively low and the sample sizes are limited, there is a need for more publications and the inclusion of large-scale, multicenter, and high-quality studies. (4) There is currently no standard guideline for the application of BOPPPS in medical disciplines in China, nor are there effective criteria for evaluating the BOPPPS teaching model.

Author contributions

YuL: Data curation, Investigation, Writing – original draft, Writing – review & editing. XL: Supervision, Validation, Writing – review & editing. YnL: Investigation, Methodology, Writing – original draft. YgL: Investigation, Methodology, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmed.2024.1319711/full#supplementary-material

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Evaluation of the quality and quantity of artificial intelligence-generated responses about anesthesia and surgery: using ChatGPT 3.5 and 4.0

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Introduction: The large-scale artificial intelligence (AI) language model chatbot, Chat Generative Pre-Trained Transformer (ChatGPT), is renowned for its ability to provide data quickly and efficiently. This study aimed to assess the medical responses of ChatGPT regarding anesthetic procedures.

Methods: Two anesthesiologist authors selected 30 questions representing inquiries patients might have about surgery and anesthesia. These questions were inputted into two versions of ChatGPT in English. A total of 31 anesthesiologists then evaluated each response for quality, quantity, and overall assessment, using 5-point Likert scales. Descriptive statistics summarized the scores, and a paired sample *t*-test compared ChatGPT 3.5 and 4.0.

Results: Regarding quality, "appropriate" was the most common rating for both ChatGPT 3.5 and 4.0 (40 and 48%, respectively). For quantity, responses were deemed "insufficient" in 59% of cases for 3.5, and "adequate" in 69% for 4.0. In overall assessment, 3 points were most common for 3.5 (36%), while 4 points were predominant for 4.0 (42%). Mean quality scores were 3.40 and 3.73, and mean quantity scores were – 0.31 (between insufficient and adequate) and 0.03 (between adequate and excessive), respectively. The mean overall score was 3.21 for 3.5 and 3.67 for 4.0. Responses from 4.0 showed statistically significant improvement in three areas.

Conclusion: ChatGPT generated responses mostly ranging from appropriate to slightly insufficient, providing an overall average amount of information. Version 4.0 outperformed 3.5, and further research is warranted to investigate the potential utility of AI chatbots in assisting patients with medical information.

KEYWORDS

ChatGPT, artificial intelligence, quality, quantity, AI chatbot

1 Introduction

Each year, approximately 4.2 million patients worldwide undergo surgical procedures under anesthesia, with reported mortality rates of 2.75% within 30 days after various surgical operations, and anesthesia-related deaths occurring at a rate of 1.72 per 10,000 procedures (1, 2). Patients facing surgery often experience anxiety and seek explanations from healthcare professionals (3). However, these explanations may be perceived as insufficient, leading patients to turn to online sources for additional information. Regrettably, online information is not always reliable, and when patients encounter incorrect or misleading data, it can potentially escalate anxiety and negatively impact surgical outcomes (4).

In November 2022, a groundbreaking artificial intelligence (AI) language model chatbot named ChatGPT was released. Unlike conventional chatbots, it is known to analyze, comprehend, and learn from text to generate human-like answers, allowing direct and meaningful interactions with users and facilitating the exchange of information (5). Impressively, ChatGPT passed the United States Medical Licensing Examination and holds the potential to offer high-level and prompt responses concerning medical information (6, 7). Ongoing efforts by researchers, educators, and professionals aim to implement ChatGPT in diverse domains, spanning from composing medical papers to educational settings (8, 9). There is a strong anticipation that ChatGPT could contribute significantly, either as a supplementary tool or, potentially, as a partial replacement for the roles of medical experts. However, few studies have specifically assessed the accuracy and relevance of medical information provided by chatbots for the general population. Furthermore, the absence of evaluations on the information provided by ChatGPT regarding anesthetic procedures underscores the necessity for well-designed investigations to assess its effectiveness in this specific medical field. Therefore, our study aims to assess the appropriateness of medical information generated by ChatGPT and determine whether this AI chatbot can effectively offer rapid and accessible medical advice to patients preparing for surgery and anesthesia. Additionally, we will compare the responses of ChatGPT 3.5 and the latest model, 4.0, to discern which version proves more beneficial.

2 Materials and methods

This study was initially submitted to the institutional review board (IRB) at our institution, seeking ethical review. After careful consideration, the IRB determined that formal review was not required, as the study does not involve human subjects. The focus lies on the analysis of data generated by the "ChatGPT" program, which does not necessitate direct interaction or involvement with individuals. The research strictly adheres to all applicable ethical guidelines and regulations, ensuring the confidentiality and privacy of any data used during the analysis process.

2.1 Study design

To address common inquiries of individuals anticipating surgery or anesthesia, two anesthesiologists crafted a set of 30 questions. These questions encompassed various topics, including the type of anesthesia, preoperative preparation, preanesthetic evaluation criteria, and the surgical and anesthetic recovery process. The formulation of these questions involved referencing educational materials provided by the Korean Society of Anesthesiologists for the public, in addition to information from relevant textbooks and research papers concerning preoperative assessments in anesthesia. All questions were composed in English and entered into both the freely accessible ChatGPT 3.5 version and the paid-only 4.0 version. Each interaction was labeled as a "new chat."

Response evaluations were carried out by 31 anesthesiologists from university hospitals in Korea. To maintain impartiality, the two authors who created the questions did not participate in the evaluation process. Each evaluator received two versions of the answer for each question without noticing which ChatGPT version produced it. The presentation of responses was randomized to ensure unbiased evaluation. The overall study design and flow are presented in Figure 1.

2.2 Evaluation: quality, quantity, overall assessment

Responses were evaluated based on three criteria: quality, quantity, and overall score. For quality evaluation, the appropriateness of responses was assessed using a 5-point Likert scale (1—very inappropriate, 2—inappropriate, 3—average, 4—appropriate, 5—very appropriate). Quantity evaluation determined if responses were insufficient or excessive, utilizing a 5-point Likert scale (−2—very insufficient, −1—insufficient, 0—adequate, 1—excessive, 2—very excessive). The overall assessment represented a comprehensive evaluation of the responses, where participants rated how well the information was provided on a 5-point Likert scale, ranging from 1 (the response should not be provided) to 5 (the response is perfect).

To evaluate in which areas ChatGPT provides better responses, the questions were divided into four categories, and additional analysis was conducted: (1) General questions about anesthesia, (2) Preoperative preparation, (3) Pre-anesthetic evaluation, (4) Postoperative recovery process.

2.3 Statistical analysis

Mean values with standard deviations were calculated for each score based on the responses from the 31 participants. A paired *t*-test was then conducted to compare the values between the 3.5 and 4.0 versions. A significance level of $p < 0.05$ was employed to determine if there was a statistically significant difference. All statistical analyses were carried out using SPSS statistical software (IBM SPSS Statistics 20; Chicago, IL, United States).

3 Results

The entire set of questions and the results of the response evaluation by 31 experienced anesthesiologists are presented in Table 1. The full text of the responses generated by ChatGPT 3.5 and 4.0 is provided in Supplementary Table S1. The overall distribution of response evaluations according to the version of ChatGPT is summarized in Table 2.

3.1 ChatGPT 3.5

The mean score for the "quality" of the 30 answers generated by ChatGPT 3.5 was 3.40 (±0.20), indicating a level between "average" and "appropriate." The highest percentage, 40%, was observed for the score of 4, indicating "appropriate," while the lowest percentage, 1%,

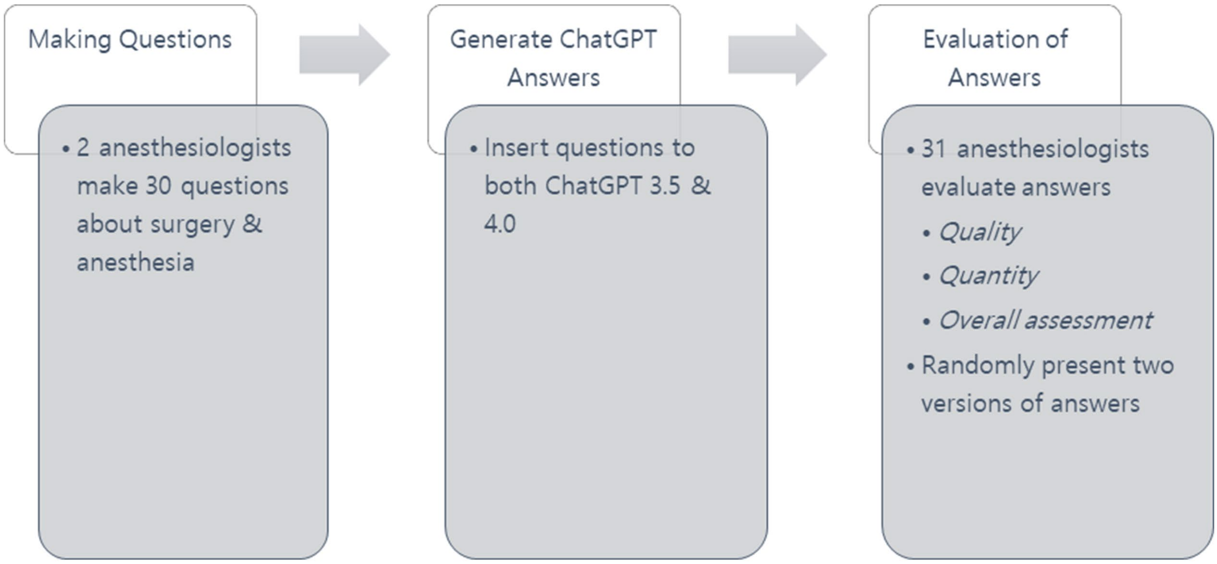

FIGURE 1
Research process.

was recorded for the score of 1, indicating "very inappropriate." Regarding the "quantity" of the answers, the score of 0, indicating "adequate," had the highest percentage at 59%, and the mean score was −0.31 (±0.18), indicating a value between "insufficient" and "adequate." The mean score for the "overall assessment" was 3.21 (±0.27), with the highest percentage (36%) observed for the score of 3.

3.2 ChatGPT 4.0

The mean score for the "quality" of the answers generated by ChatGPT 4.0 was 3.73 (±0.34), similar to ChatGPT 3.5, indicating a level between "average" and "appropriate." The score of 4 had the highest percentage, with 48% of respondents selecting it. Regarding the "quantity" of the answers, the mean score was 0.03 (±0.30), suggesting an evaluation between "adequate" and "excessive." Notably, a significant proportion of 69% rated the responses as "adequate," scoring 0 on the scale. For the "overall assessment," the mean score was 3.67 (±0.40), with the highest percentage of 42% of participants giving a score of 4, reflecting positive feedback on the responses generated by ChatGPT 4.0.

3.3 Evaluation by category

When examined by category, ChatGPT's performance for "General questions about anesthesia" showed that in version 3.5, 52% of responses were of appropriate or higher quality, 57% were of adequate quantity, and 10% received the best grade. In version 4.0, these figures were 76, 67, and 23%, respectively. For "Preoperative preparation," ChatGPT 3.5 achieved 45% in quality, 60% in quantity, and 10% for the best grade, while version 4.0 achieved 57, 66, and 18%. Regarding "Pre-anesthetic evaluation," ChatGPT 3.5 scored 49% in quality, 60% in quantity, and 6% for the best grade, whereas version 4.0 scored 67, 72, and 18%. For the "Postoperative recovery process," ChatGPT 3.5 achieved 40% in quality, 60% in quantity, and 8% for the best grade, while version 4.0 achieved 52, 70, and 13% (Table 3). In all categories, version 4.0 showed higher percentages. However, except for responses on "Preoperative evaluation" in ChatGPT 4.0, there were instances where responses were rated as very inappropriate, very insufficient, or the worst in all categories.

3.4 ChatGPT 3.5 vs. 4.0

Table 4 shows the results of the comparison of mean scores for "quality, quantity, and overall assessment" between ChatGPT 3.5 and 4.0. A significant difference was observed in all three categories. The answers generated by ChatGPT 4.0 received higher scores in terms of quality and overall assessment, indicating better performance compared to ChatGPT 3.5. For quantity, ChatGPT 4.0 was perceived to be closer to an adequate level compared to ChatGPT 3.5, which was rated as insufficient. For each of the three criteria, ChatGPT 4.0 consistently outperformed ChatGPT 3.5, receiving higher scores in terms of quality and overall assessment.

4 Discussion

In this study, we sought to evaluate the reliability of medical information related to anesthetic procedures provided by the AI language model chatbot, ChatGPT and explored potential differences between the 3.5 and 4.0 versions. By assessing responses to 30 questions, we observed that both versions of ChatGPT consistently offered reasonably accurate medical information, scoring above the midpoint in terms of quality. Notably, the 4.0 version demonstrated a higher percentage of appropriate or very appropriate responses, reaching 64%, indicating a greater reliability of medical information compared to the 3.5 version. Regarding the quantity of information, both

TABLE 1 Questions and the results of response evaluations by experts.

No.	Question	ChatGPT 3.5			ChatGPT 4.0		
		Quality	Quantity	overall	Quality	Quantity	overall
1	What is general anesthesia and how does it work?	3.61	−0.1	3.58	3.84	0.19	3.68
2	What are the possible complications after general anesthesia?	3.39	−0.06	3.32	4.29	0.23	4.23
3	What is the mortality rate from anesthesia in healthy people?	3.32	−0.19	3.32	4.1	0.06	4.03
4	What is "awakening under anesthesia"?	3.65	−0.19	3.58	3.68	0.03	3.77
5	What are the side effects of spinal anesthesia?	3.52	−0.32	3.52	4.29	0.39	4.1
6	How long does it take for sensation to return after spinal anesthesia?	3.32	−0.13	3.1	3.84	−0.03	3.94
7	When is epidural anesthesia performed?	3.42	−0.26	3.19	4.06	0.16	3.97
8	What are some of the underlying conditions that can be dangerous when receiving anesthesia?	3.71	−0.29	3.42	3.94	0.16	3.97
9	What items should be evaluated before surgery in a patient with reduced mobility?	3.29	−0.39	2.87	4.03	0.13	4.06
10	What items should be evaluated before surgery in patients with alcohol dependence?	3.45	−0.16	3.39	4	0.42	3.81
11	Is it safe for pregnant women to receive general anesthesia?	3.39	−0.52	3.16	3.97	0.26	3.87
12	Why do I need to fast before surgery?	3.13	−0.19	2.94	3.71	0.06	3.74
13	How long do I need to fast before surgery?	3.42	−0.29	3.32	3.77	0	3.87
14	Do I need to quit smoking before anesthesia?	3.29	−0.55	3.03	4.03	0.13	4.06
15	How long do I need to quit smoking to be safe during surgery?	3.35	−0.19	3.39	3.61	−0.16	3.61
16	The day before surgery, I had a fever, cough, and phlegm. Can I have general anesthesia?	3.58	−0.06	3.74	2.87	−0.87	2.68
17	I am taking anticoagulants. How long should I stop before surgery?	3	−0.71	2.71	3.42	−0.16	3.42
18	What medications do I need to keep taking before surgery until the day of surgery?	3.23	−0.58	2.9	3.52	−0.23	3.52
19	What diseases or conditions require cardiac evaluation before surgery?	3.42	−0.45	3.16	3.74	0.26	3.68
20	What diseases or conditions require lung-related evaluation before surgery?	3.52	−0.32	3.19	3.71	0.16	3.71
21	What kind of evaluation is needed for hypertensive patients before surgery?	3.39	−0.26	3.16	3.68	0.13	3.74
22	A patient with a pacemaker is scheduled to receive general anesthesia. What should I watch out for?	3.52	−0.35	3.16	3.77	0.23	3.58
23	What kind of evaluation do asthma patients need before surgery?	3.61	−0.26	3.29	3.84	0.23	3.87
24	What precautions should be taken before anesthesia for people with poor blood sugar control?	3.58	−0.32	3.29	3.81	0.29	3.87
25	What kind of evaluation do patients with psychiatric problems such as anxiety and depression need before surgery?	3.45	−0.23	3.26	3.55	0.26	3.55
26	What is the most commonly used drug for sedation or anesthesia?	3.39	−0.48	3.06	3.03	−0.71	2.61
27	How can I manage pain after surgery?	2.81	−0.65	2.58	3.71	0	3.45
28	How can I control nausea and vomiting after surgery?	3.03	−0.48	2.84	3.23	−0.23	3.03
29	How many hours after going up from the recovery room to the ward can I eat?	3.45	−0.23	3.26	3.16	−0.45	2.87
30	Sore throat after general anesthesia. What should I do?	3.61	0	3.52	3.77	0	3.77

Quality (5-point Likert scale; 1 very inappropriate, 2 inappropriate, 3 average, 4 appropriate, 5 very appropriate). Quantity (5 Likert; −2 very insufficient, −1 insufficient, 0 adequate, 1 excessive, 2 very excessive). Overall assessment (5 Likert; 1 should not be an answer to 5 perfect answer).

versions were generally perceived as providing an adequate amount of information.

Reviewing the literature, ChatGPT, as a large language model LLM, leverages extensive datasets and advanced machine learning algorithms to facilitate human-like conversations, understanding and responding to complex questions in natural language. These conversations can range from light-hearted topics to scientific discussions (10). The initial version, GPT-1, had 117 million

TABLE 2 Distribution of response evaluation by experts according to version of ChatGPT.

		ChatGPT 3.5 (%)	ChatGPT 4.0 (%)
Quality	1: Very inappropriate	1	1
	2: Inappropriate	13	6
	3: Average	38	29
	4: Appropriate	40	48
	5: Very appropriate	7	16
Quantity	−2: Very insufficient	2	1
	−1: insufficient	33	13
	0: Adequate	59	69
	1: Excessive	6	17
	2: Very excessive	0	1
Overall assessment	1: Worst	2	1
	2	22	9
	3	36	29
	4	31	42
	5: Best	9	18

parameters, but in the latest versions, GPT-3.5 and 4.0, the number of parameters has significantly increased, enabling more accurate and human-like responses. The application scope of ChatGPT has expanded to various fields, including healthcare (11). Interest in ChatGPT is growing rapidly. Within a short period of 6 months, there has been a significant increase in published papers about ChatGPT, with 533 produced (12). Among these, the most researched topics are those evaluating ChatGPT's ability to provide accurate answers and its depth of knowledge (11). ChatGPT is breaking down barriers to universal access to healthcare information, assisting in communication between doctors and patients, and providing standardized, evidence-based information, leading to significant growth in the healthcare domain (13). The role of doctors in understanding and addressing complex health issues for patients and communities is expanding, and new technologies like ChatGPT can effectively support this (14). However, despite already demonstrating impressive capabilities in natural language understanding and generation, various potential applications in the medical field, such as data extraction and decision-making in surgery, are still in the early stages of development (10, 15).

Our study contributes to the ongoing previous studies on the appropriateness of integrating generative AI into the field of medicine. Indeed, the integration of generative AI into medicine is a heavily researched area (16). The medical field accounted for the highest proportion of total publications related to ChatGPT research (11). ChatGPT distinguishes itself with remarkable proficiency in understanding and generating text, attracting attention for its versatile applications (16, 17), extending from medical education to the dissemination of patient information (18–20). Active efforts are underway to deploy ChatGPT across various domains, from crafting medical papers to educational contexts, with high expectations for potential to supplement, if not partially to replace, the role of medical experts (8, 9). However, a recent systematic review underscores persisting challenges with issues related to accuracy, authorship, and bias (20). While prior studies predominantly focused on the model's utility in assisting medical experts, our study takes a unique perspective by exploring its potential benefits for the general population seeking precise information on anesthetic procedures.

In this study, the questions input into ChatGPT were carefully selected to ensure the potential for generalization. From numerous questions, we condensed them to 30 by excluding similar ones. For instance, instead of asking all the following: (1) What is general anesthesia? What is spinal anesthesia? What is epidural anesthesia? (2) What are the side effects of general anesthesia? What are the side effects of spinal anesthesia? What are the side effects of epidural anesthesia? (3) When is general anesthesia used? When is spinal anesthesia used? When is epidural anesthesia used?," we selected one type of anesthesia for each of the questions in (1), (2), and (3). ChatGPT's responses are typically lengthy, and evaluators need to assess both versions of the responses, which means they must read a substantial amount of text. Concerned that increased evaluator fatigue could lead to inaccurate assessments, we considered this factor when determining the number of questions.

In studies assessing the reliability of ChatGPT in providing medical information, the model demonstrated accuracy in general medicine (21). Specific areas, such as cardiovascular disease or liver cirrhosis, also received adequate information (22, 23). Our study stands out among the studies evaluating the reliability of ChatGPT in providing medical information with a substantial number of evaluators. We recruited 31 anesthesiologists for response evaluation to minimize bias and enhance the reliability. Our evaluators, comprising medical staff from major university hospitals in Korea, ensured a comprehensive assessment based on the latest medical knowledge.

Another strength of this study is discerning the superiority of responses based on the model's version. Our results revealed that version 4.0 consistently demonstrated significantly higher scores than version 3.5 across all evaluation criteria (quality, quantity, and overall score). This was particularly evident within the specific categories analyzed. According to OpenAI, version 4.0 excels in understanding natural language and generating creative responses in complex

TABLE 3 Evaluation of responses related to anesthesia and surgery generated by two versions of ChatGPT by question type.

		ChatGPT 3.5 (%)	ChatGPT 4.0 (%)
General questions about anesthesia ($N = 8$)			
Quality	1: Very inappropriate	2	1
	2: Inappropriate	13	4
	3: Average	33	19
	4: Appropriate	43	54
	5: Very appropriate	9	22
Quantity	−2: Very insufficient	2	1
	−1: Insufficient	33	12
	0: Adequate	57	67
	1: Excessive	8	19
	2: Very excessive	0	1
Overall assessment	1: Worst	1	2
	2	19	8
	3	34	23
	4	35	43
	5: Best	10	23
Preoperative preparation ($N = 8$)			
Quality	1: Very inappropriate	2	1
	2: Inappropriate	17	9
	3: Average	36	33
	4: Appropriate	38	44
	5: Very appropriate	7	13
Quantity	−2: Very insufficient	2	2
	−1: Insufficient	34	21
	0: Adequate	60	66
	1: Excessive	3	11
	2: Very excessive	0	0
Overall assessment	1: Worst	4	1
	2	25	13
	3	33	31
	4	29	38
	5: Best	10	18
Pre-anesthetic evaluation ($N = 9$)			
Quality	1: Very inappropriate	0	0
	2: Inappropriate	7	2
	3: Average	44	30
	4: Appropriate	42	52
	5: Very appropriate	7	15
Quantity	−2: Very insufficient	1	0
	−1: Insufficient	34	3
	0: Adequate	60	72
	1: Excessive	5	24
	2: Very excessive	0	1

(Continued)

TABLE 3 (Continued)

		ChatGPT 3.5 (%)	ChatGPT 4.0 (%)
Overall assessment	1: Worst	1	0
	2	18	5
	3	44	31
	4	29	47
	5: Best	6	18
Postoperative recovery process ($N=5$)			
Quality	1: Very inappropriate	1	1
	2: Inappropriate	20	10
	3: Average	39	37
	4: Appropriate	34	39
	5: Very appropriate	6	13
Quantity	−2: Very insufficient	3	3
	−1: Insufficient	30	18
	0: Adequate	60	70
	1: Excessive	6	9
	2: Very excessive	1	0
Overall assessment	1: Worst	5	4
	2	30	14
	3	28	33
	4	30	37
	5: Best	8	13

TABLE 4 Comparison of response evaluations according to version of ChatGPT.

	ChatGPT 3.5	ChatGPT 4.0	*p*-value
Quality	3.40 (0.20)	3.73 (0.34)	<0.01
Quantity	−0.31 (0.18)	0.03 (0.30)	<0.01
Overall assessment	3.21 (0.27)	3.67 (0.40)	<0.01

Quality (5-point Likert scale; 1 very inappropriate, 2 inappropriate, 3 average, 4 appropriate, 5 very appropriate). Quantity (5 Likert; −2 very insufficient, −1 insufficient, 0 adequate, 1 excessive, 2 very excessive). Overall assessment (5 Likert; 1 should not be an answer to 5 perfect answer).

scenarios, but its application to providing medical information, especially in comparison to the previous version, is not fully guaranteed.[1] The exceptions noted in 3 out of 30 questions emphasize the need for continued scrutiny and improvement in the model's reliability.

An easy access to medical information for patients enables informed decisions, potentially minimizing various side effects. AI chatbots are expected to contribute to reducing unnecessary costs in the healthcare system by improving efficiency and reducing the need for additional consultations with doctors. However, the lowest scores categorized as "very inappropriate," "very insufficient," and "unable to provide as a response" accounted for 1–2% of the total evaluations. Although this is a small percentage, it does suggest that there is a potential risk that AI chatbots could provide completely incorrect medical information. This issue was similarly raised in other studies related to surgery, where AI provided mostly comprehensive answers (24). Concerns have been highlighted regarding ChatGPT's potential to deliver dangerously inaccurate information due to shortcomings in situational awareness and consistency (25). While ChatGPT exhibits promise in assisting and informing medical staff, it does not currently appear to be a complete replacement for medical professionals. Future research should focus on presenting scenarios rather than simple questions to evaluate the AI's ability to generate contextually appropriate responses and to assess the adequacy of the contextual information provided.

When considering whether AI chatbots can partially replace the role of healthcare professionals, besides the accuracy of the information provided, another crucial point of discussion is ethical issues. ChatGPT can collect and store personal health information while interacting with patients, potentially including sensitive medical data. Ensuring data security, monitoring, and implementing robust security measures would be essential for ChatGPT and healthcare institutions (26). The allocation of responsibility for the provided medical information is also important. Currently, there is a lack of supervision and standardization of the responsibility system for ChatGPT. It would be important to establish and apply relevant ethical regulations quickly, in addition to

1 https://openai.com/

detailed verification of the appropriateness of the information, to ensure the safe use of ChatGPT (27). When such protective measures are in place, the use of AI chatbot in the medical field can be meaningful.

4.1 Limitations of the study

There are several limitations in our study. First, despite a wide spectrum of surgery and anesthesia, our investigation focused on a specific subset of questions and the 30 questions we addressed may not cover the full range of potential patient inquiries. To comprehensively evaluate ChatGPT's medical knowledge in the expansive field of surgery and anesthesia, a more diverse set of questions might be necessary. Second, the 31 reviewers who conducted the evaluations were aware that they were assessing responses from ChatGPT, introducing a potential source of bias. This awareness could have influenced their scoring, making them more lenient or strict in their assessments. Future research should minimize bias by using blind evaluations that do not reveal the source of responses to evaluators. Third, comparison between human responses and ChatGPT's responses was not conducted to determine whether the AI chatbot could replace humans. However, it's important to note that when making such comparisons, variations in responses may be influenced by the level or expertise of the human respondents. Fourth, it is crucial to acknowledge that ChatGPT was not explicitly designed for medical purposes. This raises valid concerns about the reference sources for its responses and its coverage of the broad field of medicine. The model's general-purpose nature may limit its accuracy and relevance when providing medical information. Lastly, our study was conducted exclusively in English, and the applicability of our findings to different countries or linguistic contexts remains uncertain. The cultural and linguistic nuances inherent in medical information may vary across regions. Therefore, to enhance the generalizability of ChatGPT's performance, further comparative studies conducted in other languages are imperative. In the future, further research should be conducted on how much the patient's anxiety is reduced and how much the patient's information demand is satisfied by the medical information provided by ChatGPT.

5 Conclusion

Responses regarding anesthetic procedures generated by ChatGPT were overall appropriate, providing a somewhat insufficient to an average amount of information. Notably, responses from the latest version, 4.0, were deemed more accurate compared to the earlier version, 3.5. Moving forward, it is imperative to channel future efforts toward the development and enhancement of research models specifically designed to rigorously evaluate the utility of medical information delivered by AI chatbots.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

JC: Writing – original draft. AO: Writing – original draft. JP: Data curation, Methodology, Writing – review & editing. RK: Data curation, Writing – review & editing. SY: Writing – review & editing. DL: Data curation, Writing – review & editing. KY: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmed.2024.1400153/full#supplementary-material

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Listen to your heart: a critical analysis of popular cardiology podcasts

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Purpose: Podcasts are an increasingly popular medium for medical education in the field of cardiology. However, evidence suggests that the quality of the information presented can be variable. The aim of our study was to assess the quality of the most popular cardiology podcasts on existing podcast streaming services, using tools designed to grade online medical education.

Results: We analyzed the five most recent episodes from 28 different popular cardiology podcasts as of 20th of September, 2022 using the validated rMETRIQ and JAMA scoring tools. The median podcast length was 20 min and most episodes were hosted by professors, subspecialty discussants or consultant physicians (87.14%). Although most episodes had only essential content (85%), only a small proportion of episodes provided detailed references (12.9%), explicitly identified conflicts of interest (30.7%), described a review process (13.6%), or provided a robust discussion of the podcast's content (13.6%). We observed no consistent relationship between episode length, seniority of host or seniority of guest speaker with rMETRIQ or JAMA scores.

Conclusions: Cardiology podcasts are a valuable remote learning tool for clinicians. However, the reliability, relevance, and transparency of information provided on cardiology podcasts varies widely. Streamlined standards for evaluation are needed to improve podcast quality.

KEYWORDS
cardiology, medical education, cardiology podcasts, medical education podcasts, cardiology learning

Introduction

Podcasts are downloadable or streamable audio files that have become a popular medium for medical education (1–4). The convenience and ease through which information can be accessed have made podcasts an increasingly influential means of disseminating medical information. Accordingly, several prominent cardiology journals, cardiac societies, industry sponsors and universities regularly publish podcast episodes, with some podcasts reaching up to 84,000 episode-downloads per month (5).

Information accessed via podcasts can change the skillset and practice of listening clinicians (6). However, there are reports of variation in the quality of medical education podcasts by expert consensus (7, 8), and although several validated tools exist to assess medical education quality, there is currently no validated means by which to evaluate podcast quality. Without rigorous peer review, the translation of information obtained from podcasts into clinical practice may not be evidence-based.

The aim of our study was to assess the quality of the most popular cardiology podcasts on existing podcast streaming services, using tools designed to grade online medical education. Our *a priori* hypothesis was that the podcasts would score highly (>75%) among the rating scales, with podcasts from professional bodies being more likely to have a higher score.

Methods

Search method

We searched for cardiology podcasts, using the search term "cardiology" on September 30 2022, on the podcast directories, *Apple Podcasts* and *Spotify*. *Apple Podcasts* and *Spotify* were chosen as they are the world's two most used podcast platforms, accounting for 65.3% of all total listeners, with the next most used being the Web Browser which accounts for 3.5% of total listeners (9).

Inclusion criteria were any podcast with a title or author that explicitly mentioned "cardiology," "heart," or "cardiac." Exclusion criteria were: (1) the podcast had not released an episode within the last 2 years, (2) the podcast had <5 episodes, (3) the podcast was in video format, or (4) the podcast was not in English.

A consecutive sampling technique was used for both podcast directories. Podcast shows were screened in the sequence they appeared in the search results for "cardiology" on each respective platform, as of September 30 2022. The top 20 podcasts in each directory that met the inclusion criteria and demonstrated no exclusion criteria were compiled, then duplicate podcasts shows were removed. The five most recent episodes published up until September 30 2022 from the included podcast shows were retrieved and independently assessed by two authors.

Scoring tools

We assessed the podcasts using two validated scoring tools: The rMETRIQ Score and the Journal of American Medical Association (JAMA) core quality standards. The rMETRIQ score is a 7 part questionnaire that assesses an online resource with questions grouped into three broad domains: the content quality of delivery, credibility and review processes (7, 8, 10–12). Each question can receive a score between 0 and 3 and the tool specifies clearly demarcated requirements to achieve each score, with a total possible score of 21.

The JAMA Benchmark Criteria is a streamlined assessment of online medical information and requires publications to meet four fundamental standards: authorship, attribution, disclosure and currency. These criteria are precisely defined in the 1997 paper by Silberg et al. (13). The total JAMA benchmark score was determined by awarding 1 point for each criterion that was present, allowing a minimum score of zero and maximum of four points.

The aformentioned evaluation metrics (rMETRIQ and JAMA) are designed to objectively assess resources independent of subject matter expertise and thus did not require previous cardiology knowledge (10–13).

Adaptation of scoring tools to podcast format

The above tools were developed primarily for evaluation of web content. Given its audio format, implementing traditional forms of referencing can be challenging on a podcast. Accordingly, in the absence of explicit show notes with referencing, we accepted verbal citations that included year and author or the title of an article when discussing evidence in the podcast. Author disclosures and affiliations were also accepted in audio format. We searched for post-publication commentary in either *Apple Podcasts* or on the show's website. We also considered mention of feedback for a specific episode in the following episode as evidence of post-publication commentary.

Data collection

Two separate authors (HK & LH), a resident doctor and student doctor, respectively, evaluated the five most recent episodes from eligible podcasts using the rMETRIQ and JAMA instruments. We then generated mean scores for each tool. Authors did not confer with one another during the scoring process and were blinded to the scores applied by the other author. Authors were provided with information sheets about each scoring metric and were asked to submit each score using an online survey immediately after observing each episode. Variation between scores > 1 point were adjudicated by an external author not involved in the design of the study or data collection.

Additionally, we collected the following data for each podcast: date of publication, length of podcast, podcast producing body/affiliation, main theme discussed, seniority of the most senior speaker/content reviewer and the seniority of the host or content writer.

Statistical analysis

We visualized continuous variables by generating histograms, then confirmed their normality visually. We generated means with standard deviations for normally distributed variables, and medians with interquartile range (IQR) for skewed continuous variables. For categorical variables, we generated raw numbers and percentages. We did not adjust for confounding variables when presenting differences between podcast types, as our sample size was inadequately powered for this. We also examined the relationship between individual variables and both rMETRIQ scores as well as JAMA scores by conducting multiple linear regression and multiple logistic regression, respectively. Missing data was sought from Spotify/Apple Podcast databases; missing scoring data was confirmed through triangulated re-appraisals of episodes with three authors.

Finally, we calculated an intraclass correlation coefficient to evaluate the agreement between raters using the rMETRIQ and JAMA scales.

Results

This study searched for the top 20 cardiology podcast shows on two respective platforms, Spotify and Apple Podcasts, to evaluate their quality. After executing the search there were 11 duplicate shows that were present on both platforms and one show was excluded after being found not to be clinically focused (Figure 1). Thus, in total there were 28 Cardiology podcast shows which were elligible. The five most recent episodes from each show were retrieved, and so a total of 140 episodes were independently evaluated (Figure 1).

Podcast characteristics

The median episode length was 20 min. Episode length was highest among podcast episodes affiliated with universities or hospitals (see Table 1). Professors, subspecialty discussants and consultant physicians comprised most podcast hosts (87.14%) and were frequently the most senior discussants on an episode (88.57%). In contrast, doctors in training (registrars, fellows) comprised <6% of hosts and senior guests on podcast episodes.

rMETRIQ score

The mean rMETRIQ score was 13.1 (SD 3). Compared to episodes affiliated with hospitals or universities, episodes affiliated with journals ($b = 3.01$, 95% CI 1.7–4.3) or those that were unaffiliated ($b = 1.78$, 95% CI 0.46–3.1) had higher rMETRIQ scores. The rMETRIQ score difference between hospital/university and society affiliated episodes was non-significant ($b = 0.64$, 95% CI -0.74–2.03).

Less than half of all episodes provided adequate background information on the topics discussed and guided listeners to other sources of information (Table 1). This proportion was lowest among episodes affiliated with a society (9.7%). Eighty-five percent of episodes had only content that was essential, and 83% of episodes were well written and formatted in a way that optimized learning. Only 12.9% of episodes had references, either in show notes or verbally stated that mapped to specific statements within the podcast, or provided references for statements of fact that may not have been common knowledge. This was limited to a single episode among episodes affiliated with a hospital or university (OR −2.16, 95% CI −4.33 to −0.006). In other words, 87.1% of podcast episodes did not include references.

In more than two-thirds of episodes, the authors of the show were either not identified or conflicts of interest were not declared explicitly. Additionally, 86.4% of podcast episodes did not clearly describe the review process that was applied to the resource. At an equal rate of 86.4%, most podcast episodes failed to expand on their published content with robust post-publication commentary.

We observed no consistent relationship between episode length, seniority of host or seniority of guest speaker with rMETRIQ scores.

JAMA scores

Less than half of podcast episodes achieved a perfect JAMA score. Authorship was mentioned in 99.3% of episodes, and dates of content posting were provided in 98.6% of episodes. Sixty-three-point 6% of episodes provided clear references or sources, and 77.9% percent of episodes disclosed ownership and any sponsorship, underwriting or commercial funding. Episode length and seniority of speakers demonstrated no consistent relationship with the podcast's JAMA scores.

JAMA and rMETRIQ correlation

We observed a strong, positive linear relationship between rMETRIQ and JAMA scores, with a 2.5-unit rMETRIQ score increase for every unit increase in JAMA Score ($b = 2.56$, CI 1.93–3.18). However, 25% of episodes with a perfect JAMA score had rMETRIQ scores less than the mean.

rMETRIQ + JAMA

We observed a moderate to substantial inter-rater agreement among each of the rMETRIQ scoring items. Despite this agreement, inter-rater agreement on the final score was fair (kappa 0.36, SE 0.02). In contrast, interrater agreement on components of the JAMA score were near perfect (Kappa 0.94–1.00), except for currency (expected equivalent to chance).

Discussion

The popularity of podcasts as a remote learning tool for clinicians is rising, and this is one of the first studies to systematically assess the quality of English language podcasts published in the field of Cardiology.

We found that most podcast episodes were very well-written and formatted in a way to optimize learning. The podcasts we evaluated also seldom contained unnecessary, redundant, or missing content. We also observed that most episodes were delivered by content experts; in our study, professors, subspecialty discussants or consultant cardiologists led the discussion in the significant majority of episodes. Despite this expertise, we observed no association between the seniority of speakers or hosts and rMETRIQ or JAMA scores. This finding reinforces the work of a modified Delphi consensus study of 44 health profession educators by Lin et al., in which content expertise was not considered a vital quality indicator among medical podcasts (7). Based on these findings, listeners should not be discouraged from streaming content produced by healthcare professionals that are not attending physicians or professors of Cardiology.

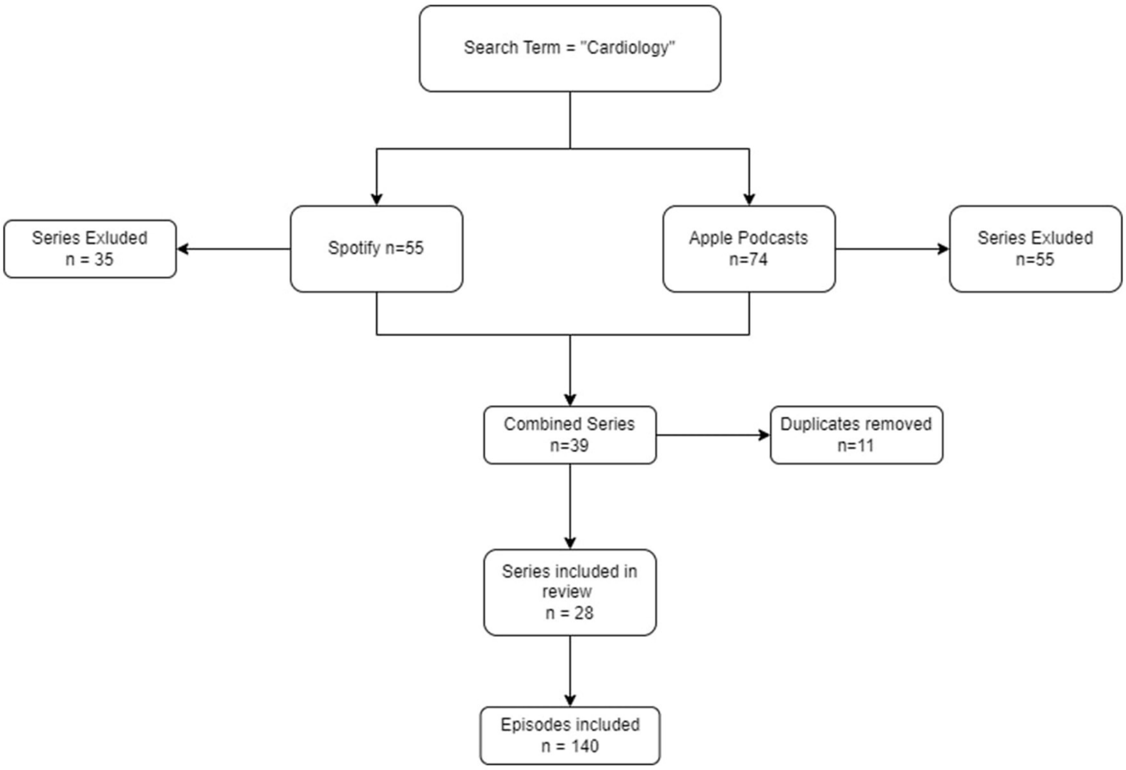

FIGURE 1
Flow diagram of cardiology podcast series inclusion and exclusion.

Our findings also showed that longer episode duration was not associated with improved podcast quality. Evidence from a recent scoping review of podcasts in medical education by Kelly et al. and data from Cosimini et al. suggests that residents and medical students consistently prefer podcast episodes between 5 and 15 min, with longer lengths serving as a barrier to uptake for listeners (6, 14). Taken together, these findings suggest that cardiology podcast producers can aim for shorter podcast episode lengths and increase audience accessibility, without sacrificing quality.

