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ЕЖЕМЕСЯЧНЫЙ НАУЧНЫЙ ЖУРНАЛ

Медицинские новости Грузии

საქართველოს სამედიცინო სიახლენი

GEORGIAN MEDICAL NEWS
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GMN: Georgian Medical News is peer-reviewed, published monthly journal committed to promoting the science and art of medicine and the betterment of public health, published by the GMN Editorial Board since 1994. GMN carries original scientific articles on medicine, biology and pharmacy, which are of experimental, theoretical and practical character; publishes original research, reviews, commentaries, editorials, essays, medical news, and correspondence in English and Russian.
GMN is indexed in MEDLINE, SCOPUS, PubMed and VINITI Russian Academy of Sciences. The full text content is available through EBSCO databases.

GMN: Медицинские новости Грузии - ежемесячный рецензируемый научный журнал, издаётся Редакционной коллегией с 1994 года на русском и английском языках в целях поддержки медицинской науки и улучшения здравоохранения. В журнале публикуются оригинальные научные статьи в области медицины, биологии и фармации, статьи обзорного характера, научные сообщения, новости медицины и здравоохранения. Журнал индексируется в MEDLINE, отражён в базе данных SCOPUS, PubMed и ВИНИТИ РАН. Полнотекстовые статьи журнала доступны через БД EBSCO.

GMN: Georgian Medical News – საქართველოს სამედიცინო სიახლენი – არის ყოველთვიური სამეცნიერო სამედიცინო რეცენზირებადი ჟურნალი, გამოიცემა 1994 წლიდან, წარმოადგენს სარედაქციო კოლეგიისა და აშშ-ის მეცნიერების, განათლების, ინდუსტრიის, ხელოვნებისა და ბუნებისმეტყველების საერთაშორისო აკადემიის ერთობლივ გამოცემას. GMN-ში რუსულ და ინგლისურ ენებზე ქვეყნდება ექსპერიმენტული, თეორიული და პრაქტიკული ხასიათის ორიგინალური სამეცნიერო სტატიები მედიცინის, ბიოლოგიისა და ფარმაციის სფეროში, მიმოხილვითი ხასიათის სტატიები.
ჟურნალი ინდექსირებულია MEDLINE-ის საერთაშორისო სისტემაში, ასახულია SCOPUS-ის, PubMed-ის და ВИНИТИ РАН-ის მონაცემთა ბაზებში. სტატიების სრული ტექსტი ხელმისაწვდომია EBSCO-ს მონაცემთა ბაზებიდან.

WEBSITE
www.geomednews.com

К СВЕДЕНИЮ АВТОРОВ!

При направлении статьи в редакцию необходимо соблюдать следующие правила:

1. Статья должна быть представлена в двух экземплярах, на русском или английском языках, напечатанная через **полтора интервала на одной стороне стандартного листа с шириной левого поля в три сантиметра**. Используемый компьютерный шрифт для текста на русском и английском языках - **Times New Roman** (**Кириллица**), для текста на грузинском языке следует использовать **AcadNusx.** Размер шрифта - **12**. К рукописи, напечатанной на компьютере, должен быть приложен CD со статьей.

2. Размер статьи должен быть не менее десяти и не более двадцати страниц машинописи, включая указатель литературы и резюме на английском, русском и грузинском языках.

3. В статье должны быть освещены актуальность данного материала, методы и результаты исследования и их обсуждение.

При представлении в печать научных экспериментальных работ авторы должны указывать вид и количество экспериментальных животных, применявшиеся методы обезболивания и усыпления (в ходе острых опытов).

4. К статье должны быть приложены краткое (на полстраницы) резюме на английском, русском и грузинском языках (включающее следующие разделы: цель исследования, материал и методы, результаты и заключение) и список ключевых слов (key words).

5. Таблицы необходимо представлять в печатной форме. Фотокопии не принимаются. **Все цифровые, итоговые и процентные данные в таблицах должны соответствовать таковым в тексте статьи**. Таблицы и графики должны быть озаглавлены.

6. Фотографии должны быть контрастными, фотокопии с рентгенограмм - в позитивном изображении. Рисунки, чертежи и диаграммы следует озаглавить, пронумеровать и вставить в соответствующее место текста **в tiff формате**.

В подписях к микрофотографиям следует указывать степень увеличения через окуляр или объектив и метод окраски или импрегнации срезов.

7. Фамилии отечественных авторов приводятся в оригинальной транскрипции.

8. При оформлении и направлении статей в журнал МНГ просим авторов соблюдать правила, изложенные в «Единых требованиях к рукописям, представляемым в биомедицинские журналы», принятых Международным комитетом редакторов медицинских журналов - http://www.spinesurgery.ru/files/publish.pdf и http://www.nlm.nih.gov/bsd/uniform_requirements.html
В конце каждой оригинальной статьи приводится библиографический список. В список литературы включаются все материалы, на которые имеются ссылки в тексте. Список составляется в алфавитном порядке и нумеруется. Литературный источник приводится на языке оригинала. В списке литературы сначала приводятся работы, написанные знаками грузинского алфавита, затем кириллицей и латиницей. Ссылки на цитируемые работы в тексте статьи даются в квадратных скобках в виде номера, соответствующего номеру данной работы в списке литературы. Большинство цитированных источников должны быть за последние 5-7 лет.

9. Для получения права на публикацию статья должна иметь от руководителя работы или учреждения визу и сопроводительное отношение, написанные или напечатанные на бланке и заверенные подписью и печатью.

10. В конце статьи должны быть подписи всех авторов, полностью приведены их фамилии, имена и отчества, указаны служебный и домашний номера телефонов и адреса или иные координаты. Количество авторов (соавторов) не должно превышать пяти человек.

