REVIEW

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Artificial Intelligence in Anesthesiology and Reanimation Education: Transforming Learning Across Perioperative Care

Anesteziyoloji ve Reanimasyon Eğitiminde Yapay Zeka: Perioperatif Bakım Süreçlerinde Öğrenmenin Dönüştürülmesi

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Abstract

Artificial intelligence (AI) is rapidly transforming anesthesiology education by introducing technology-supported learning models tailored to the specialty's data-intensive, time-critical demands. This transformation is most visible in anesthesiology, where the traditional apprenticeship remains foundational yet faces challenges such as unequal clinical exposure, supervision variability, and subjective assessment methods. AI-based educational tools are increasingly being used to reshape both theoretical and procedural skill development across perioperative care, intensive care, and pain medicine. Technologies including machine learning, deep learning, computer vision, natural language processing, and large language models are increasingly integrated into simulation systems, performance analysis, and feedback, offering structured, individualized learning. Current evidence suggests that these tools may improve clinical reasoning, support decision-making confidence, and promote more organized responses during crisis scenarios. Nevertheless, the integration of AI into education also raises important concerns regarding data security, ethical oversight, transparency, and algorithmic bias. Rather than replacing educators, AI should be viewed as a complementary instrument that enhances educational quality while preserving the core human values of empathy, responsibility, and professional judgment. When thoughtfully implemented, AI has the potential to strengthen anesthesiology education by supporting a balanced and ethically grounded learning environment.

Öz

Yapay zeka (YZ), anesteziyoloji eğitimini, bu alanın çok veri gerektiren ve hızlı karar alınması gereken yapısına uygun, teknoloji destekli eğitim yöntemleri kullanarak hızla değiştirmektedir. Bu dönüşüm en belirgin şekilde anesteziyoloji alanında görülmektedir; burada geleneksel usta-çırak eğitimi halen temelini korumakla birlikte, klinik deneyime eşit erişimin olmaması, eğitimci denetimindeki farklılıklar ve öznel değerlendirme yöntemleri gibi sorunlarla karşı karşıyadır. YZ'ye dayalı eğitim araçları; perioperatif bakım, yoğun bakım ve ağrı tıbbı alanlarında hem teorik bilgilerin hem de uygulamaya yönelik becerilerin gelişimini yeniden şekillendirmektedir. Makine öğrenmesi, derin öğrenme, bilgisayarla görme, doğal dil işleme ve büyük dil modelleri gibi teknolojiler; simülasyonlar, performans değerlendirmeleri ve geri bildirim süreçlerinde önemli bir rol oynamakta ve kişiye özel, düzenli bir öğrenme süreci sunmaktadır. Mevcut çalışmalar, bu araçların klinik düşünme becerilerini geliştirebildiğini, karar verirken hekimlerin kendine olan güvenini artırdığını ve kriz durumlarında daha düzenli ve etkili tepkiler verilmesini sağladığını göstermektedir. Ancak YZ'nin eğitime entegre edilmesi; veri güvenliği, etik denetim, şeffaflık ve algoritmalardan kaynaklanan yanlılık gibi önemli kaygıları da beraberinde getirmektedir. YZ, eğitmenlerin yerini alan bir teknoloji olarak değil; empati, sorumluluk ve mesleki yargı gibi temel insani değerleri koruyarak eğitimin kalitesini artıran destekleyici bir araç olarak görülmelidir. Dikkatli ve bilinçli şekilde uygulandığında, YZ anesteziyoloji eğitimini daha dengeli ve etik temellere dayanan bir öğrenme ortamı ile güçlendirme potansiyeline sahiptir.

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Keywords: Anesthesia, artificial intelligence, critical care, education, training

Öz

Anahtar kelimeler: Yapay zeka, anestezi, tıp eğitimi, klinik eğitim, yoğun bakım

Introduction

Anesthesiology and reanimation education (ARE) requires the ability to make rapid, high-stakes decisions while maintaining technical precision and effective teamwork in complex, safety-critical environments. Training in this specialty draws upon multiple domains of intelligence-cognitive, psychomotor, and emotional-making it particularly well-suited for technology-enhanced learning strategies (1-7). Simulation-based education, especially when combined with deliberate practice and structured feedback, has been shown to significantly enhance both technical and non-technical competencies in anesthesiology trainees (4,5,8).

