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REVIEW

Enhancing Medical Education: The Role of Artificial Intelligence Tools in the Teaching-Learning Process

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Objective: This study aimed to investigate the role of artificial intelligence (AI) tools in enhancing the teaching–learning process in medical education through a scoping review.

Methods: This study was conducted as a scoping review. A comprehensive search of published articles was performed across multiple databases, including Scopus, PubMed, Web of Science, Embase, ERIC, Emerald, and IEEE, covering the period from 2000 to 2024. After removing duplicate records using EndNote software, titles and abstracts were screened, followed by full-text evaluation. The quality of the included studies was assessed using the Critical Appraisal Skills Programme (CASP), and reporting was conducted in accordance with the PRISMA-ScR guidelines.

Results: The findings were categorized into four main themes: (1) domains of application of AI tools, (2) characteristics of AI tools in medical education, (3) applications and effectiveness of AI tools, and (4) challenges associated with AI use.

Conclusion: The integration of AI into the teaching–learning process in medical education offers significant opportunities for developing innovative educational approaches. While AI enhances student engagement, learning outcomes, and satisfaction, it also introduces challenges such as ethical concerns, potential biases, and issues related to data privacy. Addressing these challenges is essential for the effective and responsible implementation of AI in medical education.

Keywords: medical education, artificial intelligence, teaching, learning, students

Introduction

Artificial intelligence (AI) is a transformative technology capable of analyzing complex data, identifying patterns, and providing intelligent solutions. It encompasses machine learning algorithms, natural language processing, and advanced simulation techniques, which have been widely applied across various domains, particularly in healthcare.[1] By enabling personalized solutions and the analysis of large datasets, AI has the potential to enhance the efficiency and accuracy of both educational and clinical processes.[2]

AI has revolutionized medical education by providing innovative tools such as intelligent educational systems and clinical simulations. These technologies personalize learning, provide immediate feedback, and allow educators to design data-driven curricula.[3] The teaching–learning process in medical education is a combination of theoretical training, hands-on practice, and clinical experiences, aiming to train physicians who can diagnose and treat accurately.[4] This process faces challenges, including resource constraints, differences in student abilities, and time pressures. Striking a balance between scientific knowledge and practical skills requires innovative approaches to improve the quality of education.[5] AI can simulate complex clinical scenarios that enhance students' diagnostic and therapeutic skills.[6]

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However, integrating AI into medical education is riddled with challenges, including ethical concerns and algorithmic biases.[7]

AI has improved the teaching-learning process in medicine with advanced clinical simulations and large language models (LLMs). Systems such as DxR Clinician provide virtual clinical scenarios that enhance students' diagnostic skills.[8] AI-based surgical simulations also increase students' accuracy and efficiency.[9] Studies have shown that AI can improve diagnostic accuracy by up to 22% and reduce learning time.[6] LLMs are employed to automatically assess student responses and provide personalized feedback.[10] However, challenges such as algorithmic biases and ethical issues still require attention.[7]

Some disadvantages of AI in teaching and learning include ethical concerns about its use, the potential for job loss, reduced human interaction in the classroom, limitations in AI programming, additional costs imposed on educational institutions, and the potential decline of traditional teaching roles.[11] However, several studies have confirmed the positive effects of AI in medical education.[3,5,12,13] At Harvard Medical School, AI courses have been integrated to train researchers who can address complex healthcare problems.[14] AI can reduce the burden of administrative tasks, such as clinical documentation, and allow students to focus more on interacting with patients.[5] Still, more than half of medical students in a multicenter study raised concerns about AI eroding patient trust or undermining the value of the medical profession.[3] Data privacy problems and algorithmic biases are other areas of concern.[7,15]

The present study aimed to evaluate the role of AI tools in the teaching–learning process in medical education, considering both their potential benefits and associated challenges. The findings can help researchers, educators, and policymakers identify AI tools, analyze their effects on learning, improve teaching methods, develop educational content, assess student performance, create personalized learning environments, and analyze learning data.

To achieve this aim, the study addressed the following research questions:

(1) What are the main domains of AI application in medical education?
(2) What are the characteristics of AI tools used in the teaching–learning process?
(3) How effective are AI tools in improving educational outcomes
(4) What challenges are associated with the use of AI in medical education?

Method

Design

We choose a scoping review method as the most appropriate method to address our research question "what is the role of AI tools in improving the teaching-learning process in medical education using a literature review". Our review was guided by the Arksey and O'Malley framework, 2005,[16] which entails the following steps: identification of the research question; identification of relevant studies; study selection; charting the data; and collating, summarizing and reporting of the results. Here, we report results of the review guided by the 2018 Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews guidelines (PRISMA-ScR).[17]

Search Study

All the published articles in Scopus, PubMed, Emerald, ERIC, Web of Science, IEEE, and Embase were searched using an advanced search to obtain scientific evidence related to the research objective. The time limit for retrieving articles was from 2000 to 2024, according to the researchers' initial survey (scientometrics), research conducted in the field of artificial intelligence in the teaching-learning process has grown significantly since 2000, and a ten-year period was considered for a more comprehensive study. Of course, it should be noted that given that there were not many research activities focused on teaching-learning with a focus on artificial intelligence in medical education, all studies were conducted without restrictions on population or specific field. The operators included Boolean operators, parentheses, and truncation. The keywords used to retrieve articles included *artificial intelligence, medical education*, and *teaching-learning*, which were included in the search strategy along with their synonyms after reviewing the MESH. Data extraction was performed on 2024/10/12 and the total number of data retrieved from the databases was 4729 data.

The search strategy in the Web of Science is presented below as an example. A table of all database search strategies is provided in the Supplementary File.

TS=((“Artificial Intelligence” OR AI OR “AI-written” OR “AI-generated” OR chatbot* OR ChatGPT OR “ChatGPT-generated” OR “GPT3” OR “OpenAI” OR “generative artificial intelligence” OR “natural language processing” OR NLP) AND (“medical education” OR ME OR “medical instruction” OR “medical pedagog*” OR “medical teaching” OR “medical training” OR “medical tuition” OR “Medical Sciences Education” OR “Health Profession Education” OR “Biomedical Education”) AND (“teaching-learning” OR teaching AND learning OR “adult education” OR andrology OR “adult teaching” OR “adult learning”))

After searching the databases, the retrieved resources were entered into EndNote 21 software.

Eligibility for Research Question

Our research question was: what is the role of AI tools in improving the teaching-learning process in medical education using a literature review? We used the Population, Concept and Context (PCC) framework to determine the eligibility of our research question for this scoping review. Population is AI tools; Concept is teaching-learning process in medical education literatures. Context is medical education.