11. Редакция оставляет за собой право сокращать и исправлять статьи. Корректура авторам не высылается, вся работа и сверка проводится по авторскому оригиналу.

12. Недопустимо направление в редакцию работ, представленных к печати в иных издательствах или опубликованных в других изданиях.

При нарушении указанных правил статьи не рассматриваются.

REQUIREMENTS

Please note, materials submitted to the Editorial Office Staff are supposed to meet the following requirements:

1. Articles must be provided with a double copy, in English or Russian languages and typed or compu-ter-printed on a single side of standard typing paper, with the left margin of **3** centimeters width, and **1.5** spacing between the lines, typeface - **Times New Roman** (**Cyrillic**), print size - **12** (referring to Georgian and Russian materials). With computer-printed texts please enclose a CD carrying the same file titled with Latin symbols.

2. Size of the article, including index and resume in English, Russian and Georgian languages must be at least 10 pages and not exceed the limit of 20 pages of typed or computer-printed text.

3. Submitted material must include a coverage of a topical subject, research methods, results, and review.

Authors of the scientific-research works must indicate the number of experimental biological species drawn in, list the employed methods of anesthetization and soporific means used during acute tests.

4. Articles must have a short (half page) abstract in English, Russian and Georgian (including the following sections: aim of study, material and methods, results and conclusions) and a list of key words.

5. Tables must be presented in an original typed or computer-printed form, instead of a photocopied version. **Numbers, totals, percentile data on the tables must coincide with those in the texts of the articles.** Tables and graphs must be headed.

6. Photographs are required to be contrasted and must be submitted with doubles. Please number each photograph with a pencil on its back, indicate author's name, title of the article (short version), and mark out its top and bottom parts. Drawings must be accurate, drafts and diagrams drawn in Indian ink (or black ink). Photocopies of the X-ray photographs must be presented in a positive image in **tiff format**.

Accurately numbered subtitles for each illustration must be listed on a separate sheet of paper. In the subtitles for the microphotographs please indicate the ocular and objective lens magnification power, method of coloring or impregnation of the microscopic sections (preparations).

7. Please indicate last names, first and middle initials of the native authors, present names and initials of the foreign authors in the transcription of the original language, enclose in parenthesis corresponding number under which the author is listed in the reference materials.

8. Please follow guidance offered to authors by The International Committee of Medical Journal Editors guidance in its Uniform Requirements for Manuscripts Submitted to Biomedical Journals publication available online at: http://www.nlm.nih.gov/bsd/uniform_requirements.html
http://www.icmje.org/urm_full.pdf
In GMN style for each work cited in the text, a bibliographic reference is given, and this is located at the end of the article under the title "References". All references cited in the text must be listed. The list of references should be arranged alphabetically and then numbered. References are numbered in the text [numbers in square brackets] and in the reference list and numbers are repeated throughout the text as needed. The bibliographic description is given in the language of publication (citations in Georgian script are followed by Cyrillic and Latin).

9. To obtain the rights of publication articles must be accompanied by a visa from the project instructor or the establishment, where the work has been performed, and a reference letter, both written or typed on a special signed form, certified by a stamp or a seal.

10. Articles must be signed by all of the authors at the end, and they must be provided with a list of full names, office and home phone numbers and addresses or other non-office locations where the authors could be reached. The number of the authors (co-authors) must not exceed the limit of 5 people.

11. Editorial Staff reserves the rights to cut down in size and correct the articles. Proof-sheets are not sent out to the authors. The entire editorial and collation work is performed according to the author's original text.

12. Sending in the works that have already been assigned to the press by other Editorial Staffs or have been printed by other publishers is not permissible.

Articles that Fail to Meet the Aforementioned Requirements are not Assigned to be Reviewed.

ავტორთა საყურადღებოდ!

რედაქციაში სტატიის წარმოდგენისას საჭიროა დავიცვათ შემდეგი წესები:

1. სტატია უნდა წარმოადგინოთ 2 ცალად, რუსულ ან ინგლისურ ენებზე,დაბეჭდილი სტანდარტული ფურცლის 1 გვერდზე, 3 სმ სიგანის მარცხენა ველისა და სტრიქონებს შორის 1,5 ინტერვალის დაცვით. გამოყენებული კომპიუტერული შრიფტი რუსულ და ინგლისურენოვან ტექსტებში - **Times New Roman (Кириллица)**, ხოლო ქართულენოვან ტექსტში საჭიროა გამოვიყენოთ **AcadNusx.** შრიფტის ზომა – 12. სტატიას თან უნდა ახლდეს CD სტატიით.

2. სტატიის მოცულობა არ უნდა შეადგენდეს 10 გვერდზე ნაკლებს და 20 გვერდზე მეტს ლიტერატურის სიის და რეზიუმეების (ინგლისურ,რუსულ და ქართულ ენებზე) ჩათვლით.

3. სტატიაში საჭიროა გაშუქდეს: საკითხის აქტუალობა; კვლევის მიზანი; საკვლევი მასალა და გამოყენებული მეთოდები; მიღებული შედეგები და მათი განსჯა. ექსპერიმენტული ხასიათის სტატიების წარმოდგენისას ავტორებმა უნდა მიუთითონ საექსპერიმენტო ცხოველების სახეობა და რაოდენობა; გაუტკივარებისა და დაძინების მეთოდები (მწვავე ცდების პირობებში).

4. სტატიას თან უნდა ახლდეს რეზიუმე ინგლისურ, რუსულ და ქართულ ენებზე არანაკლებ ნახევარი გვერდის მოცულობისა (სათაურის, ავტორების, დაწესებულების მითითებით და უნდა შეიცავდეს შემდეგ განყოფილებებს: მიზანი, მასალა და მეთოდები, შედეგები და დასკვნები; ტექსტუალური ნაწილი არ უნდა იყოს 15 სტრიქონზე ნაკლები) და საკვანძო სიტყვების ჩამონათვალი (key words).