Additionally, our study also identified several important areas where popular cardiology podcasts could improve; only one out of 140 episodes scored a perfect rMETRIQ score whilst <½ of all episodes scored a perfect JAMA score. Less than half of podcast episodes provided sufficient background information to situate the listener *and* directed listeners to other valuable resources to the topic. Situating a listener in the broader context of a discussion is important to improve understanding and maximize engagement (12, 15). References to alternative, related material also enhances comprehension, particularly among listeners without expertise in the subject matter (4, 16). Providing essential background information may facilitate podcast material uptake, particularly among novice listeners.

Referencing was also limited in the episodes we evaluated. Some form of referencing was present in under two thirds of episodes (JAMA Attribution = 63.6%), but using the rMETRIQ tool, we found that only 12.9% of podcast episodes provided references that clearly mapped to specific statements made within the episode and provided references for statements of fact that were not common knowledge. Compared to traditional modes of medical education, the podcast format is unique in the way it facilitates both instant dissemination of information and discussion. However, statements of opinion can unintentionally be presented as statements of fact (16). Clear referencing of statements of fact not considered common knowledge is necessary to prevent listeners from conflating the two, especially among topics under active debate within cardiology.

Our study also found that evidence of peer review and post-publication commentary was limited. Only 13.6% of episodes we evaluated provided a review process *and* evidence of its application to the specific episode. Subjecting scientific discussion to peer-review is vital to identify factual errors, provide alternate points of view and identify any inherent biases within the discussion (16). Additionally, only 13.6% of episodes also provided evidence of a robust discussion of the episode's content that expanded upon the content of the episode. These findings may be due to the logistical challenges of facilitating robust discussion from listeners on a podcast. However, given that most podcast episodes provided avenues for listeners to leave feedback, discussion and exploration of this feedback may reinforce the resource's trustworthiness and enhance uptake (7, 17).

Finally, statements of authorship were almost universally present (JAMA Authorship, 99.3%), and statements regarding commercial funding were disclosed in over three quarters of episodes (JAMA Disclosures = 77%). However, statements

TABLE 1 Characteristics of cardiology podcasts.

	Cardiac society (n = 31)	Unaffiliated individuals or group (n=38)	Journal (n = 40)	Hospital or university (n = 31)	Mean (SD), median (IQR),* or number (%)
Episode length (mins)	12.7 (14.3)	19.1 (31)	18.6 (11.1)	30.6 (42.2)	20 (19)
Host					
Professor or expert	21 (24.1)	15 (17.2)	26 (29.9)	25 (28.7)	87 (62.1)
Consultant	7 (20)	10 (28.6)	13 (37.1)	5 (14.3)	35 (25)
Other	3 (100)	0 (0)	0 (0)	0 (0)	3 (2.1)
Fellow	0 (0)	4 (80)	1 (20)	0 (0)	5 (3.6)
Registrar	0 (0)	4 (100)	0 (0)	0 (0)	4 (2.9)
Not disclosed	0 (0)	5 (83.3)	0 (0)	1 (16.7)	6 (4.3)
Most senior speaker					
Professor or expert	25 (24.8)	21 (20.8)	29 (28.7)	26 (25.7)	101 (72.1)
Consultant	5 (21.7)	7 (30.4)	7 (30.4)	4 (17.4)	23 (16.4)
Allied health professional	1 (100)	0 (0)	0 (0)	0 ()	1 (0.71)
Fellow	0 (0)	1 (50)	1 (50)	0 (0)	2 (1.4)
Registrar	0 (0)	4 (57.1)	3 (42.9)	0 (0)	7 (5)
Not disclosed	0 (0)	5 (83.3)	0 (0)	1 (16.7)	6 (4.3)
rMETRIQ scores	12.3 (3.2)	13.4 (2.7)	14.6 (2.7)	11.6 (2.5)	13.1 (3)
Perfect rMETRIQ scores					
Background information	3 (9.7)	21 (55.3)	27 (67.5)	16 (51.6)	67 (47.9)
Content fits length	24 (77.4)	34 (89.5)	39 (97.5)	22 (71)	119 (85)
Writing and formatting	26 (83.9)	32 (84.2)	36 (90)	23 (74.2)	117 (83.6)
Reference citation	7 (22.6)	4 (10.5)	6 (15)	1 (3.2)	18 (12.9)
Authors and conflicts	8 (25.8)	12 (31.6)	19 (47.5)	4 (12.9)	43 (30.7)
Editorial and peer review	4 (12.9)	7 (18.4)	8 (20)	0 (0)	19 (13.6)
Post-publication commentary	4 (12.9)	6 (15.8)	8 (20)	1 (3.2)	19 (13.6)
JAMA scores					
Authorship	31 (100)	37 (97.4)	40 (100)	31 (100)	139 (99.3)
Attribution	18 (58.06)	31 (81.6)	31 (77.5)	9 (29)	89 (63.6)
Currency	31 (100)	36 (94.7)	40 (100)	31 (100)	138 (98.6)
Disclosures	18 (58.06)	25 (65.8)	37 (92.5)	29 (93.6)	109 (77.9)
JAMA perfect score	11 (35.5)	19 (50)	28 (70)	8 (25.8)	66 (47.1)

regarding the presence or absence of any conflict of interest *related to hosts or guests* were present in less than a third of podcast episodes as observed using the rMETRIQ tool (30.7%). This is an important finding, as we found that most podcasts are hosted by, or have guests that are, content experts. Content experts may be affiliated with industry (16, 18) and mention of these affiliations is important to contextualize unintentional bias inherent in the presented points of view.

Our *a priori* hypothesis was that cardiac societies would produce podcasts with higher rMETRIQ and JAMA Scores. Our findings do not support this hypothesis. Cardiac societies frequently produce peer-reviewed, evidence-based guidelines that often determine standards of care in cardiology (19). We hypothesized that this experience would translate into the production of well-produced, reliable and unbiased medical education content designed to promote evidence-based therapy among podcast listeners. However, compared to episodes from journals or episodes that were unaffiliated, cardiac society episodes scored lower rMETRIQ scores on average (vs. Journal β: −2.70, 95% CI: −3.99 to −1.42; vs. Unaffiliated β: −1.91, 95% CI: – 3.24 to −0.58;). This was mainly driven by differences in background information, mention of conflicts of interest, evidence of peer review and demonstration of post-publication commentary. We observed no other association between episode length, seniority

TABLE 2 Kappa statistic of inter-rater agreement between individual JAMA items and total score.

	Agreement (%)	Expected (%)	Kappa	Std. Err.
Authorship	100	98	1.00	0.08
Attribution	97	53	0.94	0.08
Currency	97	97	0.00	0.08
Disclosures	98	64	0.94	0.08
Total	97	42	0.95	0.06

TABLE 3 Kappa statistic of inter-rater agreement between individual rMETRIQ items and total score.

rMETRIQ item	Agreement (%)	Expected (%)	Kappa	Std. Err.
Item 1	73	40	0.55	0.06
Item 2	91	69	0.72	0.08
Item 3	87	65	0.63	0.08
Item 4	82	27	0.76	0.05
Item 5	78	41	0.63	0.06
Item 6	88	61	0.69	0.06
Item 7	86	29	0.81	0.05
Overall	42	9	0.36	0.02

of host or seniority of guest with our outcome measures (data not presented).

Our study has also highlighted the strengths and weaknesses of the rMETRIQ and JAMA tools in evaluation of podcasts. Both tools were correlated in our study, with a 2.5-unit rMETRIQ score increase for every unit increase in JAMA Score (b = 2.56, CI 1.93–3.18). However, both tools demonstrated important limitations. For instance, the JAMA tool failed to interrogate important aspects of podcast quality evaluated by rMETRIQ, such as background information, appropriateness of content for length, writing and formatting, peer-review, and post-publication commentary. Even in areas of overlap, the JAMA score was generous; in our study, 25% of episodes with perfect JAMA scores had rMETRIQ scores less than the mean (13.1). We also found the currency metric of the JAMA score to be redundant, as podcast providers automatically display the dates of publication for a given episode. Despite these limitations, we found that the JAMA score is an easy, reliable (Table 2), four-step tool that a listener can rapidly apply to gauge the quality of an episode. Although the rMETRIQ tool interrogates important aspects of a podcast, it can be time consuming, and as we have shown, has lower inter-rater reliability (Table 3). In fact, our rMETRIQ scores represented optimistic scoring; where scores did not match, a third author adjudicated the final rMETRIQ score for each episode. In 10% of cases, the final score was different to the scores generated by each of the first two authors, and in all these cases, the final score was higher. Our results suggest that neither the rMETRIQ or JAMA rating tool is perfect, and a gap in the literature exists for the development of a validated medical podcast rating tool that is reliable and conveniently applied.

Strengths and limitations

Our study has some limitations. Firstly, the podcasts evaluated were limited to English language podcasts published on *Spotify* and *Apple Podcasts*. An important limitation of this approach is that the *Spotify* and *Apple Podcasts* search algorithm return podcasts in order of relevance according to the user's profile to reproduce typical user behavior (20, 21). This means that at the time of search, behavioral data and engagement data influenced the cardiology shows displayed for any given search term, by any given consumer. To mitigate this issue, we replicated the search among two independent investigators and removed duplicates. We chose this search strategy to emulate real-world practices in podcast consumption but recognize that this may have yielded fewer podcasts for analysis. A further limitation is that the rMETRIQ and JAMA tools were generated for critical appraisal of written publications; in the absence of existing tools to evaluate podcasts, we opted to use these scoring systems given their extensive use in the literature with audio-visual and scripted formats (22–24) formats. Finally, a lack of publicly available data on podcast downloads prevented us from analyzing how podcast quality relates to listenership.

Despite these limitations, there are important strengths to our study. This study is among the first to apply critical appraisal using validated instruments to medical content in cardiology podcasts. In doing so, we provide a clear framework through which listeners can evaluate the quality of the content they consume prior to implementing this information in clinical practice. Our study also engaged authors to conduct analyses independently to avoid inadvertent bias in scoring, with engagement of a third, external author to adjudicate inconsistencies in scoring. This was done to maximize reliability and reproducibility among scoring estimates. Finally, our methodology employed a pragmatic, real-world approach to searching for and consuming medical content, designed to emulate the experience of busy clinicians and students searching for medical education.

Conclusion

Cardiology podcasts are becoming increasingly popular and have potential to influence clinical decisions worldwide. Contrary to our hypothesis, the quality of cardiology podcasts varies widely and those produced by professional bodies did not necessarily achieve higher scores on tools designed to assess online medical education. Producers should strive to increase transparency of the review process and the evidence-base driving their discussions. Future research in this area should focus on developing streamlined criteria for evaluating the quality of podcasts. Ultimately, cardiology podcasts remain a valuable remote learning tool for clinicians. Our study has identified important deficits in their evaluation and provide a framework for future efforts to ensure their reliability, relevance and transparency.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HK: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. LH: Conceptualization, Investigation, Writing – review & editing. SB: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. WM: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. AZ: Data curation, Writing – review & editing. FS: Writing – review & editing. JK: Writing – review & editing. AG: Conceptualization, Methodology, Writing – review & editing. PP: Supervision, Writing – review & editing. PK: Writing – review & editing.

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Assessing the knowledge, attitude and perception of Extended Reality (XR) technology in Pakistan's Healthcare community in an era of Artificial Intelligence

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Background and objectives: The Extended Reality (XR) technology was established by combining elements of Virtual Reality and Augmented Reality, offering users the advantage of working in a virtual environment. The study aimed to evaluate medical professionals' and students' knowledge, attitudes, and practices regarding using XR technology in Pakistan's healthcare system and identify its benefits, drawbacks, and implications for the system's future.

Methodology: A cross-sectional study was executed by circulating a self-structured online questionnaire among the Medical Community across Major Cities of Pakistan using various social media platforms as available sampling. The sample size was calculated to be 385 using RAOSOFT. Cronbach's alpha was calculated as 0.74. The Exploratory Factor Analysis (EFA) conducted on the dataset was validated using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.752 indicates adequate sampling, and Bartlett's Test was significant (χ^2 (435) = 2809.772, $p < 0.001$), confirming the suitability of the data for factor analysis. Statistical analysis was done using SPSS-25, and data description was done as frequency and percentage. Pearson correlation and regression analysis kept p-value < 0.05% significant.

Results: Approximately 54.8% of 406 participants conveyed their familiarity with XR technologies. The majority of participants (83.8%) believed that using XR technology effectively enhanced medical education and patient care in Pakistan. Regarding clinical outcomes, 70.8% believed XR improved the efficiency of procedures and 52.8% agreed XR would lead to more device-dependent systems and eradicating human error (32.4%). Major barriers to XR integration included ethical and privacy issues (63.9%), lack of technological advancements in Pakistan (70%), and lack of ample knowledge and training of XR among health care professionals (45.8%). Hypothesis testing revealed a low positive but significant correlation between the use of AI-based healthcare systems and the increasing speed and accuracy of procedures ($r = 0.342$, $p < 0.001$), supporting Hypothesis 1. Similarly, a very low positive yet significant correlation was observed between the augmentation of diagnostic and surgical procedures and addressing data security and ethical issues for implementing XR ($r = 0.298$,

$p < 0.001$), supporting Hypothesis 2. Lastly, a correlation between the mean Attitude (MA) score and the mean Perception (MP) score was found to be moderately positive and significant ($r = 0.356$, $p < 0.001$). Hence, the hypothesis 3 was supported.

Conclusion: XR technology has the potential to enhance medical education and patient care in Pakistan, but its adoption faces significant challenges, including ethical concerns, technological gaps, and inadequate training. The study's findings highlight the need to address these issues to maximize the benefits of XR in healthcare.

KEYWORDS

extended reality (XR), virtual reality (VR), augmented reality (AR), mixed reality (MR), medical education, healthcare, artificial intelligence (AI)

1 Introduction

Extended reality, which includes virtual reality, augmented reality, and mixed reality, revolutionizes people's lives by enabling collaboration between real and virtual elements. It bridges the gap between the physical and virtual worlds (1–4). In the field of clinical care and medical education, all three extended reality technologies have the potential to bring about significant changes. Mixed reality, for instance, can enhance understanding of complex surgical procedures, anesthesia, and medications. Additionally, augmented reality can generate three-dimensional holograms from MRI scans to assist in neurological procedures and stereotactic processes (5–7).

To fully comprehend the impact of enhanced simulation and extended reality on medical education and healthcare systems, high-quality studies are needed (8, 9). Furthermore, educational reforms are necessary to equip medical students and trainees with the skills needed to tackle real-world challenges. Public health education can also benefit from extended reality, as it offers a comprehensive learning experience and promotes competency in investigating public health issues and managing infectious diseases (10–12).

To address the gaps in utilizing extended reality, a workshop was organized to evaluate operational techniques. Further research is required to explore how XR technologies can be used for the diagnosis and treatment of diseases (13, 14). An integrative review of articles focusing on extended reality in the field of medical education revealed that XR technology, including virtual reality and augmented reality, is as effective as traditional teaching methods in improving learning outcomes and patient care (15–22). While extended reality has the potential to transform various aspects of life, there is a lack of well-documented literature on how XR technology should be integrated into the healthcare system (23). Currently, there is insufficient research on the implementation of XR technologies in medical education, despite their world-changing potential (24).

Extended Reality is an unstoppable force and we should be improving our teaching methods to adapt to this change. These technologies serve clinical care by offering, psychological assessment (25–27), telehealth services (28), visualizations (29), nutritional guidance (30) and communication capabilities. Utilizing 3D capabilities, applications are designed for teaching and pre-operative planning purposes. Extended reality has showcased its effectiveness during interventional procedures by offering 3D visualizations of patient anatomy, scar visualization, and real-time catheter tracking using touch-free software control. Extended reality devices find applications in education, pre-procedural planning, and cardiac interventions (31–33). Advancements in hardware and software are propelling the expansion of XR-assisted surgery. While augmented virtuality and mixed reality remain relatively unexplored, VR utilization is increasing, particularly in surgical training and pre-operative preparation. With the impact of COVID-19 restricting physical interaction and surgical procedures becoming more complex, XR-assisted surgery is poised to assume a larger role soon (34–39).

Extended Reality has also widened the horizons of visualization capabilities, particularly with microscopic images, molecular data, and anatomical datasets. An example of such advancement is the Google AR Microscope (ARM) system, which consists of an augmented bright-field microscope, a computer, and a set of trained deep-learning algorithms. This innovative system has proven to assist pathologists in reducing the time needed to scan multiple images to detect the presence of cancer (40).

As XR technology rapidly evolves, it becomes essential to evaluate healthcare professionals' current awareness and comprehension levels regarding these advancements. In response to this necessity, we conducted an extensive survey to measure the familiarity and knowledge of XR technology within the healthcare workforce.

Hypotheses:

1. There is a significant relationship between the "Use of AI-based healthcare systems" and the "Perceived increase in the speed and accuracy of procedures."
2. A correlation exists between the "Perceived augmentation of diagnostic and surgical procedures" and concerns related to "Addressing data security and ethical issues for implementing XR."
3. A correlation exists between the "level of medical education" and the "mean Attitude (MA) score and the mean Perception (MP) scores".

2 Subjects and methods

2.1 Type of study, sample size, and sampling

A descriptive cross-sectional study was conducted by administering a structured self-administered questionnaire among the Medical Community in 2023. The STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) checklist was employed in this study to enhance the quality and transparency of reporting. As this is a descriptive, observational study, the STROBE checklist provides a structured framework that ensures all critical components of the study design, data collection, analysis, and interpretation are thoroughly addressed. These elements ensure clarity, completeness, and transparency in reporting observational studies. By using this checklist, we aimed to minimize potential biases, improve the reproducibility of our findings, and ensure that our study meets the highest standards of scientific rigor and clarity. A standard sample size of 385 was selected through Raosoft for a nationwide study.

2.2 Study implementation

An online questionnaire to obtain wide coverage and a larger sample was distributed among the Medical Community across 9 major and most developed Cities of Pakistan using various Social Media platforms. These cities included Karachi, Lahore, Faisalabad, Rawalpindi, Islamabad, Multan Peshawar, Abbottabad and Muzzafarabad which represent all regions (provinces and territories) of Pakistan. Medical Students, House Officers, Medical Officers, Postgraduate Trainees, Professors, Specialists, and Consultants from all across Pakistan were included in the study. The duration of completing the questionnaire was 10–15 min.

2.3 Data collection

Knowledge, Attitude and Perception were dependent variables while socio-demographic characteristics (age, education, gender, residence and city) were independent variables. The questionnaire included sections on demographic characteristics such as gender, area of residence (rural or urban), level of medical education, major cities, and age. The questionnaire was divided into three main sections: Knowledge (9 questions), Attitude (9 questions), and Practice (11 questions). It incorporated a variety of question types, including closed-ended questions with binary responses (Yes/No/Maybe), Likert scale items (ranging from "Effective" to "Slightly Ineffective"), and multiple-choice questions offering several response options. The instrument was developed by reviewing similar studies and was modified to align with the specific context of this study. This approach ensured that the questionnaire was both comprehensive and relevant to the current research objectives.

To ensure the validity and reliability of the data collection instrument, we employed two key strategies, content validity and pilot testing. Content validity was established through expert review, where subject matter experts in XR technology, medical education, and research methodology evaluated the questionnaire to confirm that it comprehensively covered the relevant topics. Their feedback was used to refine and adjust the questionnaire, ensuring that it accurately reflected the constructs of interest. Additionally, a pilot test was conducted with a small sample of participants (20) and Cronbach's α was calculated as 0.74. This pre-testing phase provided valuable insights into the clarity, relevance, and comprehensiveness. Based on the feedback obtained, necessary modifications were made to improve the questionnaire. These validation steps collectively ensured that the instrument was well-suited for capturing the intended data and provided reliable measures for the study. Additionally, The Exploratory Factor Analysis (EFA) conducted on the dataset was validated using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.752 indicates adequate sampling, and Bartlett's Test was significant ($\chi^2(435) = 2809.772$, $p < 0.001$), confirming the suitability of the data for factor analysis. Eight factors were extracted, explaining 54.13% of the total variance. Several key variables showed strong commonalities. These findings suggest a robust factor structure, supporting the validity of the constructs measured.

Data was collected through different social media platforms using a convenient sampling technique from 1st August to 30th September 2023. 406 responses were collected from the online survey (41–44). Participants filled out an online self-structured questionnaire containing 35 questions related to research problems.

2.4 Statistical analysis

The questionnaire was designed in a way to avoid all kinds of bias. Data was entered and transferred to Statistical Package for Social Sciences version 25 for analysis. We computed frequencies and percentages for all the categorical variables. Pearson Correlation and Regression analysis were applied to covariate the knowledge and perception with attitude variables.

2.5 Ethical approval

Ethical approval was obtained from the Ethical Review Committee of the Azad Jammu and Kashmir Medical College, Muzaffarabad. Moreover, consent was also taken from the participants at the start of the online questionnaire, ensuring the safety and confidentiality of the information they were given.

3 Results

3.1 Demographic information

The survey garnered a robust response, with a total of 406 participants contributing their valuable insights. Table 1

TABLE 1 Demographic characteristics (n = 406 HCWs).

Contents				Frequency	Yes %
Gender					
Female				185	45.5
Male				221	54.3
Area					
Rural				48	11.7
Urban				359	88.2
Level of medical education					
House Officer				18	4.4
Medical Officer				32	7.9
Medical Student				316	77.6
Post-Graduate Trainee				16	3.9
Professor/Specialist/Consultant				25	6.1
Major cities					
Muzzafarabad				84	20.7%
Rawalpindi/Islamabad				77	19.0%
Karachi				63	15.5%
Others				62	15.3%
Multan				24	5.9%
Lahore				60	14.8%
Abbottabad				12	3.0%
Peshawar				19	4.7%
Faisalabad				5	1.2%
Age	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Age of respondents	406	17	70	24.41	8.109

elucidates the gender distribution, age of respondents, level of education, area of residence and city of work. A predominant proportion of respondents identified as male, comprising 54.43% (n = 221), while 45.57% (n = 185) represented the female cohort. A substantial majority hailed from urban settings, constituting 88.2% (n = 359. The mean age emerged as 24.41 years. The lion's share, amounting to 77.6% (n = 316), identified as medical students. Muzzafarabad emerged as the most prominently featured city, boasting 20.7% (n = 84) of the respondents.

3.2 Knowledge

The data shows that among the total participants, 67.7% were knowledgeable about Artificial Intelligence. About 51.2% expressed strong support for the integration of extended reality (XR) into the healthcare system. Improved patient education, therapy and management (47%) and simplified hospital navigation (44.6%) were identified as the foremost healthcare domains for utilizing extended reality (XR). Additionally, 42.61% believed it contributed to a decrease in risk during medical procedures, while 38.67% saw its value in providing limitless medical practice opportunities and personalized learning experiences for medical students. Table 2 sheds light on the mentioned knowledge information.

3.3 Attitude

48% viewed the inclusion of extended reality (XR) in Pakistan's healthcare system as a significant advancement. 80.6% of respondents believe XR technology is as effective as traditional techniques, followed by 78.6% expressing confidence in its potential to enhance medical education. Moreover, 70.8% anticipate that incorporating AI into the system will lead to faster and more accurate medical procedures. Further details on participants' attitudes towards XR technology in healthcare are presented in Table 3 below.

3.4 Perception

Some perception questions with responses are shown in Table 4. A (61.9%) express the importance of integrating AI-based healthcare systems post-COVID-19. Notably, 83.8% anticipate XR technology as the future of healthcare in resource-limited

TABLE 2 Knowledge of HCWs regarding XR technology (n = 406).

Variable		Percent
Familiarity of Healthcare professionals with XR Technology in healthcare	Heard of it but not sure about the details	54.8
	Not familiar at all	35.3
	Very familiar	9.8
How would you rate the effectiveness of XR technology in enhancing medical education and patient care?	Effective	51.1
	Ineffective	2.2
	Neutral	20.1
	Slightly effective	21.4
	Slightly ineffective	4.9
Where have you heard about Artificial Intelligence?	Conversations with family and friends	3.9
	Educational Institute	8.8
	News articles or Websites	9.8
	Social Media Platforms (e.g., Facebook, Instagram, Twitter etc.)	67.6
	Tech Conferences or events	4.7
	TV shows or Documentaries	5.2
Healthcare domains for utilizing extended reality (XR)	Improved patient education, XR assistive therapy and management	47.0%
	Augmented diagnosis and surgeries	18.0%
	Simplified hospital navigation	44.6%
	Medical education and research	15.0%
	Pharma marketing and advertising	0.0%
Benefits of integrating XR in healthcare.	Capable of telemedicine practice	21.7%
	Education and improved care for patients	51.0%
	Collaborative environments	22.4%
	Unlimited practice and personalized learning for students	38.7%
	Lower risk and higher understanding	42.6%
Is there any ethical limitation regarding XR technology in healthcare system?	No	24.0%
	No idea	35.1%
	Yes	40.8%
Can XR be used to improve the healthcare system, for advancements in medical field.	May be	17.6%
	No	2.7%
	Yes	79.6%
Do you know any organization or hospital using XR technology in Pakistan?	No	72.2%
	Yes	27.8%
Have you personally used any XR technology in medical education purpose?	No	84.0%
	Yes	16.0%

developing countries. Furthermore, 70.5% consider XR as cost-effective, supporting remote health services, while 70% believe it can minimize delays in network communication. Conversely, a minority (32.4% and 29.2%) holds concerns about XR potentially increasing medical errors and replacing doctors' in future healthcare systems. A significant majority of 83.8% anticipate XR technology as the future of healthcare in resource-limited developing countries. Participants identified high costs (67.73%) as the most potential barrier to the integration of Extended Reality into Pakistan's healthcare system.

3.5 Correlation analysis

> Hypothesis 1: Pearson product correlation between the "Use of AI-based healthcare system" and "Increasing speed and accuracy of procedures" was found low positive but significant ($r = 0.342$, $p < 0.001$). Hence, hypothesis 1 was supported (Table 5).

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TABLE 3 Attitude of HCWs regarding XR Technology (n = 406).

Variable		Percent
Do you believe that XR technology can improve medical education and training?	May be	17.2%
	No	4.2%
	Yes	78.6%
Do you consider XR technology to be as effective as traditional techniques for the healthcare system?	May be	0.2%
	No	19.2%
	Yes	80.6%
Do you think procedures will be faster and more accurate by incorporating AI into the systems?	May be	18.9%
	No	10.3%
	Yes	70.8%
Do you think revolutionizing the systems with XR technology would be more device-dependent rather than operator-dependent?	May be	26.5%
	No	20.6%
	Yes	52.8%
Are you concerned about ethical and privacy issues XR technology would raise?	May be	0.2%
	No	35.9%
	Yes	63.9%
Do you think adopting XR technologies reduces the transmission of infectious diseases?	May be	23.8%
	No	19.7%
	Yes	56.5%
Do you think XR technology will affect/limit doctor-patient interaction would lead to skepticism and legal issues?	May be	29.5%
	No	22.3%
	Yes	48.2%
Do you believe that it would promote a remote working environment in healthcare systems?	May be	19.9%
	No	11.7%
	Yes	68.3%
What are your views about incorporating XR technology in your medical practice or studies?	Insignificant	0.7%
	Neutral	16.7%
	Not much	4.2%
	Significant	48.4%
	Somewhat possible	30.0%

Hypothesis 2: Pearson product correlation between "Augmentation of diagnostic and surgical procedures" and "Addressing data security and ethical issues for implementing XR" was found to be very low positive but significant (r = 0.298, $p < 0.001$). Hence, hypothesis 2 was supported (Table 6).

Hypothesis 3: Pearson product correlation between the mean Attitude (MA) score and the mean Perception (MP) score was found to be moderately positive and significant (r = 0.356, $p < 0.001$). Hence, the hypothesis 3 was supported (Figure 1).

3.6 Regression analysis

The hypothesis tests if knowledge and perception factors have a significant impact on the attitude of healthcare professionals. The dependent variable recommendation and implication of XR technology in institutions were regressed on predicting variables high cost of XR technology, adopting new systems of healthcare would replace doctors in future, the scope of XR technology in enhancing medical curriculum, patient care, data security and ethical considerations, procedures will be revolutionized by incorporating AI into the systems, adopting AI-based healthcare system is integral after COVID-19 to test the hypothesis. The above-mentioned variables significantly predicted that the overall model is statistically significant [$F(6, 399) = 3.390$, $p = 0.003$]. This suggests that at least one of the predictors has a significant effect on the likelihood of recommending XR technology in healthcare.

Hypothesis H1 is the relationship between the belief that new healthcare systems would replace doctors in the future and the likelihood of recommending XR technology. The adoption of new systems of healthcare that would replace health professionals in future can play a significant role in implementing XR (b = 0.180, p = 0.0001). The coefficient is statistically significant (p = 0.0001), indicating a positive and significant impact on the likelihood of recommending XR technology.

Hypothesis H2 is that adopting AI-based healthcare systems is integral after COVID-19 and the likelihood of recommending XR technology. The adoption of AI-based healthcare systems after COVID-19 is statistically important in implementing the XR technology (b = 0.124, p = 0.013). The coefficient is statistically significant (p = 0.013), suggesting a potential positive influence on the likelihood of recommendation.

Hypothesis H3 is the belief that procedures will be faster and more accurate with AI incorporation and the likelihood of recommending XR technology. Lastly, healthcare procedures will be faster and more accurate by incorporating AI into the systems plays a significant role in implementing XR (b = −0.146, p = 0.088). The coefficient is marginally significant (p = 0.088), indicating a possible but not fully established impact on the likelihood of recommending XR technology (Table 7 shows the summary of the findings).

4 Discussion

The integration of Extended Reality (XR) technology in healthcare is becoming increasingly significant, especially within the context of artificial intelligence (AI). In this study, 54.43% of the participants were male, while 45.57% were female. However, in Jordan, it was found that 63.8% were female and 36.2% were male with a median age of 21 (range 21–22) as compared to ours mean age emerged as 24.41 years, accompanied by a standard

TABLE 4 Perception of HCWs related XR Technology ($n = 406$).

Variable		Percent
Do you think adopting AI based healthcare system is integral after COVID-19	May be	23.5%
	No	14.5%
	Yes	61.9%
Do you want to see XR technology as future of healthcare in developing countries like Pakistan with limited healthcare resources?	May be	0.2%
	No	16%
	Yes	83.8%
Do you think XR relatively increases chances of medical error?	May be	32.5%
	No	35.1%
	Yes	32.4%
Do you think the delay in network communication (3G, 4G) can be a limitation in adopting this system?	May be	20.3%
	No	9.6%
	Yes	70%
Do you think, XR technology would be cost-effective and promote remote health services?	May be	0.2%
	No	29.2%
	Yes	70.5%
Do you think adopting new systems of healthcare would replace doctors in future?	May be	21.8%
	No	48.9%
	Yes	29.2%
How do you perceive the adaptation of XR technology in healthcare?	Cutting-edge and transformative	20.1%
	Neutral - neither positive nor negative	24.6%
	Not convinced of its benefits at all	3.7%
	Promising but needs further development	42.0%
	Skeptical about its practicality	9.6%
Barriers perceived	High costs of XR equipment	67.7%
	Limited access to XR technology	47.8%
	Lack of evidence-based research supporting XR in healthcare	38.9%
	Concerns about patient acceptance and safety	40.6%
	Lack of knowledge/training on XR usage	45.8%
	Uncertainty of its benefits over traditional methods	0.0%
Significantly benefited areas within the healthcare sector.	Medicine (neurology, cardiology, pediatrics, dermatology, ophthalmology etc.)	45.8%
	Basic Sciences and Research	32.5%
	Gynecology and Obstetrics	18.2%
	Surgery (neurosurgery, plastic surgery, and orthopedics etc.)	65.3%
	Radiology	48.5%
Essential factors for successful XR implementation in healthcare.	Cost-Effectiveness	61.8%
	Remote Patient Monitoring and Telemedicine	27.3%
	Healthcare Professional Training and Infrastructure	56.9%
	Patient Acceptance and Education	44.1%
	Data Security and Ethical Considerations	36.5%

(Continued)

TABLE 4 (Continued)

Variable		Percent
How likely are you to recommend the use of XR technology to your colleagues or institution for healthcare applications?	Likely	37.1%
	Neutral	29.5%
	Unlikely	4.2%
	Very likely	27.0%
	Very unlikely	2.2%

TABLE 5 Correlational analysis.

	Level of Medical Education	Enhancing medical education and patient care	Increasing speed and accuracy of procedures using AI	Use of AI based healthcare system after COVID-19	XR will replace doctors in future	Recommending use of XR technology
Level of Medical Education	1					
Enhancing medical education and patient care	−0.128**	1				
Increasing speed and accuracy of procedures using AI	0.027	−0.220**	1			
Use of AI-based healthcare system after COVID-19	0.032	−0.100*	0.342**	1		
XR will replace doctors in future	0.033	−0.055	0.142**	0.190**	1	
Recommending the use of XR technology	0.137**	−0.064	−0.001	0.124*	0.180**	1

"*" means correlation is significant at 0.05, "**" means correlation is significant at 0.01.

deviation of 8.109 and a range spanning from 17 to 70 years. Our study's participant age range is notably broader, which could imply varying levels of familiarity and comfort with emerging technologies across different age groups. This statistical portrait paints a picture of a relatively youthful participant pool (45). The occupational affiliations of the respondents in our study yielded an intriguing panorama. The majority amounting to 77.6% (n = 316), identified as medical students as compared to the above-mentioned study having medicine/dentistry (47.6%) suggests that the integration and acceptance of XR technologies might differ based on the specific medical training and exposure levels. These comparative insights underscore the necessity of tailoring XR technology integration strategies to the unique demographic and occupational characteristics of target populations. As the healthcare sector increasingly adopts AI and XR technologies, understanding these nuances will be critical in ensuring effective implementation and maximizing the potential benefits of these innovations.

Our results uncovered that a substantial majority 54.9% were cognizant of XR technology, but their grasp of its practical applications in healthcare was restricted as shown in Table 2. This gap in knowledge highlights the necessity for more focused educational initiatives to bridge the divide between general awareness and practical application. Comparatively another study in Middle East showed that a significant proportion of participants claimed not to understand the basic computational principles of AI (365, 41.7%). Merely a small subset of 10% demonstrated a comprehensive understanding of the potential advantages and implementation approaches of XR technology across diverse healthcare settings, while 34.4% of respondents exhibited no awareness at all underscoring the importance of increasing exposure and education around these innovations. This is concerning, as it points to a need for more targeted educational efforts to ensure healthcare professionals can effectively harness these technologies. 67.7% were knowledgeable about Artificial Intelligence as they predominantly gather information about AI through social media platforms like Facebook, Instagram, and Twitter, followed by sources such as news articles, videos, TV shows, documentaries, tech conferences or events, and discussions with family and friends as compared to the above mentioned study as familiarity with AI nomenclature, the majority of participants were familiar with algorithms (461 and 52.7%). These results underscore a varied and comprehensive approach to acquiring AI knowledge, underscoring the significant influence of social media as a primary information source and its potential as a powerful tool for spreading awareness and education on technological advancements. A significant majority of respondents (61.9%) express the importance of integrating AI-based healthcare systems post-COVID-19 reflecting a growing recognition of the role AI

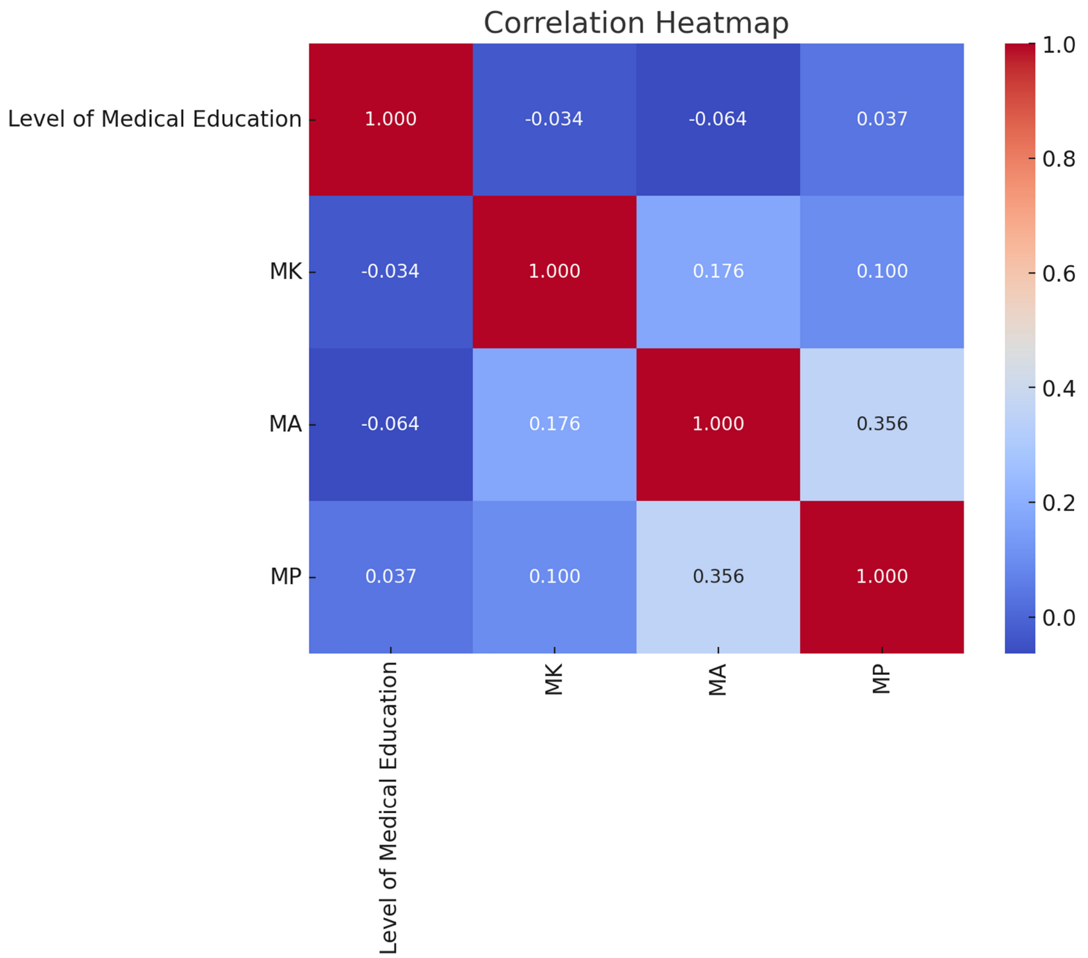

FIGURE 1
Heatmap for correlation.

TABLE 6 Correlational analysis.

	XR improves patient education, assisted therapy and management	XR augments diagnosis and surgeries	XR equipment has a high cost	XR has uncertain benefits over traditional methods	Addressing data security and ethical issues for implementing XR
XR improves patient education, assisted therapy and management	1				
XR augments diagnosis and surgeries	0.163**	1			
XR equipment has a high cost	0.165**	0.227**	1		
XR has uncertain benefits over traditional methods	.[b]	.[b]	.[b]	.[b]	
Addressing data security and ethical issues for implementing XR	0.199**	0.298**	0.205**	.[b]	1

"**" means correlation is significant at 0.01. Superscripted values were significant.

can play in enhancing healthcare delivery as compared to the above mentioned study AI application impact during COVID-19 (score 2.5 ± 2.24 out of 7). These findings underscore the urgency of developing strategies to better educate and prepare healthcare professionals for the integration of AI and XR technologies in the post-pandemic world (46).

TABLE 7 Regression analysis.

Hypothesis	Beta coefficient	R^2	F	t-value	p-value	Hypotheses supported
H1	0.180	0.033	13.611	**3.689**	0.0001	Yes
H2	0.124	0.015	6.293	**2.509**	0.013	Yes
H3	−0.146	0.049	6	**−1.710**	0.088	Marginally yes

Bold values indicate the t-value, measuring how many standard errors the coefficient is away from zero.

In addition to our findings, where 51% of participants identified the enhancement of medical education as the primary advantage of extended reality (XR) technology, there is growing evidence from other regions that supports the integration of artificial intelligence (AI) in medical training. A study conducted at Ain Shams University revealed a strong consensus among medical students regarding their familiarity with and the utilization of AI in their education. This reflects a broader recognition of the transformative potential AI holds in shaping the future of medical practice, aligning with the increasing global demand for AI literacy among healthcare professionals (47). Another study in Jordan showed the demand for AI/ML education in medical school or residency; the majority of the respondents 62.8% (n = 565) strongly agreed on the need. Moreover, a study in Jordan further underscores this trend, with 62.8% of respondents strongly agreeing on the necessity of incorporating AI and machine learning (ML) education into medical school curricula or residency programs. This overwhelming support highlights a critical shift in educational priorities, where future healthcare professionals are expected to be well-versed in AI/ML technologies, not merely as an adjunct but as an integral part of their training. The alignment of these findings across different geographical and educational contexts reinforces the urgent need for a paradigm shift in medical education, where both XR and AI are seen not just as enhancements but as essential components of a modern, comprehensive medical curriculum (48). Another study highlights the importance of conducting OSCE using an augmented reality simulator (49). Another study showed that incorporating image overlay projection, a form of augmented reality (AR), into surgical procedures has shown promise in enhancing the intuitiveness of computer-aided surgery. This technology allows surgeons to view underlying anatomical structures directly on the patient's surface, eliminating the need to divert their sight between the patient and a display screen. It also aids in the 3-D understanding of anatomical structures and the identification of critical areas during surgery (50). These insights suggest a growing recognition among medical students and educators alike of the need to adapt to technological advancements. The convergence of XR and AI in medical education offers a unique opportunity to enrich learning experiences, improve patient outcomes, and prepare the next generation of healthcare providers for the challenges and opportunities presented by these cutting-edge technologies.