Although apprenticeship-based models remain the cornerstone of anesthesiology training, their limitations have become increasingly evident. Clinical exposure often varies widely among trainees, feedback may be inconsistent, and assessments frequently rely on subjective instructor judgment (9,10). These limitations are further amplified by the increasing complexity of perioperative care and the need for standardized competency assessment. Consequently, there is a growing demand for objective, data-driven, and scalable educational frameworks that ensure consistency and transparency in learning outcomes (1,11).

In recent years, artificial intelligence (AI) has emerged as a transformative force in both clinical practice and medical education. AI encompasses a wide range of computational techniques, including machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision (CV), enabling the analysis of large and complex datasets (12-14). Within anesthesiology, AI applications span perioperative risk prediction, intraoperative monitoring and decision support, ultrasound-guided regional anesthesia, airway assessment, and intensive care management (12-18).

From an educational perspective, AI has enabled the development of intelligent simulation systems, adaptive learning platforms, and automated performance assessment tools (11,19,20). These technologies align closely with competency-based medical education (CBME) principles by offering scalability, standardization, personalization, and reflective analytics (1,21,22). For instance, AI systems can provide individualized feedback to multiple learners simultaneously, dynamically adjust case complexity based on trainee proficiency, and identify both cognitive and procedural performance gaps.

Bibliometric analyses demonstrate a rapid expansion of AI-related research in anesthesiology and critical care. Xie et al. (21) reported a five-fold increase in publications between 2004 and 2024, while Li et al. (22) showed that research output in this field has approximately doubled every three years. These findings highlight the accelerating integration of AI into both clinical and educational domains.

The coronavirus disease-2019 (COVID-19) pandemic further accelerated this transformation by necessitating the rapid adoption of digital and remote learning modalities. Virtual simulation, telesimulation, and remote debriefing platforms became essential tools for maintaining continuity in anesthesiology training programs (23,24). These developments not only enhanced accessibility but also demonstrated the feasibility of scalable and flexible education models.

Simultaneously, AI integration into medical education has driven a shift toward personalized and adaptive learning environments. AI-based educational frameworks enable continuous performance monitoring, predictive modeling of learning trajectories, and individualized curriculum design tailored to learner needs (3,25-29). Such approaches are consistent with modern educational paradigms emphasizing learner-centered and competency-driven training.

Despite these advancements, several challenges remain in integrating AI into anesthesiology education. Issues related to data quality, algorithm transparency, ethical considerations, and implementation within existing curricula continue to pose significant barriers (18,30). Beyond these structural challenges, the need to improve AI literacy among both trainees and educators has been increasingly recognized as a critical component of future medical education (26,27).

In addition, concerns related to algorithmic bias, model reliability, and the potential for overreliance on AI systems warrant careful consideration. Bias embedded in training datasets may lead to inequitable performance across different patient populations, while variability in data quality can affect the consistency and generalizability of AI-driven recommendations. Furthermore, excessive reliance on AI-supported decision-making may impair the development of independent clinical reasoning skills among trainees, raising important pedagogical and safety concerns.

Collectively, these limitations highlight the need for critical appraisal of AI applications in medical education, rather than their uncritical adoption.

Against this backdrop, the present review aims to provide a comprehensive overview of current evidence on AI integration in ARE, focusing on four key domains: (1) Perioperative training and decision support, (2) Postoperative and intensive-care learning, (3) Pain medicine and regional anesthesia education, and (4) Ethical and pedagogical perspectives shaping the future of training.

Methodological Approach

This study is a narrative review aiming to synthesize current evidence on AI in anesthesiology education. The literature was selected based on thematic relevance and representativeness rather than a predefined systematic search strategy. Therefore, no formal study selection criteria or quality assessment tools were applied.

1. Fundamental Concepts of AI in ARE

AI refers to computational systems that mimic human reasoning, learning, and decision-making through data-driven algorithms. In anesthesiology, a field characterized by high-frequency physiologic data, real-time monitoring, and rapid decision cycles, AI provides a robust framework to model clinical reasoning, automate feedback, and enhance procedural learning (1,12-14). Rather than replacing traditional instruction, AI complements it by transforming how information is analyzed and delivered. Integrated AI tools help educators uncover hidden learning patterns, quantify performance, and design adaptive pathways through enhanced learning analytics and structured feedback mechanisms (10,11,27). These capabilities position AI as a key enabler of data-driven and competency-oriented medical education frameworks.

1.1 DL: DL, a subset of ML, utilizes multi-layered neural networks to model complex non-linear relationships, such as linking anesthetic dosing with dynamic hemodynamic responses. DL-enhanced simulators are capable of reproducing realistic patient reactions and delivering quantitative, real-time feedback, thereby accelerating the acquisition of psychomotor skills in anesthesia training (8,20,31-33). Emerging evidence further suggests that DL-supported simulation environments improve pattern recognition, technical precision, and crisis response performance in high-fidelity training scenarios (20,31,32). In addition, DL models are increasingly used in perioperative data analysis and physiological signal interpretation, further expanding their relevance in both clinical and educational settings (16,17).