Inclusion and Exclusion Criteria

The inclusion criteria for articles were: relevance of the article’s subject area to the research objective and being an original article. The exclusion criteria were gray literature, theses, conference papers, review articles, languages other than English, lack of access to the full text, and being irrelevant to AI tools used in the teaching-learning process in medical education.

Study selection occurred in three stages. In the first stage, duplicate data were removed in EndNote, and then the titles and abstracts were screened (4617 literatures). Two authors independently reviewed and screened all the retrieved articles. After that, the full text of the articles was evaluated (335 literatures). In cases of consensus, the document was retained, and in cases of disagreement, a third person was asked to review the documents, and a decision was made after a discussion.

In this study, medical education was considered broadly to include bioscience education and healthcare education within medical science education (basic and clinical fields). Therefore, studies from these related domains were not excluded.

Charting of Data

We extracted data on the following: author and year of publication, objective, study design, population, field of study, AI tool charectristic and key results.

Collating, Summarizing and Reporting of the Results

We employed thematic content analysis to examine results from the selected articles (44 literatures). We utilized the maxqda24 package to identify the themes from the included articles. The data was evaluated by two reviewers. Initially, the reviewers acquainted themselves with the articles’ content. Secondly, the findings presented in the articles were classified into categories according to the study context and subsequently organized into nodes.

Quality Appraisal of Included Primary Studies

In this way, information on AI tools used in the teaching-learning process was extracted. CASP was employed to assess the quality of the retrieved studies, and PRISMA was followed in drawing up the report, which included the process of searching, screening, and selecting articles (Figure 1).

Results

This scoping review identified 4729 studies from 2000 to 2024. After removing 112 duplicates, 4617 studies were screened. Title and abstract screening excluded 4282 studies, and 335 studies remained for full-text evaluation. Finally,

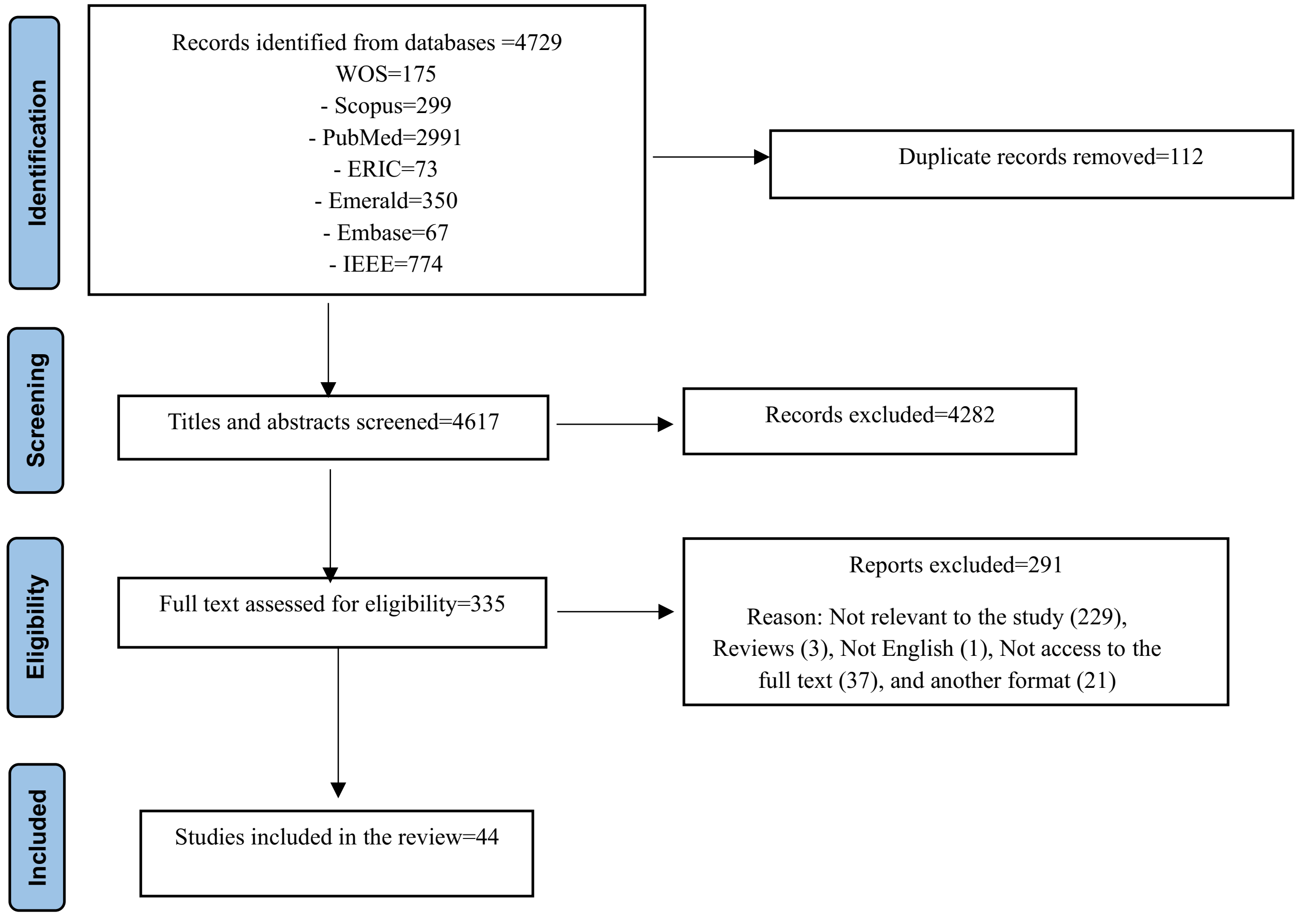

Figure 1 The process of searching, screening, and selecting articles on AI tools in the teaching-learning process in medical science education.

44 original studies related to the application of AI in the teaching-learning process in medicine were analyzed. Table 1 presents the bibliographic information of the articles, objective, method, population, AI tool used, and a summary of the effect of this tool on the teaching-learning process.

Bibliographic Information of Articles

Research methods included quantitative, qualitative, and mixed methods. Quasi-experimental designs[1,18] compared AI groups with traditional groups, such as cardiovascular disease training with AI simulation. Randomized controlled trials[12,13,39–56,59] were common in surgery, nursing, and anesthesiology and measured the effectiveness of AI. Qualitative phenomenological studies[21,34,37,38] examined students' emotional experiences, such as nurses' feelings in clinical simulations. Mixed-methods studies[1,19,23,26] combined quantitative (eg., test scores) and qualitative data (eg., student opinions). Descriptive studies[20,27,31,35,36,59] analyzed the performance of AI tools, such as ChatGPT, in tests. Cross-sectional[35] and pilot studies[39,40] evaluated the feasibility of integrating AI. This diversity of methods demonstrated multiple approaches, and heterogeneity made direct comparisons difficult.