5. ცხრილები საჭიროა წარმოადგინოთ ნაბეჭდი სახით. ყველა ციფრული, შემაჯამებელი და პროცენტული მონაცემები უნდა შეესაბამებოდეს ტექსტში მოყვანილს.

6. ფოტოსურათები უნდა იყოს კონტრასტული; სურათები, ნახაზები, დიაგრამები - დასათაურებული, დანომრილი და სათანადო ადგილას ჩასმული. რენტგენოგრამების ფოტოასლები წარმოადგინეთ პოზიტიური გამოსახულებით **tiff** ფორმატში. მიკროფოტოსურათების წარწერებში საჭიროა მიუთითოთ ოკულარის ან ობიექტივის საშუალებით გადიდების ხარისხი, ანათალების შეღებვის ან იმპრეგნაციის მეთოდი და აღნიშნოთ სურათის ზედა და ქვედა ნაწილები.

7. სამამულო ავტორების გვარები სტატიაში აღინიშნება ინიციალების თანდართვით, უცხოურისა – უცხოური ტრანსკრიპციით.

8. სტატიას თან უნდა ახლდეს ავტორის მიერ გამოყენებული სამამულო და უცხოური შრომების ბიბლიოგრაფიული სია (ბოლო 5-8 წლის სიღრმით). ანბანური წყობით წარმოდგენილ ბიბლიოგრაფიულ სიაში მიუთითეთ ჯერ სამამულო, შემდეგ უცხოელი ავტორები (გვარი, ინიციალები, სტატიის სათაური, ჟურნალის დასახელება, გამოცემის ადგილი, წელი, ჟურნალის №, პირველი და ბოლო გვერდები). მონოგრაფიის შემთხვევაში მიუთითეთ გამოცემის წელი, ადგილი და გვერდების საერთო რაოდენობა. ტექსტში კვადრატულ ფჩხილებში უნდა მიუთითოთ ავტორის შესაბამისი N ლიტერატურის სიის მიხედვით. მიზანშეწონილია, რომ ციტირებული წყაროების უმეტესი ნაწილი იყოს 5-6 წლის სიღრმის.

9. სტატიას თან უნდა ახლდეს: ა) დაწესებულების ან სამეცნიერო ხელმძღვანელის წარდგინება, დამოწმებული ხელმოწერითა და ბეჭდით; ბ) დარგის სპეციალისტის დამოწმებული რეცენზია, რომელშიც მითითებული იქნება საკითხის აქტუალობა, მასალის საკმაობა, მეთოდის სანდოობა, შედეგების სამეცნიერო-პრაქტიკული მნიშვნელობა.

10. სტატიის ბოლოს საჭიროა ყველა ავტორის ხელმოწერა, რომელთა რაოდენობა არ უნდა აღემატებოდეს 5-ს.

11. რედაქცია იტოვებს უფლებას შეასწოროს სტატია. ტექსტზე მუშაობა და შეჯერება ხდება საავტორო ორიგინალის მიხედვით.

12. დაუშვებელია რედაქციაში ისეთი სტატიის წარდგენა, რომელიც დასაბეჭდად წარდგენილი იყო სხვა რედაქციაში ან გამოქვეყნებული იყო სხვა გამოცემებში.

აღნიშნული წესების დარღვევის შემთხვევაში სტატიები არ განიხილება.

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NAVIGATING AI IN MEDICAL EDUCATION: A NARRATIVE REVIEW OF APPLICATIONS, CHALLENGES, AND FUTURE STRATEGIES

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Abstract.

The rapid evolution of artificial intelligence (AI) is driving a paradigm shift in modern healthcare, creating an urgent imperative to reform traditional medical education. This narrative review synthesizes the current landscape, core applications, challenges, and actionable pathways for responsible AI integration in medical education. AI enables personalized and adaptive learning, immersive clinical simulation, automated assessment and formative feedback, data-driven curriculum design, and efficient administrative support, while large language models (LLMs) further enhance knowledge synthesis, exam preparation, and clinical reasoning practice. However, widespread adoption remains constrained by infrastructure deficits and digital inequity, faculty AI literacy gaps, unresolved ethical concerns including algorithmic bias and data privacy risks, automation bias and potential skill degradation, and a critical shortage of rigorous longitudinal evidence on educational efficacy. This review argues that sustainable AI integration requires a shift from technological optimism to human-centered, evidence-based implementation that prioritizes human–AI collaboration, standardized governance, ethical stewardship, and equitable access. We conclude that AI, when thoughtfully deployed, can enhance competency cultivation while preserving the humanistic core of medical training, preparing future clinicians to practice safely and effectively in an AI-enabled healthcare ecosystem.

Key words. Artificial intelligence, medical education, large language models, educational technology.

Introduction.

As a cornerstone of the global healthcare system, medical education bears the responsibility of cultivating competent, compassionate, and adaptable healthcare professionals who can navigate the intricacies of modern medicine. Traditional medical education, which relies heavily on lectures, textbooks, standardized patient encounters, and clinical apprenticeships, faces growing pressures and inherent limitations. Specifically, the exponential expansion of medical knowledge not only overwhelms learners with information but also makes it unfeasible for any single curriculum to be exhaustive; the paucity of clinical cases and standardized patients curtails hands-on practice opportunities; and the "one-size-fits-all" pedagogical approach fails to cater to individual variations in learning styles and progress [1]. Adding to these challenges, medicine is experiencing a profound transformation fueled by artificial intelligence (AI)—technologies including machine learning (ML), natural language processing (NLP), and large language models (LLMs) have exhibited remarkable efficacy in diagnostic imaging, clinical decision support, and administrative workflow optimization [2,3]. This revolution in clinical practice necessarily presents a compelling case for the transformation of medical education, which must evolve to equip future practitioners with the skills to leverage these powerful tools effectively [4].