This study revealed that a majority (51.2%) of participants expressed strong support for the integration of extended reality (XR) into the healthcare system, with 48% viewing its inclusion in Pakistan's healthcare as a significant advancement. These findings underscore the growing recognition of XR's potential to revolutionize healthcare delivery. However, realizing this potential requires further research, development, and strategic implementation to ensure that XR technologies are effectively integrated and optimized for clinical use. The enthusiasm for XR in healthcare parallels findings from a study in Saudi Arabia, where more than half of the students (57.3%) recognized that AI could significantly enhance the capabilities of healthcare professionals. This alignment between XR and AI highlights a broader trend of technological acceptance within the healthcare community, where both innovations are seen as pivotal in advancing medical practice (51). In our study, participants identified improved patient education, therapy and management (47%), and simplified hospital navigation (44.6%) as the primary healthcare domains where XR could make a substantial impact. This is consistent with the Saudi Arabian study, where 56.7% of students agreed that AI facilitates patient education, suggesting a shared belief across different regions in the value of technology-driven patient engagement. These insights reflect a growing consensus on the transformative potential of XR and AI in healthcare. As these technologies continue to evolve, they are likely to play increasingly critical roles in enhancing patient care, streamlining healthcare processes, and improving overall healthcare outcomes. However, to fully harness these benefits, concerted efforts in education, training, and infrastructure development will be essential (51).

This study highlights several key applications of Extended Reality (XR) in healthcare, particularly in augmented reality (AR)-assisted diagnosis and surgeries (39%), as well as in medical education and research (36%). These findings reflect the growing interest in utilizing XR technologies to enhance various aspects of healthcare, offering immersive and interactive experiences that have the potential to revolutionize patient care, clinical practice, and medical training. Additionally, a study highlights that advanced artificial intelligence (AI) systems are emerging as pivotal players in the transformation of orthopedic surgery and post-operative rehabilitation. One notable feature of these AI systems is their ability to detect early deviations or delays in a patient's rehabilitation process. An example of such technology is WalkAI, an AI component integrated into the myMobility app within the ZBEdge ecosystem. WalkAI exemplifies how technology is advancing the quality of care provided to patients undergoing knee prosthetic surgeries, by offering personalized insights and improving overall outcomes in their recovery journey (52). In addition to the advancements in XR and AI technologies mentioned earlier, AI-based tools are increasingly being utilized throughout the entire process of anterior cruciate ligament (ACL) reconstruction. A recent review highlights the current clinical applications and prospects of AI in this field, focusing on its role in preoperative management, intraoperative assistance, and postoperative care. Before surgery, AI tools are being used for risk prediction and diagnostics, helping to identify patients who may benefit most from ACL reconstruction. During the surgery itself, AI-driven navigation systems aid surgeons by identifying complex anatomic landmarks, thereby improving the precision and outcomes of the procedure. Postoperatively, AI is playing a crucial role in patient care and rehabilitation, particularly in monitoring progress and predicting potential complications. Moreover, AI tools are becoming integral to educational and training settings, where they are used to simulate surgical procedures and enhance the training of orthopedic surgeons. The growing interest among orthopedic surgeons in AI, particularly in applications related to ACL injuries, is evident from the increasing number of studies dedicated to this area. This surge in research suggests that AI will have a significant future impact on the clinical management of ACL tears, with orthopedic surgeons paying close attention to these technological advancements. Integrating these AI-based tools into standard practice could lead to more personalized and effective treatment strategies, ultimately improving patient outcomes in orthopedic surgery (53). Another study highlights a notable feature of AI-based tools in orthopedic surgery is their high accuracy and precision, particularly when comparing implant positioning with preoperative targeted angles, with errors typically within ≤ 2 mm and/or $\leq 2°$. Despite these promising results, which demonstrate significant improvements in accuracy and precision, this technology is still far from being widely adopted in daily clinical practice (54).

The transformative potential of XR is further underscored by a study conducted in the Middle East, focusing on pharmacy students' attitudes toward AI in pharmacy and pharmacy practice. The study revealed that a significant majority believed AI would improve and revolutionize clinical pharmacy practice (67.8%) and other general pharmacy sciences (71.3%). This shared belief in the power of emerging technologies, whether XR or AI, to revolutionize healthcare practice suggests a broader trend towards the acceptance and integration of these innovations across various healthcare domains. XR, with its capability to provide immersive and interactive experiences, holds particular promise in pharma marketing, patient therapy, and pharmaceutical education. By enabling more engaging and effective ways to deliver information and training, XR can significantly enhance the efficacy of healthcare delivery, making it a valuable tool for both healthcare professionals and pharmaceutical entities. These insights highlight the necessity for continued research and development in XR and AI, particularly in understanding how these technologies can be best applied to meet the evolving needs of the healthcare sector. As these technologies become more widely adopted, they have the potential to not only enhance clinical outcomes but also to redefine the very framework of modern healthcare practices (46).

Additionally, our study uncovered that 42.61% of participants recognized the potential of extended reality (XR) to reduce risks during medical procedures, while 38.67% appreciated its value in offering limitless medical practice opportunities and personalized learning experiences for medical students. These findings underscore the growing optimism surrounding XR's ability to enhance the safety and quality of healthcare delivery, particularly in educational and procedural contexts. This sentiment is echoed in a study from Saudi Arabia, where a significant majority (69.7%) of participants strongly agreed that AI is useful in clinical decision-making, such as in the justification of examinations. The recognition of AI's role in enhancing clinical accuracy and decision-making aligns with our findings on XR, suggesting a shared belief in the power of emerging technologies to support and improve healthcare outcomes (55).

However, it's important to note that not all views are entirely optimistic. In our study, a minority of participants (32.4% and 29.2%) expressed concerns about the potential for XR to increase medical errors and even replace doctors in the future. This highlights a critical area of apprehension that must be addressed through careful implementation, rigorous testing, and ongoing education to ensure that XR technologies complement rather than compromise healthcare practice. In contrast, a study in Jordan revealed that 28.2% of participants believed clinical AI could surpass the accuracy of physicians, reflecting a growing trust in the capabilities of AI. These mixed sentiments emphasize the need for a balanced approach to integrating these technologies, ensuring that their benefits are maximized while addressing potential risks and ethical considerations (45).

This study's findings on XR are juxtaposed against broader concerns about the role of AI in healthcare and education. For instance, a study in Jordan revealed that 34.1% of participants believed that human teachers would be replaced in the foreseeable future, highlighting a significant apprehension about the impact of AI on traditional roles (45). This concern is mirrored in another study from the Middle East, where 58.9% of participants viewed AI as a partner that would assist them in performing their duties effectively, while a substantial 36.4% saw it as a competitor that could potentially take over their jobs (46). These mixed perceptions extend to the medical field as well. A study involving medical students in Jordan found that a majority (69.6%) strongly disagreed with the notion that AI will eventually replace human doctors, underscoring a strong belief in the irreplaceable value of human judgment and expertise in clinical practice. However, more than half of the respondents (60.6%) agreed that having advanced personal AI/ML knowledge would enhance their professional performance, reflecting a recognition of the benefits of AI as a tool for augmenting, rather than replacing, human capabilities (48). These findings highlight the dual nature of AI and XR technologies in healthcare and education: while they hold the potential to significantly enhance and transform these fields, they also bring with them concerns about displacement and the need for careful consideration of their integration. As we move forward, it is essential to strike a balance that maximizes the benefits of these technologies while addressing the ethical and professional challenges they present.

This study identified several key barriers to the integration of Extended Reality (XR) into Pakistan's healthcare system. The most significant challenges cited by participants were high costs (67.73%), limited access (47.78%), lack of knowledge (45.81%), patient acceptance issues (40.64%), and insufficient research (38.92%). These barriers underscore the complexities involved in adopting innovative technologies within resource-constrained environments, where financial, educational, and infrastructural limitations can hinder progress. These findings resonate with those from a study in Jordan, where 58.9% of participants recognized similar barriers to the application of AI in medicine. The most frequently reported obstacles in the Jordanian context were a lack of knowledge and expertise, followed by time constraints due to the educational burden, and insufficient access to technical equipment (52.8%, 43.1%, and 42.4% respectively) (45). The parallel between these studies highlights the universal challenges faced by developing nations in integrating advanced technologies into their healthcare systems. Whether dealing with XR or AI, the

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barriers of cost, access, and education remain pervasive. Addressing these issues will require targeted strategies, including investment in infrastructure, comprehensive training programs, and efforts to increase awareness and acceptance among both healthcare providers and patients. Ultimately, overcoming these barriers is crucial for unlocking the full potential of XR and AI in transforming healthcare, particularly in settings where resources are limited. Strategic planning and international collaboration may provide the necessary support to bridge these gaps and pave the way for more widespread and effective implementation of these technologies.

In this present study, data security and ethical considerations were highlighted by 36.4% of participants, while 27.3% emphasized the importance of remote telemedicine as a crucial aspect of healthcare delivery. These concerns reflect the growing awareness of the ethical implications and security challenges associated with the integration of advanced technologies like Extended Reality (XR) in healthcare. Comparatively, a study conducted in Jordan revealed that ethical and privacy concerns were the least frequently reported barrier, with only 34.2% of participants identifying them as significant. This difference may suggest varying levels of awareness or prioritization of ethical issues in different regions. However, the importance of addressing these concerns cannot be understated, especially as healthcare systems increasingly rely on digital and immersive technologies. Further supporting the need for ethical vigilance, a study in Saudi Arabia found that a substantial 70.1% of participants advocated for training programs aimed at preventing and resolving ethical issues related to artificial intelligence (AI) applications. This highlights a widespread recognition of the potential ethical challenges posed by AI and XR technologies, and the necessity for proactive measures to ensure their responsible use. These findings underscore the critical role of ethical management in the successful adoption of XR technology. As healthcare systems evolve, ethical considerations, data security, and privacy protections must be integrated into the design and implementation of these technologies. By addressing these issues head-on, healthcare providers can better manage costs, mitigate risks, and ensure that XR and AI technologies are used to enhance, rather than compromise, healthcare delivery.

A descriptive study conducted on older adults revealed a generally positive attitude toward the use of Virtual Reality (VR) technology, with participants perceiving it as both useful and enjoyable. These findings suggest that older adults could become a key demographic for the development of VR applications aimed at supporting active aging. The positive reception of VR among this group highlights its potential for enhancing quality of life and promoting engagement in various activities as they age (56). However, contrasting perspectives were uncovered in a separate study involving in-depth interviews with older individuals. In this research, participants expressed reservations and discomfort with VR technology, indicating that they did not view it as essential in their daily lives. This dichotomy underscores the broader challenge of societal acceptance of new technologies, particularly among older populations, where adoption may be slower due to unfamiliarity or perceived irrelevance. Despite these reservations, the study suggests that VR may find greater acceptance and application in professional domains, such as medical treatment and e-learning, where its benefits are more immediately tangible and practical (57). Moreover, the integration of Extended Reality (XR) in surgical processes has been explored in various studies, with promising results. XR-integrated platforms have been shown to provide valuable support for operating room (OR) teams, particularly in monitoring patient health during complex surgical procedures. These findings underscore the potential of XR to enhance surgical precision, improve patient outcomes, and reduce the cognitive load on surgeons and OR staff (58–61). These studies highlight the nuanced and context-dependent nature of technology acceptance. While VR and XR hold significant promise in both consumer and professional settings, their successful adoption will require addressing user-specific concerns and demonstrating clear, practical benefits. As the technology continues to evolve, targeted strategies to improve familiarity and comfort with VR and XR among older adults and healthcare professionals will be essential to fully realize their potential.

An analytical study investigating the use of Extended Reality (XR) for medical training and clinical support during space missions revealed its critical importance in such high-stakes environments. The study demonstrated that XR technology is invaluable for diagnosing conditions and planning treatment courses during emergency situations in space. This finding highlights the potential of XR to provide essential medical support in remote and resource-limited settings, where traditional medical resources are not readily accessible (62, 63). In a related study conducted at Seoul National University Hospital, researchers assessed the application of XR technology for the diagnosis, grading, staging, localization, and surgical removal of lung cancers. The results were highly encouraging, indicating that XR can significantly enhance the accuracy and effectiveness of these complex medical procedures. The study's findings underscore the transformative potential of XR in oncology, particularly in improving surgical outcomes and precision in cancer treatment (64). These studies emphasize the broad applicability of XR technology across diverse medical contexts—from the unique challenges of space medicine to the precision demands of oncological surgery. As XR continues to develop, its integration into medical practice could lead to significant advancements in both emergency care and surgical procedures, ultimately improving patient outcomes in a wide range of scenarios.

Considering these findings, the training of medical students emerges as a primary target for the integration of XR technology in the future. Our study also highlights the critical role of evidence-based research in shaping the attitudes of young medical students toward adopting XR in healthcare. Addressing the barriers to XR adoption, such as limited exposure and understanding, and promoting further research in this field, will be crucial in fostering the successful integration of XR technology into medical education and healthcare practices. By equipping future healthcare professionals with the necessary skills and knowledge, XR can be effectively leveraged to enhance both medical training and patient care (65).

A similar perspective can be applied to the fields of telemedicine and education, where XR technology offers the potential to revolutionize learning experiences. Students can access a wider range of educational opportunities globally, gaining exposure to different specialties without the constraints of time and cost. The positive feedback from medical students in major cities across Pakistan underscores the readiness for integrating XR into the country's outdated medical education system. Technological advancements, such as XR, are reshaping the landscape of medical education and training in Pakistan. As this technology continues to evolve, it becomes increasingly important for healthcare training curricula to adapt, preparing future physicians to harness these innovations. By doing so, we can achieve greater efficacy and improved outcomes in both education and patient care, ensuring that our medical professionals are equipped to meet the demands of modern healthcare (66–69).

4.1 Conclusion

The findings of this study suggest that there is a consensus on the knowledge and perception of XR among healthcare professionals. To improve the quality of health education, enhance patients' care, detect and diagnose disease before it is too late or keep a record of patients all over the country, incorporating extended reality can be a game-changing factor.

The results shows that individuals with a background in medical education and research were more likely to opt for XR technology in healthcare. These findings suggest that there is a meaningful relationship between medical education and research and the adoption of XR technology in healthcare, highlighting the importance of educational and research factors in the uptake of this innovative technology. Moreover, results are evidence of the fact that Surgery, Radiology, and Medicine were thought of as fields that significantly benefited the healthcare sector. This indicates a consensus among respondents regarding the perceived positive impact of Extended Reality technology in these specific medical fields, suggesting potential advancements and improvements in surgical, radiological, and medical practices.

In conclusion, future studies should evaluate differences between the experiences of healthcare professionals with and without an extended reality, for a better understanding of educational and surgical procedures should be sought. Featuring the use of this vital preliminary data, we will then be able to further refine and modify our survey. For instance, we might use several forms with varied question types to assess precisely how healthcare personnel who have previous knowledge of XR and those who do not see it differently. Longitudinal studies might shed light on how XR is being used in medical research and teaching. Finally, qualitative research techniques like in-depth interviews may help us comprehend the experiences of healthcare professionals using XR.

4.2 Limitations

Despite following a thorough approach, our study has several limitations. Bias is an inevitable component of the cross-sectional survey approach. The responses provided by research participants are the only factors that determine the study's outcomes. Respondent bias may exist because the researchers cannot interview respondents to clarify their views or justify their responses to specific questions. Uncontrolled variables that cause problems include individual predispositions towards technology, variability in the training curricula that are evolving, and varying exposure levels to XR technology among Pakistani institutions. Despite our study presenting an insight into the attitudes, understanding, and perceptions of XR among healthcare professionals at certain institutions across the nation, it is important to exercise caution when extending these findings to the larger medical community.

4.3 Recommendations

According to the study "Virtual Horizons: Assessing the Knowledge, Attitude and Perception of XR Technology in Pakistani Healthcare Community in an Era of Artificial Intelligence," it is advised that healthcare professionals undergo specialized training to improve their ability to use XR technology to its full potential. Educating healthcare workers about the advantages of XR technology through awareness campaigns and workshops can help to promote its acceptance and incorporation (70–72).

To protect patient privacy and trust, it is essential to establish explicit ethical principles and data security protocols for the use of XR technology in healthcare settings. Promoting cooperative research endeavors among medical establishments, technological specialists, and legislators might also investigate the possibilities of XR technology in enhancing medical education and patient treatment (73, 74).

To revolutionize Healthcare through Extended Reality, detailed research work is required. It is necessary to study the positive and negative effects of extended reality in detail along with patients' and doctors' opinions to assess its feasibility and implementation in the years to come (75–77). Factors such as cost effectiveness, technical training and social acceptance should also be considered while undertaking such long-term projects and plans (44).

5 Abbreviations

(1) Medical Community: This includes Medical Students, House Officers, Medical Officers, Postgraduate Trainees, Specialists, Consultants and Professors.
(2) Extended Reality: An umbrella term encapsulating Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), and everything in between.
(3) Augmented Reality: It is a technology that overlays digital elements, such as images, text, or animations, onto the real world.
(4) Virtual Reality: It is a technology that creates a completely computer-generated environment. It immerses users in a virtual world, blocking out the real surroundings.
(5) Major Cities: Karachi, Lahore, Faisalabad, Rawalpindi, Islamabad, Multan Peshawar, Abbottabad and Muzaffarabad. The "OTHERS" option was also given if the Medical Community from other cities wanted to participate.

Strengths and limitations

1. Conducted an analytical cross-sectional study in 2023 among 406 medical professionals in Pakistan using a self-structured online questionnaire.
2. Surveyed participants from nine major cities via social media platforms, lasting from August 1 to September 30, 2023, with 406 responses collected.
3. Analyzed data using SPSS version 25, focusing on knowledge, attitude, and perception correlations through Pearson Correlation and Regression analyses.

4. Ethical approval obtained from the Ethical Review Committee of Azad Jammu and Kashmir Medical College, ensuring participant confidentiality and safety.
5. Study limitations included inherent biases of cross-sectional surveys and uncontrolled variables influencing respondent perspectives on XR technology in healthcare.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: khan, Zoha (2024), "Virtual Horizons: Assessing the Knowledge, Attitude and Perception of XR Technology in Pakistani Healthcare Community in an Era of Artificial Intelligence", Mendeley Data, V1, doi: 10.17632/wvknnx4gry.1.

Ethics statement

Ethical approval was obtained from the Ethical Review Committee of the Azad Jammu and Kashmir Medical College, Muzaffarabad. Moreover, consent was also taken from the participants at the start of the online questionnaire, ensuring the safety and confidentiality of the information they were given.

Author contributions

ZK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. TA: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. MO: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. BK: Methodology, Validation, Writing – review and editing. MA: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Evaluation of the effectiveness of GASMAN anesthesia simulation software combined with case-based learning versus traditional lecture-based learning in inhalation anesthesia education

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Objective: To evaluate the effectiveness of integrating GASMAN anesthesia simulation software with case-based learning (IGC) compared to traditional lecture-based learning (LBL) in teaching inhalation anesthesia to undergraduate anesthesiology students.

Methods: Fourth-year students from two academic years (2022, n = 110; 2023, n = 131) enrolled in a five-year anesthesiology program were assigned to either traditional lecture-based learning (LBL) or IGC groups. The LBL group received traditional lectures using PowerPoint slides, while the IGC group engaged with GASMAN anesthesia simulation software (a tool designed for anesthesia simulation and gas monitoring) combined with case-based learning. The cases used in the IGC group were structured around realistic clinical scenarios, simulating real-world challenges in inhalation anesthesia. These scenarios were integrated with the GASMAN software to provide interactive simulations, enhancing students' understanding of pharmacokinetics and pharmacodynamics. Teaching effectiveness was evaluated through expert assessments and student feedback, with learning outcomes compared via post-course assessments.

Results: The IGC group scored significantly higher in student evaluations in areas such as comprehending and mastering theoretical knowledge, resolving clinical challenges, nurturing clinical reasoning, increasing learning interest, enhancing learning efficiency, consolidating memory, improving analytical skills, and refining application proficiency (adjusted $P < 0.001$), however, there were no significant differences between the two groups in the improvement of practical skills. Post-course test scores were also higher in the IGC group for both total post-course test and subjective questions scores (adjusted $P < 0.001$), though no difference was found for objective question scores. After applying false discovery rate (FDR) correction, expert evaluation scores showed no significant differences between the two groups.

Conclusion: The integration of GASMAN software with case-based learning significantly enhances the quality of inhalation anesthesia education by improving student engagement, critical thinking, and conceptual understanding. This approach demonstrates promise for advancing clinical education, although further research is needed to evaluate its long-term impact.

KEYWORDS

GASMAN software, inhalation anesthesia, undergraduate students, teaching, case-based learning

1 Introduction

Inhalation anesthesia is a fundamental technique in clinical anesthesia, involving the administration of volatile anesthetics via the respiratory tract, which then diffuse into the bloodstream through the alveoli and reach the brain to induce general anesthesia. This method is among the most commonly utilized in clinical settings (1). Mastering the complexities of inhalation anesthesia is essential for anesthesiology students, as the subject involves intricate pharmacokinetic and pharmacodynamic concepts. These include understanding the absorption, distribution, metabolism, and excretion of volatile anesthetics, which are critical to ensuring safe and effective patient care (2). Such complexities, particularly in pharmacological principles, are often difficult for beginners to grasp, leading to common challenges in understanding how inhalation anesthetics interact within the body (3, 4). This gap in comprehension can result in students lacking confidence during clinical practice and internships.

Traditional lecture-based learning (LBL), which remains a common instructional method in medical education, often struggles to actively engage students or to adequately develop their clinical reasoning skills. These limitations are particularly pronounced in complex subjects like inhalation anesthesia, where passive information delivery may not effectively convey the intricacies of pharmacokinetics and pharmacodynamics. Consequently, educators may find themselves re-explaining concepts multiple times to facilitate deeper understanding (5, 6).

To address these challenges, case-based learning (CBL) has been introduced as a student-centered pedagogical strategy that employs real-world clinical scenarios. In CBL, typical or challenging cases are selected to align with specific learning objectives. These cases serve as a catalyst for guided discussions, encouraging students to engage actively, apply theoretical knowledge, and develop problem-solving skills in a context that mirrors clinical practice (7). In the field of anesthesiology, CBL is particularly beneficial because it allows students to encounter and work through the complexities of anesthesia management in a controlled environment, thereby enhancing engagement and fostering clinical reasoning (8). Research has shown that CBL's emphasis on active participation and contextual learning leads to improved knowledge retention, critical thinking, and readiness for real-world clinical scenarios (9).

To further enrich CBL in anesthesiology education, the GasMan anesthesia simulation software offers an interactive and dynamic platform that simulates the pharmacokinetics and pharmacodynamics of volatile anesthetics (10). Developed by Professor Philip, GasMan models the trajectory of anesthetics as they transition from the vaporizer to the respiratory system, alveoli, bloodstream, target organs, and back for exhalation (11, 12). This detailed simulation assists students in visualizing and understanding the complex dynamics of inhalation anesthesia, which are often abstract and challenging to conceptualize in traditional learning settings (13). Additionally, GasMan allows for the replication of diverse pathological and physiological conditions—such as severe obesity, heart failure, and restrictive ventilatory dysfunction—that are difficult to simulate in clinical practice. These scenarios provide invaluable learning opportunities that would otherwise be inaccessible in a conventional classroom (14–17). The integration of GasMan with CBL in the instruction of inhalation anesthesia enhances the educational experience by enabling students to engage with complex cases in a simulated environment. The software's interactive simulations help bridge the gap between theoretical concepts and practical application, allowing students to analyze patient data, make informed clinical decisions, and witness the outcomes of their choices in real time.

Therefore, this study aims to evaluate the effectiveness of combining GasMan software with CBL compared to traditional LBL in teaching inhalation anesthesia. The objective is to provide evidence supporting potential reforms in the curriculum for inhalation anesthesia courses.

2 Materials and methods

2.1 Study design and participants

Ethics approval for this study was obtained from the Education Committee of Guizhou Medical University (Approval No. JG2021026). All participants provided informed consent prior to participation, ensuring they were fully aware of the study's objectives, procedures, and their rights to withdraw at any time without any consequences.

Participants were fourth-year students enrolled in the five-year anesthesiology program at Guizhou Medical University, from two consecutive academic cohorts: 2022 and 2023. Due to logistical constraints, students were divided by academic year into two groups: the 2022 cohort formed the traditional lecture-based learning (LBL) Group, while the 2023 cohort comprised the Integrating GASMAN software with case-based learning (IGC) Group. Although randomization was not employed, we used identical pre-course tests to control for baseline knowledge and ensure comparability between the groups.

2.2 Teaching method

Both groups shared identical learning objectives, encompassing a comprehensive understanding of inhalational anesthetics, including pharmacology, pharmacodynamics, pharmacokinetics, clinical application, and safety considerations. Below is a detailed description of the teaching methods for each group:

LBL group:

Participants: 110 students from the 2022 cohort.

Teaching method: Traditional lecture-based learning.

Course structure: The course consisted of 4 sessions, each lasting 45 min.

Content delivery: All sessions were delivered as theoretical lectures designed according to the curriculum requirements of the "Pharmacology of Anesthetics" textbook, as mandated by the National Health Commission's "13th Five-Year Plan."

Instructional tools: PowerPoint (PPT) presentations combined with teacher explanations.

IGC group:

Participants: 131 students from the 2023 cohort.

Teaching method: A hybrid approach integrating GASMAN software simulations with CBL.

Course structure: The course also consisted of 4 sessions, each lasting 45 min.

Content delivery:

Theoretical lectures: The theoretical content was streamlined into 2 sessions, similar to the LBL group, utilizing PPT presentations and teacher explanations.

Practical sessions: The remaining 2 sessions were designated for practical application. These sessions involved CBL where the instructor selected clinical cases that were representative and educationally valuable. The GASMAN software was used to simulate the absorption, distribution, and metabolism of inhalational anesthetics, reinforcing the theoretical concepts covered in the lectures.

In-Class Application: During the practical sessions, the GASMAN software served as a teaching aid. The instructor initially used PowerPoint presentations to introduce relevant clinical cases and explain the associated pharmacology, pharmacodynamics, and pharmacokinetics concepts. Then, students were divided into groups and used the GASMAN software to simulate different scenarios based on the clinical cases. Through the software's dynamic simulation features, students could observe how inhalational anesthetics behave in the body under various conditions (e.g., different ages, weights, pathological states). This process aimed to provide students with a visual understanding of how inhalational anesthetics are absorbed and metabolized. After each simulation, student groups presented their observations, and the instructor guided the discussion with targeted questions to reinforce key concepts and deepen students' comprehension of inhalational anesthetics.

Independent Exploration Outside of Class: To encourage further exploration outside of the classroom, students were assigned homework involving the independent use of the GASMAN software. They were tasked with simulating different patient profiles (e.g., those with heart failure, respiratory impairments) and adjusting drug dosages and ventilation parameters to observe how these variables affect anesthetic behavior. These out-of-class exercises were designed to foster independent learning and to enhance the students' understanding of complex clinical scenarios.

2.3 Pre-course test

Prior to the commencement of the course, both groups of students were required to take a pre- course test on foundational knowledge of inhalational anesthesia. This test was administered without any prior preparation to accurately assess the students' baseline understanding of the subject matter. The pre-class test scores served as the baseline data, providing insights into the students' existing knowledge of inhalational anesthesia before any instructional intervention.

Test details:

Content coverage: The test covered essential inhalational anesthesia knowledge that is critical for clinical practice. This included the pharmacodynamics and pharmacokinetics of inhalational anesthetics, mechanisms of action, clinical application, and safety considerations.

Question source: The questions were randomly selected by a computer from the question bank accompanying the "Pharmacology of Anesthetics" textbook, which is part of the "13th Five-Year Plan" educational materials endorsed by the National Health Commission.

Question format: The test comprised 50 objective questions, each valued at 2 points.

Scoring: The total possible score was 100 points.

2.4 Teaching evaluation

2.4.1 Teaching experts assessments

To assess the effectiveness of the teaching methods used in both the lecture-based learning (LBL) group and the IGC group, three highly experienced teaching experts in anesthesiology were selected. These experts, all holding senior academic titles, conducted evaluations based on standardized classroom teaching assessment criteria (detailed evaluation criteria can be found in Supplementary Material 1). The evaluation focused on the following five aspects:

Teaching design: Assessed the clarity of learning objectives, logical content flow, and appropriateness of teaching strategies, scored on a 0–20 scale.

Teaching implementation: Evaluated how well the teaching was delivered, including clarity of explanation and student engagement, scored on a 0–20 scale.

Classroom ambiance: Measured the level of student interaction, participation, and overall classroom dynamics conducive to learning, scored on a 0–20 scale.

Teaching effectiveness: Judged whether students met the learning objectives, with a focus on understanding and practical application, scored on a 0–20 scale.

Teacher quality: Assessed the teacher's knowledge, communication skills, and ability to engage and motivate students, scored on a 0–20 scale.

Each of these five aspects was rated independently by the three experts, and the scores for each aspect were summed to provide a total score out of 100 points.

2.4.2 Students evaluation

At the end of the course, students were asked to complete an anonymous paper-based questionnaire (see Supplementary Material 2) to evaluate the teaching methods. The questionnaire contained ten items, each rated on a 0 to 10 scale, with higher scores indicating a more favorable perception of the teaching method's effectiveness. Anonymity was emphasized to ensure honest feedback and data validity.

Comprehending and mastering theoretical knowledge: Assessed how well the teaching method facilitated students' comprehension and retention of theoretical concepts.

Improvement of practical skills: Evaluated the effectiveness of the teaching method in enhancing students' practical skills relevant to clinical practice.

Resolving clinical challenges: Measured the ability of the teaching method to help students apply their knowledge to solve real-world clinical problems.

Nurturing clinical reasoning: Assessed how well the teaching method promoted the development of critical clinical thinking skills.

Increasing learning interest: Evaluated the extent to which the teaching method increased students' interest and engagement in learning.

Enhancing learning efficiency: Measured how efficiently the teaching method helped students learn and retain information.

Consolidate memory: Assessed the effectiveness of the teaching method in helping students retain learned information over time.

Course logic: Evaluated the logical flow and coherence of the course as perceived by the students.

Improving analytical skills: Measured the ability of the teaching method to enhance students' analytical skills.

Refining application proficiency: Assessed how well the teaching method helped students apply theoretical knowledge to practical situations.

Each item was rated on a scale from 0 to 10, with higher scores indicating a stronger perceived impact of the teaching method on that specific aspect. The total score for the evaluation was 100 points.

2.4.3 Post-course tests

Upon completion of the course, students immediately participated in a post-course test to compare the effectiveness of the two teaching methods. The test items were drawn from the same test bank as the pre-course test but did not overlap with the pre-course questions. The total score for the post-course test was 100 points, with equal weight given to objective and subjective questions:

Objective Questions (50 points): These questions primarily assessed the students' grasp of basic knowledge related to inhalation anesthesia. The objective section included 20 multiple-choice questions (each worth 2 points) and 10 true/false questions (each worth 1 point), designed to evaluate the students' understanding of fundamental concepts.

Subjective Questions (50 points): This section aimed to evaluate students' ability to apply theoretical knowledge in practical scenarios. It included 4 short-answer questions (each worth 5 points) and 3 case analysis and comprehensive application questions (each worth 10 points), requiring students to analyze, synthesize, and apply their knowledge to solve clinical problems.

2.5 Limitations

This study used cohort grouping, which may lead to baseline differences between the LBL and IGC groups. Although this design was dictated by logistical constraints, we controlled for initial academic performance and background characteristics to mitigate potential biases. Additionally, student evaluations may be subject to subjectivity; therefore, a combination of expert assessments and anonymous feedback was employed to enhance reliability. Future studies should consider a randomized design to improve the generalizability and robustness of the findings.

2.6 Data analysis

Statistical analyses were performed using SPSS software version 27.0. Categorical data (e.g., gender) were presented as frequencies and percentages, and group differences were evaluated using the chi-square test. Continuous variables were first assessed for normality using visual inspection of histograms. Variables with a normal distribution (e.g., age, pre-course test scores, student evaluation scores, post-course test scores) were summarized as mean ± standard deviation (SD), and comparisons between groups were conducted using an independent-samples t-test. Variables not conforming to a normal distribution (e.g., Expert Evaluation Scores) were summarized as medians and interquartile ranges (IQRs), and group differences were analyzed using the Mann–Whitney U test. For multiple comparisons, the false discovery rate (FDR) method was applied to adjust the p-values to control for type I error. A p-value of less than 0.05 was considered statistically significant for all analyses. As there were no missing data in this study, no data deletion or imputation was required.

3 Results

3.1 Pre-course tests

The demographic characteristics and pre-test scores of students in the IGC group and the LBL group showed no significant

TABLE 1 Baseline characteristics and pre-course test scores of students in the IGC and LBL groups.

	IGC group (n = 131)	LBL group (n = 110)	P-value
Sex, female, n (%)	77 (58.8)	72 (65.5)	0.288
Age, year, mean ± SD	22.8 ± 0.9	22.7 ± 1.0	0.639
Pre-course test, mean ± SD	34.4 ± 10.1	33.2 ± 9.5	0.359

differences ($P > 0.05$). Specifically, the gender distribution was 58.8% female in the IGC group and 65.5% female in the LBL group ($P = 0.288$). The average age was 22.8 ± 0.9 years for the IGC group and 22.7 ± 1.0 years for the LBL group ($P = 0.639$). The pre-course test scores were 34.4 ± 10.1 for the IGC group and 33.2 ± 9.5 for the LBL group ($P = 0.359$) (Table 1).

3.2 Evaluation by teaching experts

The IGC group initially demonstrated higher scores than the LBL group in teaching design, classroom ambiance, teaching effectiveness, and total expert evaluation score, with statistically significant differences observed prior to applying the FDR adjustment ($P < 0.05$). However, after FDR correction, none of these differences reached statistical significance (adjusted $P > 0.05$). Consistently, there were no significant differences in teaching implementation or teacher quality between the two groups, both before and after correction ($P > 0.05$) (Table 2).

3.3 Student evaluation of teaching method

Students in the IGC group rated the teaching methods higher in several areas compared to the LBL group, with statistically significant differences in aspects such as comprehending and mastering theoretical knowledge, resolving clinical challenges, nurturing clinical reasoning, increasing learning interest, enhancing learning efficiency, consolidate memory, course logic, improve analytical skills, and refining application proficiency (adjusted $P < 0.05$). No significant differences were found in the improvement of practical skills and course logic (adjusted $P > 0.05$) (Table 3).

3.4 Post-course test

In the post-course test, the IGC group had significantly higher total post-course test scores (74.9 ± 8.9 vs. 67.3 ± 8.9, adjusted $P < 0.001$) and subjective questions scores (38.3 ± 5.9 vs. 32.4 ± 5.4, adjusted $P < 0.001$) compared to the LBL group. No significant differences were observed in objective questions scores between the two groups (36.6 ± 7.1 vs. 35.0 ± 7.5, adjusted $P = 0.089$), (Table 4).

4 Discussion

Our study investigates the effectiveness of integrating GASMAN software with case-based learning (CBL) in teaching inhalation anesthesia to undergraduate anesthesiology students. The results demonstrate notable improvements in teaching outcomes, particularly in areas involving clinical reasoning and subjective assessment, as evidenced by superior student evaluations and higher scores on subjective questions in post-course assessments, compared to the traditional lecture-based learning (LBL) approach. However, after applying the false discovery rate (FDR) correction, no statistically significant differences were found in expert evaluation scores between the IGC and LBL groups. This finding underscores the complexities of interpreting our results and suggests that while GASMAN-enhanced CBL may improve certain aspects of learning, it does not uniformly impact all areas of teaching.

Inhalation anesthesia education presents unique challenges due to the abstract and complex nature of pharmacokinetic and pharmacodynamic concepts (2, 18). Our study revealed that while the LBL group achieved an overall post-course test score rate below 70%, indicating the inherent difficulty of the material, objective test scores between the IGC and LBL groups showed no significant difference (adjusted $P = 0.089$). This lack of significant differences in objective assessments suggests that while GASMAN-enhanced CBL was effective in improving subjective understanding, it did not translate to better factual recall, which is often the focus of objective tests. This may indicate that different teaching methods impact distinct types of learning outcomes; CBL combined with GASMAN appears to enhance higher-order thinking skills and application-based understanding, rather than simple factual recall.

CBL is well-regarded in clinical education for its use of real-world scenarios to promote active learning and problem-solving (7). In our study, the IGC group demonstrated higher scores in subjective areas such as fostering clinical reasoning, increasing engagement, and enhancing analytical skills. The significant improvement in subjective test scores underscores the potential of CBL to deepen conceptual understanding and encourage critical thinking, skills essential for clinical practice. However, CBL alone may not fully address the inherent abstraction in inhalational anesthetics. The addition of GASMAN software, which simulates the pharmacokinetics of inhalational agents and allows users to manipulate parameters like body weight, cardiac output, and anesthetic concentrations, provided a visual and interactive platform to reinforce theoretical knowledge (10, 11). This dual approach seems particularly effective for fostering deep learning, as reflected in the IGC group's higher evaluations of memory consolidation and learning efficiency compared to the LBL group. These findings suggest that the interactive features of GASMAN, such as real-time adjustments and visual feedback, play a crucial role in helping students grasp complex pharmacokinetic dynamics (11).

Despite the promising results, it is important to note that expert evaluations did not show statistically significant differences between the two groups after applying the false discovery rate (FDR) correction. Several factors may explain this lack of statistical significance. One possibility is the small number of expert evaluators (n = 3 per group), which may have limited the

TABLE 2 Expert evaluation scores of teaching methods in the IGC and LBL groups.

	IGC group (n = 3)	LBL group (n = 3)	U-value	P-value	FDR adjust P
	Median (IQR)	Median (IQR)			
Teaching design	18.0 (17.5–18.5)	15.0 (14.5–15.0)	9.00	0.046	0.092
Teaching implementation	18.0 (17.5–18.0)	17.0 (16.5–17.5)	6.50	0.346	0.415
Classroom ambiance	18.0 (17.5–18.0)	15.0 (15.0–15.5)	9.00	0.043	0.258
Teaching effectiveness	18.0 (17.5–18.0)	15.0 (15.0–15.5)	9.00	0.043	0.129
Teacher quality	18.0 (18.0–18.5)	18.0 (17.5–18.5)	5.50	0.637	0.637
Total expert evaluation score	91.0 (88.0–91.0)	80.0 (78.5–80.5)	9.00	0.046	0.069

TABLE 3 Student evaluation scores for teaching methods in the IGC and LBL groups.

	IGC group (n = 131)	LBL group (n = 110)	Cohen's d	P	FDR adjust P
	Mean ± SD	Mean ± SD			
Comprehending and mastering theoretical knowledge	7.4 ± 1.8	6.4 ± 2.3	2.04	< 0.001	< 0.001
Improvement of practical skills	6.5 ± 1.8	6.5 ± 1.8	1.77	0.818	0.818
Resolving clinical challenges	8.0 ± 1.4	6.4 ± 1.7	1.58	< 0.001	< 0.001
Nurturing clinical reasoning	8.0 ± 1.5	6.7 ± 1.7	1.57	< 0.001	< 0.001
Increasing learning interest	7.9 ± 1.4	6.7 ± 1.6	1.47	< 0.001	< 0.001
Enhancing learning efficiency	7.9 ± 1.5	6.8 ± 1.6	1.52	< 0.001	< 0.001
Consolidate memory	7.8 ± 1.4	6.5 ± 1.7	1.57	< 0.001	< 0.001
Course logic	7.9 ± 1.6	7.0 ± 1.5	1.52	< 0.001	< 0.001
Improve analytical skills	8.0 ± 1.3	6.5 ± 1.6	1.48	< 0.001	< 0.001
Refining application proficiency	8.1 ± 1.5	6.0 ± 1.7	1.62	< 0.001	< 0.001
Total student evaluation score	77.5 ± 4.6	65.5 ± 5.1	2.49	< 0.001	< 0.001

TABLE 4 Post-course test scores of students in the IGC and LBL groups.

	IGC group (n = 131)	LBL group (n = 110)	Cohen's d	P-value	FDR adjust P
	Mean ± SD	Mean ± SD			
Objective questions	36.6 ± 7.1	35.0 ± 7.5	7.28	0.089	0.089
Subjective questions	38.3 ± 5.9	32.4 ± 5.4	5.67	< 0.001	< 0.001
Total post-course test score	74.9 ± 8.9	67.3 ± 8.9	8.93	< 0.001	< 0.001

statistical power of these comparisons, resulting in non-significant findings after adjusting for multiple comparisons. A larger panel of evaluators with more diverse backgrounds could reduce scoring variability and lead to more robust findings. Additionally, this outcome may reflect the subjective nature of expert evaluations, which are influenced by personal experiences and expectations.

Furthermore, the lack of significant differences in objective test scores indicates that GASMAN-enhanced CBL may not universally enhance all aspects of knowledge acquisition. While GASMAN software appears effective in promoting conceptual understanding and clinical reasoning, it may not be as beneficial for memorizing factual content. This suggests that different teaching methods may be better suited for distinct learning objectives—whether the focus is on higher-order cognitive skills or basic factual knowledge. Future research could explore whether a more targeted integration of GASMAN, perhaps by incorporating additional drills or review sessions to reinforce factual content, might help bridge this gap.

Several practical considerations must also be taken into account when implementing GASMAN-enhanced CBL. Instructors need to be proficient not only in using the software but also in understanding the pharmacological principles it illustrates. Additionally, clinical cases used in the simulation should be carefully curated to align with educational objectives and replicate real-world scenarios. A well-structured teaching schedule is also essential, ensuring an appropriate balance between theoretical learning and practical application, so students can engage meaningfully with the software and reflect on their learning.

Lastly, our study has several limitations. The sample was restricted to undergraduate anesthesiology students from a single institution, and the assessment focused on short-term learning outcomes. Consequently, the long-term impact of GASMAN-enhanced CBL on clinical performance remains unknown. Future studies should aim to include a more diverse student population and extend the follow-up period to assess the durability of learning outcomes over time.