The target population included diverse groups of learners. Medical students included 66 first-year clinical students at Nantong University,[1] 41 clinical students at Qiqihar University,[18] and 52 third-year undergraduate and first-year MSc students at the University of Zurich.[3] In addition, 728 pediatric residents and 196 faculty members from 15 universities in Indonesia participated in a cross-sectional study.[36] Other groups included 77 medical interns (42 men and 35 women) at Sun Yat-sen University,[25] nursing students in several studies on project-based learning,[34,37,38,45,50] radiology technicians in imaging training,[35] and dental students in dental morphology training.[49,52] Smaller, more specialized populations

Table 1 Characteristics of the Articles and AI Tools Affecting the Teaching-Learning Process of Medical Education

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
1	Zheng, K, 2024[1]	To study the effectiveness of an AI-empowered scenario-based simulation teaching mode in cardiovascular disease education	Quasi-experimental research design, combined with descriptive qualitative methods	66 first-year students from two classes in the clinical major at Nantong University	Medicine	Innovative teaching mode for cardiovascular diseases using the AI-empowered scenario-based simulation	Significantly improved students' performance Enhanced medical undergraduates'
2	Wang, D,2024[18]	To apply AI-assisted image diagnosis (AISD) software utilized by physicians to practical teaching of imaging, helping students observe images from a 3D perspective, and promoting the quality of teaching practical skills. To identify methods to improve academic self-efficacy and self-directed learning through the interaction between students and the AISD software	A quasi-experimental research design	41 students of clinical medicine at the Qiqihar Medical University (2017)	Clinical medicine	The AISD software utilized a cascaded Residual Network (ResU-net) algorithm to segment aneurysms on the original axial images in head and neck CT angiography, including ResU-net1 and ResU-net2 modules.	Significantly higher scores of computed tomography (CT) diagnosis, magnetic resonance (MR) diagnosis, academic self-efficacy, and self-directed learning in the experimental group Enabled students to timely obtain AI annotated lesion information and 3D images, which might help enhance their image interpretation skills, academic self-efficacy, and self-directed learning by applying the AISD software
3	Thomae AV,2024[19]	To explore the feasibility of integrating ChatGPT into teaching units and investigate the course and importance of AI-related competencies for medical students	Mixed-methods (quantitative and qualitative data)	52 medical students (third-semester bachelor's and first-semester master's) at the University of Zurich	Medicine	ChatGPT	Higher levels of satisfaction, applicability, and learning progress, especially about the ChatGPT-integrating teaching units Greater openness to digital innovation linked to higher satisfaction and, to a lesser extent, greater applicability
4	Sridharan K,2024[20]	To examine the utility of three AI platforms to identify specific learning objectives (SLOs) related to pharmacology in managing hypertension for medical students at different stages of their medical training	Descriptive proof-of-concept cross-sectional study	Department of Pharmacology & Therapeutics (NUM=5), College of Medicine and Medical Sciences, Arabian Gulf University	Pharmacology	Sage Poe: A generative AI search engine Claude-Instant: A retrieval-based AI search engine ChatGPT version 3.5: A generative architecture-based AI search engine	Useful adjuncts to, identify themes for test blueprinting, plan instructional methods, develop test items, and inform test standard-setting appropriate to learners' stage in the medical program by AI tools Need for experts to review the content validity of AI-generated output To shape the medical education landscape to empower learners and align competencies with curriculum implementation by AIs AI literacy as an essential competency for health professionals

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Table 1 (Continued).

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
5	Skryd A, 2024[21]	To identify and qualitatively assess the potential use cases and limitations of LLM technology for real-time ward-based educational contexts	Qualitative approach using phenomenological inquiry	The team included 7 members: 1 attending internal medicine physician, 1 senior medicine resident, 2 interns, 2 medical students, and 1 physician assistant student.	General internal medicine	ChatGPT	The benefits of ChatGPT were building differential diagnoses and engaging dual-process thinking, addressing medical knowledge gaps through discrete medical knowledge inquiries, enhancing complex care management by facilitating conversations with subspecialties. and challenging medical axioms, utilizing cognitive aids to support acute care decision-making. Concerns and limitations to the clinical use of ChatGPT included: misinformation, biases, ethics, and health equity.
6	Powers AY, 2024[22]	To assess the potential of ChatGPT as an educational tool for neurosurgery residents who were preparing for the American Board of Neurological Surgery (ABNS) primary examination	Quantitative study	Non-imaging questions from the Congress of Neurological Surgeons (CNS) Self-Assessment in Neurological Surgery (SANS) online question bank	Neurological Surgery	ChatGPT	An accuracy of 50.4%, with the highest and lowest accuracies, respectively, in pharmacology (81.2%, 13/16) and vascular (32.9%, 91/277) subcategories by ChatGPT ChatGPT's performance was inferior to humans overall and in the following subcategories: functional, peripheral, spine, radiology, trauma, tumor, vascular, and other
7	Hudon A, 2024[23]	To study how ChatGPT-generated SCTs compare to those produced by clinical experts on 3 elements: expert opinion, scenario (stem), and clinical questions.	Mixed method: examined 3 ChatGPT-generated SCTs with 3 expert-created SCTs using a predefined framework	120 clinician-educators in psychiatry or medical residents in psychiatry affiliated with one of Québec's 4 universities	Psychiatry	ChatGPT	No significant distinctions between the 2 types of SCTs (AI and expert-generated) regarding the scenario, clinical questions, and expert opinion, as interpreted by the respondents. Struggled to differentiate between ChatGPT- and expert-generated SCTs To accelerate SCT design, aligning properly with the Diagnostic and Statistical Manual of Mental Disorders (DSM), Fifth Edition criteria, although with a tendency toward caricatured scenarios and simplistic content by ChatGPT