In recent years, the rapid evolution of AI technology—defined by its prowess in data processing, pattern recognition, adaptive learning, and interactive simulation—has emerged as a potent tool to address the shortcomings of traditional medical education, facilitating a paradigm shift from "knowledge transmission" to "competency cultivation". Crucially, the integration of AI into medical education constitutes more than a mere technological augmentation; it represents a systemic transformation. From ChatGPT and DALL-E to AI-powered diagnostic simulation systems and adaptive learning platforms, AI technologies are infiltrating every phase of medical training, spanning undergraduate preclinical education, postgraduate residency training, and continuing medical education for practicing clinicians. AI holds the potential to alleviate key challenges of traditional models by enabling personalized learning trajectories, immersive simulation experiences, and scalable, consistent assessment [5,6]. Moreover, bibliometric analyses have indicated a striking upsurge in research on AI in medical education over the past decade, with recent focus areas centering on LLMs, VR/AR applications, and personalized learning solutions [7].

However, the path to integrating AI into medical education is not straightforward. The current landscape is characterized by a patchwork of experimental pilots, ethical uncertainties, and a notable lack of robust, longitudinal evidence [7]. The voices of educators and students reveal a complex picture of enthusiasm tempered by concerns about faculty readiness, skill degradation, and the digital divide [8,9]. This narrative review aims to move beyond a simple cataloging of AI's potential. It critically examines the current state of AI applications, dissects the multifaceted challenges impeding its progress, and offers a strategic, evidence-informed vision for the future, with a particular focus on fostering a balanced and humanistic integration of these powerful technologies.

Core Applications of AI in Medical Education.

A growing body of literature consistently demonstrates that AI plays a multifaceted and transformative role in medical education, offering innovative solutions to longstanding challenges across diverse educational domains. By leveraging its unique capabilities in data analysis, pattern recognition, and interactive engagement, AI is redefining how medical knowledge is taught, learned, assessed, and administered, thereby supporting the cultivation of competent healthcare professionals aligned with the demands of modern clinical practice. To summarize key empirical evidence, the main findings from representative studies evaluating various AI-based tools are presented in Table 1.

Enhancement of Teaching and Learning:

AI has fundamentally reshaped the instructional landscape in medical education by enabling personalized, interactive, and immersive learning experiences that address the limitations of traditional didactic approaches. AI-driven adaptive learning platforms leverage machine learning algorithms to analyze individual learner performance, learning preferences, and progress trajectories, allowing for the tailoring of educational content, pacing, and learning pathways [11,14,16,20-23]. These platforms effectively identify knowledge gaps in real time and deliver targeted resources—such as customized reading materials, interactive quizzes, and supplementary tutorials—to enhance learner engagement, deepen understanding, and improve long-term knowledge retention [13,24,25].

Concurrently, AI serves as the backbone of Intelligent Tutoring Systems (ITS) and sophisticated virtual patient simulation tools, creating risk-free, high-fidelity environments for medical trainees to practice clinical reasoning, diagnostic skills, and procedural decision-making [12,15,26]. A landmark randomized controlled trial conducted by Fazlollahi et al. further validated the efficacy of AI-based tutoring, demonstrating that trainees who received AI-guided instruction outperformed those in conventional teaching groups in acquiring simulated surgical skills, thereby providing high-quality empirical evidence for AI's value in skill development [6]. Notably, these simulations provide invaluable exposure to rare or complex clinical scenarios that are often

Table 1. *Comparison of Study Findings for AI Tools in medical education.*

Author (Year)	**Target population**	**AI tools used**	**Educational outcomes**	**Limitations**
Hashimoto et al. (2018) [10]	Surgery residents	Virtual reality curriculum	Improved FES exam scores; better endoscopic skill acquisition	Single-center; small sample; underpowered for some comparisons; limited generalizability
Cheng et al. (2020) [5]	Medical students, trainees	HipGuide	Improved trainees' medical image learning	Small sample; selection bias
Kaur et al. (2021) [11]	Medical students & staffs	Digital chatbot	Reduce tutor input and promote self-learning	Convenience sample; low participation; no member check; analyst bias
Fazlollahi et al. (2022) [6]	Medical students	AI tutoring system (Virtual operative assistant)	Improved simulated surgical skills	Cannot assess teamwork competency; selection bias; limited surgical experience; single-center design
Cassidy et al. (2022) [12]	Surgical residents	GI Mentor (A virtual reality endoscopy simulator)	Improved FES scores & pass rate; enhanced skills; saves time	Single-center; small sample; underpowered to detect group differences
Al Kahf et al. (2023) [13]	Medical students	Chatprogress (A chatbot-based serious game)	Improved pulmonology & overall PCC exam scores; high learner satisfaction	Single-center; low adherence & survey response rate; single specialty; no real-clinical performance assessment
Zhao et al. (2023) [14]	Medical students	Watson for Oncology (WFO)	Improved learning, knowledge mastery, learning interest, and course satisfaction	Small sample size; single-center; subjective questionnaire-based evaluation; no long-term outcome assessment
Xie et al. (2024) [15]	Junior doctors	LLMs (ChatGPT-4, Google Bard, Bing AI)	Supported clinical decision-making; enhanced self-directed learning	Subjective expert evaluation; single-specialty focus (surgery); outdated training data; no real clinical outcome assessment
Gan et al. (2024) [16]	Medical students	ChatGPT	Better knowledge mastery & learning efficiency	Single-center; single specialty; no visual MCQs
Sridharan et al. (2024) [17]	Medical educators	ChatGPT-3.5, Claude-Instant, Sage Poe	Generating test items related to a discipline in the undergraduate medical curriculum	Untested generalizability; no validation of item difficulty/discrimination
Majeed et al. (2024) [18]	Residents	AI-based learning software	Improved diagnostic accuracy; higher post-test scores	Small sample size; single-center; single disease focus
Mastour et al. (2025) [19]	Medical educators	Machine learning enhanced with explainable AI (XAI)	Accurately predicted high-stakes exam performance; identified at-risk students	Automation bias; no psychosocial factors included; needs prospective & external validation
Wang et al. (2025) [20]	Medical students	LearnGuide (a specialized ChatGPT tool)	Enhanced self-directed learning, critical thinking, and learning immersion	Selection bias; limited generalizability; potential over-reliance risk
Hui et al. (2025) [21]	Urology medical interns	ChatGPT assisted PBL	Improved exam scores; overall clinical competence; high student satisfaction	Small sample size; single-center; single specialty; risk of over-reliance; self-reported survey bias
Yu et al. (2025) [22]	Medical students	Simulation-based education (SBE)	Improved theoretical & practical imaging skills; enhanced learning interest, imaging thinking, teamwork & communication	Single-center; non-random group allocation; unbalanced sample size; no long-term follow-up