1.2 ML: ML algorithms are capable of detecting complex, non-linear patterns in datasets such as simulation metrics, physiological signals, and electronic health record parameters. These capabilities enable the prediction of learning outcomes, identification of individual knowledge gaps, and generation of personalized feedback through advanced analytic frameworks (12,13,20). Furthermore, ML-based predictive models support longitudinal tracking of performance in crisis management scenarios and readiness for independent clinical practice, thereby reinforcing alignment with the principles of CBME (1,11,19,34). Such predictive capabilities are also widely applied in perioperative risk assessment and decision support systems, strengthening the link between education and clinical practice (15,16).

1.3 NLP and large language models (LLMs): NLP enables computational systems to interpret and generate human language, facilitating the automated analysis of oral examinations, case discussions, and reflective debriefings in medical education. The emergence of LLMs, such as Generative Pre-trained Transformer-4, has further expanded these capabilities by supporting interactive virtual-patient dialogues and adaptive tutoring environments, which enhance learner engagement and individualized instruction (1,12,25,26). Additionally, NLP-driven systems can synthesize reflective narratives and deliver structured, competency-aligned formative feedback, contributing to more consistent and data-informed assessment practices in anesthesiology training (10,11,27). Recent developments suggest that LLM-based systems may also support curriculum design and automated knowledge assessment in medical education (28,29).

1.4 CV: CV algorithms analyze visual data, particularly ultrasound images, to support anatomical recognition and provide real-time visual guidance during procedural training. In regional anesthesia education, CV-based systems can assist in highlighting neural structures, tracking needle trajectories, and identifying safe anatomical zones, thereby enhancing technical precision and procedural safety (31,35-38). These technologies are increasingly integrated into AI-assisted ultrasound systems, improving both training efficiency and clinical accuracy (36,37).

1.5 Learning analytics: AI-based learning analytics integrate multimodal data sources, including eye-tracking metrics, task completion time, vocal characteristics, and physiological stress markers, to objectively assess cognitive load, situational awareness, and skill acquisition during simulation-based training (12,13). These insights facilitate the optimization of task difficulty, workload balancing, and the structuring of deliberate practice strategies. Collectively, such technologies contribute to the development of data-informed, adaptive, and immersive learning environments that align with contemporary CBME frameworks. As AI-driven analytics continue to evolve, their educational role is expected to extend beyond simulation, supporting ongoing performance monitoring, personalized learning pathways, and informed faculty development initiatives (7,11,27).

2. AI in Perioperative Education

AI is increasingly redefining the landscape of perioperative education. It offers anesthesia residents a richer and more structured learning experience-one that combines data, repetition, and reflection with real clinical reasoning. In a field where decisions must be both fast and precise, AI-based learning systems provide an invaluable framework for developing expertise under safe, simulated conditions (1,9,10,13). Rather than replacing traditional mentorship, these platforms extend it, ensuring that experience is reinforced by objective feedback and measurable progress (8,12,15). These systems also support standardization of training outcomes across different institutions.

2.1 Preoperative assessment and decision support: The preoperative period requires a complex interplay between analytical reasoning and patient-centered clinical judgment. AI-driven educational platforms increasingly enable trainees to engage in simulated preoperative scenarios that integrate patient history, laboratory findings, and physiologic modeling to support structured clinical decision-making. Through ML algorithms, these systems can analyze the learner's diagnostic approach, identify gaps in reasoning, and provide real-time, case-specific feedback, thereby facilitating reflective learning and progressive skill development (13,16,19). Rather than functioning solely as grading tools, AI-enhanced platforms adapt to individual learner performance by adjusting case complexity according to demonstrated strengths and areas for improvement, transforming traditional assessments into personalized clinical problem-solving experiences.

Emerging evidence suggests that exposure to AI-supported preoperative training modules is associated with improved accuracy in risk stratification and anesthetic planning when compared with conventional didactic approaches (12,15,19). Moreover, by shifting the focus from outcome-based correction to process-oriented reasoning, these platforms encourage higher-level discussion and clinical reflection, supporting alignment with the core principles of CBME (1,11). Such approaches also enhance clinical reasoning transparency and decision traceability. However, it is important to note that much of the current evidence is derived from simulation-based environments, which may not fully reflect real-world clinical complexity. Additionally, variations in study design and dataset quality may limit the generalizability of these findings across different clinical settings.