8	Beketov V, 2024[24]	To examine the impact of an intelligent learning support system on anxiety and motivation of medical students	Experimental study	246 medical students from I.M. Sechenov First Moscow State Medical University	Medicine	An intelligent learning support system	Significant increase in the motivation of medical students in the experimental group (using the intelligent learning support system) Significant reduction in the anxiety of participants in the experimental group (using the intelligent learning support system)
9	Ba H, 2024[25]	To assess the effectiveness of ChatGPT-assisted instruction vs. traditional teaching methods on pediatric trainees' clinical skills performance	A controlled experimental study	77 medical interns enrolled in Sun Yat-sen University (42 male and 35 female)	Medicine	ChatGPT	No significant difference in theoretical exams in the two groups (AI and traditional training) Significant improvement in patient communication and clinical judgment in the ChatGPT-assisted group Receiving positive feedback from most trainees, highlighting the perceived advantages of interactive learning and skill acquisition in the AI-teaching approach
10	Magalhães Araujo S, 2024[26]	To study the perceptions of students regarding the use of ChatGPT as a learning tool in their educational context and provide professors with examples of prompts for incorporating ChatGPT into their teaching and learning activities	Mixed-methods	105 students in the Faculty of Medicine of the University of Porto (FMUP) in Portugal	Medicine	ChatGPT	Satisfaction with using ChatGPT in generating academic content, brainstorming ideas, and rewriting text Improving student learning experiences and helping with project planning, programming code generation, exam preparation, workflow exploration, and technical interview preparation, thus advancing medical informatics education by incorporating ChatGPT Using ChatGPT as an assistant for simplifying the explanation of concepts, solving complex problems, and generating clinical narratives and patient simulators

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Table 1 (Continued).

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
11	Alfertshofer M,2024[27]	To evaluate the capabilities of ChatGPT in answering USMLE® Step 2CK questions, examining its performance across medical specialties, question types, and difficulty levels in a large-scale question test set to help question writers with developing AI-resistant exam questions and offer medical students a realistic understanding of how AI can improve their active learning	Survey Study	3302 USMLE® Step 2CK practice questions were extracted from the AMBOSS© study platform	Medicine	ChatGPT 3.5	Correctly answering 57.7% of all questions by ChatGPT Highest performance scores in the category of "Male Reproductive System" and the lowest in "Immune System" by ChatGPT Incorrectly answering longer questions by ChatGPT
12	Sanchez-Gonzalez M,2023[28]	To study the effectiveness of voice-over-style lectures and AI in facilitating learning outcomes as examined by test scores after participating in basic science lectures in a medical school setting	Semi-experimental study	Incoming medical students from California North State University, College of Medicine (CNUCOM), Class of 2027 (first-year students)	Medicine	A personalized ingestion engine (PIE), the platform curates diverse learning materials from expert sources worldwide. A personalized AI (PAI) then leverages natural language processing to adapt customized conversations to the current knowledge of each learner	Significantly higher quiz scores under challenging questions and less time spent in lectures in the slide decks only the traditional way+ AI group (PPT+AI) compared with the slide decks only the traditional way (PPT) group
13	Lindqwister AL, 2023[29]	To explore the implementation of a novel AI in radiology curriculum, "AI-RADS," in two educational formats: a 7-month lecture series and a one-day intensive workshop	Experimental study	40 workshop attendees, 18 residents completed the pre-session survey with 10 completing the post-session survey	Radiology	AI curriculum, AI-RADS	Well-received and satisfaction in both formats of the AI-RADS curriculum by learners, with the 7-month version and workshop An increase in perceived understanding of AI in both
14	Ghosh A, 2023[30]	To compare ChatGPT's knowledge and interpretative abilities with those of first-year medical students in India regarding medical biochemistry	Experimental study	100 students of Bachelor of Medicine, Bachelor of Surgery (MBBS)	Medicine	ChatGPT	ChatGPT scored 140 out of 200 in exams, outperformed almost all the students, and ranked fifth in the class. ChatGPT scored well in information-based multiple-choice questions (MCQs) and descriptive logical reasoning. ChatGPT performed poorly in descriptive clinical scenario-based questions. ChatGPT took significantly more time to answer logical reasoning MCQs than simple information-based MCQs.

15	Friederichs H, 2023[31]	To measure the performance of ChatGPT as a fictitious participant in Progress Test Medicine	Descriptive Study	400 multiple-choice questions (MCQs) from the progress test in German-speaking countries	Medicine	ChatGPT	ChatGPT correctly answered 65.5% of the progress test questions. ChatGPT required 22.8 s for a complete response. No correlation between the time used and word count with the accuracy of the ChatGPT response
16	Fang Z, 2022[32]	To examine the effectiveness of the AI-based pathologic myopia (PM) identification system in the ophthalmology residency training program and evaluate the residents' feedback on this system	Experimental study	90 residents participating in the ophthalmology residency training program at the Second Affiliated Hospital of Zhejiang University	Ophthalmology	AI-based pathologic myopia (PM)	The post-lecture scores were significantly higher than the pre-lecture scores in the group with AI-based pathologic myopia. All the participants were satisfied and agreed with the AI-based PM. Effective and helpful for acquiring PM identification, myopic maculopathy (MM) classification, and "Plus" lesion localization by AI-based PM
17	Wu D, 2020[33]	To assess the effectiveness of AI-tutoring problem-based-learning (PBL) in ophthalmology clerkship and to evaluate the student evaluations of this module	Experimental study	38 grade-two students in the ophthalmology clerkship at Sun Yat-Sen University	Ophthalmology	AI-tutoring problem-based-learning module by exploring and operating an AI diagnosis platform	Significant improvement of group A (AI-tutoring PBL module) in the sign and diagnosis test than group B (traditional lecture) No difference in the improvement in the treatment plan test between the two groups Well-satisfied and agreed that AI-tutoring PBL was helpful, effective, motivating, and beneficial to developing critical and creative thinking
18	Kong W,2024[34]	To study the realistic feelings and experiences of nursing undergraduates participating in different stages of AI + project task driven learning To provide a foundation for AI participation in nursing education	Qualitative study	16 third-year students from the school of nursing	Nursing Research Course	AI + project task driven learning	The learning experience of nursing undergraduate students in participating in AI + project task-driven learning was not static but presented a dynamic and changing process with the continuous deepening of course learning. Students participating in class teaching with AI experienced diverse emotional experiences from the initial stage to the adaptation stage and then to the end stage.

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Table 1 (Continued).