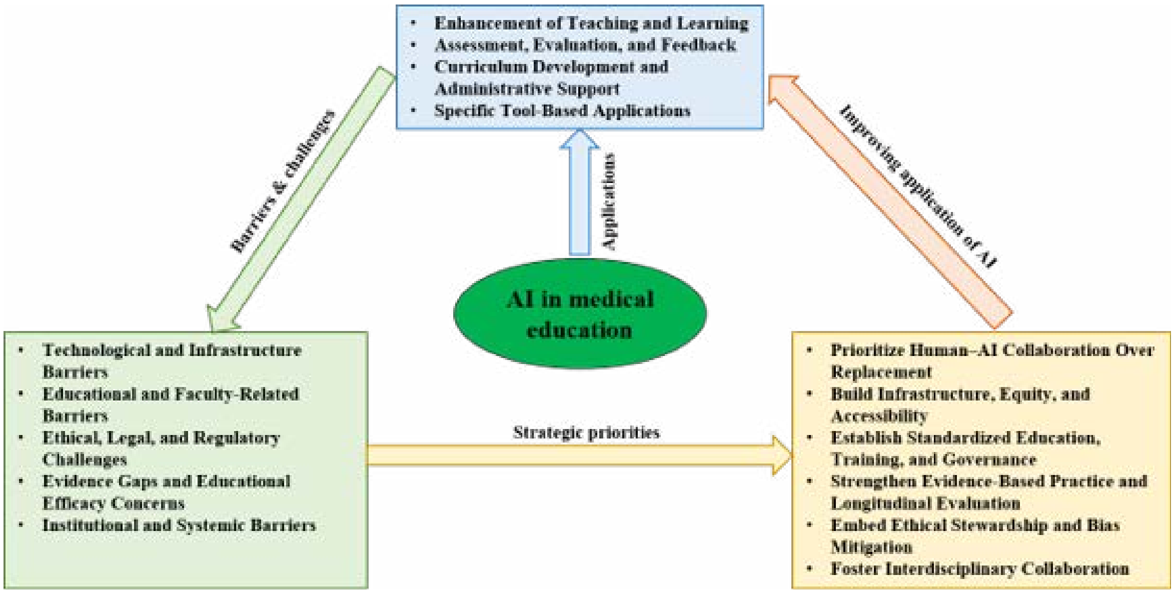

Figure 1. *Framework for AI integration in medical education: applications, challenges, and strategic priorities. The framework depicting the interrelationships between AI applications, implementation barriers, and strategic priorities in medical education. The central focus is on "AI in medical education," with three interconnected components: (1) key applications of AI in enhancing teaching, assessment, and administrative workflows; (2) multi-level barriers including technological infrastructure, faculty readiness, ethical concerns, evidence gaps, and institutional support; and (3) actionable strategic priorities to advance human-AI collaboration, equity, governance, and evidence-based practice in educational settings.*

inaccessible in traditional clinical settings, allowing learners to refine their skills without endangering patient safety [6,27,28].

Immersive technologies augmented by AI, such as virtual reality (VR) and augmented reality (AR), further enhance the learning experience by facilitating the visualization of complex anatomical structures and clinical procedures [10,12,29]. For instance, AI-integrated VR platforms allow students to manipulate 3D models of the human body, enabling a deeper understanding of spatial relationships that are difficult to convey through 2D textbooks [1]. Additionally, specialized AI tools designed for medical image interpretation—particularly in radiology and pathology—provide direct, real-time feedback on trainee performance, helping to refine their ability to identify abnormal findings and significantly improving diagnostic accuracy over time [5,30]. These AI-enhanced tools act as "super mentors," empowering learners to engage in self-directed, efficient learning while building confidence in their clinical skills.

Assessment, Evaluation, and Feedback:

AI has introduced a paradigm shift in medical education assessment, moving away from traditional, resource-intensive methods toward more automated, personalized, and predictive approaches. Natural Language Processing (NLP), a core subset of AI, is increasingly employed to automate the grading of written clinical summaries, reflective essays, and even performance in Objective Structured Clinical Examinations (OSCEs) [17,18,31]. Compared to human assessors, NLP-driven grading systems offer greater consistency, scalability, and efficiency, reducing inter-rater variability and enabling the timely evaluation of large cohorts of learners [32,33]. Beyond mere grading, AI systems excel at providing learners with immediate, detailed, and actionable feedback on their performance in quizzes, simulation exercises, and clinical reasoning tasks. This just-in-time, formative feedback allows trainees to identify their weaknesses, correct misunderstandings, and reinforce their strengths in real time, fostering a continuous learning cycle that accelerates skill development [34]. Predictive analytics, a powerful application of machine learning, further enhances assessment by analyzing longitudinal performance data—including test scores, simulation outcomes, and participation metrics—to forecast student success and identify individuals at risk of academic underperformance [19]. This proactive approach enables educators to implement targeted support interventions, such as additional tutoring or personalized study plans, marking a critical shift from reactive to preventative academic advising [35].