In conclusion, while our findings demonstrate that integrating GASMAN software with CBL can enhance the teaching of inhalational anesthesia, particularly in developing clinical reasoning and deep understanding, the intervention does not appear to uniformly improve all types of learning outcomes. A balanced approach that considers the strengths and limitations of each teaching method is essential for optimizing anesthesia education. This study contributes to the ongoing effort to innovate medical education, highlighting the need for adaptive, evidence-based teaching strategies in a field that is constantly evolving.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CC: Formal analysis, Funding acquisition, Investigation, Writing – original draft. SY: Data curation, Investigation, Writing – original draft. XX: Formal analysis, Data curation, Investigation, Software, Writing – review and editing. YS: Conceptualization, Investigation, Software, Writing – review and editing. ZZ: Formal analysis, Investigation, Software, Writing – review and editing. JS: Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmed.2024.1472404/full#supplementary-material

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Body donor reperfusion and re-ventilation in medical training: an Italian study testing SimLife®

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Background: Medical simulations have emerged as a valuable tool in anatomical-medical training, allowing healthcare professionals to gain hands-on experience in a controlled and safe environment. One such simulation platform is SimLife®, which uses the Pulse for Practice (P4P) system to enable realistic restoration of airflow ("re-ventilation") and blood flow ("revascularization") in bodies donated to science.

Objective: This study aimed to evaluate the feasibility of introducing SimLife® technology in Italy. Additionally, it assessed the impact of this technology across various medical specialties, utilizing a minimal number of donated bodies.

Methods: The study utilized the existing body donation program and dissection rooms at the Anatomy Center of the University of Bologna. 62 participants from 13 medical specialties performed simulations using the SimLife® P4P platform. Post-simulation, structured interviews were used to collect data on the interventions performed, participant perceptions of the technology's usefulness, enjoyment, and willingness to repeat the experience, as well as critical issues encountered.

Results: Key findings include that 86% of participants rated SimLife® technology as extremely useful for *post-lauream* training, while 84% found it highly beneficial for team-building activities. A total of 31 interventions were successfully performed across various anatomical regions, with participants reporting high satisfaction and a strong willingness to repeat the simulation experience.

Conclusion: The findings support the effectiveness of SimLife® technology for body donor re-ventilation and revascularization, reinforcing its value for medical training across various specialties.

KEYWORDS

medical simulation, body donation, surgical training, technology innovation, SimLife® technology

Introduction

Ethical foundations and importance of simulation in medical training

Primum non nocere ("first of all, do no harm") is a fundamental principle in medical education, emphasizing the ethical responsibility of healthcare professionals to prioritize patient safety. Modern medical training recognizes the importance of not only minimizing physical harm but also fostering emotional and psychological well-being through compassionate care—a concept referred to as "pedagogy of kindness" (1, 2). This approach highlights the need for comprehensive training that integrates technical skills with empathetic, patient-centered care. However, traditional training models often lack the immersive and safe environments required to adequately prepare medical professionals.

Challenges with existing models

The evolution of medical and surgical disciplines has exposed limitations in traditional training methods, such as the Halstedian apprenticeship model ("see one, do one, teach one") (3). In this scenario, simulation models have proven to be valuable tools to improve and assist medical training (4, 5, 6, 7, 8). Synthetic simulators, while offering risk-free practice, frequently lack anatomical fidelity and are costly to produce and maintain (9, 10, 11). Organic simulators, such as animal models, face ethical restrictions and limited applicability due to anatomical differences (12). Human cadavers, though invaluable for understanding anatomy (13, 14, 15), fail to replicate dynamic physiological conditions like blood flow, bleeding, and ventilation, essential for developing advanced surgical skills (16, 17).

SimLife® technology

To address these limitations, innovative solutions like SimLife® have emerged. SimLife® technology integrates "re-ventilation" (restoration of airflow to the lungs) and "revascularization" (restoration of blood flow through a simulated circulatory system) to dynamically animate bodies donated to science. These features enable simulations that closely mimic real-life surgical conditions, offering a unique blend of anatomical precision and physiological realism. Several studies have demonstrated the benefits of perfused human body models in enhancing realism in surgical training, improving skills acquisition, and trainee satisfaction (18–20, 21, 22). SimLife® builds on these advancements, addressing critical gaps in simulation fidelity, such as replicating dynamic physiological processes like blood flow and ventilation, and providing anatomically precise models for complex surgical procedures (23, 24, 25, 26).

Study goals and broader significance

This study aimed to test the feasibility of introducing SimLife® technology in Italy and to evaluate its impact across multiple medical specialties while maximizing the use of body donors. By leveraging the body donation program at the Anatomy Center of the University of Bologna, this study explored SimLife®'s potential for improving medical education, team training, and surgical skills acquisition. Beyond assessing feasibility, this research sought to underscore the broader implications of adopting dynamic simulation technologies. Indeed, SimLife® not only advances surgical training capabilities but also highlights the ethical significance of body donation, paving the way for transformative educational practices in Italy and globally.

Materials and methods

Study objectives

The present study aimed to evaluate the impact of SimLife® P4P technology on medical education and formation through a comprehensive investigation based on two hypotheses. The first hypothesis aimed to identify the medical fields where SimLife® technology could have the most significant impact. The second hypothesis focused on evaluating how SimLife® technology could enhance medical training and education. To address these hypotheses, a wide-spectrum simulation approach was employed, involving 62 medical and surgical participants from 13 different specialties. This approach was chosen to comprehensively evaluate the versatility and applicability of SimLife® technology across various medical fields. By testing the platform on diverse procedures and anatomical regions, we aimed to identify its strengths and limitations, ensuring its broad utility in medical training. At the end of the simulation, participants were asked to answer a structured interview to determine their anatomical districts of interest, and the different interventions performed during the SimLife® simulation. Interventions success rates were also assessed. Success rate was determined based on participants' ability to successfully complete the intended surgical or medical procedures and measured through participant self-assessment. Participants were asked to self-evaluate the execution of procedural steps and the achievement of procedural objectives. Additionally, participants' perception regarding the usefulness and impact of SimLife® technology for research, *pre-lauream* (*pre-graduate*) and *post-lauream* (*post-graduate*) training, and team-building were assessed through 6-points Likert-scale questions. Finally, the limitations and the general opinion on the simulation were examined through open-answer questions.

Study setting

The Anatomy Centre of the University of Bologna provided the setting for this study, with two fully equipped dissection rooms and an established body donation program that supports both educational and research activities (27). This infrastructure was instrumental in organizing the simulation sessions detailed in this study. The Anatomy Centre hosts two fully equipped dissection rooms: the main dissection room, equipped with four workstations and an audio-video-endoscopic system for recording and streaming activities, and a high-technology anatomical room with a modular system for two surgical workstations. In 2023, the Anatomy Centre organized a total of 584 h of dissection room activities, including 250 h for *post-lauream* training, 224 h for *pre-lauream* training, and 115 h for advanced courses. These activities reflect the Centre's commitment to advancing medical education and research through its body donation program. The dissection room activities for this study were supported by the Anatomy Centre's Near-Peer Teaching (NPT) program, which involves senior medical students assisting in educational and training activities. This program, active since 2003, played a key role in facilitating the organization and execution of the simulations, leveraging its structured framework to support participants during the SimLife® sessions. Further details on the NPT program are available in Orsini et al. (28).

Body donors' preparation

Two bodies donated to science via the Anatomy Centre body donation program were defrosted three days prior the simulation in a room at 18°C. Age, sex, height, body type and cause of death of the two body donors are reported in Table 1.

The day before the simulation, the body donors were prepared by Simedys specialized personnel according to a new configuration, different from that described by Delpech et al. (24), allowing many more surgical simulations to be carried out.

The preparation process involved the following steps:

1 Cannulation for vascular access:

- Right common carotid artery and right internal jugular vein: two arterial and two venous cannulas were placed. For each pair, one cannula was directed centrally toward the heart, and the other peripherally toward the head. A pressure sensor was positioned on the right to measure aortic pressure.
- Femoral arteries and veins: two arterial and two venous cannulas were inserted in each femoral vessel, with central and peripheral directions for each pair. For the right femoral vessel, cannulas were placed as low as possible to simulate extracorporeal membrane oxygenation (ECMO) or interventional radiology procedures.
- Brachial arteries and veins: two arterial and two venous cannulas were inserted into the brachial vessels, with central and peripheral directions for each pair.

2 Tracheotomy and re-ventilation:

- A tracheotomy was performed to facilitate re-ventilation of the lungs. Alternative intubation techniques were avoided due to the risk of accidental esophageal intubation, which could compromise the model.

3 Nasogastric tube insertion:

- A nasogastric tube was inserted to aspirate gastric fluids and prevent complications during simulations.

TABLE 1 Profile of the body donors object of the SimLife® simulation.

	Body donor 1	Body donor 2
Age	80 y.o.	76 y.o.
Sex	Male	Male
Height	166 cm	172 cm
Body type	Obese	Overweight
Death cause	Chronic respiratory insufficiency	Cerebral ischemia

4 Vascular tree cleansing:

- The vascular system was flushed with 12 liters of water at 37°C using low pressure (0.4 bar or 300 mmHg).
- Alternating injections into arterial and venous cannulas ensured the removal of native blood and clots, leaving the system clear.

5 Connection to SimLife® module:

- On the day of the simulation, arterial and venous cannulas were connected to the Pulse for Practice (P4P) SimLife® Control module using 2–4 mm diameter pipes.
- A peristaltic pump (a pump that uses a rotating mechanism to compress and push fluid through flexible tubing) injected a water-based blood avatar heated to 37°C into the vascular system.
- Solenoid valves (electromechanically controlled devices used to regulate fluid flow) on arterial inputs created pulsatile flow to mimic heartbeats. These valves were synchronized using a programmable logic controller (PLC), a digital device designed to automate processes through precise timing and coordination.

A schematic representation of the P4P SimLife® technical module principle of action and of the vascular and aerial accesses are reported in Figure 1.

Simulation process

Two bodies donated to science through the University of Bologna body donation program were defrosted and prepared for SimLife® simulation. Each body donor was placed in a separate dissection room and was connected to a distinct P4P SimLife® module 30 min before the start of the simulations. The functionality and performance of the SimLife® module were priorly presented to the teams in order to appreciate its capabilities. The presentation was held by SimLife® specialized personnel, who also answered any question asked by the teams. The activities were organized in two consecutive days in order to allow the participation of 62 medical professionals belonging to 13 different medical specialties and divided into 18 teams. Each team was given a total of 2 h to perform the simulation. The general information regarding the timetable of the activities is reported in Table 2. Detailed demographic information, including age, gender, and specialty distribution, is presented in the Results section under "Participant Demographics."

Data collection

After the 2-h simulation sessions, spread over 2 days, participants were interviewed. The structured interview consisted in 10 questions divided into 3 parts, respectively investigating the anatomical districts of interest and the intervention performed (part 1), the overall activity evaluation (part 2) and the general comments on the simulation (part 3). The questions' structure was mixed, including open answer questions and 6-points Likert scale questions. The meaning of each point on the Likert scale was verbally explained to all participants to ensure a consistent understanding of the scale. This explanation was provided by the

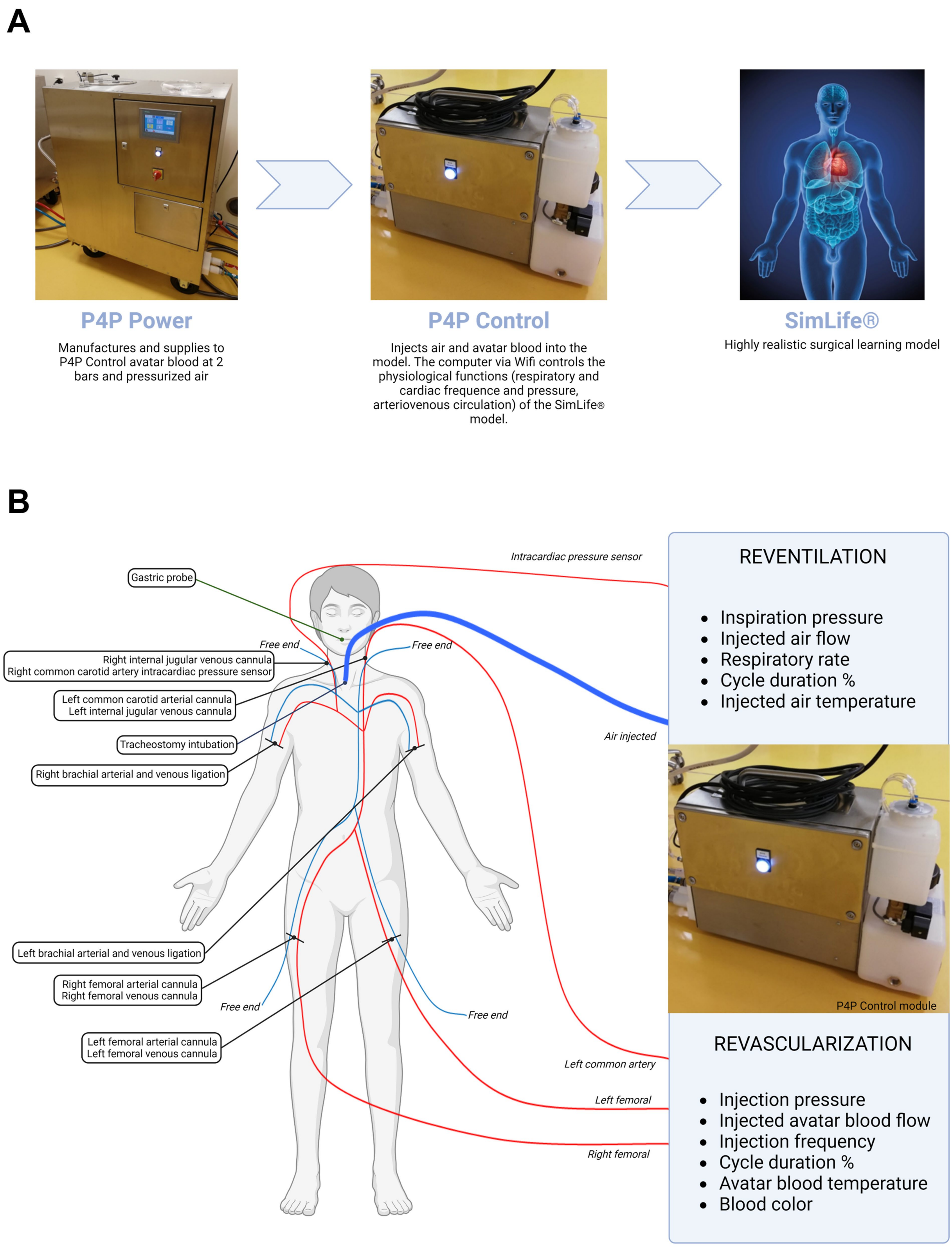

FIGURE 1
Schematic representation of P4P SimLife® technology. **(A)** Principle of action. **(B)** Vascular and aerial accesses and related connections to the P4P Control module. The principle of action of SimLife® technology has been described in detail by Delpech et al. (24).

TABLE 2 Timetable of the activities for the two days Siemedys SimLife® P4P simulation.

Day 1				Day 2			
Body donor 1		Body donor 2		Body donor 1		Body donor 2	
8 am–10 am	General surgery team	8 am–10 am	Otorhinolaryngology team	8 am–10 am	Neurosurgery team 2	8 am–10 am	Vascular surgery team
10 am–12 pm	Oral and Maxillofacial surgery team 1	10 am–12 pm	Neurosurgery team 1	10 am–12 pm	Cardiothoracic surgery team	10 am–12 pm	Orthopedic surgery team 2
12 pm–2 pm	Gynecology team 1	12 pm–2 pm	Oral and Maxillofacial surgery team 2	12 pm–2 pm	Orthoplastic surgery team	12 pm–2 pm	Orthopedic surgery team 3
2 pm–4 pm	Gynecology team 2	2 pm–4 pm	Orthopedic surgery team 1	2 pm–4 pm	Anesthesiology team	2 pm–4 pm	Urology team
4 pm–6 pm	Radiology team	4 pm–6 pm	Anatomists team and Anatomy tutors team				

same facilitator for all participants prior to completing the survey, ensuring standardization across the study. The scheme of the structured interview is reported in Supplementary material 1.

Data analysis

SPSS statistical package, version 25.0 (IBM Corp., Armonk, NY, USA) was used to statistically analyze the collected data. The Kruskal-Wallis test for independent samples was selected as a non-parametric alternative to ANOVA due to the small sample sizes and the non-normal distribution of the data, which was confirmed using the Kolmogorov–Smirnov test. Similarly, Fisher's Exact Test was chosen for categorical data analysis because it is robust for small sample sizes, providing accurate results where chi-square tests may be unreliable. Only p-values <0.05 were considered statistically significant. Moreover, frequency was calculated for every answer. GraphPad Prism, version 8.0 (GraphPad Software, Boston, MA, USA) was used to graphically visualize the structured interviews answers. The open answers were transcribed *verbatim* by using the Nvivo12 software (QSR International, Melbourne, Australia), a computer-assisted qualitative analysis tool that allowed empirical material to be more easily organized and managed. The Nvivo12 software allows the analysis of unstructured or semi-structured data, such as interviews, enabling the coding and organization of information so that its content could be explored, and theories could be built and tested on the textual data. The descriptive data from the interviews were then analyzed using thematic analysis – in which common topics, ideas and patterns of meaning were identified in categories – to examine and understand the data at a general level (29). To ensure inter-coder reliability, two researchers independently coded a subset of the responses and compared their results. Discrepancies were resolved through discussion and consensus, and the final coding framework was applied to the entire dataset. The thematic analysis identified common topics, ideas, and patterns of meaning, which were categorized into macro-themes for a comprehensive understanding of the data.

Results

Participant demographics

A total of 62 participants, representing 13 medical specialties, participated in the study. The majority were specialists (71%), with the remaining 29% consisting of medical residents undergoing specialized training. The age distribution ranged from 19 to 44 years, with an average age of 40 years, reflecting the inclusion of both seasoned professionals and trainees. The demographic breakdown, including gender and specialty distribution, is summarized in Table 3.

Anatomical districts of interest and interventions performed

The anatomical district of interest of every participant and the interventions performed in this SimLife® simulation were investigated through open-answer questions. Among the 62 participants, 29% declared that their anatomical district of interest was the head and neck region. Another 31% declared to be interested in the thorax/abdomen/pelvis region. The 26% declared to be interested in the lower limbs, while the 8% declared to be interested in the upper limbs. Finally, another 6% declared to be interested in the spine/peripheral nervous system (PNS) (Figure 2).

Overall, a total of 31 different interventions were performed. These varied from explorative/dissecting interventions such as gallbladder exploration and ankle dissection to more complex surgical operations such as heart and lungs asportation and galeo-pericranial microvascular free flap. The complete list of the interventions performed during the two-days SimLife® simulation is reported in Table 4. Figure 3 reports exemplificative images of some of the surgical interventions performed. Moreover, shortcuts of the galeo-pericranial microvascular free flap intervention and of the knee medial and lateral ligament reconstruction are reported, respectively, as Supplementary Videos S1, S2. Finally, the success rate of the interventions was assessed. 100% of the participants declared that the intervention they performed was successful.

SimLife® simulation evaluation

The activity evaluation, represented by the participants' perception about the usefulness of SimLife® technology, the participants' enjoyment/appreciation and the participants' willingness of repeating the experience, was assessed using 6-points Likert-scale questions. Overall, the participants' perception about the usefulness of SimLife® simulation was extremely positive. Out of the 62 responders, 69% affirmed that SimLife® technology is

TABLE 3 Demographics of the participants.

Demographics	Participants
Gender	
Female	19
Male	43
Age	
19–23	5
24–30	13
30+	44
Medical specialty	
Anatomist (Anatomy tutor)	13 (5)
Anesthesiology	3
Cardiothoracic surgery	3
General surgery	3
Gynecology	4
Interventional neuroradiology	3
Neurosurgery	3
Oral and maxillofacial surgery	7
Orthopedic surgery	8
Orthoplasty	2
Otorhinolaryngology	2
Urology	2
Vascular surgery	5
	Total participants = 62

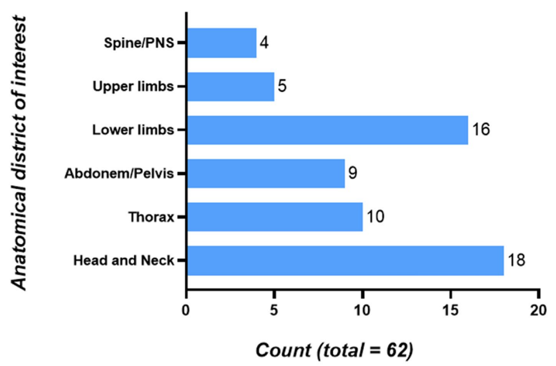

FIGURE 2
Anatomical districts of interest of the participants. 18 people were interested in the Head and Neck region; 10 people were interested in the Thorax region; 9 people were interested in the Abdomen/Pelvis region; 16 people were interested in the Lower limbs region; 5 people were interested in the Upper limbs region; 4 people were interested in the Spine/PNS region. PNS, Peripheral Nervous System.

absolutely useful for research. The 61% affirmed that this technology is absolutely useful for *pre-lauream* training. The 86% declared that SimLife® technology is absolutely useful for *post-lauream* training. Finally, 84% of participants affirmed that this technology is absolutely useful for team-building. The median and the interquartile range (IQR) for each 6-points Likert-scale question on this section is reported in Figure 4.

TABLE 4 Interventions performed during the SimLife® simulation.

Anatomical district	Interventions performed
Head and neck	• Maxillary lateral sinus lift • Endoscopic endonasal approach to skull base • Middle ear endoscopy • Parotidectomy • Pterional craniotomy • Transethmoidal approach to sella and parasellar area • Galeo-pericranial microvascular free flap • Neck dissection
Thorax/Abdomen/Pelvis	• Laparoscopic sleeve gastrectomy • Lobectomy • Chest muscles dissection • Heart and lungs asportation • Right-hemisphere gastrectomy • Bilateral radical nephrectomy with open anterior trans-peritoneal approach and bilateral subcostal incision • Exposure of aorta and vena cava • Lysis of intestinal and omental adhesions • Exploration of gallbladder • Intra-operative ICG fluoroangiopathy • Bladder exposure
Upper limbs	• Radial forearm flap • Radial artery graft • Pulsed wave doppler ultrasound of the radial artery • Wrist dissection
Lower limbs	• Femoral popliteal bypass • Medial collateral ligament surgery • Total hip arthroplasty with ilioinguinal approach • Knee medial and lateral ligament reconstruction • Ankle dissection • Knee dissection
Spine/PNS	• Anterior lumbar interbody fusion • Vagous nerve exposure

To determine if there were statistically significant differences in the perception of SimLife® technology's usefulness across different medical specialties, the Kruskal-Wallis test was performed between the medical specialty indicated by the participants and the answers to the 6-Points Likert scale question "Evaluate the usefulness of this type of technology for the following scope: research, training *pre-lauream*, training *post-lauream*, team-building," with 1 = not useful at all and 6 = extremely useful. The results were subsequently utilized to conduct pairwise comparisons between the different medical specialties. The application of the Kruskal-Wallis test revealed statistical significance in the variability of responses only for the *pre-lauream* training and *post-lauream* training categories. The graphical visualization of the results of the two tests are reported in Figures 5A,B, respectively. While the majority of medical specialties have reported a good or very good perception (mean score 5 and 6) of the SimLife® technology's usefulness in both categories, some medical specialties reported a lower utility. In particular, regarding the *pre-lauream* training category, the otorhinolaryngology specialists expressed a less favorable opinion compared to other specialties (mean

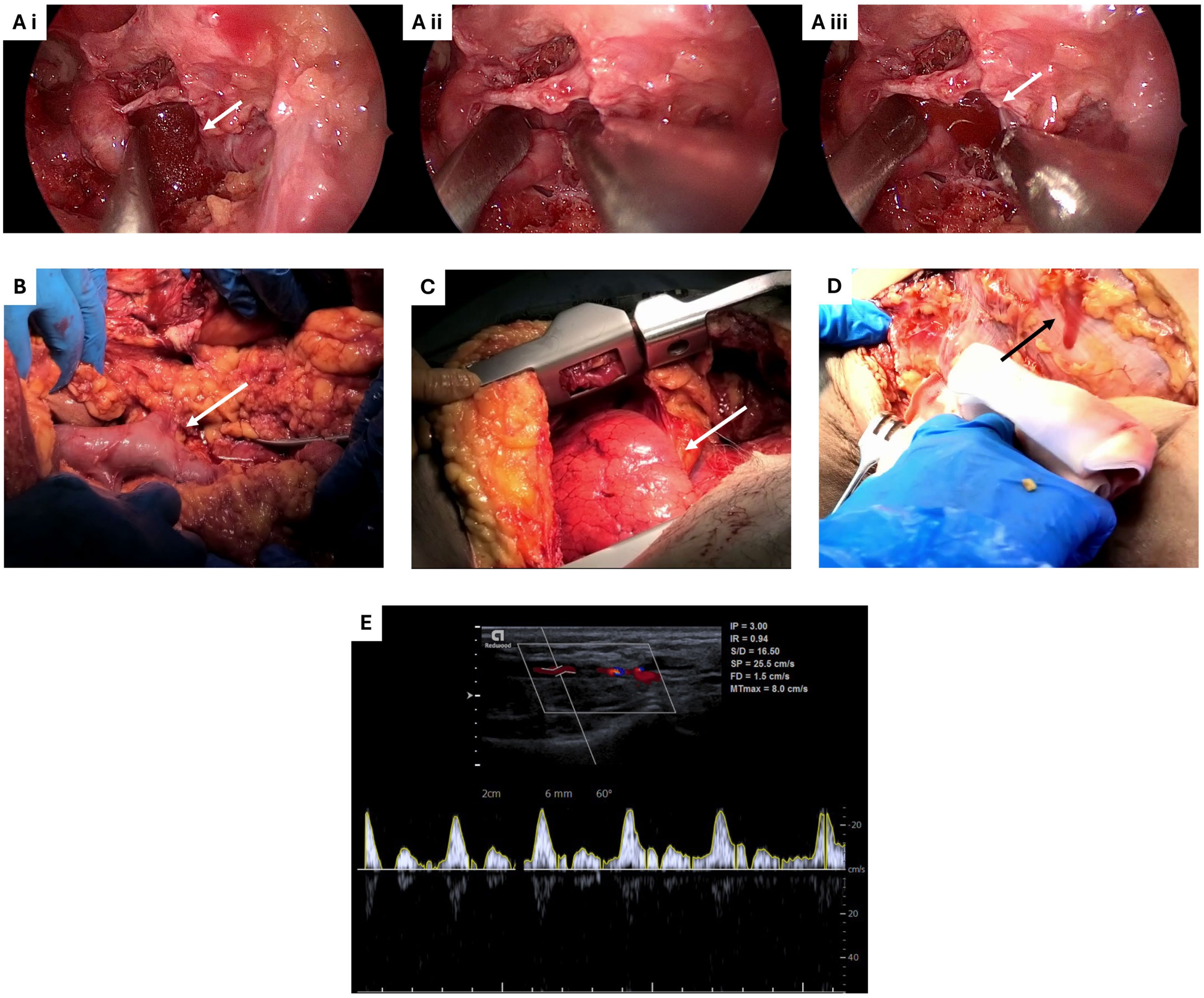

FIGURE 3
Exemplificative images of some of the surgical interventions performed during Simedys simulation. **(Ai–iii)** Endoscopic endonasal approach to skull base, highlighting the bleeding of the internal carotid artery. White arrows indicate the avatar blood. **(B)** Exposure of inferior vena cava, highlighting the turgidity of the vein due to reperfusion (white arrow). **(C)** Lungs asportation, highlighting the right lung expansion phase during re-ventilation (white arrow). **(D)** Knee dissection, highlighting the bleeding of superficial vessels (black arrow). **(E)** Pulsed wave doppler ultrasound of the radial artery. The image illustrates the velocity waveform obtained from the radial artery, demonstrating characteristic systolic peaks followed by diastolic flow, indicative of the efficacy of the simulated arterial blood flow. The scale on the right represents velocity (cm/s), and the time (sec) is shown on the horizontal axis.

score 3). Concerning the pairwise comparison for this category, significant differences were highlighted between this specialty and several others. For example, otorhinolaryngology specialists have expressed a significant lower opinion compared to the anatomy specialists ($p = 0.017$), the vascular surgery specialists ($p = 0.004$), the urology specialists ($p = 0.017$), and the cardiothoracic surgery specialists ($p = 0.009$). Regarding the *post-lauream* training category instead, the vascular surgery specialists expressed a less favorable opinion compared to other specialties (mean score 4). Also in this case, the pairwise comparison for this category has highlighted significant differences with other medical specialties. For example, vascular surgery specialists have expressed a significant lower opinion compared to the maxillofacial surgery specialists ($p = 0.001$), the anatomy specialists ($p < 0.001$), and the cardiothoracic surgery specialists ($p = 0.001$).

The participants' enjoyment/appreciation resulted to be very high. Indeed, 100% of the participants declared that they enjoyed the activity (97% absolutely yes and 3% yes). Moreover, 99% of the participants declared that they would like to repeat the SimLife® simulation (98% absolutely yes and 1% yes). The median and IQR for both of these two 6-points Likert-scale questions are reported in Figure 6.

To determine if there were statistically significant differences in the enjoyment of the simulation across different medical specialties, the Kruskal-Wallis test was performed between the medical specialty of the participants and the answers to the 6-Points Likert scale questions "How much did you enjoy, overall, this type of simulation" and "Would you like to repeat this experience," respectively. However, this analysis did not provide statistically significant results ($p = 0.734$ and $p = 0.556$ respectively).

Critical issues and general comments on the simulation

At the end of the interview, participants were asked to indicate any critical issue they encountered and to express any other comment

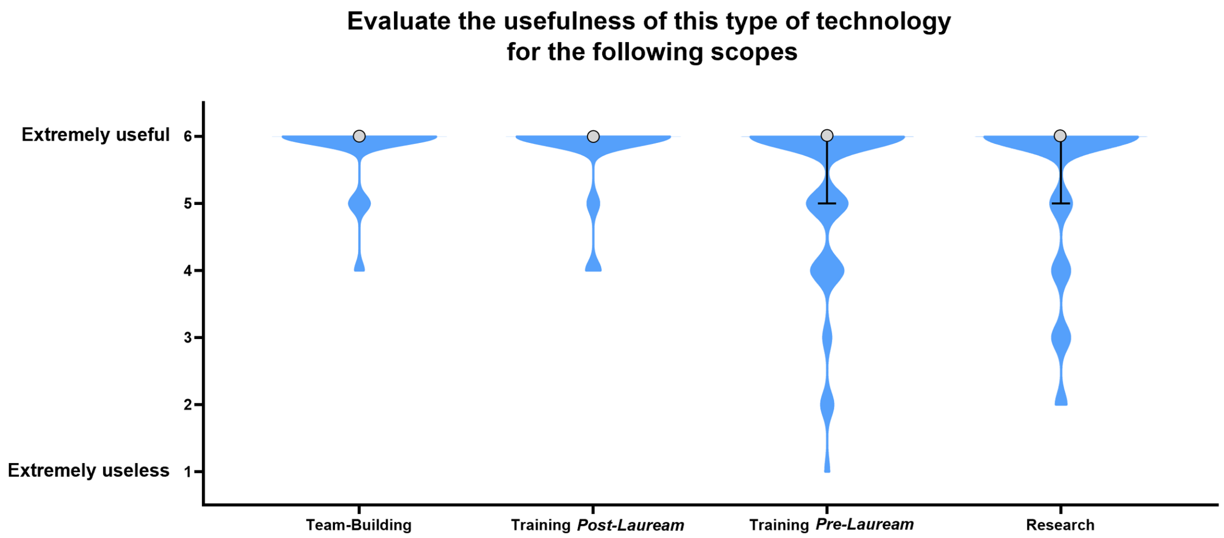

FIGURE 4
Evaluation of the usefulness of SimLife® technology for various applications: Team-Building, Training *Post-Lauream*, Training *Pre-Lauream*, and Research. Violin shape shows the distribution of participant responses. The circle indicates the median response value, and the error bars represent the interquartile range (IQR). Where error bars are not visible, the IQR = 0, indicating uniform participant responses for that category.

they had. Regarding the question "Did you notice any critical issue in this type of simulation?," 4 main themes emerged from the thematical analysis:

- Bleeding of small vessels: although SimLife® P4P system ability of recreating blood flow in the major vessels was highly appreciated, some concerns were raised about the small ones. Example: «*The system is very efficient in recreating the circulation of large vessels, but unfortunately not the small ones*».
- Lack of coagulation: another issue that was reported was the lack of coagulation. Example: «*[One problem is the] lack of coagulation, which makes difficult to control bleeding*».
- Body donor preparation: the length of the preparative phase and the vascular accesses were also addressed. Example: «*Vascular access technique and preparation time could be improved*».
- Body donor position and characteristics: finally, the impossibility of moving the human bodies and the problems related to their characteristics were reported. Examples: «*Inability to obtain additional body positions*»; «*Difficulty with the obese subject*».

To establish whether the observed problems encountered during the SimLife® simulations were randomly distributed among the various anatomical districts or whether there was a statistically significant correlation, the Fisher Exact test was performed between the anatomical district of interest indicated by participants and the question "Did you notice any critical issue in this type of simulation?." The results indicate that there was no relation between the critical issues encountered during the simulation and the anatomical district of interest ($p = 0.598$).

Finally, the sentiment derived from the answers to the final open question ("Other comments") was assessed. The general sentiment about the SimLife® P4P simulation was good, with 100% of the responders reporting a positive experience. Examples: «*[…] It proves to be a valid tool for simulations*»; «*Very useful for medical training*»; «*[…] I would recommend this kind of training to anyone in the medical field*».

Discussion

Medical simulations have revolutionized the landscape of medical education and training, offering a myriad of benefits to both aspiring healthcare professionals and seasoned practitioners (30). Traditionally, medical training relied heavily on observation and apprenticeship, where novice practitioners learned under the guidance of experienced mentors. While this approach is valuable, it can be limited by the unpredictability and the variability of real-life patient cases, and most importantly by patient safety concerns. To overcome the traditional training related problematics, the integration of simulation platforms has become increasingly crucial. Indeed, medical simulations have become an indispensable tool in medical formation due to their ability to create a safe, risk-free learning environment that grants medical students and professionals the skills, knowledge, and confidence necessary to deliver high-quality patient care (31, 32). One such cutting-edge simulation platform that has gained widespread recognition is SimLife®, a state-of-the-art system designed to provide realistic scenarios and immersive experiences to medical participants. In this study, the success of 31 interventions across various anatomical regions demonstrated the technology's capacity to replicate real-life scenarios, offering a highly effective platform for surgical training and skill acquisition. The SimLife® platform is based on the dynamization of body donors by the pulsatile revascularization with simulated ("avatar") blood warmed to 37°C and re-ventilation (24). In this way, SimLife® represents an innovative tool that allows the creation of a realistic, safe, and controlled environment by implementing a futuristic technology to bodies donated to science. The present study aimed to perform a wide-spectrum test of the SimLife® platform, involving several medical specialties. 62 medical professionals participated to

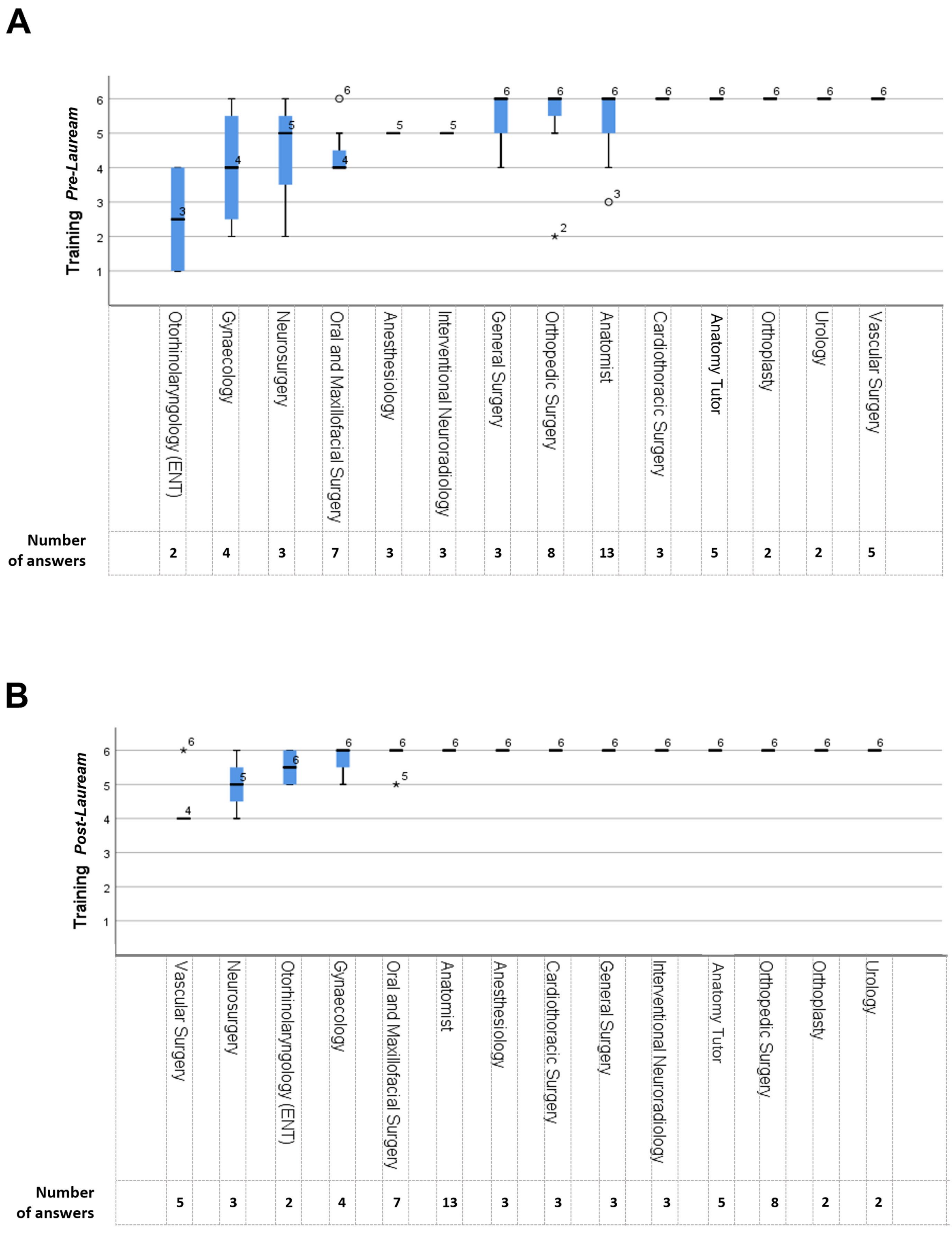

FIGURE 5
Perceived usefulness of SimLife® technology across medical specialties. **(A)** Perceived usefulness of SimLife® for *pre-lauream* training. **(B)** Perceived usefulness of SimLife® for *post-lauream* training. Y-axis indicates the perceived usefulness score (1 = Not useful at all, 6 = Extremely useful), while X-axis reports the different medical specialties. Each boxplot represents the interquartile range of responses, with the line indicating the median score and the whiskers showing the overall range. The circles indicate the mild outliers, representing responses that are outside the interquartile range, while the stars indicate the extreme outliers, representing responses well outside the typical range.

this study. The simulation, that lasted two days, took place at the dissection rooms of the Anatomy Centre of the University of Bologna and involved 2 bodies donated to science that were each connected to a SimLife® P4P console. After the simulation, participants were interviewed to determine their anatomical district of interest and the interventions performed during the simulation. Moreover, all the

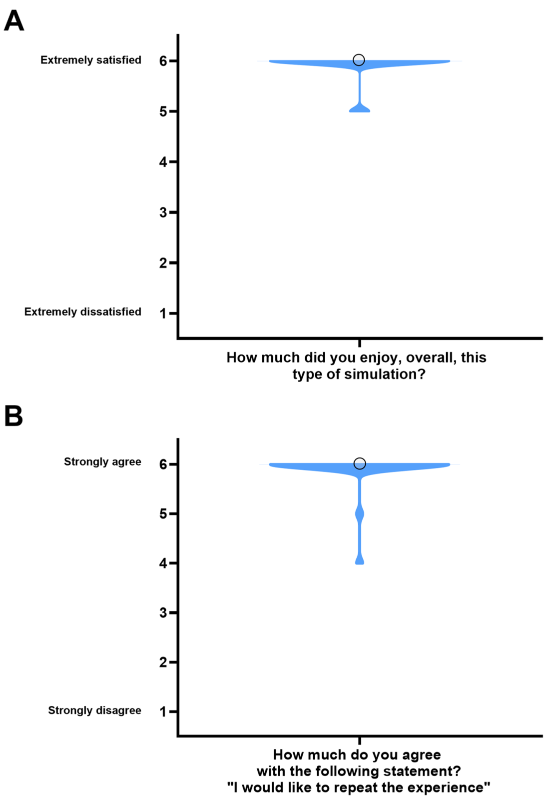

FIGURE 6
Participants' evaluation of the simulation experience. **(A)** Participants' overall satisfaction with the simulation. The violin plot represents the distribution of participants' responses. The circle indicates the median score. **(B)** Participants' willingness to repeat the experience. Violin shape shows the distribution of responses. The circle indicates the median score. For both panels, the IQR = 0 and is therefore not displayed.

participants were asked for their perception on the simulation. Finally, critical issues encountered during the simulation and the general sentiment of the experience were also assessed. 29% of the participants were interested in the head and neck region, while another 31% were interested in the thorax/abdomen/pelvis region. 26% declared interest in the lower limbs, while the upper limbs and the spine/peripheral nervous system (PNS) received, respectively, 8 and 6% of interest. The SimLife® simulation encompassed a total of 31 different interventions, ranging from simple explorative/dissecting procedures to more complex surgical operations. All the interventions were successful, underlining the efficiency of this simulation system even though the interventions were performed on a limited number of bodies donors. Moreover, this result is important because it underlines the possibility of using similar settings for team training. Team training refers to a structured process or program designed to enhance the effectiveness, collaboration, communication and performance of a group of individuals who work together as a team. The goal of team training is to improve communication, coordination, problem-solving, and overall team dynamics, leading to better outcomes and higher productivity. Indeed, team training is particularly important in the medical fields, and the value of simulations for enhancing the medical team training experiences is widely recognized (33). The participants' perception of SimLife® simulation was extremely positive. According to the Likert-scale responses, 69% of the responders believed that SimLife® technology was absolutely useful for research, 61% for *pre-lauream* training, 86% for *post-lauream* training, and 84% for team-building purposes. The high percentages of positive responses demonstrate that SimLife® successfully addresses various educational and training requirements for medical professionals. To delve into the nuances of participants' perceptions across different medical specialties, the Kruskal-Wallis test was employed. This analysis was pivotal in uncovering specific areas where the platform's perceived utility varied, particularly in relation to *pre-lauream* and *post-lauream* training requirements. The Kruskal-Wallis analysis revealed significant differences in participant perceptions across specialties, providing critical insights into how SimLife® technology meets the unique needs of various fields. Otorhinolaryngology participants reported lower satisfaction, particularly regarding its utility for *pre-lauream* training. This likely reflects the high precision and tactile feedback demands of this specialty, where procedures often involve delicate structures and intricate techniques. Expanding SimLife® to include finer tactile tools or modules specifically designed to replicate small, delicate procedures could significantly enhance its value for otorhinolaryngology and similar specialties. Similarly, vascular surgery participants expressed lower satisfaction with *post-lauream* training, which may be attributed to the lack of microvascular simulation capabilities. Future advancements in SimLife® could incorporate models that mimic microvascular conditions, enabling high-fidelity simulations for specialties that demand precision at a microscopic level. These improvements would broaden the platform's applicability and better address the diverse requirements of medical and surgical training. SimLife® demonstrated considerable potential for team-building activities, as 84% of participants stated to find this technology absolutely useful for team-building. Moreover, 100% of participants reported enjoyment and 98% expressed a willingness to repeat the simulation. Taken together, these findings highlight the platform's ability to foster collaboration and enhance intra-team dynamics in a controlled environment. Regular team-building simulations using SimLife® could address real-world challenges, such as improving intra-team communication, coordination, and decision-making under pressure—skills that are critical during high-stakes medical procedures. By simulating realistic scenarios, SimLife® enables teams to practice resolving conflicts, adapting to unforeseen complications, and making collective decisions, ultimately translating these skills into clinical practice. The consistent positive feedback underscores the value of integrating team-based simulations into routine training programs to strengthen team cohesion and effectiveness. Indeed, these results are concordant with the other studies using this technology that are present in literature (34–37). Despite the overall positive sentiment emerged from the general comments on the simulation, participants did identify some critical issues. Through a thematic analysis, four main themes emerged:

- Bleeding of small vessels: While the system demonstrated excellent efficiency in recreating blood flow in major vessels, concerns were raised about the representation of smaller vessels. Indeed, for logistical reasons, Simedys personnel was unable to prepare the body donors as soon as they arrived at the Bologna Anatomy Center. The preparation of the human bodies shortly after death/thawing is strongly recommended for the successful outcome of the simulation and therefore this could have affected the blood flow in the small vessels. However, if delayed preparation eventually affects micro-vascularization is still to be investigated. Future versions of the technology could incorporate models that simulate small vessel bleeding using controlled flow mechanisms, enhancing the fidelity of surgical scenarios.