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
19	Stogiannos N, 2024[35]	To evaluate educators' levels of AI knowledge, status quo of AI educational provisions, perceived challenges of AI education, and key factors for future advancements	A cross-sectional study utilizing an online survey	5,066 educators working in all disciplines related to imaging and radiation therapy in clinical and didactic settings in USA	Medical imaging and radiation therapy	An online survey in Checkbox The survey questions were based on previously applied surveys on AI usage with input from AI experts in medical imaging and radiation therapy	Good baseline knowledge of AI general concepts AI in US educators of medical radiation technology Improving teaching and the use of AI in medical radiation curricula Educators highlighted institutions' support for AI.
20	Pudjiadi AH, 2024[36]	To examine the readiness of Indonesian teaching staff and pediatric residents for integrating AI into the curriculum	A cross-sectional study	196 teaching staff and 728 pediatric residents from 15 national universities	Pediatrics	IT and AI in child health education questionnaire	Ready to apply AI in medical education to become familiar with terms among pediatric residents and teaching staff Most pediatric residents and teaching staff agreed that IT and AI had simplified the learning of theories and skills. Basic training provided before introducing IT and AI technology in medical education could improve proficiency.
21	Driesnack S, 2024[37]	To examine the opportunity for AI-empowered evaluation of freeform answers	Designing a course	46 medical students who self-selected into the elective course	Antimicrobial therapy	N/A	The AI-based review of freeform answers revealed students' learning gaps and identified topics in which students required more teaching.
22	Leon CGRMP,2022[38]	To examine the emotions of nursing students undergoing a maternal-child clinical simulation	An observational study	28 undergraduate nursing students (sex not specified)	Maternal nursing	AI tools: facial recognition (33 facial points), tone analyzer (NLP and emotional tone detection), voice analysis using MFCC and Log Energy.	Negative emotions like fear and stress were predominant during maternal-child simulation. A positive tone emerged more in voice analysis. Simulation was viewed as stressful but valuable for learning. AI tools provided detailed emotional mapping via voice analysis, facial recognition, and tone analyzer.
23	Linganna RE,2020[39]	To determine whether a smartphone-based asynchronous educational application could enhance TEE knowledge among residents	Randomized controlled trial (RCT) comparing a smartphone application with traditional learning methods	Medical residents (specific demographics not provided)	Trans-esophageal Echocardiography	Smartphone application with image-based questions (AI features not explicitly mentioned)	Using the mobile application enhanced TEE knowledge compared to traditional methods. Showed the effectiveness of asynchronous learning, although AI-specific features were not explicitly described.

24	Malpani A,2020[40]	To evaluate the effect of automated teaching cues in a VR simulator on the performance of surgical techniques for robot-assisted minimally invasive surgery	Pilot RCT	Non-surgeon participants (specific demographics not provided)	Surgical training for robot-assisted minimally invasive surgery	Automated teaching cues within a VR simulator	Automated teaching cues significantly enhanced the performance of surgical techniques in a VR simulator. Revealed the utility of AI for guiding technical skills in robot-assisted surgery.
25	Mlika M,2022[41]	To examine the efficacy of face-to-face learning methods compared with utilizing serious games to teach critical appraisal practice to medical students	Cluster RCT	Medical students (specific demographics not provided)	Critical appraisal in medical education	Serious game incorporating AI elements for educational purposes	The AI-enhanced serious game affected the teaching of critical appraisal. Offered a valid alternative to traditional face-to-face educational methods.
26	Patton JL,2004[42]	To examine a new iterative algorithm that generated custom training forces to change the participants' target-directed reaching movements, aiming to teach specific movement patterns	Experimental study using a robot-assisted adaptive training system	80 healthy right-handed adults with no history of orthopedic or neurological disorders	Motor skill learning and neuro-rehabilitation	Robot-assisted adaptive training system with custom force fields	The robot-assisted adaptive training system enhanced motor skill learning. AI-generated custom force fields changed reaching movements to support neuro-rehabilitation through implicit learning.
27	Pioche M,2016[43]	To explore the effect of self-learning software on the learning curve of endoscopic submucosal dissection (ESD) trainees	Prospective, randomized, comparative study	39 students experienced in interventional endoscopy	Endoscopic submucosal dissection training	ESD self-learning software	The ESD self-learning software group demonstrated improved quality of resection. The AI-enhanced software effectively supported the learning curve in endoscopic procedures.
28	Plackett R,2020[44]	To investigate the acceptability, feasibility, and potential effects of eCREST (an electronic Clinical Reasoning Educational Simulation Tool)	Feasibility randomized controlled trial	Final-year undergraduate medical students	Clinical reasoning in medical education	eCREST (electronic Clinical Reasoning Educational Simulation Tool)	Students using eCREST had enhanced clinical reasoning. The tool potentially contributed to decreasing diagnostic errors.
29	Poulton T,2014[45]	To examine the efficacy of decision-PBL (D-PBL), a variant form of PBL that replaces linear PBL cases with virtual patients	RCT comparing D-PBL with linear PBL	Medical students (details on sex and degree not specified)	Medical education, specifically problem-based learning	Web-based interactive virtual patient cases	Decision-based PBL (D-PBL) users outperformed in exams than those using linear PBL. The AI-driven virtual patient scenarios were effective.
30	Pun SK,2016[46]	To assess the effectiveness of a computer-based training system developed to teach healthcare workers catheter-access hemodialysis management	Controlled trial with nurses randomly assigned to conventional training or conventional plus computer-based training	40 nurses (details on sex and occupation not provided)	Nursing education, specifically hemodialysis management	Computer-based training system for catheter-access hemodialysis management	Nurses in the computer-based training group performed significantly better. Confirmed the effectiveness of AI-enhanced hemodialysis education.

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Table 1 (Continued).

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
31	Qin Y,2022[47]	To investigate the effect of practice-based learning using smart class on students' application ability and satisfaction in undergraduate radiology education	Applying a smart class model in radiology education and assessing its outcomes	Undergraduate medical students (specific details not provided)	Radiology education	Smart class using the PACS simulator and e-learning components	Smart class enhanced application ability and satisfaction in radiology education. Combined PACS simulator and e-learning as an effective AI-supported strategy.
32	Rajan, K.K,2022[48]	To compare the effectiveness of an interactive eModule vs. a Wikipedia-like page without interactivity in teaching clinical neuroscience	Randomized control trial with medical students	Medical students (specific details not provided)	Clinical neuroscience education	Interactive eModule integrating virtual clinical cases	Interactive eModule led to higher engagement, enjoyment, and usefulness compared to non-interactive content. Supported interactive AI tools in neuroscience education.
33	Randell T,2007[49]	To examine the effectiveness of DTkid, an interactive simulation software, in teaching discrete trial training (DTT) skills to novice tutors of children with autism spectrum disorder (ASD)	Experimental studies assessing procedural and declarative knowledge gains	Novice tutors of children with ASD (specific details not provided)	Special education and ASD therapy training	DTkid interactive simulation software	DTkid software significantly enhanced both procedural and declarative knowledge. Useful for novice tutors in ASD therapy training.
34	Reich S,2007[50]	To compare the effectiveness of two digital learning concepts for teaching tooth morphology	RCT	Dental students (details on sex/level not specified)	Dentistry – Tooth morphology	Interactive 3D software and a digital learning environment	The digital tool with higher interactivity was more effective in teaching tooth morphology. Showed cognitive benefits of AI-enhanced 3D learning.
35	Rodríguez-López ES,2020[51]	To compare traditional and new technological approaches for teaching musculoskeletal anatomy	Randomized clinical trial	Undergraduate nursing students (details on sex not specified)	Anatomy in nursing education	Multimedia and interactive 3D software	Students using 3D software outperformed on post-tests. Reported higher engagement and satisfaction than with traditional methods.