Curriculum Development and Administrative Support:

AI also provides significant value in optimizing the backend operations of medical education institutions, supporting curriculum development and streamlining administrative tasks to reduce faculty burden. In curriculum design and analysis, AI algorithms can process vast datasets—including learner performance data, clinical practice trends, and evolving competency frameworks—to evaluate the effectiveness of existing curricula, identify redundancies or gaps, and suggest evidence-based re-alignments [25,36]. This data-driven approach ensures that medical curricula remain relevant to the changing needs of clinical practice, particularly as AI continues to reshape healthcare delivery. Generative AI and large language models (LLMs) are increasingly utilized for automated educational content generation, including the creation of diverse clinical vignettes, practice questions, and preliminary drafts of teaching materials [16,37]. However, it is critical to emphasize that expert review by medical educators remains non-negotiable to ensure clinical accuracy, avoid misinformation, and align content with educational objectives [38].

On the administrative front, AI streamlines a wide range of routine tasks, such as admissions screening, clinical rotation scheduling, plagiarism detection, and the management of student inquiries. By automating these time-consuming processes, AI reduces the operational burden on faculty and administrative staff, freeing them to focus on more impactful educational activities—such as mentorship, hands-on training, and curriculum innovation [39].

Specific Tool-Based Applications: The Rise of Large Language Models (LLMs) and Chatbots:

Certain AI technologies, particularly LLMs such as ChatGPT, GPT-4, and Claude, have carved out distinct, high-impact roles in medical education, thanks to their advanced natural language understanding and generation capabilities. LLMs are extensively used to support medical literature review and synthesis, helping trainees efficiently navigate the vast volume of medical research, summarize key findings, and identify relevant studies [40-42]. They also serve as valuable study aids for exam preparation, including high-stakes licensing exams such as the USMLE, with studies demonstrating that GPT-4 can achieve passing scores on these assessments, highlighting its potential as a personalized study partner in knowledge acquisition.

Beyond knowledge acquisition, LLMs facilitate the practice of patient communication skills through realistic role-play scenarios, allowing trainees to refine their ability to explain complex medical concepts, deliver difficult news, and build rapport with patients [43]. Additionally, these tools foster critical thinking by engaging learners in Socratic dialogue, challenging their assumptions, and prompting them to justify their clinical decisions [41]. Pioneering integrations are embedding LLMs directly into Learning Management Systems (LMS) to offer personalized study aids, such as customized flashcards and topic summaries, or into clinical training systems to assist students with tasks like drafting differential diagnoses, writing SOAP notes, and interpreting clinical data during clerkships [44]. Several leading medical schools have implemented structured, curriculum-integrated pilots of generative AI and large language models, with documented educational outcomes and practical challenges. Harvard Medical School has incorporated AI into core preclinical and graduate training, including mandatory AI literacy courses and LLM-based simulated patient tools, while addressing concerns such as AI hallucinations, data bias, and preservation of clinical reasoning and humanistic care [45]. Stanford Medicine has established universal AI education for all medical students, deploying Clinical Mind AI and AI Clinical Coach to enhance history-taking and clinical reasoning skills; key challenges include rapid technological evolution, curriculum alignment, and model generalizability [46]. The University of Cincinnati College of Medicine has developed the CAR-E AI coaching platform to foster reflective practice and personalized learning, with implementation challenges including algorithm transparency, content validity, and responsible scaling [47]. Collectively, these real-world initiatives confirm the feasibility of integrating LLMs into routine medical education while highlighting consistent barriers: ensuring accuracy and fairness, supporting faculty adaptation, and maintaining robust ethical governance.

Challenges and Barriers to AI Integration.

Despite the transformative potential of AI in medical education, its widespread and effective integration is hindered by a complex interplay of technological, educational, ethical, and institutional barriers. These challenges are not isolated but interconnected, often compounding one another to impede progress, and they require targeted strategies to address—particularly as the field continues to evolve with advancements in LLMs, VR/AR, and other AI technologies. Below is a comprehensive analysis of the key obstacles shaping the current landscape of AI integration in medical education.

Technological and Infrastructure Barriers:

A foundational barrier to AI integration lies in inadequate technological infrastructure and unequal access to AI tools across medical education institutions. Many medical schools—especially those in low- and middle-income countries, or smaller institutions with limited funding—lack the necessary hardware, software, and high-speed internet connectivity to support AI-driven educational tools [32,48]. This digital divide exacerbates educational inequity, as trainees in resource-constrained settings are denied access to AI-enhanced simulation platforms, adaptive learning systems, and LLM-powered study aids that their peers in well-resourced institutions take for granted. Even in institutions with basic infrastructure, compatibility issues between existing learning management systems (LMS) and new AI tools often arise, creating technical bottlenecks that frustrate educators and learners alike [44].

Furthermore, the rapid pace of AI technological evolution presents a persistent challenge: many institutions struggle to keep pace with updates to AI tools, leading to outdated systems that fail to leverage the latest advancements in ML, NLP, or LLMs. Maintenance and technical support for AI tools are also often insufficient, with few institutions employing dedicated personnel to troubleshoot issues, update software, or train users. This lack of ongoing technical support undermines the reliability of AI tools, eroding trust among educators and trainees and discouraging consistent use. Additionally, the high cost of acquiring and maintaining advanced AI systems—such as high-fidelity virtual patient simulators or enterprise-level adaptive learning platforms—places them out of reach for many institutions, further widening the gap in AI access [1].