- Lack of coagulation: Participants pointed out the absence of coagulation, which made it challenging to control bleeding during certain scenarios. However, SimLife® simulation models are to be considered hemophilic patients and therefore require the usage of a mono or bipolar electric scalpel. Indeed, this requirement makes the interventions challenging as indicated by several participants. Developing clotting simulation models, such as using biochemical agents or programmable flow restrictors, could address this issue and expand the utility of SimLife® for hemostatic training.
- Body donor preparation: Some participants expressed concerns about the length of the preparative phase and the difficulty with vascular access. Improving the vascular access technique and minimizing preparation time could enhance the overall efficiency of the simulation. To achieve this, the programming of surgical simulations needs to be improved, and the simulated operating technique needs to be known in advance. Unfortunately, this step was not possible due to logistical reasons.
- Body donor position and characteristics: Participants highlighted the inability to move body donors due to connections to the P4P Control module and issues related to body characteristics, such as obesity. Similarly to what concerns the body donor preparations, to grant the best outcome of the simulation Simedys personnel should know the surgical technique object of the simulation in advance. Indeed, this knowledge allows to define the body donor's operating position beforehand. However, due to logistical reasons and also to the wide-spectrum approach that was followed, this step was not possible. On the other hand, technological innovations such as lightweight or modular configurations for the P4P module, could allow for greater flexibility and a wider range of positional adjustments during simulations.

These findings collectively underscore the imperative for ongoing advancements to address the identified limitations, ultimately fostering a more comprehensive and realistic training environment for medical professionals. Nevertheless, participants consistently conveyed an overwhelmingly positive sentiment, with a unanimous 100% reporting a favorable experience. Respondents expressed the simulation's utility as a valid tool for medical simulations, emphasizing its significance in medical training. While the positive feedback highlights the SimLife® P4P simulation's strengths, the identified areas of improvement, including issues with small vessel representation, coagulation dynamics, body donor preparation, and adaptability to diverse body mass index, offer a constructive roadmap for refining and expanding the simulation's capabilities in future iterations. Such a balanced evaluation acknowledges both the notable successes and the avenues for enhancement, contributing to the ongoing discourse on advancing medical simulation technologies for comprehensive training in the healthcare domain. Finally, given the results presented in this study, it is relevant to point out that SimLife® technology transcends its role as a very useful tool in medical training, embodying also a pivotal innovation that emphasizes the invaluable contribution of body donation to medical science. Indeed, by integrating realistic simulation environments with the anatomical precision provided by actual human bodies, SimLife® technology not only enhances the educational landscape for medical professionals but also serves as a profound tribute to the generosity of body donors. Several recent studies point out the ethical considerations that are part of implementing body donation to medical training, such as the respect and dignity owed to the body donors (the "silent teachers") (38, 39) and the critical importance of body donations in advancing medical education and research (40, 41). The ethical dimensions of body donation remain a cornerstone of simulation-based medical training, providing a foundation for advancing both education and research. Technologies like SimLife® amplify the value of body donors by creating opportunities for dynamic and realistic training scenarios, ensuring that their contributions have maximum impact. This synergy between technological advancement and ethical considerations highlights how innovation can complement respect for donor dignity. As simulation technology evolves, ethical frameworks must adapt to ensure the continued dignity and recognition of body donors. Simulation platforms like SimLife® enhance this respect by transforming static anatomical models into dynamic, life-like systems, thereby elevating the educational and training value of donated bodies. Future advancements could include donor recognition programs or digital memorials that acknowledge the invaluable role of donors in advancing medical education, further integrating ethical considerations with technological progress.

Conclusion

In conclusion, this comprehensive study aimed to assess the impact of SimLife® P4P technology on medical training and education in Italy. The wide-ranging simulation approach involving 62 medical and surgical participants from 13 specialties successfully identified the technology's potential impact across diverse medical fields. The simulation, conducted at the Anatomy Center of the University of Bologna, showcased the overall efficiency of SimLife® for various medical fields. The simulations, encompassing 31 different interventions, were universally successful, underlining the system's effectiveness and the potential for specialized training settings even with a limited number of body donors. Despite the overwhelmingly positive perceptions of participants, highlighted by Likert-scale responses indicating the utility of SimLife® technology for research, *pre-lauream*, *post-lauream* training, and team-building, our study has also highlighted notable variations in its perceived utility across the various medical specialties. These insights underscore the importance of tailoring the simulation experience to meet the distinct demands of each medical field. Indeed, addressing the specific requirements identified could be pivotal in refining the SimLife® platform. Moreover, critical issues were identified through thematic analysis, including concerns about small vessel representation, lack of coagulation, body donor preparation time and access, and limitations in body donor positioning. Addressing these aspects could give important added value to the simulation experience. While acknowledging the need for ongoing advancements to address these limitations, the study underscores the transformative potential of SimLife® in creating realistic, safe, and controlled environments for medical training and education. The overwhelmingly positive participant experiences and enthusiasm for repetition substantiate SimLife®'s efficacy and potential for further refinement in shaping the future of medical simulation technologies. Looking forward, addressing these limitations through innovations such as enhanced microvascular simulation, clotting models, and flexible donor configurations could significantly broaden SimLife®'s applicability. These advancements have the potential to reshape medical training globally, particularly in underserved specialties requiring high precision, such as otorhinolaryngology and vascular surgery. Additionally, future research could explore tailoring questionnaires to specific specialties, with a focus on understanding how *pre-lauream* trainees perceive the differences between reperfused and non-reperfused body donors. Another important direction would be to analyze the detailed positive feedback given by specialties that found the simulation most beneficial compared to traditional surgical practice. SimLife® technology stands as not only a pivotal tool in medical training for its technological prowess but also as a beacon of ethical stewardship, ensuring that the legacy of body donors is honored. By continuing to integrate technological innovation with robust ethical frameworks, SimLife® has the potential to redefine the landscape of medical education and create a lasting impact on the next generation of healthcare professionals.

Limitations of the study

The present study represents a significant advancement in medical education, offering a highly realistic platform for surgical and medical training. However, despite these positive attributes, the study faces several limitations. One primary limitation is the dependency on body donations, which can be unpredictable in terms of the number and characteristics of human bodies available. This limitation impacts the scope and diversity of simulations possible. Additionally, the limited time for conducting the simulations with human bodies is a significant constraint, as the body donors can only be used for a certain period before they become unsuitable for the simulations. Technical and organizational challenges also exist, including the complexity of preparing body donors for reperfusion and re-ventilation, as well as ensuring the proper functioning of SimLife® technology. These factors together limit the scale and variety of training scenarios that can be realistically simulated, which could affect the study's generalizability and applicability to a broader range of medical and surgical training contexts. In addition to the limitations related to body donors, the study also faces constraints stemming from its design. The methodology employed may not fully replicate real-life clinical scenarios, potentially affecting the validity and applicability of the results. There is also a risk of bias due to the small sample size and the potential variability in human body conditions, which could impact the consistency and reliability of the findings. Furthermore, the study's design might not adequately address all relevant variables in medical training, thus limiting the comprehensiveness of the conclusions that can be drawn from this research. Finally, mastering SimLife® technology also requires a learning curve itself. Therefore, it is necessary to perform more simulations to obtain better outcomes. With this future perspective in program, the Anatomy Center of the University of Bologna aims to become a national reference center for this groundbreaking technology.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of Bologna Bioethical Board (Prot. N. 0102300 of 10/04/24). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

IN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. GV: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. AF: Investigation, Methodology, Validation, Writing – review & editing. MM: Investigation, Methodology, Validation, Writing – review & editing. F-DK: Investigation, Methodology, Validation, Writing – review & editing. EB: Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing. SL: Investigation, Methodology, Validation, Writing – review & editing. GM: Investigation, Methodology, Validation, Writing – review & editing. MQ: Investigation, Methodology, Validation, Writing – review & editing. AB: Investigation, Methodology, Validation, Writing – review & editing. AR: Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing. CaB: Investigation, Methodology, Validation, Writing – review & editing. CyB: Conceptualization, Investigation, Methodology, Project administration, Resources, Validation, Writing – review & editing. AP: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. VM: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. LM: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – review & editing. SR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

Cyril Brèque is founding CEO of Simedys and inventor of SimLife® technology (patent WO2017076717).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Implementation and evaluation of online and offline blended teaching model in laboratory course of Clinical Laboratory Hematology

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This study explores the implementation and evaluation of online and offline blended teaching model in the Clinical Laboratory Hematology (CLH) laboratory course at Chengdu Medical College. To this end, 90 students majoring in medical laboratory technology in 2020 were selected as research subjects and randomly divided into experimental and control groups. The experimental group adopted an online and offline blended teaching model, while the control group adopted a traditional one. After-class tests, laboratory examinations, questionnaire surveys, and student interviews were conducted to evaluate the teaching effectiveness. The average scores of both tests and examinations in the experimental group were significantly higher than those in the control group ($p < 0.05$). Furthermore, the results of the feedback questionnaire showed that the satisfaction and self-evaluation of the learning effect of students in the experimental group were significantly better than those in the control group ($p < 0.05$). The blended teaching model has been successful and popular in CLH. This is a useful teaching mode worth applying to laboratory teaching in medical courses.

KEYWORDS

online and offline, blended teaching model, Clinical Laboratory Hematology, laboratory course, medical laboratory

Introduction

During the past 3 years of Corona Virus Disease 2019 in China, the medical laboratory profession has responded magnificently to various challenges (Zhang et al., 2020). Education in medical laboratory is also required to improve the quality of talent training to address these challenges. Clinical Laboratory Hematology (CLH) is one of the core professional courses in medical laboratory and is recognized as practical, intricate, and multidisciplinary (Rizk, 2018). Students in this course are required to develop practical skills, especially in cell morphology recognition.

Clinical Laboratory Hematology is generally divided into theoretical and laboratory courses. In the traditional laboratory classroom, the teacher first gave a short lecture referring to key and difficult aspects of the current laboratory course. Subsequently, the students followed instructions to observe marrow cell morphology with marrow smears through microscopes step-by-step (Bian et al., 2018). However, the majority of the bone marrow smears and microscopes in use are outdated, primarily due to two main reasons. First, the bone marrow smears utilized in our course's laboratory teaching have deteriorated in quality over time from extensive use and cleaning, which significantly impacts students' experiences when examining slides under the microscope. These slides are mostly provided by clinical technicians from the affiliated hospital's laboratory department. The high demand for teaching slides, coupled with the time-consuming processes of slide preparation and staining, and the busy schedules of clinical technicians, result in a delay in replenishing and replacing the aging teaching materials. Second, the frequent use of microscopes has led to severe wear and tear, further affecting students' slide-reading experiences. The high cost of microscopes and the large quantities required for procurement also mean that it is impractical to replace outdated microscopes in a timely manner. This situation has led to a concerning finding: after completing the course, most students exhibit weak cell morphology recognition skills. This deficiency in basic skills has a domino effect, resulting in weaker practical skills during the clinical practice stage. Moreover, this presents a significant challenge for CLH educators, who must address the issue of outdated teaching materials and equipment to ensure that students develop the necessary skills for their future careers in clinical.

The online and offline blended teaching aims to lead students from a superficial to a deep and full understanding of the courses. It offers a promising way of transforming teaching methods in educational careers and has been reported to positively affect many subjects (Guillén-Gámez et al., 2024; Palacios-Rodríguez et al., 2025; Talan et al., 2024; Goldberg and Crocombe, 2017; McLaughlin et al., 2015). With the spread of wireless fidelity on Chinese campuses and the increasing availability of online teaching systems and platforms, educators at Chinese universities are instigating a wave of blended teaching reforms (Shang and Liu, 2018).

The flipped classroom is a pedagogical approach where learning activities are rearranged to be effective in providing the educators more face-to-face interactions with students (Fatima et al., 2017; Rotellar and Cain, 2016). This teaching method is constructively based on the student-centered teaching concept, and gives full play to students' subjective initiative, so as to improve the learning outcomes (Cho et al., 2021; Dooley et al., 2018).

To improve students' learning effect of laboratory courses in CLH as well as skills in cell morphology recognition and study motivation, an online and offline teaching model with flipped classroom for our laboratory course has been designed and implemented in the medical laboratory major of our school. Meanwhile, the implementation effect was evaluated by an after-class test, laboratory examination, questionnaire survey, as well as student interviews and compared with the traditional teaching model.

Materials and methods

Participants

This study was conducted at the School of Laboratory Medicine at Chengdu Medical College. Accordingly, 90 undergraduates in the third grade majoring in medical laboratory technology were selected as research subjects. Subsequently, 30 students from Class 1 were divided into an experimental group using online and offline blended teaching model with flipped classroom. The remaining 60 students, Classes 2 and 3, were divided into control group, using a traditional teaching model, respectively. Students from the three classes were evenly assigned to parallel classes based on their college entrance examination scores, including Chinese, Mathematics, English and Science Comprehensive subjects scores. There were no significant differences in age or sex between the two groups ($p > 0.05$, Supplementary material). All students took theory courses in CLH in the same class. All procedures in this study were approved by the Ethics Committee of Chengdu Medical College, and informed consent was obtained from all students (2021NO. 09).

Teaching method

The online and offline blended teaching model

The experimental group used blended online and offline teaching model. A blended teaching model was built using an online cell morphology resource library.[1] The online resource library contains both normal and pathological marrow cell morphology related to textbooks. Students can view the photographs of single marrow cells and the marrow images in an online resource library with a magnifying or contractible view. The correct answers of the cells were clicked to reveal. Thus, the problem of time-worn marrow smears and microscopes was solved online.

Teaching content

According to the teaching objectives, syllabus, and textbook content, important laboratory teaching content of cell morphology was selected using the online and offline blended teaching model with flipped classroom (Table 1).

Teaching implementation

Before laboratory class

In the CLH curriculum system, the students acquired cell morphology knowledge in theory courses and then practiced in the laboratory class to develop cell morphology-recognized skills. For example, the teaching content of the first laboratory class included normal marrow cell morphology, including granulocytes, normoblasts, and megakaryocytes. First, the teacher taught professional knowledge of cell morphology in a theory class. After the theory class, the teacher uploaded the learning goals of the laboratory class to the online teaching platform and required students to look through the cell morphology online to preview before the laboratory class.

In laboratory class

First, knowledge review: the teacher systematically summarized the key and difficult aspects of morphology taught in theory class. Then, an observation assignment was given to the students to finish in class.

1 http://e-lab.cmc.edu.cn/virlab/

TABLE 1 The difference between the on-line and off-line blended teaching model and traditional teaching model.

Order	Teaching content	Online and offline blended teaching model			Traditional teaching model	
		Teaching period	Flipped classroom	Teaching model	Teaching period	Teaching model
1	Normal marrow cell morphology (granulocytes, normoblasts, and megakaryocytes)	3 classes, last class for flipped classroom (120 min)	Briefly describe the cell morphology of granulocytes, normoblasts, and megakaryocytes	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
2	Normal marrow cell morphology (lymphocytes, monocytes and plasmacytes)	3 classes, last class for flipped classroom (120 min)	Briefly describe the cell morphology of lymphocytes, monocytes and plasmacytes	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
3	Observation of normal marrow cell morphology with microscopes	3 classes, last class for flipped classroom (120 min)	Briefly describe the diagnostic criteria for a normal bone marrow	Off line students observed marrow cells with marrow smears through microscopes.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
4	Marrow cell morphology in cytochemical stain	3 classes, last class for flipped classroom (120 min)	Briefly describe the clinical significance of the several types of cytochemical stain	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
5	Anemia marrow cell morphology	3 classes, last class for flipped classroom (120 min)	Clinical case analysis of megaloblastic anemia	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
6	Cytochemical stain experiment and observation of anemia marrow cell morphology with microscopes	3 classes, last class for flipped classroom (120 min)	Clinical case analysis of iron deficiency anemia	Off line students observed marrow cells with marrow smears through microscopes.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
7	CL marrow cell morphology (CML and CLL)	3 classes, last class for flipped classroom (120 min)	Clinical cases case analysis of CML	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
8	AL marrow cell morphology (AML and ALL)	3 classes, last class for flipped classroom (120 min)	Clinical case analysis of APL	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
9	MM and MDS marrow cell morphology	3 classes, last class for flipped classroom (120 min)	Clinical case analysis of MM	On line students observed marrow cells with an online resource library.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.
10	Observation of leukemia, MM and MDS marrow cell morphology with microscopes	3 classes, last class for flipped classroom (120 min)	Briefly describe the key points in differentiating the above diseases with their bone marrow morphology	Off line students observed marrow cells with marrow smears through microscopes.	3 classes without flipped classroom (120 min)	Off line students observed marrow cells with marrow smears through microscopes.

MgA, megaloblastic anemia; IDA, iron deficiency anemia; CL, chronic leukemia; CML, chronic myelogenous leukemia; CLL, chronic lymphocytic leukemia; AL, aucte leukemia; AML, aucte myelogenous leukemia; ALL, aucte lymphocytic leukemia; APL, acute promyelocytic leukemia; MM, multiple myeloma; MDS, myelodysplastic syndrome.

Second, online observation of cell morphology: the students used an online resource library to observe marrow cells. Offline observation of cell morphology: the students observed marrow cells with marrow smears using a microscope. Either through online or offline observation, students could communicate with the teacher at once if they had any questions about the marrow cell morphology they were observing.

Finally, flipped classroom: during the last 40 min of the class, the teacher set up several questions or a case analyses of the current class's teaching content. Students then worked in groups to discuss and analyze the questions and case raised by the teacher and used the morphological knowledge they had mastered to answer and solve the problems. Teachers would correct their mistakes and supplement their answers.

After laboratory class

Students were required to review the cell morphology learned in class using an online resource library after class.

The traditional teaching model

The control group used a traditional offline teaching model. The control and experimental groups were taught by the same teacher, and the teaching content and duration were the same. However, students in the control group observed marrow cells with marrow smears through microscopes without an online resource library. Finally, the teacher made a summary speech on the students' performance in the classroom. Additionally, students are also required to preview and review laboratory learning content before and after class using textbooks instead of the online resource library.

Effect evaluation

The after-class test

After each laboratory class, as shown in Table 1, approximately 10 choice questions were selected to test the students' skills in cell morphology recognition. Next, we compared the average test scores of the two groups using the different teaching models.

The laboratory examination

After completing the whole laboratory course, a laboratory examination was conducted to evaluate students' mastery of cell morphology recognition skills. The examination contained 10 choice questions about normal marrow cell morphology and 10 choice questions about pathologic marrow cell morphology. Finally, the average test scores of the two groups were compared.

The questionnaire survey

At the end of the course, a questionnaire was distributed to students in the form of an online electronic questionnaire. Students completed the questionnaires independently and anonymously. The questionnaire was designed based on validated questionnaires from previous studies (Diel et al., 2021; Hameed et al., 2020). The responses were scored using a 5-point Likert scale (ranging from 1 = strongly disagree to 5 = strongly agree) to evaluate the satisfaction and learning effects of the teaching models on students. The reliability of the scale was assessed using Cronbach's alpha (Bian et al., 2018). The Cronbach's alpha for the student satisfaction questionnaire on the current teaching model and the self-assessment questionnaire on learning effectiveness are 0.89 and 0.86, respectively.

Statistical analysis

Data were statistically analyzed using the SPSS software (version 25.0; International Business Machines Corp., Armonk, NY, USA). Both the test and examination scores were analyzed using an independent sample t-test. The Wilcoxon signed-rank test was used to compare questionnaire survey responses between the two groups. The distribution of the questionnaire scores was skewed. $p < 0.05$ is considered statistically significant.

Results

After class test score

As shown in Figure 1, the average test score of the experimental group was significantly higher than that of the control group ($p < 0.01$, Figure 1).

Experimental examination score

Furthermore, the experimental examination score was significantly higher in the experimental group than in the control group ($p < 0.05$, Figure 1).

Students' questionnaire results

We sent 90 copies of the questionnaires to the students, and 90 copies were received, with a recovery rate of 100%.

Table 2 shows the two groups of students' responses to their satisfaction with the current teaching model. We found that the degree of satisfaction in the experimental group was much higher than that in the control group. In addition, to determine how satisfied students were with the frequency of online laboratory classes and the online cell morphology resource library, we designed questions 4 and 5 for the experimental group students only. It was found that 90% of the students in the experimental group were satisfied with the frequency of online classes. Subsequently, 93.33% of the students were satisfied with the online library.

Moreover, the Wilcoxon test showed that higher scores for the three questions were obtained in the experimental group than in the control group ($p < 0.01$) (Figure 2). Compared with the traditional

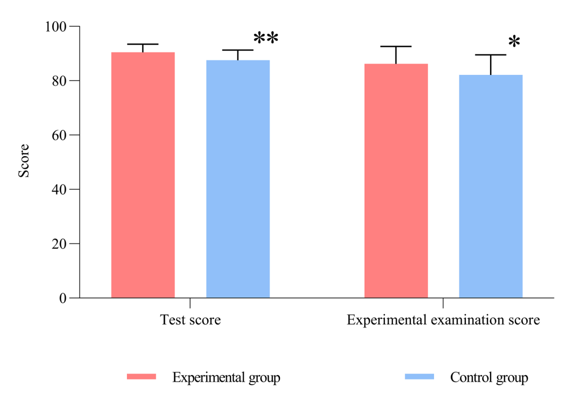

FIGURE 1
Comparison of average scores in after-class tests and laboratory examinations between experimental and control groups. *$p < 0.05$, **$p < 0.01$ vs. Control group.

TABLE 2 Responses from students regarding the satisfaction to current teaching model.

Question number	Question	Experimental group (*n* = 30)			Control group (*n* = 60)		
		SA\A (%)	U (%)	D\SD (%)	SA\A (%)	U (%)	D\SD (%)
Q1	You satisfied with the current teaching model.	90.00	10.00	0	55.00	30.00	15.00
Q2	You satisfied with the contents of the current teaching model.	93.33	3.33	3.33	66.67	26.67	6.66
Q3	You satisfied with the organization and preparedness for the current teaching model.	96.67	3.33	0	63.33	25.00	11.67
Q4 For experimental group only	You satisfied with the frequency of online laboratory classes.	90.00	6.67	3.33			
Q5 For experimental group only	You satisfied with the online cell morphology resource library for laboratory course.	93.33	6.67	0			

SA, Strongly agree; A, Agree; U, uncertainty; D, Disagree; SD, Strongly disagree.

teaching model, the degree of satisfaction of students with the blended teaching model was significantly improved ($p < 0.01$), including greater satisfaction with the teaching content ($p < 0.01$) and organization and preparedness for laboratory courses ($p < 0.01$). These results suggest that the novel teaching model was more popular than the traditional one.

The results of the feedback survey administered to students regarding the learning effects of the current teaching model are summarized in Table 3. The Wilcoxon test showed that the blended laboratory courses exhibited more positive scores for each of the five questions relative to the neutral response value ($p < 0.05$) (Table 3 and Figure 3), indicating that students with blended teaching model had better self-evaluations of learning effects than those with the traditional model.

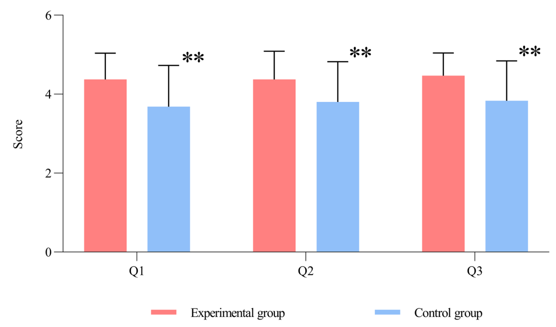

FIGURE 2
Comparison of course satisfaction scores between experimental and control groups. **$p < 0.01$ vs. Control group.

Discussion

It is widely believed that Clinical Laboratory Hematology, with its tedious and intricate content, covers a wide range of disciplines (Qutob, 2022). Furthermore, marrow smears and microscopes used in nearly all laboratory classes were too dated for practical use. As a result, the traditional laboratory course further reduced students' learning enthusiasm and initiative. Thus, students could not understand or master morphology knowledge, and their cell morphology recognition skills were weaker, which was a major challenge for educators.

This study aims to explore how to apply the online and offline blended teaching model in a CLH laboratory course to make difficult and tedious content easier to understand. Thus, students can improve their learning effect and enhance their practical skills in cell morphology recognition. Moreover, the application effect of this teaching model was evaluated through tests and questionnaire surveys, then compared with the traditional teaching model. The multidimensional evaluation indicators revealed that the teaching effect of the novel model was significantly better than that of the traditional teaching model ($p < 0.05$).

It is reported that blended teaching provides better teaching outcomes than either offline or online teaching alone (Liu et al., 2016; Vallée et al., 2020), consistent with our study. The blended teaching model was significantly different from the traditional model in terms of the design before class, in class, and after class (Bajpai et al., 2019; MacNeill et al., 2023). First, a preview section was created before the class. According to the learning goals uploaded by the teachers online in advance, the students were required to scan the morphology content online for a preview. Therefore, students' fear of tedious and difficult morphological knowledge was appropriately reduced.

The second was a class study section. As shown in Table 1, we set up online classes before offline classes, and the content of the online classes was easier than that of the offline ones. In the online class, students were required to observe single cells first and then observe the marrow images after gaining a certain understanding of single-cell

TABLE 3 Responses from students regarding the self-evaluation in learning effect.

Question number	Question	Experimental group (n = 30)			Control group (n = 60)		
		SA\A (%)	U (%)	D\SD (%)	SA\A (%)	U (%)	D\SD (%)
Q1	The current teaching model were better at fulfilling learning objectives	90.00	6.67	3.33	58.33	26.67	15.00
Q2	The current teaching model stimulate your learning interest in Clinical Laboratory Hematology.	86.67	10.00	3.33	51.67	35.00	13.33
Q3	The current teaching model improve the ability of cell morphology recognition.	86.67	6.67	6.67	56.67	25.00	18.33
Q4	The current teaching model enhance you understanding the theory knowledge	90.00	10.00	0	68.33	11.67	20.00
Q5	The current teaching model develop your ability to analyze and solve problems.	90.00	6.67	3.33	55.00	21.67	23.33

SA, Strongly agree; A, Agree; U, uncertainty; D, Disagree; SD, Strongly disagree.

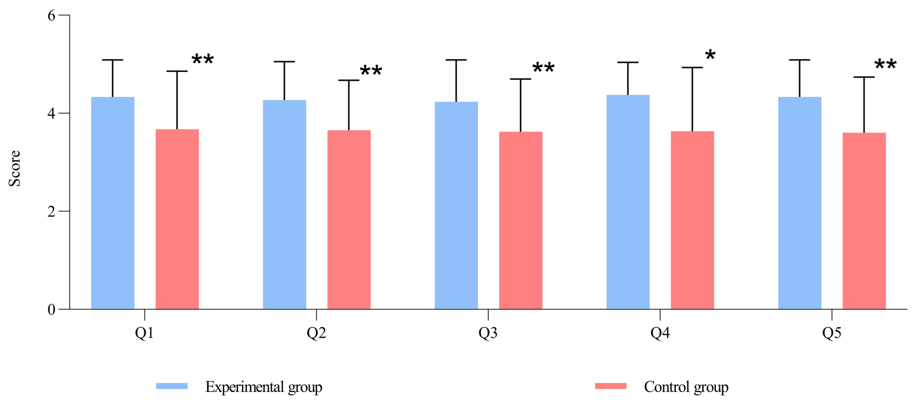

FIGURE 3
Comparison of self-evaluation in learning effect scores between experimental and control groups. *p < 0.05, **p < 0.01 vs. Control group.

morphology. They must recognize the cells by themselves and then click on the cell to view the answers. After completing one or more online laboratory classes, students were arranged to take one offline class to observe marrow smears with microscopes. This arrangement of laboratory courses conformed to students' cognition so that they acquired the knowledge and mastered the skills which were considered tedious and difficult well (Chen et al., 2020; Shang and Liu, 2018). In addition, we conducted a classroom interaction as a flipped classroom in the last period of the class. This can significantly stimulate students' enthusiasm for learning and develop their abilities to analyze and solve problems (Granero Lucchetti et al., 2018; Zhang et al., 2019).

Finally, a review was conducted after the class. Students can access the online resource library anytime via phone or computer. Thus, the fragmentation time can be used to review cell morphology to improve the learning effect (Daniel et al., 2021). In summary, through the novel teaching model, students' learning enthusiasm and initiative were stimulated, the learning effect was improved, and cell morphology-recognition skills were enhanced.

To the best of our knowledge, this study provides the first report of that the online and offline blended teaching model combining with flipped classroom were implemented in laboratory course of CLH. The research results indicate that this novel teaching model has been successful. Why is a blended laboratory course successful? Besides student cooperation, educators' cognition and accumulation in the past, extended preparation time were also important reasons (Chen et al., 2022; Zeng et al., 2021). The pre-class preparation, in-class implementation, and post-class evaluation of the blended teaching model, which educators designed, demonstrated their teaching ability and experience. Specifically, the school leader drawn up a plan and allocated the tasks. Both doctors in clinical laboratories and professional teachers in schools cooperated to select the morphology content to be taught using a blended teaching model. Scientific and technical corporations manufactured the online resource library. Teachers taught students using the blended teaching model in class and evaluated the teaching effect using multidimensional indicators after class. Finally, the data were analyzed to evaluate the implementation effect of the blended teaching model. All members of the CLH teaching team performed the entire process. Thus, the teachers' teaching ability improved significantly, and the cohesive force of the team was enhanced.

While our research has yielded positive results, there are still certain limitations. We only selected a single batch of students receiving blend or traditional teaching model as our research subjects, which, due to the limitations of sample size and batches, may introduce some bias into the results (Bock et al., 2021). In our next phase of research, we intend to broaden our scope by including multiple batches of students under instruction to increase the sample size, allowing for a more in-depth validation of our research findings. Furthermore, using an online resource library for the review of bone marrow smears has solved the problem of poor student learning experience caused by outdated bone marrow slides and microscopes in real-life teaching. Although we arranged offline laboratory sessions for students to observe bone marrow cells under microscopes, it has also reduced the frequency with which students use microscopes. This could potentially lead to a decrease in students' proficiency in using microscopes. To counteract this drawback, teachers should pay more active attention to each student's use of microscopes during offline microscope slide observation laboratory sessions, providing timely guidance to help students become proficient in using microscopes for the observation of bone marrow smears, thereby consolidating students' microscope operation skills.

Conclusion

The blended teaching model with flipped classroom was successful and welcomed by both students and teachers in CLH course. Thus, education in medical laboratory should not be conservative. Professional education should be innovative to improve student learning effect and enhance practical skills. Then, the training level of laboratory talent can be improved to address the challenge of identifying known and unknown diseases. In future studies, virtual simulation technology will be used in our laboratory course for an online laboratory class on leukemia flow cytometry experiment. We are unremittingly innovating medical laboratory education.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics Committee of Chengdu Medical College. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DL: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Project administration. FW: Conceptualization, Writing – original draft, Writing – review & editing. XZ: Methodology, Resources, Writing – original draft. KP: Methodology, Resources, Writing – original draft. LZ: Writing – review & editing, Formal analysis, Visualization. HY: Data curation, Formal analysis, Writing – original draft. XL: Data curation, Formal analysis, Writing – original draft. JZ: Writing – original draft, Writing – review & editing, Conceptualization, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1497477/full#supplementary-material

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Technology-enhanced practice competencies: scoping review and novel model development

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Introduction: With technology routinely integrated into healthcare, it is essential that practitioners obtain skills in the numerous competencies required. Unfortunately, literature to guide use remains inconsistent and fragmented. The current scoping review identified technology-enhanced practice competencies for healthcare practitioners among peer-reviewed literature.
Methods: A review of PubMed, Scopus, Web of Science, PsycInfo, Global Index Medicus, and Journal of Technology in Behavioral Science was conducted between November 2022 and March 2023.
Results: 10,583,799 articles were identified, with 109 included in the final review. Seventeen primary competencies were identified with ethics (77.1%), legality (68.8%), and data security (65.1%) among the top three.
Conclusions: Although multiple technologies across specialties were identified, limited literature comprehensively defined technology-enhanced practice competencies to guide practitioner education. To address this gap, the Intersectional Technology Education and Competency in Healthcare (iTECH) Model was created to clarify educational targets for the use of technology in healthcare practices. Model development and finding applications are discussed.

KEYWORDS
telehealth, telemedicine, technology, competency, training, education

Introduction

Technology-enhanced practices, broadly defined for the current study as practices involving practitioner and patient interactions with a technology that includes some level of practitioner involvement and/or oversight for the purpose of healthcare-related information collection or intervention services (1), have been utilized in healthcare for over a century (2). Such practices are categorized as synchronous (i.e., live, interactive), asynchronous (i.e., non-live), or hybrid (i.e., combination of synchronous, asynchronous, and in-person) (3, 4). Despite use, adoption among healthcare specialties (e.g., medicine, psychology, nursing, social work, counseling, physical therapy, occupational therapy) was suggested as relatively slow (5). While universally-accepted reasons for slow adoption are not well-defined, hypothesized reasons include limited training in the technologies leading to a lack of comfort, financial barriers to implementation, and a lack of organizational infrastructure to support the ongoing use of technologies (6–9). Limited usage continued until the late 1990s and early 2000s;

coinciding with technology becoming smaller, cheaper, more powerful, more readily accessible, and more interconnected (10, 11). Among all technologies, telecommunication technologies uniquely demonstrated an unexpected and unprecedented growth in integration and expansion in response to the COVID-19 pandemic (12, 13). Expansion across time, combined with both practitioner and patient satisfaction (14–16) suggested that the integration of technologies into healthcare services is not only here to stay, but warrants clarification of relevant competencies to ensure that healthcare practitioners are effectively harnessing the technologies within their practices.

A cursory review of the technology-focused competency literature suggests the large emphasis on telehealth, or the integration of telecommunication technologies with healthcare services (e.g., videoconferencing, telephone, email, messaging programs), which has frequently been heralded as the future of medical and mental health-related healthcare (17, 18). While still considered limited, telehealth literature across healthcare specialties has demonstrated attempts to standardize competencies, including consolidated discussion by the American Telemedicine Association (19–21), the American Psychological Association (22), the American Psychiatric Association (23), and the American Medical Association (24). Nevertheless, literature remains fragmented, as well as varying in focus and elaboration by resource. More specifically, competencies across discussions have included, but are not limited to: awareness of research related to technologies, methods of adapting in-person strategies for digital administration, ethics of practice, legality, data security, troubleshooting technology, interpersonal skills, and interprofessional communication (11, 25–28).

While a positive first step, the landscape of healthcare technology has rapidly evolved beyond the narrow confines of telehealth alone. Recent literature underscores the research-validated utility of a diverse array of technologies in patient care, including virtual/augmented/extended reality (VR, AR, XR) (29, 30); robotics (31), video games (32), wearable technologies (33), artificial intelligence (AI) (34), and web-based self-guided assessment and intervention packages (35). This expansion necessitates a broader conceptualization of technology-enhanced practices that extends far beyond telecommunication alone.

Unfortunately, the rapid evolution of healthcare technology outpaced current educational paradigms, creating a critical gap between innovation and practitioner competencies. This disparity threatens the ethical, legal, evidence-informed, and safe integration of novel technologies into patient care (11). Proficient use of technology in healthcare demands more than both general knowledge and applied skills; it requires a nuanced understanding of diverse applications across various settings and populations. Simply put, being an excellent practitioner and adept at general technology use does not necessarily make one readily able to successfully integrate novel technologies into healthcare practices due to the large number of unique and unknown challenges that may arise.

As guiding healthcare organizations, ethical codes, and regulatory/licensing boards continue to promote evidence-informed education for technology-enhanced practice, clarification of relevant competencies to guide integration and continuing education remains prudent. Towards this end, there remains an urgent need for evaluation of available evidence-informed recommendations that address the broad spectrum of technology-enhanced practices in healthcare to inform practitioners' judicious use of these diverse technologies and ensure their effective integration into clinical practices. This endeavor can identify relevant documentation, as well as ongoing field gaps. Unfortunately, to date, no known work has evaluated the literature for technology-enhanced practice competencies (beyond telehealth), either independently or across healthcare specialties. This study aims to address this notable gap in the literature by conducting a scoping review of technology-enhanced practice competencies among peer-reviewed literature across healthcare specialties. Utilizing a comprehensive approach, we examine synchronous, asynchronous, and hybrid practitioner-patient interactions within various technological contexts. The investigation is guided by two primary research questions: (1) Which technology types are discussed in competency frameworks across healthcare specialties, and (2) What technology-enhanced practice competencies are recommended in the literature to guide practitioner use? By synthesizing findings from peer-reviewed sources, this study seeks to provide insights into the current landscape of technology competencies in healthcare, and may inform the development of more cohesive, multiprofessional approaches to technology integration in clinical practice.

Methods

Identifying relevant studies and study selection

The review utilized the Preferred Reporting Items for Systematic Review and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR) reporting standards (36) (Supplementary Figure S1), as well as published scoping review methodologies (37, 38). More specifically, as based upon the study's primary questions, a modified population, concept, and context (PCC) framework was utilized in which the population was defined more broadly as healthcare specialties rather than specific population characteristics (e.g., age, race), concept was defined broadly as technology competencies, and the context included the setting of the technology use (39, 40). PubMed, Scopus, Web of Science, PsycInfo, and Global Index Medicus were reviewed between November 2022 and March 2023 (see Supplementary Table S1 for Boolean operators). Due to a high number of competency- and training-focused works being published in the Journal of Technology in Behavioral Science, yet not all works being identified on searched databases, this journal was also specifically reviewed with the same search methodology. Rayyan, a web-based application for conducting structured literature reviews, was utilized to organize data and remove duplicates (41).