AI has also been extensively investigated for perioperative risk assessment and clinical decision support beyond educational simulation. Recent studies have demonstrated that AI-based predictive models can effectively estimate postoperative complications, intensive care unit admission, ASA classification, and overall perioperative outcomes. These systems utilize large-scale clinical datasets and ML algorithms to enhance risk stratification accuracy and support anesthesiologists in complex decision-making processes. Incorporating these developments into anesthesiology education not only strengthens clinical reasoning but also familiarizes trainees with data-driven approaches that are increasingly integrated into modern perioperative practice (39-41).

2.2 Intraoperative management and crisis simulation: AI has shown increasing potential in preparing residents for the intraoperative phase, where uncertainty, time pressure, and rapid clinical judgments are integral. AI-supported simulation environments enable trainees to engage with complex, dynamic scenarios that reflect realistic hemodynamic changes associated with anesthetic administration, hemorrhage, and airway compromise. These systems provide immediate visual and performance-based feedback, facilitating the development of adaptive decision-making and psychomotor proficiency within high-fidelity training contexts (5,17,20,31).

Rather than relying solely on static scenario progression, AI-enhanced simulators can respond to user input in real time, allowing learners to directly observe the physiological consequences of delayed interventions or suboptimal management decisions. This interactive feedback mechanism supports experiential learning and promotes reflective clinical reasoning.

Furthermore, post-simulation performance data can be processed through learning analytics to generate structured, objective debriefings. Metrics such as response times, intervention patterns, and teamwork indicators provide residents with quantifiable insights into their performance, complementing instructor-led feedback and reinforcing deliberate practice (11,24,34). These systems also contribute to improved crisis resource management and team-based decision-making.

In addition to simulation-based training, AI has been increasingly applied to intraoperative monitoring and real-time clinical decision support. ML algorithms can analyze electroencephalographic signals to predict depth of anesthesia, while predictive models have demonstrated the ability to anticipate intraoperative hypotension and hemodynamic instability before clinical manifestation. Furthermore, AI-driven systems have been explored for automated ASA classification and prediction of postoperative intensive care unit admission, highlighting their potential to assist anesthesiologists in complex intraoperative decision-making processes. Integrating these technologies into training environments may enhance situational awareness, improve response timing, and support the development of data-informed clinical judgment (42-44). Nevertheless, the reliability of these systems remains dependent on data quality and model validation, and their performance in real-world clinical settings requires further investigation.

2.3 AI-assisted airway assessment: Airway management is a critical component of anesthesiology practice, and AI has increasingly been explored to improve the prediction and management of difficult airways. Recent studies have utilized facial image analysis, radiographic evaluation, and ML-based predictive models to identify patients at risk of difficult intubation. CV techniques enable automated recognition of facial features associated with airway difficulty, while DL algorithms applied to imaging data can support endotracheal tube positioning and airway assessment. Furthermore, predictive models have been developed to estimate extubation failure and postoperative airway complications. Incorporating these technologies into anesthesiology education may enhance preoperative airway assessment skills, reduce complications, and support more objective and data-driven clinical decision-making (45-49).

2.4 Cognitive load and personalized feedback: Modern anesthesiology training no longer focuses solely on manual dexterity; increasing attention is now directed toward situational awareness, emotional regulation, and cognitive adaptability as key determinants of clinical performance. AI-based learning analytics can capture subtle indicators of cognitive load by integrating multimodal data sources, including eye-tracking metrics, heart rate variability, and vocal characteristics, enabling a more objective assessment of mental workload during simulation-based training (11,20). These insights allow educators to tailor challenge levels to each learner's cognitive threshold. For example, trainees exhibiting early stress responses may initially be assigned less complex scenarios, whereas those demonstrating sustained composure can be progressively exposed to higher levels of difficulty. Sazuka et al. (20) demonstrated that such multimodal AI-based assessment can differentiate productive mental effort from cognitive overload, facilitating precision feedback that surpasses the limitations of human observation alone. Over time, this personalized feedback supports the development of reflective awareness and cognitive resilience skills essential for effective real-time decision-making in anesthesia practice (11,27). This approach promotes sustainable learning and reduces the risk of cognitive fatigue in high-stress training environments.

Ultimately, AI does not replace the mentor-student relationship that defines ARE; rather, it strengthens it by combining the consistency of data-driven insight with the contextual judgment of human guidance, fostering a more personalized, transparent, and ethically grounded educational environment (18,30).