Educational and Faculty-Related Barriers:

The successful integration of AI in medical education hinges on the preparedness and willingness of faculty to adopt and effectively utilize these technologies—a area where significant gaps persist. Many medical educators lack the necessary digital literacy and AI competence to incorporate AI tools into their teaching practices [49]. Unlike younger trainees who may be more familiar with digital technologies, many senior faculty members have not received formal training in AI concepts, tools, or pedagogical strategies for integrating AI into curricula, leading to anxiety, resistance, or superficial use of AI tools that fail to maximize their educational potential [50].

Compounding this issue is a lack of standardized training programs for medical educators on AI integration. Few institutions offer structured professional development opportunities that teach educators how to leverage AI to enhance teaching, assess learner performance, or develop AI-augmented curricula [51]. As a result, even educators who are open to AI adoption often struggle to integrate these tools in meaningful ways, relying on trial-and-error rather than evidence-based practices. Additionally, faculty workload is a significant barrier: many educators are already burdened by clinical responsibilities, curriculum development, and administrative tasks, leaving little time to learn, test, and implement new AI technologies. There is also a pervasive fear among some educators that AI may replace their role in medical education, leading to resistance to adoption and a reluctance to invest time in learning these tools [52].

Ethical, Legal, and Regulatory Challenges:

AI integration in medical education raises complex ethical, legal, and regulatory questions that have yet to be fully addressed, creating uncertainty that hinders widespread adoption. A primary ethical concern is the potential for bias in AI tools, which can perpetuate disparities in medical education and clinical practice [53]. AI algorithms are trained on large datasets, and if these datasets are biased—for example, underrepresenting certain patient populations or clinical scenarios—AI tools may provide inaccurate or inequitable feedback to trainees, reinforcing harmful stereotypes or gaps in knowledge. This is particularly problematic in diagnostic simulation tools and LLMs, where biased outputs can mislead trainees and undermine the development of culturally competent clinical skills.

Privacy and data security are additional critical ethical and legal concerns. AI tools in medical education often collect and process sensitive data, including trainee performance metrics, personal information, and clinical case data [54]. Ensuring compliance with data protection regulations—such as the General Data Protection Regulation (GDPR) in Europe, the Health Insurance Portability and Accountability Act (HIPAA) in the United States, and the Personal Information Protection Law (PIPL) of China—poses substantial challenges for institutions. Notably, substantial discrepancies exist among cross-national data governance frameworks, which complicate cross-border data sharing, international collaborative research, and large-scale deployment of unified AI education platforms. Variations in standards for data localization, consent requirements, anonymization protocols, and cross-border data transfer create legal barriers and operational complexities for global AI education initiatives. These regulatory inconsistencies hinder the development of interoperable, globally accessible AI tools and limit the generalizability of cross-national educational research, further slowing the standardized integration of AI in medical education worldwide. As AI systems may store data across multiple servers or third-party platforms, increasing the risk of data breaches. There is also a lack of clarity regarding ownership of data generated by AI tools in medical education, raising questions about who has access to trainee data and how it can be used for research or quality improvement [25].

Regulatory frameworks for AI in medical education are also underdeveloped, with few clear guidelines governing the development, validation, and use of AI tools in educational settings. Unlike AI tools used in clinical practice, which are subject to rigorous regulatory scrutiny by bodies such as the U.S. Food and Drug Administration (FDA), AI educational tools often lack standardized validation processes to ensure their accuracy, reliability, and educational effectiveness. This regulatory ambiguity creates uncertainty for institutions, which may be hesitant to adopt AI tools due to concerns about liability or non-compliance.

Evidence Gaps and Educational Efficacy Concerns:

Despite the growing enthusiasm for AI in medical education, there remains a notable dearth of robust, longitudinal evidence supporting its long-term educational efficacy [55]. Most existing studies are short-term, small-scale pilots that focus on learner satisfaction or immediate performance improvements, rather than long-term outcomes such as clinical competence, patient outcomes, or professional development. This lack of high-quality evidence makes it difficult for institutions to justify the significant investment required to adopt AI tools, as they cannot be certain of the return on investment in terms of improved learner outcomes.

Additionally, there is a lack of standardized metrics for evaluating the educational impact of AI tools, leading to inconsistent research findings and difficulty comparing the effectiveness of different AI applications [56]. Many studies rely on subjective measures, such as learner surveys, rather than objective assessments of clinical skill acquisition or knowledge retention [57]. There is also growing concern that over-reliance on AI tools may erode critical thinking and clinical reasoning skills among trainees, who may become overly dependent on AI-generated answers rather than developing the ability to analyze complex clinical scenarios independently [58,59]. This risk is particularly acute with LLMs, which can generate plausible but inaccurate clinical information if not properly validated.

Institutional and Systemic Barriers:

Institutional and systemic factors further hinder the integration of AI in medical education, including limited funding, misaligned incentives, and fragmented leadership. Funding for AI initiatives in medical education is often scarce, with institutions prioritizing clinical care and research over educational technology. Even when funding is available, it is often allocated to short-term pilot projects rather than long-term, systemic integration, leading to fragmented adoption that fails to transform the broader educational landscape [28].

Misaligned incentives also play a role: many medical educators are evaluated based on their clinical productivity and research output, rather than their contributions to educational innovation or AI integration. This creates little motivation for educators to invest time and effort in adopting AI tools or developing AI-augmented curricula. Additionally, the lack of cross-disciplinary collaboration between medical educators, AI developers, and educational technologists hinders the development of AI tools that are tailored to the unique needs of medical education [60]. Without input from educators, AI tools may be technically sophisticated but pedagogically ineffective, failing to address the real-world challenges of medical training.

Finally, fragmented leadership and inconsistent policies across institutions and regions create barriers to standardized AI integration. There is no unified vision or strategy for AI in medical education, leading to disjointed efforts that vary widely in quality and scope. This lack of coordination makes it difficult to share best practices, scale successful initiatives, or address common challenges, slowing the overall progress of AI integration in the field.