Inclusionary criteria

Following the removal of duplicates, an item was included in the final dataset if it was written in English, was a manuscript in a peer-reviewed journal, focused on technology, focused on healthcare, focused on the education of a healthcare practitioner (i.e., graduate-level training through licensed professional), and included a direct naming of a specific competency or educational target combined with at least one statement defining/detailing the competency (i.e., a manuscript stating "data security" was not included, while a manuscript saying "data security" and also detailing that this is inclusive of passwords and/or encryption standards was included). This approach was designed to eliminate papers that were merely listing topics, and thus less helpful for practitioners seeking applied knowledge for their practices. A competency was defined for the current review as a designated target of practitioner knowledge and/or applied skill for the specific technology to ensure an ethical, legal, safe, and evidence-informed service. This definition aligns with similar review literature defining the term competency or competencies (33, 42–46). As the use of technology in healthcare can be traced back to the 1800s (2), to ensure comprehensive review, no year-related criteria were applied (i.e., all manuscripts through March 2023 were eligible for inclusion).

Data cleaning and screening processes

In line with suggestions for screening very large amounts of data, a title-first approach was utilized (47). This approach has been suggested as more efficient, yet comparable to screening both titles and abstracts together. To account for Rayyan's lack of sequential Boolean operator-based screening, titles were first screened by education-, teaching-, and training-related keywords; then technology-related keywords; and finally, healthcare-related keywords for relevancy. Standardized keywords were collectively identified by the authors as relevant to the scoping review (Supplementary Table S2). Among the remaining items, abstracts were screened for additional applicability. Each potential item was reviewed by three sets of two authors, with a third author as a tie breaker, as needed. Following training by the primary author, interrater reliability kappa values for all pairs were ≥0.99, suggesting "almost perfect" levels of agreement (48). Finally, full texts of remaining items were screened and coded to identify technology-focused competencies (e.g., ethics, legality) relevant to healthcare services. Coding was completed by the two first authors to establish consensus. Prior to discussion of disagreements until consensus was reached (42), interrater reliability kappa value was 0.93 for overall agreement for inclusion/exclusion of each identified manuscript.

As further detailed in Table 1, manuscripts were coded across the variables of: paper type, publication date, author location, specialty area, whether the discussion was interdisciplinary (i.e., discussed more than one specialty), career stage, location of discussion, types of technology, and identified competencies.

Results

The initial search yielded 10,583,799 records (Supplementary Figure S1). One hundred and nine met inclusionary criteria and were included in the final review (Tables 1, 2).

Summary findings

Paper type

Among included manuscripts ($N = 109$), 14 (12.8%) were coded as quantitative, 91 (83.5%) were coded as qualitative, and 4 (3.7%) were coded as mixed method. Among the 14 quantitative manuscripts, 6 (42.9%), were coded as a general one-time survey or assessment, and 8 (57.1%) were coded as a pre-post test or multiple time points survey or assessment. Among the 91 qualitative manuscripts, 71 (78.0%) were coded as a general description, viewpoint, discussion, qualitative analysis, or nonsystematic review; 10 (11.0%) were coded as a program-specific outline or discussion; and 10 (11.0%) were coded as a review article (e.g., formal systematic, scoping, or narrative review with a database search, goals, and/or search terms). Among the 4 mixed-method manuscripts, 1 (25.0%) was coded as a one-time survey or assessment and qualitative output, while 3 (75.0%) were coded as a pre-post test or multiple time points survey or assessment and qualitative output.

Publication date

All included manuscripts ($N = 109$) were published between 2000 and 2023, with a substantially greater number of publications per year in or following 2020 as compared to 2019 and earlier.

Author location

Among included manuscripts ($N = 109$), most authors had affiliations within the United States (86, 78.9%).

Specialty area

Specialty area of manuscript discussions ($N = 109$) varied widely across both mental health and medical domains. Psychology- (50, 45.9%), psychiatry- (28, 25.7%), and social work-focused manuscripts (21, 19.3%) were the three most discussed types of specialty areas.

Interdisciplinary discussion

Among included manuscripts ($N = 109$), 22 (20.2%) included more than one specialty as a focus of discussions.

Career stage

Of the total manuscripts ($N = 109$), 75 (68.8%) focused discussions on licensed practitioners, 34 (31.2%) focused on graduate level students/trainees, 28 (25.7%) focused on residents, interns, or fellows, one (0.9%) focused on paraprofessionals, and one (0.9%) focused on non-professional health operators.

Location of discussion

Of the total manuscripts ($N = 109$), 15 (13.8%) focused on school/academic locations, 6 (5.5%) focused on medical centers, 2 (1.8%) focused on primary care clinics, and 1 (0.9% each)

TABLE 1 Frequencies of coded variables Among included manuscripts ($N = 109$).

Year published	Number of manuscripts	Percentage of total ($N = 109$)
2000	1	0.9%
2002	1	0.9%
2003	1	0.9%
2004	1	0.9%
2005	4	3.7%
2006	1	0.9%
2008	3	2.8%
2010	1	0.9%
2011	6	5.5%
2012	5	4.6%
2013	4	3.7%
2014	4	3.7%
2015	7	6.4%
2016	3	2.8%
2017	5	4.6%
2018	5	4.6%
2019	5	4.6%
2020	13	11.9%
2021	25	22.9%
2022	11	10.1%
2023	3	2.8%
Author location[a,b]	**Number of manuscripts**	**Percentage of total ($N = 109$)**
Algeria	1	0.9%[d]
Australia	9	8.3%[d]
Bahrain	1	0.9%[d]
Canada	8	7.3%[d]
Egypt	1	0.9%[d]
India	1	0.9%[d]
Iran	1	0.9%[d]
Iraq	1	0.9%[d]
Italy	1	0.9%[d]
Jordan	1	0.9%[d]
Kuwait	1	0.9%[d]
Lebanon	1	0.9%[d]
Libya	1	0.9%[d]
Morocco	1	0.9%[d]
Northern Ireland	1	0.9%[d]
Palestine	1	0.9%[d]
Qatar	1	0.9%[d]
Saudi Arabia	3	2.8%[d]
South Africa	3	2.8%[d]
Spain	1	0.9%[d]
Syria	1	0.9%[d]
Switzerland	2	1.8%[d]
The Netherlands	1	0.9%[d]
Tunisia	1	0.9%[d]
United Arab Emirates	1	0.9%[d]
United Kingdom	2	1.8%[d]
United States	86	78.9%[d]
Type of paper	**Number of manuscripts**	**Percentage of total ($N = 109$)**
Quantitative	14	12.8%
Qualitative	91	83.5%
Mixed Method	4	3.7%
Type of quantitative paper[e]	**Number of manuscripts**	**Percentage of sub-total ($N = 14$)**
One-Time Survey or Assessment	6	42.9%
Pre-Post Test or Multiple Time Points Survey or Assessment	8	57.1%
Type of qualitative paper[e]	**Number of manuscripts**	**Percentage of sub-total ($N = 91$)**
General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	71	78.0%

(*Continued*)

TABLE 1 Continued

Type of qualitative paper[e]	Number of manuscripts	Percentage of sub-total (N = 91)
Program-Specific Outline or Discussion	10	11.0%
Review Article	10	11.0%
Type of mixed method paper[e]	**Number of manuscripts**	**Percentage of sub-total (N = 4)**
One-Time Survey or Assessment and Qualitative Output	1	25.0%
Pre-Post Test or Multiple Time Points Survey or Assessment, and Qualitative Output	3	75.0%
Specialties[a,c]	**Number of manuscripts**	**Percentage of total (N = 109)**
Addition Medicine	4	3.7%[d]
Allergy	1	0.9%[d]
Assistive Technology	1	0.9%[d]
Audiology	1	0.9%[d]
Behavior Analysis	7	6.4%[d]
Cardiology	1	0.9%[d]
Counseling	13	11.9%[d]
Dermatology	1	0.9%[d]
Dietic/Nutrition	2	1.8%[d]
Emergency Medicine	1	0.9%[d]
Family Medicine	1	0.9%[d]
Genetics	1	0.9%[d]
Immunology	1	0.9%[d]
Marriage and Family Therapy	12	11.0%[d]
Music Therapy	1	0.9%[d]
Nephrology	1	0.9%[d]
Neurology	6	5.5%[d]
Neuropsychology	1	0.9%[d]
Nursing	14	12.8%[d]
Nurse Practitioner	7	6.4%[d]
Occupational Therapy	4	3.7%[d]
Oncology	2	1.8%[d]
Orthopedic	1	0.9%[d]
Orthotist	1	0.9%[d]
Pathology	1	0.9%[d]
Pediatrics	3	2.8%[d]
Pharmacy	3	2.8%[d]
Physical Therapy	4	3.7%[d]
Psychiatry	28	25.7%[d]
Psychology	50	45.9%[d]
Radiology	1	0.9%[d]
Rehabilitation Medicine	1	0.9%[d]
Rheumatology	4	3.7%[d]
Social Work	21	19.3%[d]
Speech Therapy	4	3.7%[d]
Surgery	2	1.8%[d]
Urology	1	0.9%[d]
Interdisciplinary discussion[c]	**Number of manuscripts**	**Percentage of total (N = 109)**
Yes	22	20.2%
Career stage focus[a,c]	**Number of manuscripts**	**Percentage of total (N = 109)**
Graduate Level Trainee/Student	34	31.2%[d]
Licensed Practitioner	75	68.8%[d]
Non-Professional Health Operator	1	0.9%[d]
Paraprofessional	1	0.9%[d]
Resident, Intern, Fellow	28	25.7%[d]
Location of discussion[a,c]	**Number of manuscripts**	**Percentage of total (N = 109)**
College Counseling	1	0.9%[d]
Home-Based	1	0.9%[d]
Medical Center	6	5.5%[d]
Primary Care	2	1.8%[d]

(*Continued*)

TABLE 1 Continued

Location of discussion[a,c]	Number of manuscripts	Percentage of total (*N* = 109)
School/Academic	15	13.8%[d]
University Outpatient Clinic	1	0.9%[d]
Veterans Affairs	1	0.9%[d]
Type of technology discussed[a,c]	**Number of manuscripts**	**Percentage of total (*N* = 109)**
App	29	26.6%[d]
Artificial Intelligence (AI)	2	1.8%[d]
Email	44	40.4%[d]
Internet (Broadly Defined)	1	0.9%[d]
Messaging Program	35	32.1%[d]
Nanomachine	1	0.9%[d]
Robotic	2	1.8%[d]
Social Media	19	17.4%[d]
Telephone	62	56.9%[d]
Video	91	83.5%[d]
Video Game	1	0.9%[d]
Wearable	11	10.1%[d]
Web-Based Assessment or Intervention	12	11.0%[d]
VR, AR, XR	3	2.8%[d]
Competencies discussed[a,c]	**Number of manuscripts**	**Percentage of total (*N* = 109)**
Adaptations of Assessment	44	40.4%[d]
Adaptations of Communication	52	47.7%[d]
Adaptations of Intervention	25	22.9%[d]
Administrative Responsibilities	42	38.5%[d]
Data Security	71	65.1%[d]
Diversity, Equity, Inclusion	32	29.4%[d]
Ethics	84	77.1%[d]
Interprofessional Collaboration	15	13.8%[d]
Legal	75	68.8%[d]
Appropriateness Evaluation	41	37.6%[d]
Patient Safety	42	38.5%[d]
Professionalism	42	38.5%[d]
Learning/Teaching Others	23	21.1%[d]
Research	1	0.9%[d]
Self-Care	1	0.9%[d]
Techno-Etiquette	60	55.0%[d]
Troubleshooting	27	24.8%[d]

[a]Some manuscripts had multiple applicable selections.
[b]Author affiliation as provided on manuscript.
[c]Not all papers clearly defined characteristics. Only those with clear indications of relevant variables were included in this coding scheme.
[d]Given that manuscripts could have multiple selections per variable, numbers are relative to the total and may not add to 100%.
[e]"One-time Survey" was defined as a survey completed at one time-point only; "Pre-Post Test or Survey" was defined as an assessment or survey completed before and after an implemented process (e.g., intervention); "General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review" was defined as a description, viewpoint, discussion, analysis, or review of a field or specific topic without a formal review methodology, detailed description of a program, or quantitative analysis; "Program-Specific Outline or Discussion" was defined as a description, outline, or general discussion of a specific program, or program implementation, without quantitative analysis of the program; "Review Article" was defined as an article reviewing a field or specific topic in detail through the defining of database and search criteria, including systematic, scoping, or narrative review methodologies.

focused on college counseling, home-based, university outpatient clinic, and Veterans Affairs.

Types of technology

Of the total manuscripts (*N* = 109), video (91, 83.5%), telephone (62, 56.9%), and email (44, 40.4%) were the three most discussed types of technology.

Identified competencies

Of the total manuscripts (*N* = 109), ethics (84, 77.1%), legal considerations (75, 68.8%), and data security (71, 65.1%) were the three most discussed types of competencies.

Additional considerations

Many excluded manuscripts focused on: (a) applications of technology in general healthcare service without discussion of competencies or training, (b) methods of training healthcare skills through the use of technology (e.g., e-learning), (c) practitioner or patient attitudes towards technology, (d) satisfaction with technology use, and (e) programmatic descriptions of technology integration with general healthcare clinics without detailing the applied competencies. Across studies with diverse focuses, authors consistently emphasized the necessity for more extensive training in both graduate education and professional practice to foster a comprehensive

TABLE 2 Characteristics of included studies ($N = 109$)[a].

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• Abbott et al. • Australia • 2008	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone	• AC, AE, AI, DS, E, L, P, T-E
• Alkureishi et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• Telephone • Video	• AC, T-E
• Almubark et al. • Saudi Arabia • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Occupational Therapy • Physical Therapy • Speech Therapy	• Licensed Practitioner	• None	• E-Mail • Telephone • Video	• AA, AE, E
• Arends et al. • United States • 2021	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Nurse Practitioner	• Graduate Level Trainee/Student	• School/ Academic	• None	• AA, AC, AR, E, L, P, T-E
• Armstrong • United States • 2019	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Counseling • Nursing • Pharmacy • Psychology • Social Work	• Licensed Practitioner	• None	• App • Telephone	• AC, AI, AR, DEI, DS, E
• Baker and Bufka • United States • 2011	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Video	• AR, DS, E, L
• Baltimore • United States • 2000	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Counseling	• Licensed Practitioner	• None	• E-Mail • Video	• DS, E
• Baumes et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Behavior Analysis • Pediatrics • Psychology • Social Work	• Licensed Practitioner	• None	• None	• AE, AI, AR, DEI, DS, E, L, PS, T-E
• Brimley et al. • United States • 2021	• Qualitative: Review Article	• Urology	• Licensed Practitioner	• None	• App • Telephone • Video	• AE, AR, DS, E, L, T-E
• Casline et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Graduate Level Trainee/Student	• School/ Academic	• Video	• AA, E, L/T, T-E
• Caver et al. • United States • 2020	• Qualitative: Program- Specific Outline or Discussion	• Psychiatry • Psychology • Social Work	• Licensed Practitioner	• Veterans Affairs	• Video	• E, L/T, L, PS, T
• Chike-Harris et al. • United States • 2022	• Mixed Method: Pre-Post Test or Multiple Time Points Survey or Assessment, and Qualitative Output	• Nursing • Nurse Practitioner	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• School/ Academic	• Video	• AC, DS, P, T-E
• Chipps et al. • South Africa • 2012	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner	• None	• Video	• AE, AR, DS, L, T-E
• Cooper et al. • United States • 2019	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Telephone • Video	• AC, AE, AI, AR, DEI, DS, E, L/T, L, P, T-E, T
• Costich et al. • United States • 2021	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Pediatrics	• Resident, Intern, Fellow	• Medical Center	• Video	• T-E
• Daniel and Sulmasy • United States • 2015	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Licensed Practitioner • Resident, Intern, Fellow	• Primary Care	• None	• AE, DEI, DS, E, L
• de Leo et al. • Italy • Switzerland • 2003	• Qualitative: Program- Specific Outline or Discussion	• Emergency Medicine	• Non-Professional Health Operator	• Medical Center	• VR, AR, XR	• AI, T-E

(*Continued*)

TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• DeJong • United States • 2014	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner	• None	• Social Media • Telephone	• AR, DS, E, L, P, PS, T-E
• DeJong et al. • United States • 2012	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Resident, Intern, Fellow	• None	• E-Mail • Social Media	• AC, DS, E, L, P
• DeJong et al. • United States • 2015	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• None	• None	• None	• AA, AC, AE, IC, L
• Dopp et al. • United States • 2021	• Mixed Method: One-Time Survey or Assessment and Qualitative Output	• Psychology	• Graduate Level Trainee/Student	• School/ Academic	• App • E-Mail • Messaging Program • Telephone • Video • Web-Based Assessment or Intervention	• AC
• Drude et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Addiction Medicine • Behavior Analysis • Counseling • Marriage/Family Therapy • Nursing • Nurse Practitioner • Psychiatry • Psychology • Social Work	• Graduate Level Trainee/Student	• None	• App • Social Media • Telephone • Video	• AC, AR, IC, E, L/T, L, T-E
• Drum & Littleton • United States • 2014	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Telephone • Video • Web-Based Assessment or Intervention	• AC, AR, E, L, P, T-E
• Farmer et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• Video	• AA, AC, AE, DEI, E, L, T-E
• Fitzgerald et al. • Canada • United States • 2010	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• None	• None	• E-Mail • Messaging Program • Telephone • Video	• DS, E, L, P, PS
• Frankl et al. • United States • 2021	• Mixed Method: Pre-Post Test or Multiple Time Points Survey or Assessment, and Qualitative Output	• None	• Graduate Level Trainee/Student	• School/ Academic	• Video	• AA, AE, AI, DEI, P, T-E, T
• Fuertes-Guiró and Velasco • Spain • 2018	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Surgery	• Licensed Practitioner	• None	• Robotic • Video	• AI, DS, E, L/T, L, T-E
• Gibson et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Nursing	• Graduate Level Trainee/Student	• School/ Academic	• Video	• AC, T-E, T
• Gifford et al. • United States • 2012	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Counseling • Psychology • Social Work	• Licensed Practitioner • Paraprofessional	• None	• Telephone • Video	• E, L, PS, T-E
• Govindarajan et al. • United States • 2017	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Neurology	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• Video	• AA, AR, DS, E, L/T, L, P, T-E

(*Continued*)

TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• Hames et al. • Canada • United States • 2020	• Quantitative: One-Time Survey or Assessment	• Psychology	• Graduate Level Trainee/Student	• None	• Telephone • Video	• AA, AC, AE, AI, AR, DEI, DS, E, L/T, L, SC, T-E, T
• Hart et al. • United States • 2022	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• None	• Graduate Level Trainee/Student	• None	• Telephone • Video	• AA, AC, AE, AR, DEI, E, IC, L, P, PS, T
• Haydon et al. • Australia • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Video	• AC, AE, DS, E, P, PS, T-E, T
• Hertlein et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Marriage/Family Therapy	• Graduate Level Trainee/Student • Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video	• AA, AC, AE, AI, AR, E, L, P, PS, T-E, T
• Hertlein et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Marriage/Family Therapy	• Licensed Practitioner	• None	• App • Artificial Intelligence • Social Media • Telephone • Video • Wearable	• AC, AE, E, L/T, L, T-E
• Hilty et al. • United States • 2019	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Telephone • Video	• AA, AC, AE, AI, AR, DEI, DS, E, L/T, L, P, PS, T-E, T
• Hilty et al. • United States • 2020	• Qualitative: Review Article	• Behavior Analysis • Counseling • Marriage/Family Therapy • Nursing • Psychiatry • Psychology • Social Work	• None	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable	• AA, AC, E, L/T, P, PS, T-E, T-E
• Hilty et al. • Canada • United States • 2015	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• Video	• AA, AC, AI, AR, DEI, DS, E, L, P, PS, T-E, T
• Hilty et al. • United States • 2017	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Behavior Analysis • Counseling • Marriage and Family Therapy • Psychiatry • Psychology • Social Work	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Telephone • Video	• AA, AC, AR, DEI, DS, E, IC, L, P, PS
• Hilty et al. • Canada • United States • 2018	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable • Web-Based Assessment or Intervention	• AA, AC, AR, DEI, DS, E, IC, L/T, L, P, PS, T-E
• Hilty et al. • United States • 2021	• Qualitative: Review Article	• Psychiatry	• Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Telephone • Video • Wearable	• AA, AC, AE, AI, AR, DS, E, IC, L/T, L, P, PS, T-E, T
• Hilty et al. • United States • 2021	• Qualitative: Review Article	• Counseling • Marriage/Family Therapy • Psychiatry • Psychology • Social Work	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable	• AA, AC, AE, AI, AR, DEI, DS, E, L/T, L, P, PS, T

(*Continued*)

TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
					• Web-Based Assessment or Intervention	
• Jagolino et al. • United States • 2016	• Quantitative: One-Time Survey or Assessment	• Neurology	• Licensed Practitioner	• None	• None	• AA, AC, AI, IC, P, T
• Jarvis-Selinger et al. • Canada • 2008	• Qualitative: Review Article	• Cardiology • Dermatology • Family Medicine • Genetics • Nephrology • Neurology • Nursing • Occupational Therapy • Orthopedics • Pathology • Pediatrics • Pharmacy • Physical Therapy • Psychiatry • Radiology • Rehabilitation • Rheumatology • Social Work • Speech Therapy • Surgery	• Licensed Practitioner	• None	• Video	• DS, IC, L, T-E, T
• Johnson[7] • Canada • 2014	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Telephone • Video	• AA, AC, AE, AI, DS, E, L, P, PS, T-E
• Joint Task Force for the Development of Telepsychology Guidelines for Psychologists • United States • 2013	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Social Media • Telephone • Video • Web-Based Assessment or Intervention	• AA, AE, AR, DS, E, L, P, PS
• Jones et al. • United Kingdom • 2006	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner	• None	• Video	• AC, DS, E, T-E, T
• Karcher and Presser • United States • 2016	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• App • Messaging Program • Telephone • Video	• AA, AE, AR, DEI, DS, E, L/T, L, P, PS
• Keswani et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Allergy • Immunology	• Graduate Level Trainee/Student • Resident, Intern, Fellow	• School/ Academic	• Messaging Program • Telephone • Video	• AA, AC, DS, L, P, T-E
• Khan et al. • United States • 2021	• Quantitative: One-Time Survey or Assessment	• Psychiatry	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• Video	• AA, AC, IC, L, P, PS, T-E
• Khan and Ramtekkar • United States • 2019	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner • Resident, Intern, Fellow	• None	• Video	• AC, T-E, T
• Koh et al. • United States • 2013	• Quantitative: One-Time Survey or Assessment	• Psychiatry	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Social Media • Telephone • Video	• E, L, P
• Lockwood et al. • United States • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Rheumatology	• None	• None	• Telephone • Video • Wearable	• AA, E, T-E

(*Continued*)

TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• Loman et al. • United States • 2021	• Qualitative: Program- Specific Outline or Discussion	• Neuropsychology	• Licensed Practitioner	• Medical Center	• Video	• AA, AE, DS, P, T-E, T
• Lustgarten and Elhai • United States • 2018	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone • Video	• DS, E, L, P, PS
• Maheu et al. • United States • 2018	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Addiction Medicine • Behavior Analysis • Counseling • Marriage/Family Therapy • Nursing • Nurse Practitioner • Psychiatry • Psychology • Social Work	• Licensed Practitioner	• None	• Video	• AC, AE, AR, DEI, DS, E, L, P, PS
• Maheu et al. • United States • 2017	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Addiction Medicine • Behavior Analysis • Counseling • Marriage/Family Therapy • Nursing • Pharmacy • Psychiatry • Psychology • Social Work	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable	• AA, AC, AE, AI, AR, DEI, DS, E, IC, L/T, L, P, PS, T-E, T
• Maheu et al. • United States • 2018	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Addiction Medicine • Behavior Analysis • Counseling • Marriage/Family Therapy • Nursing • Psychiatry • Psychology • Social Work	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable	• AA, AC, AE, AI, AR, DEI, DS, E, IC, L/T, L, P, PS, T-E, T
• Maheu et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• Telephone • Video	• AA, AC, AI, AR, DEI, DS, E, IC, L/T, L, P, PS, T-E, T
• Mallen et al. • United States • 2005	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone • Video	• AC, AI, DEI, DS, E, L/T, L, PS
• Martin et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Web-Based Assessment or Intervention	• AA, AC, AE, AI, DEI, DS, E, L, P, PS, T-E
• McCord et al. • United States • 2020	• Qualitative: Review Article	• Psychology	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Telephone • Video • Web-Based Assessment or Intervention	• AA, AC, AE, AI, AR, DEI, DS, E, IC, L/T, L, P, PS, R, T-E, T
• McCord et al. • United States • 2015	• Qualitative: Program- Specific Outline or Discussion	• Psychology	• Graduate Level Trainee/Student	• University Outpatient Clinic	• Telephone • Video	• AA, AC, AE, AI, DEI, DS, E, IC, L, P, T
• McCrickard and Butler • United States • 2005	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Counseling	• Licensed Practitioner	• None	• Internet (Broadly)	• AA, DS, E, PS
• McInroy • United States	• Qualitative: Program- Specific Outline or Discussion	• Social Work	• Graduate Level Trainee/Student	• School/ Academic	• App	• DS, E, L/T, L, P

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TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• 2021					• Messaging Program • Social Media • Telephone	
• Menzano et al. • United States • 2011	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Licensed Practitioner	• College Counseling	• Telephone • Video	• AE, AR, DS, E, L, PS, T-E
• Merrill et al. • United States • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Social Work	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Social Media • Telephone • Video • Wearable	• AR, DS, E, L
• Miller et al. • United States • 2005	• Qualitative: Program- Specific Outline or Discussion	• Psychiatry	• Licensed Practitioner	• None	• E-Mail • Telephone • Video	• DS, E, L, T-E
• Miller et al. • United States • 2008	• Qualitative: Program- Specific Outline or Discussion	• Nursing • Psychiatry • Psychology • Social Work	• Licensed Practitioner	• Medical Center	• Video	• E, L
• Misra et al. • India • 2005	• Qualitative: Review Article	• Neurology	• Licensed Practitioner • Resident, Intern, Fellow	• School/ Academic	• Telephone • Video	• DS
• Murphy and Pomerantz • United States • 2016	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone • Video	• AR, DS, E, L, P, PS, T
• Nelson and Velasquez • United States • 2011	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• Video	• AC, AR, DS, E, L, PS, T-E
• Newby et al. • Australia • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry • Psychology	• Licensed Practitioner	• None	• Web-Based Assessment or Intervention	• AE, AI, PS
• Noronha et al. • The Netherlands • United States • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• Video	• AC, DEI, E, PS, T-E
• Panos et al. • United States • 2002	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Social Work	• Graduate Level Trainee/Student	• None	• Video	• AR, DEI, DS, E, L
• Parish et al. • United States • 2021	• Qualitative: Program- Specific Outline or Discussion	• Counseling • Marriage/Family Therapy • Nursing • Nurse Practitioner • Psychiatry • Social Work	• Licensed Practitioner	• None	• App • E-Mail • Messaging Program • Telephone • Video	• DS, L, PS
• Patel et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Graduate Level Trainee/Student • Licensed Practitioner	• None	• Video	• AA, DS, E, L/T, L, PS
• Perle • United States • 2020	• Mixed Method: Pre-Post Test or Multiple Time Points Survey or Assessment, and Qualitative Output	• Psychology	• Graduate Level Trainee/Student	• School/ Academic	• App • Artificial Intelligence • E-Mail • Messaging Program • Nanomachine • Robotic • Social Media • Telephone • Video • Video Game	• AR, DEI, DS, E, L, T-E

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TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
					• VR, AR, XR • Wearable • Web-Based Assessment or Intervention	
• Perle et al. • United States • 2022	• Quantitative: One-Time Survey or Assessment	• Psychology	• Graduate Level Trainee/Student	• School/ Academic	• App • E-Mail • Messaging Program • Telephone • Video	• DS, E, L
• Perle et al. • United States • 2023	• Quantitative: One-Time Survey or Assessment	• Psychology	• Graduate Level Trainee/Student • Resident, Intern, Fellow	• None	• App • E-Mail • Messaging Program • Telephone • Video	• AA, AR, DS, E, L, T-E
• Phillips et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Graduate Level Trainee/Student • Resident, Intern, Fellow	• School/ Academic	• Video	• DEI, E, L/T
• Prabhakar • United States • 2013	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Counseling • Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone • Video	• AE, DEI, DS, E, L
• Qureshi et al. • Australia • Saudi Arabia • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Assistive Technology • Audiology • Dietic/Nutrition • Nursing • Occupational Therapy • Orthotist • Physical Therapy • Psychology • Social Work • Speech Therapy	• Licensed Practitioner	• Home-Based • Medical Center	• None	• AE, DEI, DS, E, L, T-E, T
• Rabe • South Africa • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Licensed Practitioner	• Primary Care	• E-Mail • Telephone • Video	• AC, AE, DS, E, PS, T-E
• Reamer • United States • 2013	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Social Work	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Social Media • Telephone • Video • Web-Based Assessment or Intervention	• AR, DS, E, L, P
• Rees and Haythornthwaite • Australia • 2004	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• Video	• AC, E, L
• Rezai-Rad et al. • Iran • 2012	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• None	• None	• None	• E-Mail • Telephone	• DS
• Roth et al. • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Licensed Practitioner	• None	• Video	• AA, AC, AR, E, P, PS, T-E, T
• Rutledge et al. • United States • 2017	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Nurse Practitioner	• Graduate Level Trainee/Student	• School/ Academic	• Video	• AR, DS, E, IC, L, T-E
• Rutledge et al. • United States • 2011	• Qualitative: Program-Specific Outline or Discussion	• Nurse Practitioner	• Graduate Level Trainee/Student	• None	• Social Media	• DS, T
• Sabin & Skimming • United States • 2015	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Licensed Practitioner	• None	• Video	• AE, DEI, DS, E, L, P, PS, T-E

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TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• Saeed et al. • United States • 2017	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychiatry	• Resident, Intern, Fellow	• None	• Video	• AA, AE, AR, DEI, DS, E, L, PS
• Schwartz and Lonborg • United States • 2011	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Telephone • Video	• DS, E, L
• Shandley et al. • Australia • 2011	• Qualitative: Program-Specific Outline or Discussion	• Psychology	• Resident, Intern, Fellow	• School/ Academic	• E-Mail • Video	• AC
• Sherbersky et al. • Northern Ireland • United Kingdom • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Marriage/Family Therapy	• Graduate Level Trainee/Student • Licensed Practitioner	• None	• App • Telephone • Video	• E, L/T
• Simpson et al. • Australia • 2014	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Psychology	• Graduate Level Trainee/Student • Resident, Intern, Fellow	• School/ Academic	• E-Mail • Telephone • Video	• AA, AC, DS, E
• Smith et al. • United States • 2023	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Marriage/Family Therapy	• Licensed Practitioner	• None	• Telephone • Video	• AA, AC, AI, T-E
• Spelten et al. • Australia • 2021	• Qualitative: Review Article	• Dietic/Nutrition • Music Therapy • Nursing • Occupational Therapy • Oncology • Physical Therapy • Psychology • Social Work • Speech Therapy	• None	• None	• App • E-Mail • Telephone • Video • Web-Based Assessment or Intervention	• AR, E, L
• Stoll et al. • Switzerland • 2020	• Qualitative: Review Article	• Psychiatry • Psychology • Social Work	• None	• None	• E-Mail • Messaging Program • Social Media • Telephone • Video	• AC, AE, AI, AR, DS, E, L, P, PS
• Strowd et al. • Australia • United States • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Neurology • Oncology	• Licensed Practitioner	• None	• Telephone • Video	• AA, AC, AE, DEI, T-E
• Sunderji et al. • Canada • 2015	• Qualitative: Review Article	• Psychiatry	• Resident, Intern, Fellow	• None	• Video	• AC, L, PS, T-E
• Taylor and Fuller • United States • 2021	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Nursing	• Graduate Level Trainee/Student • Licensed Practitioner	• None	• App • E-Mail • Telephone • Video	• DS, L, T-E
• Townsend et al. • Canada • South Africa • 2019	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• None	• Licensed Practitioner	• None	• Telephone • Video • Wearable	• AA, DS, E
• Webb and Orwig • United States • 2015	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• E-Mail • Messaging Program • Telephone • Video • Web-Based Assessment or Intervention	• DS, E, L, T
• Weisenmuller and Luzier • United States • 2022	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Graduate Level Trainee/Student • Licensed Practitioner • Resident, Intern, Fellow	• None	• None	• AA, AE, DS, E, L
• Yellowlees et al. • United States • 2012	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Psychology	• Licensed Practitioner	• None	• VR, AR, XR	• AE, DS, E, L

(*Continued*)

TABLE 2 Continued

Author, affiliation, and year	Type of paper	Specialty area	Career stage focus	Setting	Technology type	Identified competencies[b]
• Zha et al. • United States • 2020	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Neurology	• Resident, Intern, Fellow	• Medical Center	• Video	• AA, AC, AR, T-E
• Ziade et al. • Algeria • Bahrain • Egypt • Iraq • Jordan • Kuwait • Lebanon • Libya • Morocco • Palestine • Qatar • Saudi Arabia • Syria • Tunisia • United Arab Emirates • 2022	• Quantitative: Pre-Post Test or Multiple Time Points Survey or Assessment	• Rheumatology	• Licensed Practitioner	• None	• Telephone • Video	• AA, AE, AR, DS, E, L, T-E
• Zickuhr et al. • United States • 2023	• Qualitative: General Description, Viewpoint, Discussion, Qualitative Analysis, or Non-Structured Review	• Rheumatology	• Licensed Practitioner • Resident, Intern, Fellow	• None	• App • Messaging Program • Telephone • Video	• AA, AC, AE, DEI, E, L, PS

[a]The table summarizes information that was clearly identifiable in the coded manuscripts. A lack of coding (i.e., "none" or not listed in a specific column) does not necessarily suggest that the manuscript and its information is not applicable to a wider audience than what it indicated in the current table.

[b]AA = Adaptations of assessments (i.e., Detailing of changes or considerations for assessment processes in terms of delivery or interpretation when integrating technology with healthcare services; e.g., modifying methods, normative data for technology-driven administration); AC = Adaptations of communication (i.e., Detail of changes or considerations for communication processes in terms of delivery or interpretation when integrating technology with healthcare services; e.g., modification of verbal communication, consideration of nonverbal communication); AE = Appropriateness Evaluation (i.e., Detailing of changes or considerations for evaluating whom technology is optimal or less optimal for when integrating technology with healthcare services; e.g., patient-specific factors or pathology); AI = Adaptations of interventions (i.e., Detailing of changes or considerations for intervention processes in terms of delivery or interpretation when integrating technology with healthcare services; e.g., adapting in-person methods for digital administration); AR = Administrative responsibilities (i.e., Detailing of changes or considerations for administrative responsibilities when integrating technology with healthcare services; e.g., documentation, billing, quality improvement analyses); DS = Data security (i.e., Detailing of changes or considerations for data security when integrating technology with healthcare services; e.g., encryption, passwords, technology destruction); DEI = Diversity, Equity, Inclusion (i.e., Detailing of diversity, equity, and/or inclusion when integrating technology with healthcare services; e.g., considering the role of race or ethnicity in the use of technology in clinical services); E = Ethics (i.e., Detailing of changes or considerations for ethics when integrating technology with healthcare services; e.g., ethical guidebooks, informed consent practices); IC = Interprofessional communication (i.e., Detailing of changes or considerations for interprofessional communication when integrating technology with healthcare services; e.g., methods of effectively sharing electronic patient data); L/T = Learning/Teaching of Others (i.e., Detailing of changes or considerations for educating others in the use of technology when integrated with healthcare services; e.g., methods of training in graduate or continuing education, methods of supervision); L = Legal (i.e., Detailing of changes or considerations for legality when integrating technology with healthcare services; e.g., interjurisdictional practice); PS = Patient safety (i.e., Detailing of changes or considerations for ensuring patient safety when integrating technology with healthcare services; e.g., safety plans); P = Professionalism (i.e., Detailing of changes or considerations for professionalism when integrating technology with healthcare services; e.g., professional boundaries); R = Research (i.e., Detailing of changes or considerations for research practices when integrating technology; e.g., influence of technology on self-tracking); SC = Self-care (i.e., Detailing of changes or considerations for self-care practices when integrating technology with healthcare services; e.g., ocular or muscular-skeletal adjustments to foster healthy use of technology); T-E = Techno-etiquette (i.e., Detailing of changes or considerations for techno-etiquette when integrating technology with healthcare services; e.g., technology selection processes, environment set-up, telepresence); T Troubleshooting (i.e., Detailing of changes or considerations for troubleshooting of technology when integrating technology with healthcare services; e.g., methods of self-addressing of technological issues, whom to contact to address technological issues).

understanding and appreciation of the various competencies required for effective technology-enhanced practice.

In addition to the majority of included manuscripts focusing on mental health-focused specialties, it was recognized that among manuscripts not included, several other specialties have discussed or been discussed to utilize technology-enhanced practices, such as anesthesiology. Settings among manuscript not included, yet discussed as integrating technology, were also highly variable and included: childcare center, community mental health clinic, federally-qualified healthcare center, government agency (e.g., Department of Defense), mobile unit, prison/ corrections, private practice, and military.

Discussion

The current scoping review is believed to be the first to consolidate literature from across healthcare specialties to clarify competencies relevant to technology-enhanced practices. Among the 109 included manuscripts, all were published since 2000, with the majority being published during or post 2020. While the current study did not evaluate reasons for this finding, it was hypothesized that since a significant portion of the included manuscripts focused on telecommunication technologies, the increase in telehealth utilization post-COVID-19, combined with technology becoming more readily available and applied (12, 13), led to an increased recognition of the importance of competencies related to technology, thus fostering increased publication of study-relevant literature.

Related to the competencies themselves, as well as research question 1, literature discussed numerous modalities ranging from telecommunication technologies (e.g., video, telephone) to more esoteric technologies (e.g., wearable, VR/AR/XR). Findings not only suggested ongoing expansion of novel technologies into healthcare services, but also growing abilities of healthcare practitioners to harness the technologies to overcome historical barriers precluding effective healthcare. As one example, the use of wearable technologies permits ongoing physiological monitoring without relying on a patient to track their progress on paper-and-pencil forms, allowing for live and more accurate progress monitoring.

Related to research question 2, despite a multitude of articles suggesting the importance of developing competencies for the various technologies, relatively few highlighted specific competencies needed for different technologies. Fewer yet ($N = 109$) included a basic definition or operationalization of competencies to guide practitioners in the specifics of what to learn and how to adapt the technologies in order to effectively integrate them into their day-to-day practices. Additionally, among those detailing the competencies, the majority focused on ethical and legal considerations, as well as data security, with significant variability among the remaining competencies. Although specific reasons for why these three emerged as the most common are not currently clear, since the majority of the manuscripts included focused more on telehealth-related competencies (i.e., video, telephone) relative to other technologies (e.g., virtual reality, robotics), it was hypothesized that the marked increase in telehealth-related work following COVID-19 (12, 13) that coincided with the increased focus in ethical and legal practices emphasized by governing organizations (e.g., American Medical Association, American Psychiatric Association, American Psychological Association, National Association of Social Workers), licensing boards, and researchers, led to an increased recognition of the importance of ethics, legal, and data security specifically above and beyond any other possible competencies.

Finally, while some quantitative studies were reviewed, the majority of included publications were qualitative, and generally comprised of reviews, descriptions, viewpoints, recommendations, or program-specific overviews. As a result, it becomes clear that additional study is required to not only test often-suggested recommendations to better clarify what competencies are required as varying by technology, location, and specialty, but also how to best teach/acquire such information.

While not a primary target of the current study, some additional interesting findings were recognized. The review concluded that although a wider range of specialties than what was included in the final analysis were suggested to utilize technology in practice, discussions of competencies remain limited for many of these specialties. This becomes especially impactful for more specialized practitioners who may not seek cross-discipline journal articles to inform their practice, thus potentially missing relevant technology-related literature. For instance, although multiple manuscripts discussed the application of robotics (e.g., surgery), few manuscripts included in the final review discussed relevant competencies or means to gain such knowledge for the use of robotics in healthcare services.

Integration and clinical application – iTECH model

Upon review of the findings, it became apparent that due to fragmentation and variability, no singular discussion was applicable to all specialties or technologies, or comprehensive enough to cover the wide range of possible service variations that may present for healthcare practitioners. To address this challenge, findings were organized into domains of competency to create the Intersectional Technology Education and Competency in Healthcare (iTECH) Model: a model designed as a comprehensive, intersectional, versatile, and multiprofessional means to guide practitioner education and training to foster optimal use of technologies in healthcare-related practices. The model is not only believed to influence educational and training activities, but also foster improved patient outcomes and practitioner effectiveness through guiding practitioners to the most pertinent competencies relative for their unique healthcare service.

Creation of the model was a multi-step process involving integration of study outcomes in combination with author consensus for grouping and naming. This approach aligned with past methodologies for telehealth/technology competency scoping reviews and model creation (26). In this way, information gathered from the study characteristics outlined in Table 2 (i.e., identified competencies, technology type, setting, career state focus, specialty area) created the foundation of domains for the novel model. Authors then combined their individual and collective experiences in training, research (including knowledge of the current study's non-included review articles), and professional work related to technology-enhanced practices to supplement the core information. Through this method, a domain for the model was established when consensus was reached that the identified domain was not only directly applicable to a healthcare practitioner's technology-enhanced practice, but provided a meaningful distinction from other domains, even if one influences another (26). This method (Figure 1) yielded six broad domains: (1) primary knowledge; (2) service type; (3) modality type; (4) delivery format; (5) setting; and (6) diversity, equity, inclusion, and justice (DEIJ). A seventh domain was also identified; however, based on author review of the literature, this domain, titled "supplemental knowledge," was believed to be informative for practitioners, but nonessential (e.g., history of technology use). Each included domain is believed to be equally important to consider for any technology-enhanced practice, and can influence the others. For example, modality type can influence the types of services that could be provided, as well as the primary knowledge considerations required for effective use of that technology. While aspirational in nature, the model can be viewed as a means to guide an ethical, legal, evidence-informed, and safe practice through the selection of relevant competencies, while removing those less relevant to one's unique role. The healthcare practitioner can then utilize relevant competencies to focus readings, trainings, consultation, or other methods of gaining knowledge on these specific targets.