3. AI in Postoperative and Intensive Care Education

The postoperative and intensive care settings represent some of the most data-dense and cognitively demanding environments in anesthesiology. Within these contexts, AI has emerged as a valuable educational adjunct, supporting trainees in managing information overload while enhancing diagnostic reasoning and clinical situational awareness. By transforming continuous streams of physiological and performance-related data into structured, interpretable learning inputs, AI-driven systems facilitate the integration of theoretical knowledge with real-world clinical application and reflective practice (7,11,12,20). These characteristics make critical care environments particularly suitable for data-driven educational innovations.

3.1 Predictive simulation and digital twins: AI-supported simulation platforms increasingly enable the modeling of complex critical illness scenarios, allowing trainees to engage with dynamic representations of physiological instability within controlled educational environments. Through advanced data analytics, these systems support the anticipation of evolving clinical trends and promote proactive decision-making, facilitating earlier recognition of physiological deterioration during intensive care simulations (7,20,31).

While the concept of “digital twins” represents an emerging paradigm, early educational applications suggest the potential for creating individualized virtual patient models that approximate real-world clinical patterns. Such simulation environments allow residents to explore different therapeutic strategies, including fluid management and ventilatory adjustments, in a risk-free setting, thereby strengthening clinical reasoning and reinforcing adaptive learning processes (8,11). Emerging studies also highlight the potential of AI-driven models in predicting sepsis progression and hemodynamic instability in ICU settings (7,18). However, these approaches remain in early stages of development, and their clinical validity and generalizability have yet to be fully established.

3.2 Data visualization and decision support: Anesthesiology and critical care demand clarity within environments characterized by high data density and rapid decision-making. AI-driven visualization and decision-support systems consolidate information derived from physiological monitors, ventilators, and laboratory data into structured, interpretable displays that facilitate real-time clinical insight and support more informed decision-making during training. By transforming complex, multidimensional data streams into comprehensible visual patterns, these systems enable trainees to recognize trends in oxygenation, perfusion, and hemodynamic stability more efficiently, thereby supporting faster and more confident clinical responses (12,16,17,20).

Learning analytics frameworks further enhance this process by strengthening residents’ capacity to interpret and utilize clinical data effectively. Chan et al. (11) highlighted that the integration of analytic tools into medical education contributes to improved data literacy and performance awareness, reinforcing sustained competency development in complex clinical environments. By reducing cognitive burden and enhancing transparency, such AI-supported visualization tools make critical care training more accessible and less intimidating for learners. Such systems also support early warning mechanisms and risk stratification in critical care decision-making.

Beyond data visualization, AI has been extensively investigated in critical care for predictive analytics and clinical decision support. ML models have demonstrated the ability to detect early signs of sepsis, predict hemodynamic instability, and estimate intensive care unit outcomes using large-scale physiological and clinical datasets. In addition, recent studies have explored the use of LLMs in interpreting complex clinical data, such as blood gas analysis, and in predicting ICU admission requirements. These AI-driven approaches support timely clinical interventions and enhance diagnostic accuracy in high-risk environments. Integrating such tools into anesthesiology education may improve trainees’ ability to manage critically ill patients and strengthen data-driven clinical reasoning skills (50-53).

3.3 Remote and collaborative learning: The COVID-19 pandemic catalyzed a significant transformation in medical education, particularly through the rapid expansion of tele-simulation and remote learning strategies. Virtual platforms have enabled instructors and residents to connect across institutions, facilitating collaborative participation in synchronized simulation scenarios and structured real-time debriefings, thereby ensuring educational continuity during periods of restricted in-person training (23,24).

Beyond geographical limitations, these digital learning environments promote greater accessibility and inclusivity, allowing trainees from diverse regions to engage in standardized, high-fidelity educational experiences. By supporting remote collaboration, shared clinical reasoning, and reflective discussion, such platforms have contributed to a more interconnected and equitable framework for ARE. AI integration further enhances these platforms by enabling automated feedback, performance tracking, and adaptive scenario design (25,27).

AI should therefore be regarded not as a distant or purely theoretical concept in critical care training, but as an increasingly integral educational tool that promotes adaptive learning, fosters collaborative engagement, and supports continuous professional development. As these technologies evolve, they are likely to further enhance postgraduate training by uniting data-driven precision with human-centered clinical mentorship.

4. AI in Pain Medicine and Regional Anesthesia

AI is progressively reshaping training approaches in pain medicine and regional anesthesia by supporting both technical proficiency and structured clinical reasoning.