36	Cai N,2022[13]	To examine the impact of AI perceptual learning when performing the ultrasound-guided popliteal sciatic block	Randomized clinical trial	Residents receiving standardized training or a refresher program in the Department of Anesthesiology of Beijing Jishuitan Hospital	Anesthesiology	The AI-assisted identification system for ultrasound guided nerve block	Lower complication rate of paresthesia during puncture in the AI teaching group residents compared to the traditional teaching group. Lower complication rate of paresthesia/pain during injection in the AI teaching group compared to the traditional teaching group. No significant differences in blood vessel perforation complication rates between the two groups Higher self-rating scores after training in the AI teaching group compared to the traditional teaching group
37	Barthelemy FX,2017[12]	To compare two teaching modalities (e-learning and lecture-based courses) to enhance the electrocardiogram (ECG) interpretation skills of Emergency Department (ED) residents	Randomized control trial	First-and second-year ED residents	Cardiovascular	The e-learning course included five online resources based on PowerPoint (Microsoft Corp., Redmond, WA, USA) presentations and quizzes	Significant increase in ECG interpretation skills globally, with progression in both eLearning and lecture-based groups Significant enhancement in diagnosing atrial flutter in eLearning group Significant improvement in detecting the misplacement of peripheral electrodes in the eLearning group
38	Bateman J,2012[52]	To investigate the impact of two potentially important design features on clinical reasoning skills and students' experience	Randomized 2×2 factorial design study (two independent variables of Virtual patients' design, branching (present or absent), and structured clinical reasoning feedback (present or absent)	First-year students of medicine (volunteers) from three medical schools in the United Kingdom, Warwick, Keele and Birmingham	Medicine	Virtual Patient software information technology	Robust evidence supporting the effectiveness of different virtual patient designs based on student performance and evaluation
39	Bock A,2021[53]	To evaluate the impact of an eLearning program, including automatic speech recognition, on outcome assessment in interpreting panoramic radiographs at a dental school	Randomized control trial 36 participants divided randomly into 3 seminar groups. Group A used the new PantoDict digital e-learning program for training. Group B utilized both PantoDict and conventional face-to-face classroom instruction. Group C received conventional instruction only.	Dental students	Dentistry	PantoDict program	No significant differences among the three groups Positive feedback on PantoDict included motivation to learn more about reporting panoramic radiographs and a desire for continuous use Digital group (Group A) students expressed a need for a conventional seminar on formulating reports for panoramic radiographs. The tutorials were good but the students preferred having a lecturer for the initial explanation

(*Continued*)

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Table 1 (Continued).

No.	First Author (Citation)	Objective	Method	Population (Sex, Degree, Job)	Course/Field of Study	AI Tool (Name, Feature)	Key Results
40	Boet S,2010[54]	To assess virtual fibreoptic intubation' (VFI) software as an adjunct to the traditional fibreoptic intubation teaching	Randomized control trial (42 undergraduate medical students into two groups. The control group was taught conventionally by an expert bronchoscopist with a 1 h lecture. the VFI group was given the VFI CDROM, and students self-trained with the software.	Undergraduate medical students	Medicine	Virtual computer program	Higher fibreoptic intubation success rate in the VFI group compared to the control group
41	Cendan JC,2011[55]	To determine whether student knowledge and satisfaction Differed between participation in web-based and manikin simulations for learning shock physiology and treatment and to determine whether a specific training sequencing had a differential influence on learning	Randomized control trial 40 second-year medical students into two groups: Group 1 participated in a web-based simulation followed by a manikin simulation and Group 2 participated in the reverse order.	Second-year medical education at University of Central Florida	Medicine	Web-based and manikin simulators	Similar usefulness of web-based and manikin simulations in helping with the understanding of the physiology of shock. Most students preferred the manikin simulation for learning the physiology and treatment of shock.
42	Fernández-Alemán JL,2016[56]	To evaluate a formative mobile approach to provide students with intelligent diagnostic feedback and test its educational effectiveness	RCT	First-year medical students	Medicine	i-SIDRA, a tool for intelligent feedback	More correct answers, satisfaction with the content, and feedback in The i-SIDRA group
43	Gasco J,2014[57]	To compare the effectiveness of 3D virtual simulation training (ImmersiveTouch) vs. traditional teaching for pedicle screw placement in neurosurgery trainees	Randomized controlled	26 Neurosurgery residency medical students	Neurosurgery	ImmersiveTouch®: VR spine simulator with haptic, audio, and visual feedback	Fewer errors per screw after one simulation session Non-experts could teach a highly technical procedural task, like pedicle screw placement using computer-based simulation.
44	Fergusson SJ,2023[58]	To compare the effectiveness of mixed reality (HL2) vs. traditional video-based teaching for basic surgical skills in novices	Single-blind randomized controlled	36 novice clinical medical students	Medicine	Mixed reality headset (3D holographic interactive content)	Higher, more consistent surgical proficiency and instrument selection scores in the HL2 group No difference in suture quality Greater gains for various learning styles in the HL2 group Positive feedback in both groups

included 26 neurosurgery students[56] and 8 healthy adults in neurological rehabilitation.[41] Lack of sex-related information in most studies limited sex-related analyses.

The fields of study were mostly general medicine.[1,12,18,19,21,24–28,30,31,36,39–41,44,45,53,54,59] Sub-disciplines of medicine included radiology[29,35,46,47] for image interpretation training, ophthalmology[14,15] for identifying pathological myopia, psychiatry (23) for designing educational tests, neurosurgery[22,56,57] for practicing surgical techniques, and pharmacology[20] for identifying learning objectives. Nonmedical disciplines included nursing[34,37,38,50] for project-based training, dentistry[49,52] for learning dental morphology, anesthesiology[13,51] for ultrasound-guided nerve blocks, cardiology[1,13,18] for educational simulations, antimicrobial training,[37] trans-esophageal echocardiography,[39] neurological rehabilitation,[41] and hemodialysis training.[45] This diversity demonstrates AI's ability to cover specialized and inter-disciplinary fields, but general medicine remained dominant.