As an example of model application, consider a hospital-based child psychiatrist wanting to utilize an AI chatbot that tracks daily patient mood and patient-reported skill use. They may begin their application of the model by first clarifying the AI technology as their *delivery format*, with the *service type* focusing

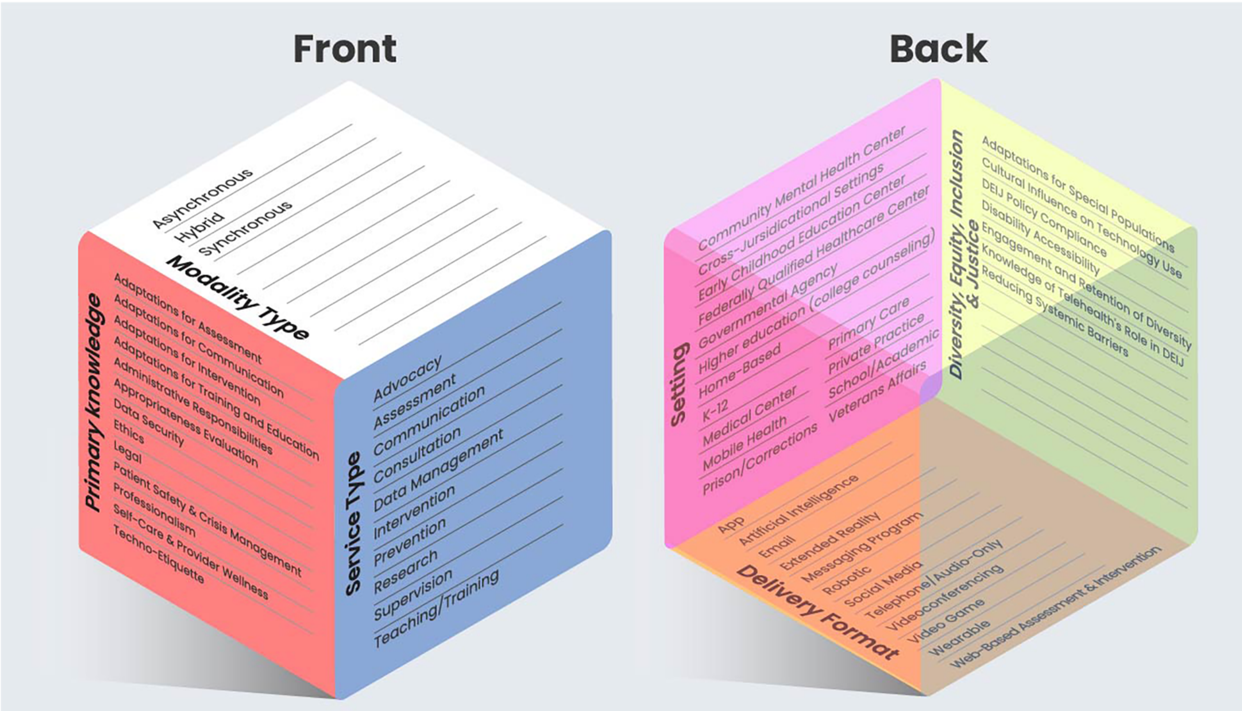

FIGURE 1
Intersectional technology education and competency in healthcare (iTECH) model.[a]Modality Type = The method in which technology is applied; Service Type = How the technology is used; Primary Knowledge = The type of technology-focused information practitioners should know to ensure ethical, legal, evidence-informed, and safe technology-enhanced practices; Delivery Format = The type of technology utilized; Setting = The locations in which the technology is utilized; Diversity, Equity, Inclusion, and Justice (DEIJ) = Consideration of factors relevant to the use of, and attitudes towards, the use of technology. [b]The model can be adapted and applied for emerging technologies, settings, and uses.

on assessment (i.e., data collection), the *modality type* as asynchronous, and the *setting type* as both a hospital (for practitioner) and home-based (for patient). The psychiatrist can use this information to educate themselves on *primary knowledge* relevant topics, including, but not limited to, differences between pencil-and-paper tracking vs. digital methods in terms of outcomes, data security considerations of sending and receiving patient data, and safety planning should a mood-related crisis arise. Additionally, the psychiatrist can explore setting-specific guidelines/requirements/restrictions of their organization for the use of AI. Finally, *DEIJ factors*, such as the role of systemic barriers and means of engagement and retention, should be considered, including the potential for financial-related data limitations (i.e., data allotment by plan) and how that can affect ongoing use of the chatbot. Additionally, biases (e.g., language) that could be introduced through the machine learning and natural language processing developmental operations of the AI chatbot should be considered (49).

Limitations

Study findings should be interpreted within the context of recognized limitations. First, similar to other scoping reviews, literature may have been missed or omitted due to database selection, language criteria, and Boolean operators not matching all relevant manuscript meta data (50). Additionally, although the sequential adding of search terminology aligned with past literature and use of Rayyan, it is recognized that this could have resulted in some relevant literature being excluded due to not meeting full search term criteria for further review. Similarly, while published research procedures were followed, a screening of title and abstract may have inadvertently removed some literature that would have been relevant, but not clearly indicated as such in the title or abstract information. While attempts were made to control for human error (e.g., multiple coders, spot checking), given the large amount of data and subjective nature of the coding, human error cannot be fully ruled-out. Nevertheless, overall reporting is believed representative of the constructs within the literature. Although a decision was made to exclude non-peer-reviewed outlets (e.g., certificate programs), some non-studied outlets may include competency-related information not accounted for in peer-reviewed literature. Additionally, the lack of grey literature imposes a publication bias. Finally, in line with other scoping review methodologies (51, 52), the study was descriptive in nature and did not include an appraisal of the quality of the literature.

Future directions

Future work related to the current study should include more databases and literature that were published following the current study's review period in order to determine any subsequent developments in technology-enhanced practice competencies. Additionally, a wider scope should be considered, including both peer-reviewed and non-peer-reviewed literature. For example, organization guidebooks (e.g., American Psychological Association, American Telemedicine Association), certificate programs, books, book chapters, and grey literature can be considered for inclusion. Future work should also seek to create universally-accepted standards for competency acquisition for technology-enhanced practices. More specifically, tighter operational definitions of a skill, testing and refinement, and proximal and distal (i.e., longitudinal) evaluation should be established. Standardization and long-term review can foster more objective measurement to evaluate successful methodologies, as well as areas for improvement. Additionally, standardization can allow for more direct evaluation of relevant outcome measures, such as cost-benefit assessments for the individual, the organization, and the patient in terms of positive outcomes and financial costs. Finally, future work should seek to further explore the iTECH model through two means. First, the model should be compared to other known models/recommendations of technology-related competency acquisition by guiding organizations, including the American Medical Association (24), the American Psychological Association (22), American Psychiatric Association (23), American Telemedicine Association (21), World Health Organization (9), and the American medical Informatics Association (53), as well as researcher-based models/recommendations [e.g., (26)]. This comparison can allow for identification of strengths and areas of improvement for the iTECH model. Second, it is essential that the model is implemented and assessed in healthcare practitioner's training curriculum to determine its influence in fostering both knowledge and hands-on competencies. This evaluation can consider usability and adaptability to different healthcare specialties and technologies. Pre- and post-education assessment can clarify trainer attitudes towards the model, trainee attitudes towards the model, and educational outcomes in terms of both evidence-informed understanding of utilized technologies and application. Once determined useful, the model can serve as a guide to create technology-enhanced practice curriculum for training programs in terms of coursework, applied hands-on work, and supervision. As the model is implemented, it is important to utilize an established framework for skill acquisition and education. One recommended method is the Kirkpatrick Model (54), as this model has been heavily cited within the literature for such purposes (55, 56). This model focuses on four levels of evaluation: reaction, learning, behavior, and results. Reactions focus on how trainees like a particular training model. Such an evaluation could include both quantitative (e.g., surveys/ratings of satisfaction) and/or qualitative (e.g., focus groups) assessments to measure trainees' perceptions of the model (54, 55). Effective learning assessment measures both program acceptance and knowledge transfer while gathering feedback to enhance future training. When trainees view a program positively, they are more likely to engage with and retain the material (54). Of important note, it is essential that evaluation objectively measures the amount of learning that takes place in addition to subjective experiences. Such evaluations can be completed through performance testing, simulations, case studies, and pre to post assessments (55). Behavior evaluates real-world behavior change with comparison of an intervention group to a control group. According to Kirkpatrick (54), this approach demands a scientific methodology using systematic before-and-after performance evaluations (examining both proximal and distal outcomes) with statistical analyses to measure behavioral changes. Finally, results evaluate system-wide or organizational impacts of the training program, such as improved evidence-informed practices, reduced costs, higher quality, increased production rates of satisfaction, varying based on specific program goals (54, 55). Graduate education presents an optimal opportunity to integrate the iTECH model with Kirkpatrick's method, enabling evaluation of technology-enhanced practices by training directors across various levels including practicum, internship, fellowship, and residency programs, depending on the healthcare specialty. Following evaluation, the iTECH model's implementation can be modified through an iterative approach to implementation. As trainee's advance through their training, milestone levels can be evaluated through the Dreyfus and Dreyfus model (57, 58), which evaluates the acquisition of expertise as a developmental process through five primary steps: novice, to advanced beginner, competent, proficient, and expert. As adapted by Hilty et al. (55), novice could be equated to a graduate student, advanced beginner to a first-year resident, competent to a senior resident, proficient to a graduating resident, and expert as a competent and licensed practitioner.

Utilizing such an educational framework, integration of the iTECH model can occur at multiple stages of one's professional development to account for the need for both didactic and hands-on experiential training (11). First, didactic information regarding relevant technologies can be provided during or following the introduction of general healthcare strategies. More specifically, the application of healthcare techniques (e.g., assessment, interventions) can be discussed in terms of both traditional and technology-enhanced methods. Such discussion can focus on general use of the technologies, relevant research, and both benefits and limitations of usage relative to non-technology methods in order to foster critical thinking of the use of the technologies (11). For example, a course describing ethical and legal healthcare can also include a discussion of jurisdictional practices and differences when implementing video or robotics (e.g., surgery) that may span different states, provinces, territories, or countries. Methods of learning about such differences, as well as how to safely account for and navigate such differences can also be outlined. Supplementing general discussions, advanced coursework can be created for either the broad integration of technology, or for specific technologies, such as a class on robotics for surgery, artificial intelligence in the use of medical research, or video for psychotherapy. While limited discussions of such coursework are available in the literature, and predominantly focus on telehealth rather than other technologies, courses and curriculums that can provide templates from which additional technology-focused work can be derived include Perle's Introduction to Telehealth for Clinical Psychologists (59), the University of Illinois College of Medicine at Peoria's robotic surgery training curriculum (60), and Greenberg and colleague's description of a pilot robotic surgery curriculum (61). Following the trainees acquisition of didactic information, hands-on experiences should be completed with classroom-based role play and simulation labs, as well as through real-world application in placements (e.g., practicum, internship, fellowship, residency). All work should be supervised with scheduled and/or live supervision, as appropriate to the site and training model. Technology-focused supervision must not only include consideration of the general healthcare practices and patient outcomes, but also numerous technology-focused considerations. For instance, supervision should include discussions of how the technologies were used, how they compared to non-technology-enhanced methods, the benefits of the integration of the technologies, limitations of the technologies, how any arising issues were addressed, how the technologies were perceived by the practitioner, how the technologies were perceived by the patient, and how the technologies interacted to change the healthcare service being provided. Training and supervision requirements can be guided by principles and standards set by governing organizations of the healthcare specialty, such as the American Psychological Association's Commission on Accreditation (62) and the Accreditation Council for Graduate Medical Education (63, 64). To monitor the impact of the novel curriculum and methodologies, graduate programs should implement both objective and subjective methods of assessment outside of the coursework and fieldwork. Assessment can include measurement of the improvement in both knowledge and hands-on technology-enhanced competencies as defined by the iTECH model and available literature, as well as aligning standards set forth by accreditation governance. Assessment can also evaluate attitude changes towards technologies, perceived ease of use of the technologies, perceived benefits and limitations of the technologies, supervisor challenges with teaching technologies, and trainee challenges with learning the technologies. Finally, distal assessment should evaluate if the training fostered ongoing use of technologies, as well as which types, into the future (11). Given rapid developments, ongoing continuing education post graduate education is essential. As a result, training institutions (e.g., universities, hospitals, licensing boards, professional organizations) must design new self-guided and professionally-led continuing education series to foster ongoing education of specific technologies for specific healthcare specialties. Such strategies can include self-education through continuing education literature, didactic presentations either live or via webinar, and hands-on training workshops. Well-rounded training and knowledge are believed necessary to foster optimal technology-enhanced healthcare services that adapt as the field continues to evolve to yield new technologies and competencies. Education is not only to ensure a practitioner's ability to effectively integrate and maintain the technologies, but also to ensure that practitioners are equipped with research-informed rationales for what technology works best for who, as well as which may be contraindicated or to be used with caution. Further, as not all individuals may equally respond to different technologies and strategies, methods of how to adapt the technologies for unique population demographics (e.g., age, education, race, language, disability, socioeconomic status, technology comfort level) and pathologies are essential.

Conclusions

The current scoping review suggested ongoing expansion of technology into healthcare practices, indicating the need for greater practitioner resources to ensure their acquisition of necessary competencies to foster ethical, legal, evidence-informed and safe practices. In doing so, practitioners can acquire necessary knowledge to be able to tailor technologies and clinical services to unique services, population demographics, and pathologies. Nevertheless, findings also indicated that few peer-reviewed manuscripts highlighted and expounded upon specific competencies needed or recommended for practice. Additionally, despite the review yielding a variety of technologies used across healthcare specialization, the review process allowed for recognition that a wider range of technologies are believed to be utilized across a larger scope of healthcare specialties than what was recognized in the final scoping review as based upon the inclusionary criteria (e.g., many studies did not expound upon competencies), necessitating the need for greater competency development and dissemination to inform practitioners. To address this gap, the iTECH Model was created to guide a practitioner's technology-enhanced practice. The model is believed to assist practitioners in identifying relevant competencies to ensure knowledge and hands-on experiences relevant to their unique practices in order to foster optimal care and patient outcomes, while reducing possible issues. Although believed helpful, the current work is viewed as a first-step. There remains a need for additional study to not only better understand literature-suggested competencies, as evolving over time, but also to explore best methods for integrating the iTECH model into graduate coursework, real-world experiences, and continuing education to enhance its utility for diverse healthcare practitioners.

Author contributions

JP: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Data curation, Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization. DC: Data curation, Methodology, Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Investigation, Supervision. EB: Data curation, Investigation, Writing – original draft, Writing – review & editing. MC: Data curation, Investigation, Writing – original draft, Writing – review & editing. JD: Data curation, Investigation, Writing – original draft, Writing – review & editing. PN: Data curation, Investigation, Writing – original draft, Writing – review & editing. GM: Data curation, Investigation, Writing – original draft, Writing – review & editing. JJ: Conceptualization, Formal analysis, Funding acquisition, Methodology, Visualization, Writing – original draft, Writing – review & editing, Data curation, Investigation.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

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Online scenario simulation teaching in airway management for undergraduate anesthesia students

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Background: The rapid growth of online education has led to the extensive exploration of innovative teaching methods to improve learning outcomes in medical training. This study aimed to evaluate the effectiveness of online scenario-based simulation in an airway management course for undergraduate anesthesia students.

Methods: A total of 130 undergraduate students participated in an online airway management course. The primary objective was to assess the effectiveness of this teaching method by comparing post-class quiz scores. Secondary outcomes were evaluated based on technical and non-technical skills scores across four simulation scenarios. An anonymous questionnaire was also distributed to gather students' perceptions and experiences.

Results: The simulation group exhibited a significant improvement in post-class quiz scores compared to the traditional group ($p < 0.001$). In the second simulation, students showed enhanced technical skills across all four scenarios ($p = 0.030$, $p = 0.037$, $p = 0.028$, $p = 0.028$, respectively), as well as improved non-technical skills, including task management, teamwork, communication, vigilance, crisis identification, decision-making, and self-confidence. Questionnaire responses indicated that students found the course both enjoyable and beneficial in improving their problem-solving abilities. Additionally, 97.3% of participants felt the course enhanced their self-learning and teamwork skills, while 97.22% reported it facilitated mastery of anesthesia techniques.

Conclusion: Online scenario-based simulation teaching has proven to be a highly effective and engaging educational tool for undergraduate anesthesia students. It significantly improves both technical and non-technical skills while promoting critical thinking and problem-solving development.

KEYWORDS

online teaching, scenario simulation teaching, anesthesia, airway management, undergraduate students

1 Background

The rapid advancement of mobile Internet technology has positioned online medical education as a pivotal approach in medical training, primarily due to its flexibility and accessibility, which overcome the traditional limitations of time and space (1). This integration of medical education with online platforms has led to the emergence of various innovative educational models (2, 3). During the COVID-19 pandemic, our institution, like many others globally, shifted to online teaching (4). However, this transition presented significant challenges, especially in courses focusing on clinical skills. The conventional online teaching model often struggles to foster active student participation and engagement in the learning process (5, 6). Traditional teaching methods typically rely on one-way knowledge transmission through lectures, theoretical instruction, and limited video demonstrations, providing few opportunities for students to actively engage or participate in hands-on practice (7, 8). These challenges are amplified in an online setting, where the absence of immediate interaction and feedback—typical in face-to-face communication—further reduces student engagement (9). Given the highly practical nature of anesthesiology and the limited existing research on web-based anesthesia education, it is essential to explore and develop effective online teaching strategies for professional skills training to enhance the quality of teaching and learning in this domain.

Simulation training, which involves creating realistic medical scenarios where students assume various roles, is a valuable teaching method (10). It not only organizes and integrates theoretical knowledge but also effectively bridges the gap between foundational knowledge and clinical practice (11). Furthermore, it helps students enhance their teamwork, critical thinking, and clinical decision-making skills (12). Given the limited clinical experience of undergraduate students, which often results in challenges in applying knowledge flexibly and difficulties in crisis management and diagnosis (13), online simulation-based teaching can effectively address these gaps. Additionally, it can stimulate students' interest in learning and improve their clinical reasoning and communication abilities (14, 15).

Students' limited clinical experience was found to hinder their performance during initial simulation exercises in previous simulation-based teaching activities (13). To enhance the effectiveness of simulation training, a question-and-answer session was incorporated prior to the simulation activities. This session was designed to help students consolidate theoretical knowledge and prepare for the practical scenarios they would encounter. Additionally, debriefing is commonly integrated into the teaching process to optimize the outcomes of simulation training (16). In this phase, instructors guide students to critically evaluate the simulation process and review their clinical performance, fostering systematic and reflective learning while addressing areas for improvement (16, 17). This approach is particularly crucial in medical education, as it emphasizes collaboration, situational learning, and the development of presentation and decision-making skills (12, 18). With this method, students are more engaged in the online course, while instructors maintain greater control over the learning process, ultimately enhancing teaching quality (19).

Airway management is a critical responsibility for anesthesiologists. The identification and management of difficult airways present significant challenges, as inadequate management can lead to severe complications (20). To tackle these challenges, this study focused on teaching content related specifically to difficult airway management. Initially, students consolidated their theoretical knowledge of difficult airways through a question-and-answer session. Following this, online simulation teaching was implemented, incorporating effective debriefing techniques. In summary, this study aims to evaluate the efficacy of scenario-based simulation teaching in an online airway management course.

2 Materials and methods

2.1 Ethical approval and informed consent

The entire training process was conducted online via Tencent Meeting, with the simulation teaching facilitated through vital signs simulation software. No patients were involved or harmed during this study. The study was covered under the ethics review of the First Affiliated Hospital of Dalian Medical University and received approval from the teaching management of Dalian Medical University. The curriculum followed the teaching standards of Dalian Medical University. This study adhered to the Declaration of Helsinki and the ethical review guidelines of the First Affiliated Hospital of Dalian Medical University. All procedures were conducted in compliance with relevant guidelines and regulations, including but not limited to the use of online teaching platforms, confidentiality of student data, and privacy protection. Formal consent was obtained from all participants.

2.2 Sample and sample size

The sample size was calculated based on the primary outcome variable, measured by post-class quiz scores. According to our pilot study, the mean post-class quiz score in the traditional group was 29.03 with a standard deviation of 6.27. This study hypothesized a five-point difference in post-class quiz scores between the traditional group and the simulation group. Thus, a sample size of 84 students was required, assuming $\alpha = 0.05$ and $\beta = 0.05$. To account for potential data loss, 130 participants were enrolled. All students were in their fourth year of university, with 65 participants in the simulation teaching group and 65 in the traditional teaching group. The sample size calculation was performed using PASS version 15.0.

2.3 Preparation phase

A total of 130 students participated in the study. All participants had previously completed the theoretical course in anesthesia and relevant training in tracheal intubation. Before the course, students were provided with study materials, including the latest airway management guidelines (20), in both Chinese and English. Each student was required to review these materials alongside the textbook before attending the class.

2.4 Pre-class quiz

The detailed process of the web-based anesthesia teaching study is outlined in Figure 1. All students first completed a 20 min quiz assessing their knowledge of airway management. The quiz covered topics including: (1) how to perform airway assessments in patients with head and neck trauma; (2) preparation for tracheal intubation and extubation precautions in patients with pharyngeal tumors; (3) causes of hypoxia after anesthesia induction in patients with normal preoperative airway assessment; (4) measures to take after multiple failed intubations during general anesthesia induction. The instructor did not provide answers during the quiz, and the results were kept concealed. The same topics were retested at the end of the class to evaluate changes in students' proficiency in professional knowledge.

2.5 Question and answer session

To enhance the effectiveness of simulation training, a question-and-answer session was introduced prior to the simulation exercises, aimed at reinforcing students' theoretical knowledge and preparing them for the practical scenarios they would face. Students were randomly assigned to eight groups, each consisting of four members. Eight questions of comparable difficulty were prepared, with each group assigned one question to answer, and their responses were scored. Once a group completed its answer,

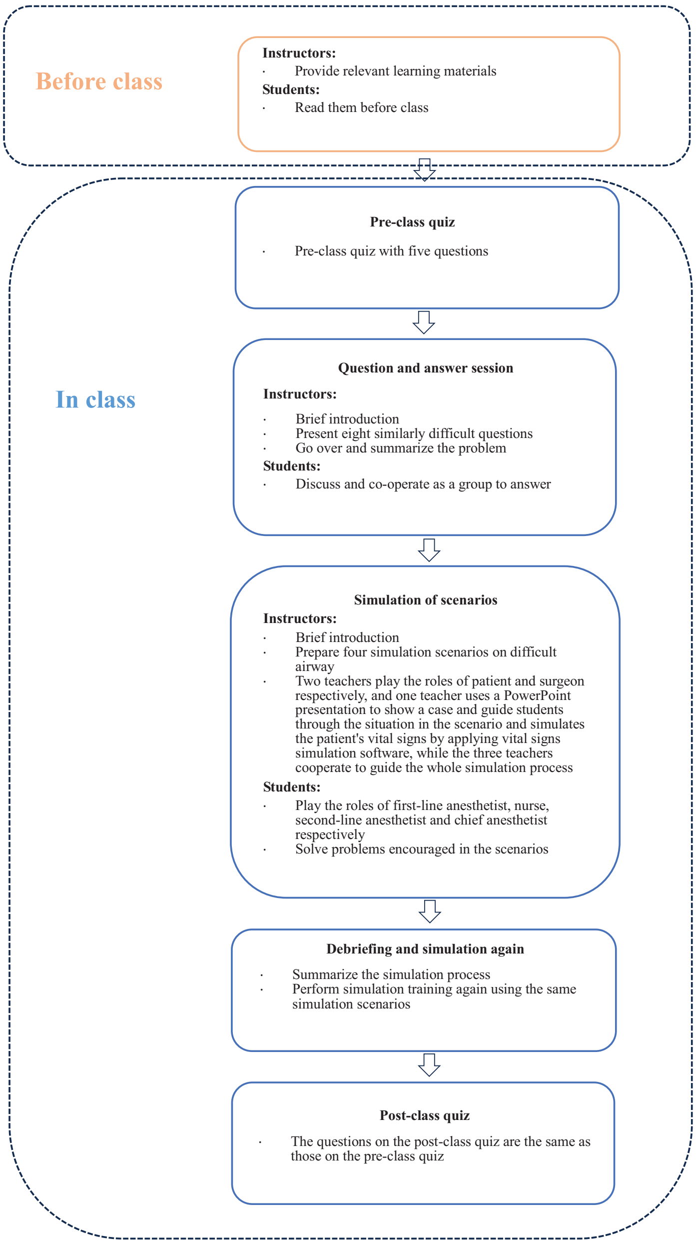

FIGURE 1
Implementation process of web-based anesthesia teaching study.

other groups were invited to provide supplementary responses and earn points for correct answers. Following the session, detailed explanations were provided for each question. Topics covered included: (1) risk factors for difficult mask ventilation; (2) risk factors for difficult tracheal intubation; (3) methods for awake tracheal intubation; (4) strategies for managing anticipated difficult tracheal intubation; (5) grading of laryngoscopic exposure; (6) treatments for bronchospasm; (7) techniques for establishing an invasive airway; and (8) considerations for extubating patients with difficult tracheal intubation.

2.6 Scenario simulation training process

Prior to the training, roles were assigned to participants: two first-line anesthesiologists, two second-line anesthesiologists, an anesthesia director, and a nurse. To support the simulation, two instructors took on the roles of patient and surgeon, respectively (the structure and scenarios of the online simulation are illustrated in Figure 2). The instructor provided a thorough briefing on the simulation process, outlining the method and the responsibilities of each role. The simulation was designed to closely replicate the clinical workflow, including a preoperative patient visit and scenarios where first-line anesthesiologists sought assistance from second-line anesthesiologists or the director when encountering challenges. Four simulation scenarios were prepared: two for anticipated difficult airways and two for unanticipated difficult airways (Table 1). Virtual props, such as laryngoscopes, laryngeal masks, light sticks, fiberoptic bronchoscopes, and other relevant tools, as well as drugs used in simulations, were provided to the students. One instructor utilized a PowerPoint presentation to present case details (patient history, past medical history, relevant examinations, type of surgery, etc.) and a simulated training scenario in the operating room. Vital signs simulation software was employed to simulate the patient's real-time vital signs, adjusting them based on the students' actions. The other instructor played the role of the patient, simulating stress responses (e.g., choking, nausea, dyspnea) in reaction to the students' interventions. The instructor guided the students through appropriate responses, utilizing PowerPoint to present emergency scenarios during the simulation (a demonstration of specific parts of the simulation is available in Supplementary Material 1). Students had the opportunity to communicate with both the patient and the surgeon at any point to gather information on the patient's medical history and the surgical procedure. Each scenario lasted 20 min, followed by a teacher-led debriefing that addressed both technical and non-technical aspects of the simulation. Afterward, the same students participated in a second simulation. The instructor assessed and scored their performance across both simulations. Upon completion of each case, the instructor provided a comprehensive summary, including an analysis of any adverse patient effects and an evaluation of whether appropriate actions and precautions were taken.

2.7 Evaluation of scenario simulation training

The instructor evaluated the entire simulation process using both technical and non-technical criteria. Technical points were awarded according to the following scoring system: two points for each completed exercise, two points for completing all exercises, one point for completing more than 50% of the exercises, and 0.5 points for completing less than 50%. Non-technical points were assessed based on the criteria established by the Stanford Anesthesia Cognitive Aid Group (21), covering aspects such as task management (e.g., task allocation, equipment preparation), teamwork, communication, sustained vigilance, crisis identification, decision-making, and self-confidence (non-technical criteria detailed in Supplementary Material 2). Each fully completed item earned 1 point, partially completed items were awarded 0.5 points, and incomplete items received 0 points. The detailed scoring scale for scenario simulation teaching is provided in Table 1.

2.8 Post-class quiz

A post-class quiz was administered at the end of the course, using the same questions as the pre-class quiz, to assess the

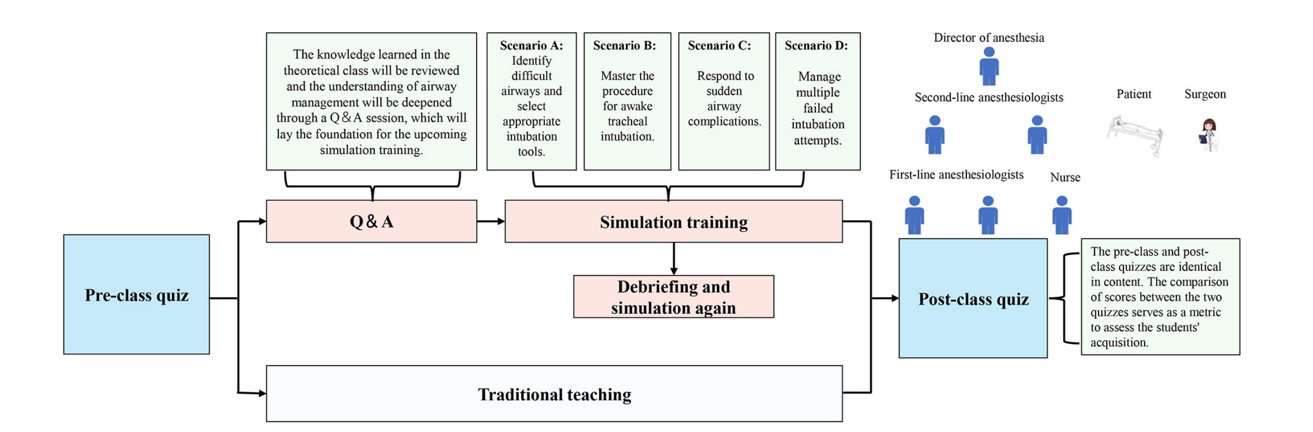

FIGURE 2
The structure and scenarios of the online simulation.

TABLE 1 Simulation scenarios and technical and non-technical scoring criteria.

Scenarios	Technical skills	Non-technical skills
A) In the aftermath of a traumatic car accident, the patient sustained the cervical spine fracture combined with skull base fracture, then internal fixation will be per formed under general anesthesia. However, the patients limited head tilt and the mentum-to thyroid distance of less than 6cm pose challenges.	Identify difficult airway Fix cervical vertebrae and avoid nasotracheal intubation Select video-assisted laryngoscopy	Task management Teamwork Communication Sustained vigilance Crisis identification Decision making Self-confidence
B) In the case of a patient with ankylosing spondylitis undergoing laparoscopic gastrectomy under general anesthesia, the limited head tilt, the mentum-to thyroid distance of less than 6cm, and the mouth opening of less than 3cm all pose risks	Identify difficult airway Use awake tracheal intubation guided by fiber bronchoscopy Correct process of awake tracheal intubation	–
C) A radical thyroid surgery under general anesthesia is planned with no airway abnormalities on preoperative evaluation. Unfortunately, bronchospasm occurred due to multiple attempts at intubation after the failure of a direct laryngoscopic intubation	Attempt with the video-assisted laryngoscopy Seek assistance from a more experienced medical professional Solve bronchospasm	–
D) For a laparoscopic appendectomy under general anesthesia with no airway abnormalities on preoperative evaluation, direct laryngoscopic intubation failed and several alternative approaches were attempted without success.	Attempt with video-assisted laryngoscopy Seek assistance from a more experienced medical professional Find alternative approaches after three failed intubations (Laryngeal mask airway, wake up the patient, tracheotomy)	–

effectiveness of the teaching modality by comparing pre- and post-class quiz scores.

2.9 Questionnaire

An anonymous online questionnaire was distributed to gather student feedback. The questionnaire included the following questions: (1) Are you satisfied with scenario simulation teaching? (2) How does this course compare to previous traditional courses? (3) Difficult airway simulation teaching feels incredibly real. (4) Does this course effectively improve problem-solving skills? (5) Does this course effectively improve self-learning ability? (6) Does this course effectively improve teamwork skills? (7) Does this course effectively increase interest in professional knowledge learning? (8) Difficult airway learning provides great benefits in improving anesthesia skills? (9) I am able to grasp the content of this course.

2.10 Statistical analysis

This study was a controlled trial, with students assigned to either the simulation or traditional teaching groups to evaluate the effectiveness of the online simulation. The primary objective was to assess the impact of the teaching modality by comparing post-class quiz scores. Secondary outcomes were evaluated based on technical and non-technical skills scores across two simulation scenarios. Data were presented as mean ± standard deviation. Post-class quiz scores were compared using a t-test. Both technical and non-technical skills in each of the four scenarios were analyzed using a paired t-test. Descriptive statistics were employed to summarize the questionnaire data, with frequency distributions and percentages used to illustrate the proportions within each category. A significance level of $\alpha = 0.05$ was applied, with $p < 0.05$ considered statistically significant.

3 Results

3.1 Student basic information

Table 2 provides a comprehensive overview of participant information. All students had successfully completed theoretical coursework and practical exams; however, they had not undergone clinical practice.

3.2 Web-based anesthesia simulation teaching enhanced students' understanding of airway management

Figure 3 illustrates the quiz scores of 130 students, showing a significant increase in post-class scores for the simulation group compared to the traditional group ($p < 0.001$). There were no significant differences in pre-class scores.

3.3 Web-based anesthesia simulation teaching demonstrated high effectiveness

Table 3 presents the evaluation of technical and non-technical points across four scenarios: two anticipated difficult airway scenarios and two unanticipated difficult airway scenarios. While

TABLE 2 Demographic characteristics of participants.

Variable	Number	Percentage (%)
Gender		
Female	86	66.2
Male	44	33.8
Age		
25	2	1.5
24	6	4.6
23	22	16.9
22	73	56.2
21	27	20.7
Normal training phase		
Theory qualified	130	100
Technical qualified	130	100
Clinical experiences		
Yes	0	0
No	130	100

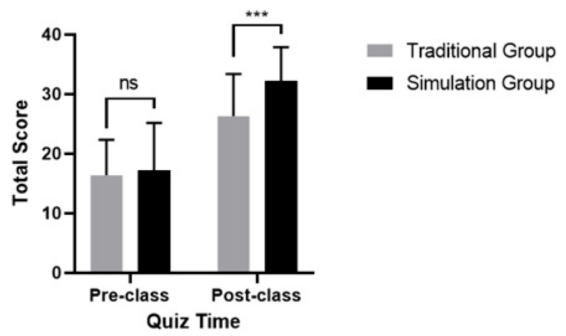

FIGURE 3
Comparison of post-class quiz scores between traditional group and simulation group. Post-class quiz scores are presented as means ± SD. Significantly different from the simulation group at ***$P < 0.001$.

no significant differences were observed in technical and non-technical points across the scenarios, the total scores (technical + non-technical) for all four scenarios demonstrated a statistically significant improvement during the second attempt compared to the first ($p < 0.05$).

3.4 Course feedback and satisfaction survey results

The survey results (Figure 4) revealed that all students expressed a preference for scenario simulation teaching, finding it superior and more engaging than their previous learning methods. The students highly valued this teaching approach. Specifically, 88.89% of participants found the simulation scenarios in the airway management course to be realistic. Additionally, 97.3% of students reported that the course enhanced their self-learning and teamwork skills, while 97.22% indicated that it improved their abilities in difficult airway management. A majority of students (83.33%) felt confident in their mastery of the course content. Overall, the survey responses unanimously indicated that the course effectively fostered independent exploration and problem-solving skills, with students subjectively reporting that this teaching method positively impacted their learning outcomes.

4 Discussion

The COVID-19 pandemic has profoundly reshaped the landscape of medical education, accelerating the widespread adoption of online teaching methods (22). While traditional online approaches offer increased accessibility, they often struggle to engage students effectively and fail to foster clinical reasoning (23), particularly in hands-on fields like anesthesia. Online scenario simulation teaching presents a promising solution to these limitations (23).

Simulation-based learning, long valued for its ability to replicate realistic clinical scenarios, allows students to apply theoretical knowledge in a controlled, risk-free environment (12). By integrating online platforms with simulation training, the flexibility and accessibility of the Internet can be combined with the interactive and immersive nature of simulation exercises (24). This hybrid approach not only enhances students' technical competencies but also promotes the development of essential non-technical skills, such as teamwork, communication, and crisis management (12, 18, 25). Online simulation training offers students the opportunity to encounter and manage a variety of airway scenarios, including both anticipated and unanticipated difficult airways, without the risks associated with real clinical settings (26). For undergraduate students preparing to enter clinical practice, this simulation course equips them with the confidence needed to navigate complex clinical situations in their future careers (27). Moreover, the online format eliminates the need for physical presence in a simulation center, increasing accessibility for a larger number of students while reducing costs and enhancing convenience compared to traditional simulation training (24).

To maximize the effectiveness of simulation training, we facilitated students' consolidation of knowledge related to difficult airways by posing a series of open-ended questions prior to the simulation exercises. This method not only fostered critical thinking but also maintained high levels of student engagement and motivation throughout the training (28, 29).

Our findings indicated that web-based anesthesia simulations significantly enhanced students' understanding of airway management, facilitated the translation of theoretical knowledge into practical skills, and improved performance in subsequent simulations. Additionally, non-technical skills—such as task management, teamwork, communication, sustained vigilance, crisis identification, decision-making, and self-confidence—also showed marked improvement. The benefits of this simulation training included increased confidence, reduced anxiety, and improved proficiency (30). In the present study, post-class quiz scores from the simulation group significantly outperformed those from the traditional group, confirming the effectiveness of scenario simulation training.

Questionnaire results revealed that all students found the approach beneficial, enhancing their learning efficiency and interest

TABLE 3 Comparing performance in the first and second simulations.

Classification	Term	First time	Second time	*P*-value
Scenario A	Technical points	2.25 ± 0.354	5.00 ± 0.000	0.058
	Non-technical points	2.25 ± 0.354	4.75 ± 1.061	0.126
	Overall score	4.50 ± 0.707	9.75 ± 1.061	0.030
Scenario B	Technical points	2.75 ± 1.061	4.50 ± 0.707	0.090
	Non-technical points	3.00 ± 0.000	5.50 ± 0.707	0.126
	Overall score	5.75 ± 1.061	10.00 ±1.414	0.037
Scenario C	Technical points	3.00 ± 0.000	5.75 ± 0.354	0.058
	Non-technical points	1.75 ± 0.354	4.75 ± 0.354	0.105
	Overall score	4.75 ± 0.354	10.50 ± 0.000	0.028
Scenario D	Technical points	2.75 ± 1.061	5.25 ± 0.354	0.126
	Non-technical points	2.25 ± 0.354	5.50 ± 0.707	0.144
	Overall score	5.00 ± 0.707	10.75 ± 1.061	0.028

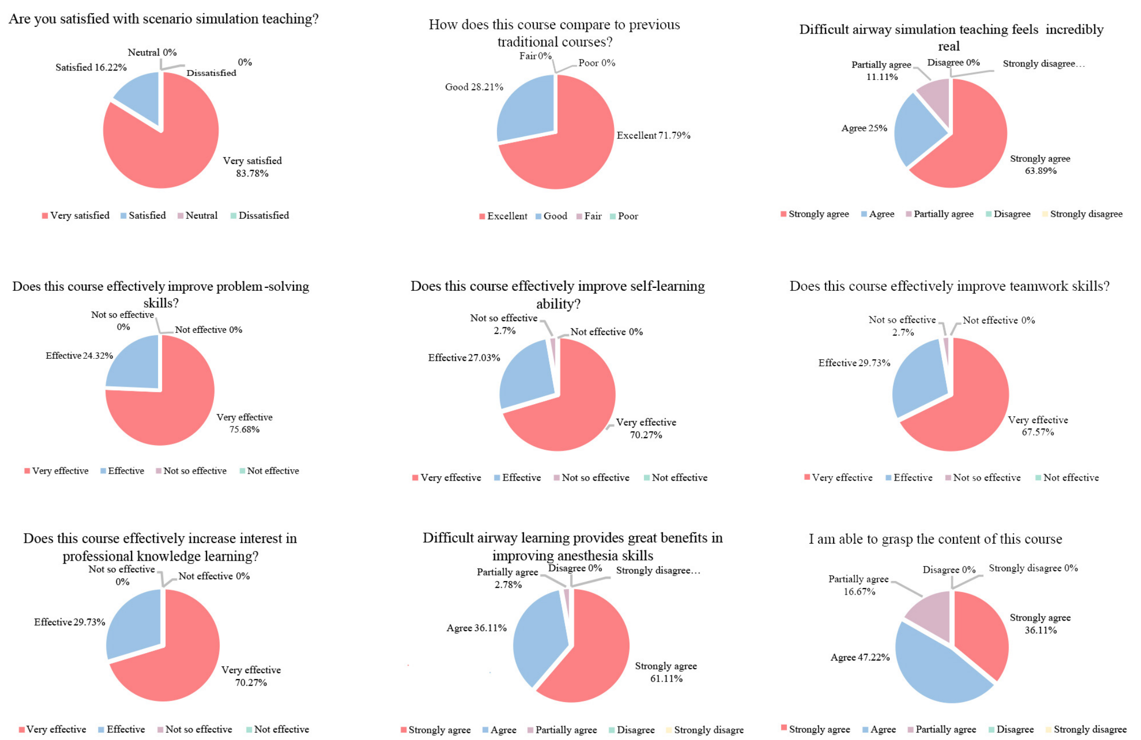

FIGURE 4
Questionnaire results on course feedback.

in systematic professional development. Specifically, 97.3% of students reported improvements in self-learning and teamwork skills, while 97.22% felt the course enhanced their difficult airway management capabilities and believed the teaching method positively impacted their learning outcomes. Through the integration of online teaching and scenario simulation, undergraduate anesthesia students developed essential crisis management skills, crucial for addressing practical clinical challenges.