Through the integration of CV, ML, and simulation-based learning environments, AI contributes to safer procedural practice and enhances the objectivity of educational assessment within multimodal analgesic management frameworks (1,8,13,14). This integration reflects an evolving paradigm in which technical accuracy and patient-centered care are increasingly viewed as complementary components of professional development. These developments also support standardization and reproducibility in procedural training.

4.1 Ultrasound-guided regional anesthesia: Ultrasound-guided regional anesthesia requires advanced visuospatial perception and precise hand-eye coordination, presenting a significant learning curve for novice trainees. AI-assisted technologies, particularly those incorporating CV and DL, have demonstrated the ability to support real-time recognition of peripheral neural structures, identification of tissue planes, and guidance of needle trajectories, thereby enhancing procedural safety and technical performance during training (31,35-38).

These systems provide visual overlays that assist in highlighting anatomical landmarks and reinforcing optimal procedural pathways, contributing to improved learning efficiency and confidence in early practice settings (8,31-33). While primarily designed as assistive tools, emerging evidence suggests their potential as formative educational resources that promote structured skill acquisition and reflective technical learning (31,36). Such systems may also reduce complication rates by improving anatomical accuracy and procedural consistency. This field has rapidly evolved with the integration of AI-based ultrasound interpretation tools, particularly those utilizing CV techniques. Recent studies have demonstrated that AI-assisted systems can accurately identify anatomical structures, support sonoanatomy learning, and guide needle placement during regional anesthesia procedures. In addition, simulation-based educational platforms enhanced by AI provide real-time feedback and objective performance assessment, facilitating skill acquisition in a controlled learning environment. These developments highlight the growing role of AI in improving procedural accuracy, training efficiency, and learner confidence in regional anesthesia education (54-56).

4.2 Pain assessment and personalized analgesia: Pain education remains challenging due to its inherently subjective nature. AI-driven analytic systems have been explored as supportive tools in standardizing assessment processes by integrating physiological and performance-related data to complement traditional clinical evaluation. Such approaches enable learners to compare clinical impressions with data-informed insights, fostering reflective understanding of pain processing and analgesic decision-making (11,13,20).

In parallel, ML applications are increasingly used in educational contexts to illustrate principles of personalized analgesia. By analyzing demographic, procedural, and pharmacologic factors, these models support training in evidence-informed analgesic strategies and highlight the rationale behind opioid-sparing approaches, thereby reinforcing responsible pain management practices (11,12,14,19). These approaches also contribute to more individualized and evidence-based pain management strategies.

4.3 Virtual and tele-pain education: The communicative and empathic dimensions of pain medicine education are being supported through virtual simulation and remote learning platforms, particularly in scenarios focused on complex patient interaction and chronic pain management (23,24). These environments allow trainees to practice clinical communication, shared decision-making, and patient engagement within structured, reflective educational settings. Rather than replacing human interaction, such platforms complement traditional mentorship by enhancing accessibility to guided feedback and structured reflection, supporting the development of patient-centered communication skills in pain medicine training. AI integration further enhances these environments through automated feedback and adaptive communication scenarios (25,27).

Collectively, these developments underline a paradigm shift in pain education, extending beyond procedural and pharmacologic instruction to encompass a broader understanding of patient experience. In this context, AI does not depersonalize care; instead, it supports the cultivation of informed, empathetic, and reflective clinicians by integrating technological precision with human-centered clinical values (18,30).

5. Pedagogical and Ethical Perspectives

5.1 Educational transformation: The integration of AI into anesthesiology education is reshaping both learning and teaching dynamics. Educators are no longer confined to the role of passive information transmitters; rather, they are evolving into mentors and facilitators who interpret, contextualize, and guide the application of AI-derived insights. AI-driven adaptive systems enable personalized learning pathways by analyzing individual performance and dynamically adjusting content complexity, supporting self-directed learning in alignment with the principles of CBME, where progression is determined by demonstrated competence rather than time-based exposure (8,11,19,27).