Overall, research conducted on AI and medical education pursued broad and common goals focusing on improving students' learning experience and capabilities. A central objective was to strengthen self-efficacy and develop self-directed learning among students; in other words, AI tools were designed and used in a way that allowed students to learn with greater confidence and independence.[18] In addition, special attention was paid to the impact of these technologies on students' mental and motivational state; research shows intelligent systems, when used correctly, can increase motivation and reduce anxiety in educational processes.[24] Ultimately, all these efforts were aimed at comprehensively improving students' clinical skills; AI, as a powerful auxiliary tool, played a significant role in improving the practical and clinical abilities of the future generation of physicians.[25] A review of the selected studies suggests that using AI in medical education can be explained in terms of several main factors, including domains of use, tools used, application and effectiveness, and challenges associated with AI use.

Domains of Use of AI Tools

The scope of application of AI tools in medical education is very wide, covering various domains. In cardiovascular diseases, simulation approaches aided by AI have helped improve students' performance and clinical thinking.[1] Similarly, in medical imaging, AI-assisted diagnostic software (AISD) has facilitated understanding of 3D images and image interpretation skills.[18] AI-based training in radiology has also received positive feedback.[29] In other fields, such as pharmacy, AI platforms have been utilized to identify learning objectives and generate questions related to medications and antihypertensive treatments.[20] This technology has also been employed in clinical and hospital settings to address medical knowledge gaps, aid decision-making, and manage complex care.[21]

At a more specialized level, neurosurgery has been using ChatGPT for board exam preparation.[22] In addition, in psychiatry, the tool has been used to generate training scenarios and compare them with human scenarios.[23] Ophthalmology has utilized AI systems for disease diagnosis[32] and AI-guided problem-based learning modules.[33] Finally, pediatric education has focused on the assessment of clinical skills and readiness for AI integration.[25,36]

AI Tools in Medical Education (Specifications)

Among the various AI technologies, ChatGPT has been recognized as one of the most prominent and widely used tools.[19,25,30] It has shown great potential in facilitating learning, improving communication and clinical skills, and even competing with students in specialized exams. Other LLMs have also been considered as powerful tools to support learning and clinical processes.[21,26] In addition, a wide range of other innovative tools has been investigated. These include AI-powered scenario-based simulation software[1] used for cardiovascular disease education; AI-assisted image recognition (AISD) software using advanced algorithms such as ResU-net for 3D image analysis;[18] various AI platforms such as Sage Poe and Claude-Instant used as AI search engines or information retrieval in pharmacy education;[20] AI-enhanced serious games for teaching critical appraisal skills;[41] robot-based adaptive learning systems to train specific motor patterns;[42] self-learning software to enhance clinical skills in specialized areas;[43] virtual simulator-based tools and virtual patients improving clinical reasoning and problem-based learning;[44,45] smart classrooms combined with PACS simulators and electronic content;[47] and interactive educational modules and 3D software significantly assisting student learning in areas such as neurology and anatomy.[48,50,51]

Application and Effectiveness of AI Tools

A wide range of AI tools has been used in medical education, each with its unique advantages. For example, LLMs such as ChatGP have been effective in bridging knowledge gaps, aiding differential diagnosis, and content creation.[19,21,25–27,36] Furthermore, AI-based simulations and scenarios are effective tools for teaching surgical techniques and clinical diagnosis, as well as understanding physiological concepts.[1,38,40,44,45,54,59] In addition, image analysis and diagnosis software, such as those using advanced algorithms[18] and smart classrooms,[47] have helped improve students' diagnostic and practical skills. Besides, interactive tools, simulators, and educational games[28,41,48–51,54] have been increasingly incorporated into the educational process and have demonstrated their effectiveness in learning. Overall, the findings of this section are divided into two subgroups: (a) improving students' performance and skills, and (b) increasing their satisfaction, motivation, and learning experience.

Improving Students' Performance and Skills

Several studies have demonstrated significant positive effects of AI-based tools and approaches on improving students' academic performance and clinical skills.[1,12,13,18,25,28,38,40–51,56,59] These improvements include increased scores on diagnostic tests, improved academic self-efficacy, enhanced self-directed learning, and improved clinical reasoning.[18,54] Compared with traditional methods, combining AI-based approaches such as PPT+AI has resulted in higher scores on challenging tests.[28] Tools such as eCREST have also been effective in improving clinical reasoning and reducing diagnostic errors.[44] Besides, web-based virtual patients (D-PBL) outperformed linear PBL on exams.[45] Reducing side effects and increasing self-assessment scores are the other benefits of using AI.[13]

Increasing Student Satisfaction, Motivation, and Learning Experience

Many studies have emphasized increasing student satisfaction and motivation by integrating AI technologies. In general, AI tools have increased student satisfaction, improved learning experience, and even reduced anxiety.[13,19,21,26,27,29,36,37,47,48,51,53,56,57] For example, LLMs such as ChatGPT have been widely utilized in content creation, ideation, and simplification of concepts to enhance the learning experience.[26,27] Interactive and 3D tools and new approaches, such as AI-RADS[29] and smart classrooms, can also enhance student satisfaction and enjoyment in the learning process.[47,48,51]

Challenges of AI Use

Besides numerous benefits, studies have highlighted key challenges and considerations in using AI in medical education. One of the most important challenges is the accuracy and validity of AI-generated content, which highlights the need for expert review.[20,22,27,36] Concerns have also been raised about biases, misinformation, and ethical issues in the use of these technologies.[21] Some studies have emphasized the need for initial guidance and training for students.[53,57] Student preferences can also influence the adoption of different tools; for instance, some students' preference for traditional simulations over web-based simulations suggests the importance of considering diversity in learning styles.[55]

Discussion

The present study conducted a scoping review to examine the role of AI tools in improving the teaching–learning process in medical education and to discuss the challenges of using AI in this field. In this section, the main findings are discussed in four categories: (1) domains of use of AI tools, (2) characteristics of AI tools in medical education, (3) application and effectiveness of AI tools, and (4) challenges of using AI.

Domains of Use of AI Tools

AI tools have been used in teaching–learning processes in medical education across various disciplines, including cardiology, medical imaging, psychiatry, pediatrics, ophthalmology, and pharmacy. Their application spans theoretical training, preclinical education, and clinical practice,[60] This broad integration reflects the increasing need to bridge the gap between theoretical knowledge and clinical application. AI enables students to engage in clinical decision-making within controlled and simulated environments,[61] which is particularly valuable given the ethical and practical limitations of training with real patients.