Overall, our findings indicate that online scenario simulation training is both highly effective and engaging for anesthesia education. These results align with studies in nursing and pharmacy education, which have shown that online simulation teaching improves students' learning outcomes and offers a positive educational experience (31, 32). Furthermore, students have demonstrated enhanced execution and leadership skills in crisis situations (33). Another study found that students involved in online simulation-based teaching exhibited significant improvements in knowledge acquisition, with the interactive nature of simulation-based learning proving particularly effective in fostering enthusiasm for the subject matter (34).

In online simulation teaching, active student engagement is essential. However, instructors often face challenges in closely monitoring student involvement and accurately assessing participation rates in an online environment (35). This lack of control can directly affect the quality of instruction and hinder the achievement of desired learning outcomes (18). Direct debriefing effectively addresses these challenges by extending teaching sessions, motivating students, and enhancing instructors' control over the online classroom (36). Based on the learning outcomes observed during the direct debriefing phase, instructors can guide students back into simulation scenarios, help them identify areas of weakness, supplement their knowledge, and integrate it into a coherent framework (37). Additionally, debriefing encourages students to articulate their thoughts and emotions, promoting reflection on both individual and collective experiences (38).

Despite these promising results, several limitations exist in this study. First, the absence of blinding led to potential bias in the analysis of subjective observations. Second, the study did not include follow-up assessments to evaluate the long-term impact of online simulation training on students' clinical practice. Future work will involve tracking these students' progress over the long term to assess the continued influence of this teaching method. Additionally, multicenter, randomized controlled trials with larger sample sizes will be conducted to further investigate the effectiveness of this approach.

5 Conclusion

In conclusion, online scenario simulation training has proven to be a highly effective and engaging educational tool for undergraduate anesthesia students. Incorporating this training into the curriculum not only enhances students' technical and non-technical skills but also fosters the development of critical thinking and problem-solving abilities.

Data availability statement

The datasets analyzed in this study are available from the corresponding authors on a reasonable request.

Ethics statement

The studies involving humans were approved by First Affiliated Hospital of Dalian Medical University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

YL: Writing – original draft, Writing – review and editing, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. T-tW: Writing – original draft, Writing – review and editing. Y-yH: Investigation, Software, Supervision, Validation, Visualization, Writing – review and editing. X-yL: Conceptualization, Project administration, Writing – review and editing. L-jG: Software, Writing – review and editing. SH: Writing – review and editing. PG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. Q-pW: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmed.2025.1563540/full#supplementary-material

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NurseVerse: nursing in the metaverse era

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Although the metaverse is still in its early exploratory stage in the field of nursing, it is gradually demonstrating its potential in digital health and telemedicine care, transforming the traditional nurse–patient interaction model through digital tools and the internet. The "metaverse" represents the merging of two worlds into an immersive, online, virtual, connected environment in which participants actively engage with 3D content and interact using digital avatars. The metaverse entails many possibilities and challenges in attempts to introduce new methods of nursing. This technology has many applications, particularly with respect to assisting in surgery, enhancing chronic disease management, reshaping nursing education, promoting telemedicine, and facilitating psychological interventions. While obstacles may be encountered in various areas, such as trust and security, technology, legislation and regulation, the use of non-fungible tokens as a secure asset for patient data is a potential solution to these issues.

KEYWORDS
metaverse, virtual reality, augmented reality, remote nursing, nursing education, artificial intelligence

The rise of the metaverse

The term "metaverse" was first used in Neal Stephenson's 1992 science fiction novel Snow Crash to describe technology that uses the internet to combine the real and virtual worlds, in which our online presence is as important as our physical presence (1). In December 2021, Mark Zuckerberg, who invested considerable resources in the development of a three-dimensional virtual world network focused on social media connectivity, announced that Facebook would officially be renamed Meta to highlight its ambitious goals (2). Since that time, the concept of the metaverse has attracted considerable attention.

What is the metaverse?

The metaverse is a digital three-dimensional (3D) environment, generated by a combination of augmented reality (AR), virtual reality (VR), and artificial intelligence (AI), in which individuals can use personalized digital avatars that mimic real-life contexts to engage in various financial and social interactions, among other types of engagement (3). This vast network of immersive virtual environments, powered by advanced technologies, leading to a significant paradigm shift in various aspects of human life, including healthcare and nursing.

The metaverse is a pioneering technology in the field of nursing practice (4, 5). The integration of VR and AR into nursing offers a simplified model for the practical application of patient care. Real-time guidance using 3D models can assist with puncture procedures and support surgical operations, improving the accuracy of punctures and enhancing surgical quality (6). Immersive training helps providers develop clinical skills (7) and emergency response capabilities. Wearable devices and lifelogging technologies enable remote health monitoring (8), thereby enhancing the continuity and personalization of care for chronic conditions and elderly individuals. Virtual hospitals and digital interactive platforms extend the spatial boundaries of nursing services, thus improving accessibility and efficiency in care delivery (9).

Researchers have divided the metaverse into two axes (10) comprising four sections, namely, augmented reality, life log, the mirrored world, and the virtual world (Figure 1); these sections all have the potential to revolutionize digital life. In the quadrant-based introductory map to the metaverse, the vertical axis includes augmentation and simulation techniques that determine the relationship between reality and innovation. Augmentation enhances people's sensory experiences through auditory, visual, and other sensory stimuli, thereby integrating new functions into real-world environments. In contrast, simulation of reality takes the form of a virtual world that replicates reality (1, 10). The horizontal axis includes metaverse technologies that facilitate the empirical relationship between the technology and its users. The left side reflects the external environment, whereas the right side reflects the user's personalized experience (1, 10). The metaverse is situated within the external environment, and this external perspective is user-centered and focused on guiding the user's interactions with these environmental features. The intimate element provides an internal perspective that focuses on technologies that guide personalized behavior on the basis of customized data.

Augmented reality (AR) is a technology that enhances the real world by overlaying virtual imaging onto it. AR is typically experienced through smart glasses, smartphones, tablets, or AR head-mounted displays (11). This technology can create realistic visualizations, such as those of vascular anatomy and subcutaneous structures (6), thereby facilitating venipuncture as well as serving as a valuable tool for emergency preparedness and training scenarios that are difficult to replicate. It supports novice doctors and nurses in performing clinically precise procedures. In mass casualty incidents, smart glasses equipped with AR have been used for triage, enabling digital documentation of triage results. Compared with traditional methods, AR approaches not only improve tactical response at the scene but also support decision-making and accelerate the overall workflow (12, 13). Furthermore, AR technology can assist in wound care management using smart glasses (14) and enhance students' learning experiences by improving their knowledge, understanding, and practical skills—thus transforming medical and nursing education (15, 16).

Lifelogging refers to the use of smart devices—such as smartwatches, smartphones, and wearable sensors—to record one's daily life activities via the internet or associated platforms (e.g., Instagram, health monitors) (1, 17). By combining such devices and mobile applications, users can document health-related information, including daily activities, dietary habits, step count, blood pressure, and body weight, which can help improve lifestyle behaviors (8). Wearable sensors and devices offer a more comprehensive way to track individuals' activities and physical conditions in daily life (18). Additionally, these devices can provide essential health indicators by continuously or intermittently monitoring physiological signals such as electrocardiograms (ECGs) and electroencephalograms (EEGs). This technology is particularly valuable for issuing early warnings before health abnormalities occur, thereby supporting early diagnosis and timely treatment (19). To manage patients with chronic conditions, healthcare providers can use lifelogging data to dynamically adjust rehabilitation plans or medication regimens. Lifelogging also enhances patients' engagement in their own health management, promoting self-care and health empowerment.

Mirror worlds represent simulations of map-based external environments (e.g., educational spaces, Google Maps, Google Earth). In the healthcare context, mirror worlds use digital technologies—such as the Internet of Things (IoT), AI, and 3D modeling—to map physical medical and nursing environments, patient data, and equipment status into virtual spaces in real time. This technique enables the construction of interactive, visualized, and analyzable digital twin systems. In China, the city of Shanghai has already established metaverse-based smart hospitals and specialty hospitals whose physical and digital hospital spaces are deeply integrated. Through digital twin technologies, physical environments are reconstructed that empower employees to achieve more efficient and intelligent nursing and medical management (9). Digital twins of human organs can facilitate personalized treatment strategies and predictive modeling of disease progression (20). However, current technologies still face challenges in accurately modeling and simulating precise biological digital twins (20).

Virtual worlds are computer-generated, persistent 3D digital environments that, when accessed through head-mounted displays, create a fully immersive online 3D reality (21). Within these environments, individuals interact, communicate, learn, entertain, and even work solely through virtual avatars; examples include online multiplayer games, virtual hospitals, and consultation rooms. In the virtual world, virtual clinics can be designed to meet both patient needs and the professional requirements of doctors and nurses. For example, when a patient is receiving consultation for liver surgery, the virtual clinic can include educational materials related to liver disease. To enhance the patient experience during waiting periods, a virtual waiting area can provide an overview of the condition, using 3D models to illustrate relevant anatomical structures, thereby helping patients better understand their health status (22). Moreover, virtual reality within virtual worlds can be used to deliver psychological interventions, thereby helping reduce patient anxiety and depression (23, 24).

The metaverse has seen widespread development across various fields. In industry, beyond employee training, the metaverse is driving significant societal advancements by enabling immersive human–machine interactions, potentially revolutionizing production and remote collaboration. The industrial metaverse seamlessly integrates within digital ecosystems, fostering engagement and innovation, and is paving the way for Industry 5.0 (25). In business, the metaverse provides shoppers with immersive shopping experiences and virtual product demonstrations within digital worlds, offering new opportunities for interactive marketing campaigns. Businesses can attract customers through virtual storefronts, showcase products in 3D, and leverage real-time

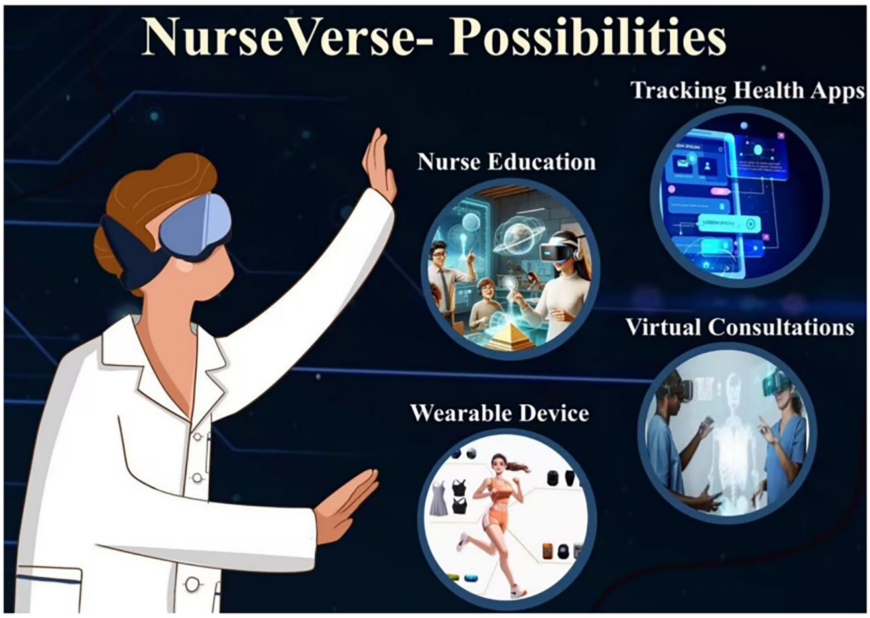

FIGURE 1
The modified NurseVerse model based on the axes and types of metaverse. The 4 types and 2 axes proposed for the metaverse can be accordingly applied to the NurseVerse concept.

data analytics to streamline supply chain operations (26). In architecture, the metaverse has numerous long-term impacts on the construction industry, such as enhancing building energy efficiency, optimizing materials and workforce management, reducing construction waste, minimizing environmental footprints, improving collaboration and communication among industry stakeholders, and significantly contributing to the circular economy through circular architecture (27). In entertainment, the metaverse enhances entertainment experiences by enabling virtual events, immersive gaming, virtual concerts, and interactive storytelling. Users can immerse themselves fully in virtual worlds, where they can engage in entertainment and social interactions with others (26). In healthcare, integrating the metaverse represents a major technological advancement with the potential to transform various aspects of medical practice. Technologies such as VR, AR, and other immersive tools can bridge the gap in clinical consultations by overcoming distance barriers, allowing patients to better understand their conditions within 3D VR environments, ultimately optimizing treatment plans and improving patient care (28).

Developing the NurseVerse

The term NurseVerse is a fusion of "Nursing" and "Metaverse," leveraging technologies such as VR, AR, AI, blockchain, and IoT to create an immersive and interconnected digital nursing environment. The NurseVerse specifically enables nurses to harness the power of the metaverse, allowing nursing professionals, patients, and other healthcare practitioners to engage in training, diagnosis, collaboration, and research within a virtual space. Additionally, it supports data sharing and personalized nursing services, thus introducing a groundbreaking digital world full of possibilities for the field of nursing.

Although healthcare and life sciences have been slow to embrace the ability of technological change to shape the ways in which people work (29, 30), the nursing community continually explores the best ways to apply modern and innovative technologies in clinical settings (31, 32). The NurseVerse continues to evolve on the basis of existing digital health foundations, with key distinctions between the NurseVerse and current digital health solutions (Table 1). We explore the potential applications of the NurseVerse and the corresponding challenges, particularly with respect to the various benefits of this digital trend for nursing. The revised model of the nursing metaverse, which is based on 2 axes and 4 types of metaspaces, is shown in Figure 1. Initially, the possibilities and cutting-edge nursing applications offered by the nursing metaverse seem to be very broad (Figure 2); however, this technology simultaneously entails many safety, technical, and ethical issues (Figure 3).

Surgical assistance

In addition to existing applications of surgical robotics integrated with AR, VR and AI, the metaverse has the potential to enhance healthcare professionals' technical skills and their awareness of potential risks and complications (34). Employing this technology—from initial patient consultation and preoperative planning to intraoperative 3D navigation and postoperative follow-up—provides patients with a comprehensive understanding of the entire surgical process (38). Simulated training in a virtual environment using VR technology is not only highly feasible in real-world contexts but also represents a vital component of future intelligent surgical collaboration systems. In virtual operating

TABLE 1 Differences between NurseVerse and existing digital health solutions.

Comparison dimension	NurseVerse solution	Existing digital health solutions	References
Technological foundation	Based on metaverse technologies (VR/AR, AI, blockchain)	Mainly mobile applications, remote monitoring devices, etc.	(33)
Interactivity	Immersive 3D interaction (VR/AR)	Primarily 2D interfaces (apps/videos)	(34)
Nursing education	Virtual wards, simulated patients, interactive operations	Online courses, video-based learning	(35)
Remote nursing	Nurses can interact with patients in the virtual world	Remote monitoring, video consultations	(36)
Personalization	AI-driven personalized nursing plan generation and optimization	Lower level of personalization, mostly standardized services	(34)
Operability	Nurses can simulate nursing operations in the virtual environment	Mainly data monitoring and information transmission	(37)

rooms, nursing students can engage in the complete workflow of a scrub nurse, including preparing sterile fields, performing preoperative "time-out" verifications, counting instruments and sharps, passing instruments, and handling surgical specimens (37). Virtual simulation provides nurses with a safe, standardized, repeatable, and highly controlled learning environment in which they can familiarize themselves with complex procedures and clinical scenarios (39), thereby significantly reducing the risk of errors during real surgeries. Moreover, virtual reality simulations offer an immersive experience that allows nursing students to interact with members of the virtual surgical team, thus enhancing intraoperative communication and teamwork skills (37).

Through medical-enhanced VR/AR (MER), vital signs, laboratory data, and imaging results can be overlaid in real time onto the visual field of healthcare professionals, enabling more accurate intraoperative decision-making. This integrated information display reduces the need for clinicians to shift their gaze between the patient and external monitoring devices, thereby enhancing situational awareness and decision-making efficiency during surgery (40). Intraoperatively, AR can project anatomical structures—such as blood vessels or organs—directly onto the patient's body, helping surgeons locate the surgical site precisely while allowing nurses to quickly identify relevant areas of focus. This spatial visualization capability aids in accurate targeting and reduces the risk of damaging critical structures, thereby lowering the incidence of surgical errors. Currently, leading healthcare institutions have begun exploring the integration of the metaverse into clinical nursing practice. The following cases illustrate typical applications of the metaverse in real-world healthcare settings: physicians at Stanford Medical Center have integrated AR tools into surgical practice by using the Apple Vision Pro headset to visualize data in real time during procedures, which has the potential to significantly improve teamwork and collaboration within the surgical team (41).

However, virtual reality simulations (VRS) are still in the early stages of development (42), and existing research on virtual simulation presents known methodological limitations, such as small sample sizes, a lack of reliability reporting, and the limited use of validated surveys (43). Moreover, current AR systems have not yet been widely deployed in the nursing field; nevertheless, they have demonstrated clear potential in enhancing intraoperative information synchronization, optimizing task collaboration, and strengthening nurse engagement.

Strengthening chronic disease management

The metaverse can facilitate timely and long-term follow-up for chronic diseases, and patients and nurses can meet in 3D virtual spaces using AI to provide better user experiences in the context of telemedicine care services. Regardless of the physical location of the patient (44), the nursing specialist or caregiver can conduct virtual consultations and follow up with the patient to assess the progression of the disease and understand its prognosis and outcomes. AI devices can be used to monitor the patient's body temperature, heart rate, blood pressure, blood sugar level, and even 12-lead ECG devices (45). AI technology has been used to analyze the data collected by smart socks, thus facilitating efficient gait analysis (46). This technology can offer personalized activity guidance to patients with diabetes and obesity and suggest appropriate activity intensities and times for each individual to improve the efficiency of fat reduction efforts. Patients can use AI-based systems and wearable technology to monitor their health status 24 h a day, enabling AI to identify threats in a timely manner. Through avatars, existing remote consultations using video phones can be transformed into more engaging interactions between doctors and patients or between nurses and patients. Patients can ask doctors and nurses for relevant consultations, personalized care, and patient education without the need to make doctor appointments or visit hospitals personally; moreover, the process is highly accessible to elderly people, people living in remote areas, and people with disabilities. However, AI detection occasionally encounters anomalies, false positives, and false negatives. Therefore, healthcare professionals need to assess results in conjunction with patient symptoms, verify AI findings through multiple sources, pay special attention to vulnerable populations, and ensure data security to maximize the value of AI while minimizing its risks. In the metaverse, wearable devices provide safe and efficient data to facilitate the early detection, diagnosis and treatment of chronic diseases. The metaverse can assist in the prevention and management of chronic diseases and is highly convenient for patients with chronic diseases.

Based on the above functional descriptions and analysis of potential advantages, the following presents practical applications of the metaverse in chronic disease management. Currently, Gwangmyeong Hospital of Chung-Ang University in South Korea

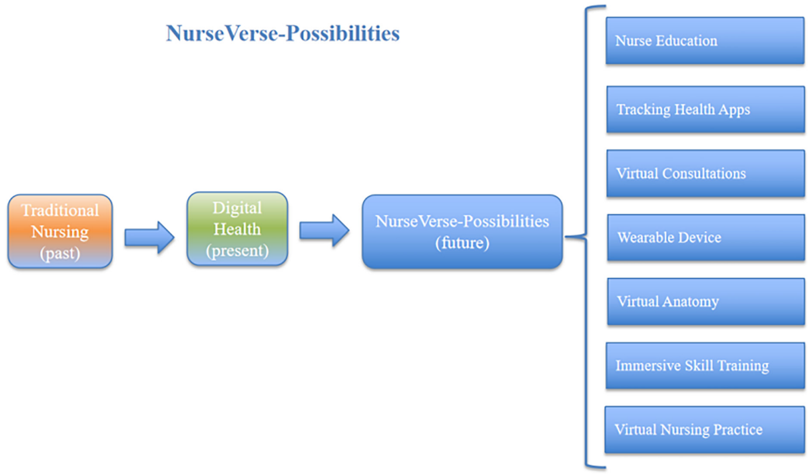

FIGURE 2
The possibilities of the NurseVerse.

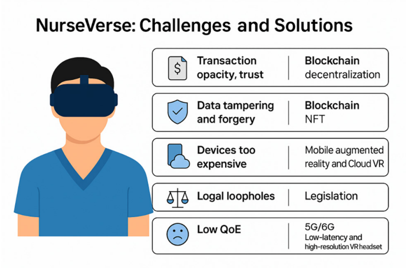

FIGURE 3
The challenges and solutions of the Nurseverse. Illustration was created using artificial intelligence. AI name: ChatGPT, model version: GPT-4.5 (GPT-4-turbo), source: Developed by OpenAI.

has utilized digital twin and metaverse technologies to create a virtual hospital called "Metaversepital." This facility allows users to receive medical consultations and treatments without physically visiting the hospital (47), which enhances remote management capabilities for patients with chronic diseases. Constance Johnson and colleagues established the "Second Life Impacts Diabetes Education & Self-Management" (SLIDES) community on the virtual platform *Second Life*, providing education and support for individuals with type 2 diabetes (48).

Reshaping nursing education

The adoption of the metaverse in nursing education seems to offer unlimited potential. For nurses or nursing students, because training varies by time and region, all trainees can receive the same standardized education through metatime, regardless of where or when they can access such education (49). The combined use of AR, VR and AI highlights new horizons for nursing training with respect to viewing virtual patients for the purposes of diagnosis and evaluation. The metaverse could even allow nurses to "enter" a virtual human body, thereby observing a 360-degree panoramic view of the cardiovascular system or simulating a real piercing process that could reduce the risk of accidental injury due to needles or other sharp instruments, mitigate occupational exposure and improve the safety of clinical nurses' attempts to perform invasive procedures. Since onsite training opportunities for peripherally inserted central catheter (PICC) insertion are not always easily accessible, in light of the growing demand for such opportunities and the lack of adequate training centers, virtual education courses may be a reasonable and appropriate option in this context. In January 2022, students at Queen Mary Hospital in London observed the first lecture in the metaverse, in which context participants were connected through a VR computer app and VR headset, which offered them a more amazing and interactive experience in the metaverse than would be possible through traditional online experiences. Many students and medical practitioners reported a high level of satisfaction with this situation, which they stated had a positive effect on their virtual learning (50). The metaverse has great potential in the context of nursing training, and this hyperspace is likely to revolutionize nursing education (51).

For patients, traditional explanations using charts and flat surfaces are difficult to understand. Through the use of simple 3D animation and VR devices, patients can discover their own health problems, understand the basic information about the disease, and participate fully in treatment and care decisions, such as those regarding peripheral or central venous treatment, thereby improving patient compliance and reducing the incidence of disease. The advantages of the metaverse in the context of nursing education include safety, repeatability, universality, cost and time benefits, and the lack of any risk of harm to patients (43, 52). The implementation of nursing teaching in the metaverse is a viable pedagogical strategy that can provide collaborative opportunities to nurses, nursing students, and teachers, and its increasingly widespread use is expected to have profound impacts on nursing education.

The latest developments provide concrete examples of how the metaverse is reshaping nursing education and facilitating its translation into clinical nursing practice. The University of Florida has established simulation laboratories that integrate virtual reality technology to provide nursing students with immersive learning experiences. These labs allow students to practice scenarios such as measuring blood pressure, administering injections, changing dressings, and simulating childbirth (7). UbiSim, a company dedicated to creating immersive VR training platforms for nurses, has already implemented VR-based training for nursing professionals (53). The UbiSim platform offers a variety of virtual nursing scenarios to help students safely practice and enhance their clinical skills (54).

Connection to telemedicine care technology

In light of the ongoing pandemic, the metaverse can allow patients to participate in consultations at home, which can enable patients in remote areas to obtain more comprehensive services of identical quality and reduce the risk of infectious diseases in medical institutions (55), which is beneficial for patients, doctors and nurses.

Current telemedicine relies primarily on video consultations in which healthcare providers and patients communicate remotely through 2D screens. While this approach overcomes geographical barriers, it offers limited interactivity and lacks a sense of realism. AI-assisted diagnostics also depend mainly on 2D medical imaging (such as X-rays, computed tomography [CT] scans, and magnetic resonance imaging [MRI]) and electronic health records for analysis. In contrast, metaverse-based healthcare enables the construction of 3D virtual consultation rooms in which healthcare providers and patients can communicate face-to-face. This immersive 3D environment enhances the realism and depth of remote medical encounters, thus allowing clinicians to assess patients' conditions more intuitively (34). Moreover, the integration of AI with digital twin technology allows for the creation of individualized 3D physiological models of real patients. Within immersive environments, clinicians can rotate and magnify these models and interact with AI in real time, improving the precision and personalization of diagnostics (56).

In fact, following the COVID-19 pandemic, the number of healthcare facilities in the United States with the ability to provide remote services increased from 43% to 95% (57). Compared with current telemedicine care services (including telemedicine models, AI-based diagnostics, and video conferencing) or face-to-face conversations, the metaverse approach facilitates interaction in a nearly face-to-face, 3D virtual space, which enables doctors and nurses to talk with and observe patients more closely. This approach is especially useful for regular follow-up, as it allows nurses to monitor basic conditions such as blood sugar, blood pressure, and ECG parameters (21). Wearables are important in nursing because they have the potential to overcome the challenges associated with traditional nursing, in which nurses' interactions with patients are all face-to-face and functional assessments are limited by physical barriers. The incorporation of innovations in telemedicine care into metaspaces has been recognized as a key component of a functional, concrete, and evolving NurseVerse.

Based on the above technological advantages, a growing number of applications connecting the metaverse with remote healthcare and nursing services have gradually emerged worldwide. Currently, the Shanghai Metaverse Specialty Hospital has developed metaverse + 5G glasses-free 3D slit-lamp microscopy technology for remote diagnosis and treatment (9). Chung-Ang University Gwangmyeong Hospital in South Korea has also utilized digital twin and metaverse technologies to create a virtual hospital named "Metaversepital," enabling users to receive remote medical consultations, treatments, and nursing care (47).

Psychological intervention therapy

Finally, the NurseVerse has unlimited potential with respect to psychological intervention therapy. Through the use of VR technology, the metaverse can greatly reduce the various psychological (such as anxiety and depression) and pain problems experienced by patients and reduce the length of their hospital stay; it can also help caregivers reduce stress and enhance their mood. The use of VR can help reduce anxiety and depression among breast and lung cancer patients (23, 24). VR-based mindfulness training can significantly reduce anxiety, depression and cancer-related fatigue among ovarian cancer patients in the context of chemotherapy (58). In a study that presented immersive VR environments such as cliffs or dream castles to 67 patients after heart surgery and used a Likert scale to evaluate the results, 90% of patients reported reduced pain levels after receiving VR treatment (59). The use of VR by burn patients has also been shown to play a positive role in relieving pain (60). VR is a safe and effective technology that offers the advantages of immersion, interactivity and conceptualization. During the COVID-19 pandemic, Min He et al. used fifth-generation plus VR (5G + VR) equipment to establish a visiting channel, and after treatment, patients' anxiety and depression decreased significantly (61). Home care and employee stress care based on VR technology have also been demonstrated as highly desirable in normal contexts (62–64). Among intensive care unit (ICU) nurses who used VR technology to relax during breaks, 62% reported that such technology helped reduce stress (65). For patients, metaverse technology can alleviate the pain and anxiety caused by their disease. For doctors and caregivers, metaverse technology can reduce the stress of both work and life. The emergence and progress of the metaverse are highly valuable to the medical community. Despite the great potential of VR/AR technology in this field, its implementation in real-world practice requires careful consideration of its side effects. One such issue is that prolonged VR use may cause dizziness, nausea, eye fatigue, and spatial disorientation, similar to motion sickness, especially in highly immersive virtual environments (66). Additionally, most studies on VR in psychological interventions have small sample sizes and short follow-up periods, limiting the evidence of its long-term efficacy (43).

These theoretical advantages have begun to show initial results in some practical scenarios. The following applications further illustrate the use of the metaverse in alleviating psychological stress for patients and healthcare providers: Stanford University's Lucile Packard Children's Hospital has implemented VR technology in its pediatric medical procedures, such as intravenous insertions and wound dressing changes. By engaging children in games or exploratory activities within a virtual environment, the technology helps reduce their pain perception and anxiety levels (67). During the COVID-19 pandemic, the University Medical Center Groningen (UMCG) in the Netherlands introduced a VR application called "VRelax" for ICU nurses. This app offers various natural scenes—such as swimming with dolphins or walking through forests—and has been effective in reducing stress among nursing staff (68).

Challenges

While the NurseVerse has the potential to advance the field of nursing, the various challenges associated with its use must also be considered. These challenges pertain to different areas, such as trust and security, technology, legislation and regulation.

Trust and security

Although the NurseVerse shows great potential in the field of medical and nursing care, some patients remain skeptical about its application. Health data is highly sensitive information, and patients question the reliability and authenticity of the NurseVerse. They worry that doctors and nurses may be unable to assess their conditions accurately through a virtual platform, raising concerns about trust in the system. These concerns are especially pronounced among elderly patients, who often have limited adaptability to emerging technologies and may be reluctant or unable to use NurseVerse-based healthcare services.

The NurseVerse requires the storage and sharing of a large amount of patient health information. In this environment, users interact through virtual identities, which offer a more flexible and immersive experience but also introduce risks of privacy breaches and illegal activities (1). Major data breaches involving insurance companies such as Anthem (69) and Humana (70) have heightened these concerns. Hackers or malicious users may exploit virtual identities to commit fraud, engage in identity theft, or disseminate false healthcare information, thereby compromising patient safety. Moreover, the open nature of virtual healthcare platforms makes patients more vulnerable to misleading medical advice, which could result in inappropriate treatment or delays in care.

Harassment and potential abuse have already been observed in traditional social media metaverse platforms (71). Therefore, ensuring legal protection and avenues for the prosecution of such behavior in the NurseVerse will be critical. Identity theft and verification also represent key challenges in the NurseVerse context. Doctors, nurses, or their avatars must be reliably identified as legitimate and licensed healthcare professionals. This challenge highlights the need not only for mutual recognition among real humans in virtual spaces but also for the ability to distinguish between human users and avatars generated entirely by AI (72).

Blockchain (73) and non-fungible tokens (NFTs) (74) are regarded as important tools to increase patient trust, ensure the security of healthcare data, and support digital identity verification (75). Blockchain (73) is a decentralized and distributed database used to record information that can ensure data security, transparency, and immutability. It relies on cryptographic algorithms and consensus mechanisms to guarantee the authenticity and reliability of data without the need for a central authority such as a hospital or a healthcare institution's centralized database. Traditional medical data is typically stored on servers managed by hospitals or healthcare institutions, which may lead to data silos, difficulties in data sharing between different entities, and issues of information opacity, where users cannot verify the authenticity of the data. Blockchain enables decentralized storage of patient health records, thus enabling patients to authorize different medical institutions to access their medical histories without relying on a single hospital's database. The transparency and traceability of blockchain ensure that every access or modification of data is recorded, which can prevent tampering. Running the NurseVerse on a blockchain-based decentralized system introduces different encrypted methods for handling patient data and ensures strict compliance with medical and nursing standards in practice and processes. The decentralization, immutability, and reliability of blockchain can significantly increase patient trust and safety.

An NFT is a unique set of computer code registered on a blockchain that records the ownership of digital assets (76). NFTs can store large amounts of data, contain transaction IDs, and maintain detailed historical records, enabling them to function as certificates of authenticity or digital fingerprints for data (77). NFTs can help promote a more democratic, transparent, and efficient health information exchange (HIE) system in which patients are empowered to participate in decisions about how and with whom their personal (sometimes known as "protected") health information (PHI) is shared (76). However, despite the enhanced data security offered by NFT and blockchain technologies, significant challenges remain. The legal and regulatory frameworks surrounding blockchain are still evolving, and unified global standards remain lacking. Additionally, blockchain consumes substantial storage and computational resources, which may lead to performance bottlenecks in healthcare scenarios that require frequent access to medical data.

Technology

The development of the NurseVerse requires state-of-the-art technology, but the corresponding hardware is not light, portable, or inexpensive. A considerable amount of hardware, such as VR headsets, wireless heart rate and blood pressure monitors, gait analyzers, and the most up-to-date computer processors, is needed to maximize the development of the metaverse, which requires sophisticated technology that entails high costs. Economic and technological inequalities lead to health inequalities for economically disadvantaged groups and countries, and accessing metaverse services is more difficult in this context.

For users who cannot afford high-end equipment, mobile augmented reality (mobile AR) (78) and cloud-based virtual reality (cloud VR) (79) can serve as alternatives to promote digital equity. Mobile AR is a solution based on smartphones or tablets, eliminating the need for users to purchase expensive AR headsets and enabling users to access the technology anytime and anywhere. With advantages such as low cost, high portability, and ease of use, mobile AR is widely applicable in fields such as education, healthcare, and nursing (78, 80). Cloud VR uses cloud servers for rendering and computing, allowing users to access high-quality VR content through standard devices such as smartphones, tablets, or regular computers, thereby reducing the cost of use. Moreover, cloud VR offers low latency and visual continuity (81), enabling more users—especially those with limited resources, such as older adults and people in remote areas—to enjoy immersive healthcare experiences (79).

The compounded risk of cybersickness and motion sickness caused by VR devices has become a barrier to the quality of experience (QoE) for users in the metaverse (66). This issue is particularly evident in immersive settings such as virtual remote consultations, where prolonged use of head-mounted VR displays increases the likelihood of discomfort due to mismatches between visual and vestibular sensory input. Symptoms may include dizziness, nausea, reduced attention span, pain, and blurred vision (66, 82). Users can alleviate these symptoms by prioritizing the use of low-latency, high-resolution VR headsets combined with precise head- and eye-tracking technologies. These features help reduce sensory lag and screen tearing, thereby mitigating the discomfort associated with cybersickness and motion sickness. In addition, the high bandwidth and low latency offered by 5G/6G networks further enhance the immersive and seamless nature of the VR experience, ultimately improving users' overall QoE (66).

Another challenge in the metaverse is identity theft, which can be exploited to fraudulently obtain health insurance benefits. Malicious actors may hack into personal accounts and impersonate legitimate users—such as by stealing their avatar information (83) or mimicking their behavioral traits—to fabricate identities. They might also collect identity-related data such as avatar appearances and gestures (84), using this information to create fake doctors or patients. These fake doctors can then provide false medical consultations or issue prescriptions, while impersonated patients "receive" costly healthcare services in the virtual environment—services that were never actually delivered—ultimately defrauding insurance companies.

Although various preventive measures have been introduced, such as regularly changing avatar appearances (85), splitting personal information across internet networks (83), and using biometric and digital information for authentication (86), these strategies must continually evolve alongside technological advancements. Detection technologies, including algorithms for analyzing the authenticity of potentially AI-generated content, are also emerging (87). However, such technologies not only require ongoing refinement but may also be exploited by criminals to facilitate other illicit activities (88). Given that victims and perpetrators of the same case may be located in different parts of the world (89), international cooperation is becoming increasingly vital. It is essential to address identity-related crimes in the metaverse to promote information sharing and establish unified technical standards.

Regulation and legislation

Patients who visit the hospital can store their entire medical history, medication history, medical conditions, and allergies in their own personalized NFTs, which can only be viewed by the patient and their doctor or anyone else to whom the patient offers access. This approach can save time, effort and money for patients as well as time and human resources for hospitals. Patient conditions and data are among the most valuable assets in healthcare, and their safe use, management and sharing are continual requirements for healthcare professionals. Despite the many benefits of NFTs to both patients and hospitals, regulation and standardization remain necessary to build trust in technological enablers and test their performance in real-world settings.

Who is responsible when a patient receives inappropriate medical care? Liability is a key issue in the use of technology in healthcare (90). Metaverse providers hold responsibility for compliance with device specifications. However, when the NurseVerse becomes an integral part of the doctor–patient or nurse–patient relationship, its providers become participants in the care process. When an error occurs and a decision is made on the basis of perceptions or information obtained from the virtual world, it is essential to determine who should be held accountable. As in any other area of healthcare, doctors and nurses ultimately remain responsible for the care they provide.

Cybersecurity and patient safety must be strictly protected under the law. Although existing data privacy regulations (91) require organizations or institutions to use encryption or pseudonymization for emails, messages, notes, and cloud storage whenever feasible, to reduce the risk of patient data being misused or illegally accessed, the importance of addressing issues such as identity theft, misidentification, medical errors, and data breaches in the metaverse goes far beyond the need for technical upgrades. It is essential to establish comprehensive policies and regulatory frameworks with clear legal provisions to protect patients from harm caused by incorrect medical practices or technological vulnerabilities. Insurance companies need to revise their policies to adapt to emerging forms of healthcare in the metaverse. Medical device companies must ensure that their equipment complies with safety standards and undergoes regular security assessments. Governments must take the lead in the legislative process by coordinating input from the healthcare industry, technology companies, legal experts, and ethicists. They should formulate specialized laws for metaverse-based medical systems and establish dedicated regulatory bodies to continuously monitor and assess technologies, data usage, and medical practices. Involving all stakeholders and addressing legal and regulatory challenges will be essential to ensure safe, ethical, and effective healthcare in the metaverse.

Limitations

Although this article systematically explores the application of metaverse in nursing practice from multiple dimensions—including surgical assistance, strengthening chronic disease management, reshaping nursing education, connection to telemedicine care technology, psychological intervention therapy—several limitations remain: as research on the metaverse in the nursing field is still in its early exploratory stage, existing studies on its practical application are limited, mostly involving small-scale implementations (9, 48, 67, 68). There is a lack of large-scale, systematic empirical data. Therefore, some of the viewpoints presented in this review need to be validated by future studies with larger sample sizes and stronger empirical designs. Nursing is a discipline that emphasizes humanistic care, emotional communication, and ethical decision-making. Certain nursing practices—such as end-of-life and palliative care, psychological care for patients with depression, support for individuals with cognitive impairments and communication during acute clinical deterioration—are difficult to replicate or replace fully through virtual means. While this review discusses the technical advantages of the metaverse, it does not delve deeply into its impact on the humanistic and ethical aspects of nursing care, nor into how to strike a balance between technology and compassion. There are significant differences in the acceptance of metaverse technologies among nurses and patients of different ages, cultural backgrounds, and levels of digital literacy. This review does not offer a detailed analysis of how such differences may affect the implementation and scalability of the metaverse in nursing settings. Furthermore, the readiness of the nursing profession to adopt metaverse-based tools varies considerably. While some departments and professionals demonstrate enthusiasm, others remain cautious due to concerns about the maturity of the technology and associated practical challenges. Although components of the metaverse—such as virtual reality, augmented reality, artificial intelligence, and digital twins—have shown early development at the technical level, their large-scale application in real-world nursing practice still faces barriers including cost, hardware requirements, data privacy, and ethical considerations. This review does not comprehensively assess how these real-world constraints might limit the effectiveness of implementation. The full realization of a metaverse-supported nursing ecosystem remains a goal for the future.

Conclusion

In summary, owing to the development of the core technologies associated with metaverse-augmented reality, life logs, mirrored worlds, and virtual worlds, the entire world is undergoing a digital healthcare revolution that can introduce an extraordinary dimension to the nursing environment for both nurses and nursing students. Although the application of the metaverse in nursing is still in its early exploratory stage, it has the potential to effectively complement traditional nursing approaches and may offer patients more options. A variety of AI models often serve as the foundation and fundamental components of the metaverse innovation model, and the NurseVerse has great potential to change the model of care by utilizing cutting-edge AI technologies; however, the transition from AI to the NurseVerse is not immediate, and further research on the ethical and credibility issues that emerge in this context is needed. Only by finding solutions to the issues associated with the process of adapting care to the NurseVerse in an evidence-based and ethically responsible way can we truly generate positive impacts on both individual and public health.

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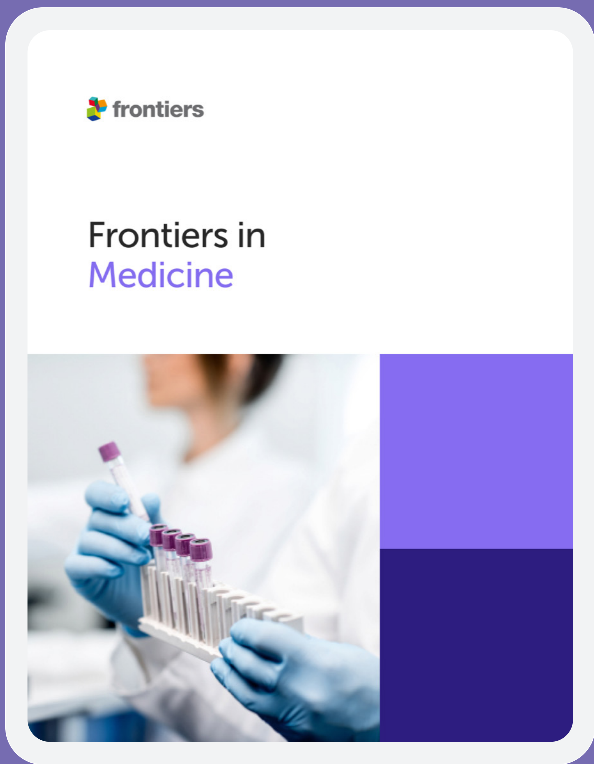

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