Key Insights and Future Strategic Priorities.

The integration of artificial intelligence into medical education represents not merely a technological upgrade, but a profound paradigm shift that demands deliberate, ethical, and learner-centered governance. While the preceding sections have documented AI's transformative applications and multifaceted barriers, this discussion synthesizes key insights and advances a cohesive, actionable roadmap to guide responsible, equitable, and sustainable AI adoption in medical education (Figure 1).

Prioritize Human–AI Collaboration Over Replacement:

At the core of effective AI integration lies a foundational principle: AI should augment, not replace, human expertise and clinical empathy. Medical education remains deeply rooted in communication, compassion, ethical reasoning, and professional identity formation—qualities that no algorithm can fully replicate [61]. Rather than positioning AI as a substitute for faculty mentoring, bedside teaching, or patient interactions, institutions should frame AI as a collaborative tool that automates routine tasks, amplifies personalized instruction, and expands educational capacity. This human-in-the-loop framework preserves educators' roles as mentors, critical thinking facilitators, and guardians of clinical ethics while leveraging AI for data-driven customization, scalable assessment, and immersive simulation. When designed around human needs, AI strengthens rather than diminishes the humanistic foundations of medical training [62].

Build Infrastructure, Equity, and Accessibility:

To overcome systemic inequities highlighted earlier, stakeholders must prioritize inclusive infrastructure development and cross-institutional resource sharing. The digital divide in AI access perpetuates global disparities in medical training quality and must be addressed through targeted investment in cloud-based platforms, low-cost AI tools, and shared educational repositories. International collaborations and open-access initiatives can democratize access to high-quality AI-driven learning modules, virtual patients, and LLM-assisted education, especially for low-resource settings. Furthermore, interoperability between AI systems and existing learning management systems must be prioritized to reduce technical barriers and ensure seamless integration into existing curricula. Standardized application programming interfaces (APIs) and modular AI designs can simplify adoption across diverse institutional contexts [63].

Establish Standardized Education, Training, and Governance:

Sustainable AI integration requires structured faculty development, clear pedagogical standards, and accountable governance. Medical educators need formal, competency-aligned training in AI literacy, tool evaluation, and evidence-based instructional design—not only technical tutorials but also guidance on ethical implementation and bias mitigation. Regulatory and educational bodies should collaboratively develop standards for AI tool validation, transparency, and reporting in educational settings [64]. The AITEL checklist proposed by Masters and Salcedo offers a practical framework to improve rigor, replicability, and accountability in AI-enhanced education research [32]. By establishing shared standards, the medical education community can minimize low-quality pilots, reduce ethical risks, and accelerate trustworthy innovation.

Strengthen Evidence-Based Practice and Longitudinal Evaluation:

Current enthusiasm for AI in medical education currently outpaces robust empirical evidence, highlighting a critical gap that must be addressed through large-scale, longitudinal, and multi-institutional studies. Future research should move beyond cross-sectional satisfaction surveys to focus on objective, competency-aligned outcomes, including clinical performance, diagnostic accuracy, knowledge retention, professionalism, and long-term impacts on clinical practice. Predictive analytics, formative feedback systems, and AI-enhanced assessment platforms can serve as research instruments to track learning trajectories and iteratively refine educational interventions. To strengthen the evidence base, future randomized controlled trials (RCTs) and cohort studies evaluating AI tools in medical education should adopt a standardized, multi-dimensional framework of primary and secondary endpoints directly tied to core medical education competencies, such as improvements in OSCE performance or reductions in diagnostic error rates in clinical settings. Centralized data repositories and open research practices will further facilitate high-quality meta-analyses and evidence synthesis, enabling the field to transition from innovation-driven to rigorously evidence-based adoption.

Embed Ethical Stewardship and Bias Mitigation:

Ethics must be embedded at every stage of AI design, deployment, and evaluation in medical education. Institutions should implement proactive safeguards against algorithmic bias, data privacy risks, misinformation, and automation bias. Key practices include: rigorous validation of AI-generated content by clinical educators; transparent disclosure of AI limitations to learners; regular auditing for demographic, clinical, or contextual bias; secure data management compliant with global privacy regulations. Ethics education should also be integrated into AI-enabled curricula, teaching future physicians to critically evaluate AI outputs, recognize uncertainty, and uphold patient-centered values in an increasingly automated healthcare landscape.

Foster Interdisciplinary Collaboration:

Successful AI translation requires sustained partnership between clinicians, educators, computer scientists, ethicists, and learners. Too often, AI tools are developed without pedagogical expertise or clinical realism; conversely, educators frequently adopt technologies without understanding algorithmic limitations. Co-design processes—where AI developers and medical educators collaborate from conception to implementation—yield tools that are both educationally effective and clinically meaningful. Learner and faculty feedback loops further ensure that AI systems evolve responsively to real-world educational needs.

Conclusion.

This review synthesizes the transformative role, applications, challenges, and future directions of artificial intelligence in medical education. AI has emerged as a powerful enabler to personalize learning, enhance immersive simulation, automate reliable assessment, and optimize educational administration, effectively addressing key limitations of traditional training models. However, its sustainable integration is hindered by infrastructure gaps, faculty preparedness, ethical concerns, algorithmic bias, data privacy risks, and insufficient longitudinal evidence. To realize AI's full potential, stakeholders must prioritize human–AI collaboration, bridge the digital divide, establish standardized governance and validation frameworks, embed ethical stewardship, and strengthen evidence-based practice. With deliberate, learner-centered, and responsible implementation, AI can drive a paradigm shift in medical education that enhances both competency and humanistic care, preparing future clinicians to thrive in an increasingly digital healthcare landscape.

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