AI-based virtual reality and simulation platforms allow learners to interact with virtual patients in realistic scenarios, enabling repeated practice in a safe environment.[62] This repeated exposure is likely to strengthen clinical reasoning through pattern recognition and experiential learning. Supporting this, immersive AI-driven platforms such as *medical tr. AI.ning* provide interactive, context-rich training environments that facilitate clinical decision-making and enhance experiential learning.[62]

While AI-driven tools, particularly generative AI (GenAI), have demonstrated strong potential in supporting cognitive and decision-making skills, their effectiveness in developing hands-on clinical and procedural skills remains limited. AI-based environments cannot fully replicate the complexity, unpredictability, and nuanced interpersonal dynamics of real patient interactions. Therefore, AI should be considered a complementary tool rather than a replacement for real clinical experience.

Characteristics of AI Tools in Medical Education

AI tools can be broadly categorized into (a) generative language models, such as chatbots, and (b) AI-driven tools designed to facilitate teaching–learning processes. This distinction highlights two complementary dimensions of AI in education: cognitive support and experiential training. Evidence suggests that the future of medical education will be significantly influenced by the integration of these technologies.[63] Generative models, such as ChatGPT, extend beyond information retrieval by enabling interactive reasoning and supporting knowledge synthesis.[21] In contrast, AI-driven systems, including simulation platforms and diagnostic tools, enhance procedural and applied skills. The combined use of these tools contributes to improvements in both knowledge acquisition and clinical competence.

However, these tools should be used as adjuncts rather than replacements for traditional education. Concerns regarding bias, misinformation, and reliability in AI-generated outputs require careful supervision and alignment with evidence-based medical resources.[21,64] Furthermore, the future development of AI tools depends on effective multi-disciplinary collaboration among clinicians, educators, and technical experts. Without appropriate guidance, there is also a risk that students may become overly reliant on AI tools, potentially weakening independent clinical reasoning.

Application and Effectiveness of AI Tools

The functions of AI in medical education can be categorized into (a) improving students' performance and skills and (b) enhancing satisfaction, motivation, and learning experience. The findings of this review indicate that AI-based approaches consistently improve clinical performance, diagnostic accuracy, and self-directed learning. These effects are largely driven by personalized learning pathways and immediate feedback mechanisms, which promote deeper engagement.[21]

Empirical evidence further supports these findings. AI-based simulation approaches significantly improve clinical thinking and practical skills compared to traditional methods.[1] Similarly, AI-assisted diagnostic tools, such as AISD software, enhance image interpretation skills, self-efficacy, and learner autonomy through real-time feedback and 3D visualization.[18]

The effectiveness of GenAI is highly dependent on instructional design. AI tools are most beneficial when integrated into structured learning environments with clear objectives, guided interaction, and opportunities for critical evaluation of outputs. In contrast, unstructured use may result in passive learning and superficial understanding. Consistent with previous evidence,[24,65] AI integration is also associated with increased motivation and reduced anxiety, reflecting a shift toward more learner-centered educational models.

Challenges of Using AI

While AI offers substantial benefits, its implementation in medical education is associated with several ethical, technical, and organizational challenges.[65–67] Ethical concerns include algorithmic bias, lack of transparency, and potential inaccuracies in AI-generated content, which may affect learning quality and clinical decision-making.[21]

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Information security is another critical issue, particularly in the context of sensitive medical data. Although some AI platforms claim to provide enterprise-level data protection, concerns remain regarding data storage, unauthorized access, and potential misuse of user inputs.[65–67]

In addition, although some AI tools are freely available, the large-scale implementation of AI in educational institutions often requires significant investment in infrastructure, integration, training, and maintenance. These hidden costs may limit accessibility, especially in resource-constrained settings.

From a pedagogical perspective, overreliance on AI tools may reduce critical thinking and independent problem-solving skills. Furthermore, variability in study designs and outcomes highlights the lack of standardized evaluation frameworks for AI in medical education. Addressing these challenges requires clear policies, ethical guidelines, and the promotion of AI literacy to ensure safe and effective integration.

Conclusion

The findings of this scoping review demonstrate that artificial intelligence plays a transformative role in enhancing the teaching–learning process in medical education. A wide range of AI tools—including large language models such as ChatGPT, AI-driven virtual patient platforms, immersive simulation systems (eg., medical tr.AI.ning), and AI-assisted diagnostic tools such as AISD software—have shown significant potential in improving clinical reasoning, diagnostic accuracy, and student engagement.

These technologies support personalized learning, provide immediate feedback, and facilitate the integration of theoretical knowledge with practical clinical skills. In particular, simulation-based and AI-driven interactive tools enable safe, repetitive practice in complex clinical scenarios, thereby enhancing experiential learning and competency development.

However, despite these benefits, challenges such as algorithmic bias, data privacy concerns, lack of transparency, and the risk of overreliance on AI remain critical issues that must be addressed. Therefore, the effective implementation of AI in medical education requires the development of clear guidelines, ethical frameworks, and robust evaluation systems.

Future efforts should focus on integrating AI literacy into medical curricula, strengthening infrastructure, and conducting longitudinal and comparative studies to better understand the long-term impact of AI on clinical competence and professional development. A balanced and evidence-based approach will be essential to ensure that AI serves as a complementary tool that enhances, rather than replaces, the role of educators in medical training.

Future research may also focus on specific learner populations, such as undergraduate students, postgraduate trainees, or residents, to better understand how AI-based educational tools influence teaching–learning processes within each group.

To maximize the effectiveness of AI tools in medical education, educators should integrate them within structured learning designs that include clear objectives, guided interaction, and opportunities for critical evaluation of AI-generated outputs. AI tools are most effective when used to support active learning, clinical reasoning, and personalized feedback rather than passive information retrieval. Conversely, uncritical reliance on AI outputs, lack of supervision, and substituting AI for real clinical experience should be avoided, as these practices may hinder the development of independent thinking and practical skills.

Implications for Stakeholders and Policymakers

The findings of this study suggest that policymakers and educational stakeholders should develop clear guidelines for the ethical and effective integration of AI in medical education. Investment in infrastructure, faculty training, and AI literacy programs is essential to support implementation. In addition, regulatory frameworks should be established to address data privacy, transparency, and algorithmic bias. Collaboration between educators, clinicians, and technology developers is also recommended to ensure that AI tools align with educational needs and standards.

AI Declaration

Artificial intelligence was not used in this article.

Data Sharing Statement

The data can be requested from the corresponding author.

Ethical Considerations

This research received ethical approval (IR.IUMS.REC.1403.695) from Iran University of Medical Sciences.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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