Grounded in cognitive load theory, AI-supported instructional scaffolding helps balance task difficulty and cognitive processing demands, minimizing unnecessary load while sustaining engagement and learning efficiency (20). Learning analytics further allows educators to monitor learner progress longitudinally, identify performance patterns, and provide structured, evidence-informed feedback that promotes continuous improvement (11,26). Collectively, these innovations reflect a broader shift toward learner-centered education that prioritizes reflective practice, continuous feedback, and measurable competency development over traditional episodic assessments. Such systems also contribute to early identification of struggling learners and targeted educational interventions (28,29). In parallel, recent advances in AI have significantly expanded the role of simulation and digital learning environments in anesthesiology education. AI-driven simulation platforms, virtual patient systems, and LLMs are increasingly being utilized to create interactive, adaptive, and learner-centered training experiences. These technologies enable the generation of dynamic clinical scenarios, personalized feedback, and real-time performance assessment, thereby enhancing both cognitive and procedural skill acquisition. Furthermore, generative AI tools have demonstrated potential in producing educational materials, simulating patient interactions, and supporting self-directed learning among anesthesia trainees. Such developments highlight the growing importance of AI in shaping modern anesthesiology education and underscore the need for its deeper integration into structured training programs (57-61).

5.2 Ethical considerations: As AI becomes increasingly embedded in medical education, ethical concerns surrounding transparency, fairness, and accountability have gained prominence. The reliability of AI systems is inherently dependent on the quality and representativeness of the data used for model training, raising potential risks of bias in performance evaluation and learner assessment. Moreover, the limited interpretability of complex algorithms may challenge trust, necessitating careful oversight in their implementation.

To address these concerns, educational institutions are encouraged to adopt governance frameworks that promote transparency, informed consent, and responsible data stewardship. Multidisciplinary oversight committees play a crucial role in ensuring ethical deployment, safeguarding learner rights, and maintaining the integrity of educational evaluation processes. When appropriately regulated, AI reinforces rather than undermines educational equity by supporting fairness, consistency, and accountability in assessment practices, aligning with broader discussions on responsible AI integration and performance governance in medical education (1,11,18,30). Furthermore, overreliance on AI systems may introduce risks in clinical training by reducing opportunities for independent decision-making. The “black box” nature of some AI models also raises concerns regarding explainability and accountability, particularly in high-stakes clinical environments.

5.3 Human-AI collaboration: AI in ARE should be viewed as an augmentative tool that enhances, rather than replaces, the role of human educators. While AI systems offer rapid data analysis and standardized performance feedback, they cannot replicate the empathy, ethical reasoning, and contextual judgment intrinsic to effective clinical teaching. Optimal integration, therefore, relies on collaborative intelligence, in which educators and AI systems operate synergistically to support learner development.

Faculty involvement remains essential for interpreting analytic outputs, guiding nuanced decision-making, and fostering reflective learning. Consequently, faculty development initiatives focusing on digital literacy, data interpretation, and responsible AI use are increasingly recognized as integral components of contemporary anesthesiology training programs (11,20,26,27). Ultimately, the goal is not autonomous education, but the cultivation of clinicians who can harmonize technological precision with human compassion. Such initiatives also facilitate the safe and effective integration of AI into existing curricula (28,29).

However, while the current literature highlights the potential benefits of AI in anesthesiology education, the overall evidence base remains heterogeneous in terms of study design, outcome measures, and educational settings. Many studies are simulation-based or exploratory in nature, which may limit their generalizability to real-world clinical environments. In addition, variations in dataset quality, institutional infrastructure, and implementation strategies make direct comparisons across studies challenging.

Moreover, although AI-driven tools appear to support performance assessment and feedback processes, there is still limited high-quality evidence demonstrating sustained improvements in long-term clinical competence or patient-related outcomes. These findings suggest that AI should be considered as a supportive and evolving educational tool rather than a definitive solution. Future research should therefore focus on standardized evaluation frameworks, multicenter validation, and longitudinal outcome assessment to better define its role in anesthesiology education.

6. Future Directions

AI in ARE represents a rapidly evolving domain with significant potential for reshaping pedagogical strategies. While many applications are still in developmental or early implementation phases, emerging evidence suggests that AI will progressively transform the ways anesthesiologists acquire, apply, and refine clinical knowledge. These developments hold promise for enhancing personalization, improving accessibility and fostering a more integrated interaction between human learning processes and intelligent technologies (1,8,28,29). These trends reflect a broader transition toward data-driven and learner-centered medical education ecosystems.

6.1 Generative AI (GenAI) and adaptive curriculum design: GenAI is increasingly being explored as a supportive tool for adaptive and flexible educational design in anesthesiology training. By enabling the creation of diverse, variable clinical scenarios, GenAI holds potential to enrich simulation-based learning and expose trainees to a broader range of clinical conditions. This capability supports the development of curricula that adapt to individual performance levels and encourage self-directed progression within structured learning frameworks (3,8,25,27).

Preliminary educational experiences suggest that AI-assisted content generation may enhance learner engagement and support instructional efficiency when appropriately supervised. However, careful integration is essential. Without robust oversight and validation, generative systems may introduce inaccuracies or reinforce underlying biases in training materials. Therefore, institutional governance, expert review, and cross-institutional collaboration remain critical to ensuring pedagogical reliability and patient safety in the evolving application of GenAI within anesthesiology education (1,12,30). These considerations highlight the importance of balancing innovation with responsible implementation. In addition, generative AI systems may produce inaccurate or misleading information (“hallucinations”), underscoring the need for continuous supervision and expert validation in educational use.

6.2 Digital twins in anesthesia training: The concept of digital twins, defined as virtual models informed by physiological and pharmacologic parameters, represents an emerging direction in high-fidelity simulation for anesthesiology training. While current applications remain largely conceptual or in early developmental stages, preliminary educational implementations highlight the potential of such models to support scenario-based rehearsal, enable safe exploration of complex clinical decision-making, and enhance predictive reasoning within controlled simulation environments (7,8,20,31).

As digital-model fidelity advances, these systems are anticipated to contribute to more individualized and data-informed simulation experiences. Their integration with monitoring data holds promise for strengthening decision-support training, although further validation is needed before routine clinical incorporation (11,16). Future developments may also enable real-time integration with clinical datasets, further enhancing training realism.

6.3 Metaverse-based collaborative learning: Immersive virtual learning environments continue to expand the scope of simulation-based education, facilitating remote collaboration among trainees and instructors. Through advanced tele-simulation and shared virtual platforms, learners can participate in structured crisis management scenarios, communication exercises, and team-based simulations across institutional and geographic boundaries (23,24).

Such platforms support interactive engagement and foster collaborative learning dynamics, contributing to broader accessibility and inclusivity in ARE. While large-scale outcome data remain limited, emerging experiences suggest their potential to enrich learner engagement and promote reflective team-based practice (8,25,27). Integration of AI-driven feedback systems further enhances the educational value of these immersive environments.

6.4 Policy, accreditation, and ethical governance: As AI becomes increasingly integrated into medical education, evolving regulatory and accreditation frameworks will play a critical role in ensuring its responsible implementation. Contemporary anesthesiology curricula are progressively incorporating foundational competencies in AI literacy, ethical data use, and simulation-based proficiency as components of structured training programs (11,12,26).

Professional organizations and educational institutions are increasingly emphasizing the importance of transparency, accountability, and equitable access in the integration of AI technologies, underscoring the need for multidisciplinary collaboration among clinicians, educators, data scientists, and policy stakeholders to guide sustainable and ethically sound adoption (1,11,18,30). Such governance structures are essential to maintain trust and ensure long-term sustainability of AI integration in education.

Conclusion

AI is not replacing ARE; rather, it is progressively transforming how education is delivered, experienced, and evaluated. The field is evolving from a predominantly apprenticeship-based model toward a more flexible, data-driven, and learner-centered framework supported by simulation, learning analytics, and adaptive feedback systems (1,11,28). These approaches may enhance both clinical reasoning and technical skill acquisition, ultimately contributing to safer, more standardized, and evidence-informed anesthetic practice. However, given the heterogeneity of existing studies and the narrative nature of this review, these findings should be interpreted with caution. Further high-quality and systematic research is needed to better define the role and impact of AI in anesthesiology education.

Despite these technological advancements, the core of medical education remains inherently human. Attributes such as empathy, ethical sensitivity, communication, and professional responsibility cannot be replicated by algorithmic systems and must continue to be actively cultivated throughout training. Accordingly, AI should be viewed as an augmentative tool that enriches educational processes by providing structure, consistency, and insight, while preserving the relational and humanistic dimensions of clinical teaching (18,30). Its integration should therefore be approached with careful validation, educational oversight, and consideration of potential risks.

Looking ahead, the anesthesiologist of the future will not be defined by competition with technology, but by the ability to effectively collaborate with it. This next-generation clinician will integrate digital literacy with clinical judgment, combine analytical precision with compassionate care, and balance innovation with ethical responsibility. In this context, the true value of AI lies not in replacing human expertise, but in enhancing learning depth, strengthening reflective practice, and supporting the development of resilient, adaptive, and ethically grounded physicians.

Footnotes

Authorship Contributions

Surgical and Medical Practices: S.K.S., K.E., S.D., Concept: S.K.S., K.E., S.D., Design: S.K.S., K.E., S.D., Data Collection or Processing: S.K.S., K.E., S.D., Analysis or Interpretation: S.K.S., K.E., S.D., Literature Search: S.K.S., K.E., S.D., Writing: S.K.S.

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