



Artificial intelligence in anaesthesiology – a review

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Abstract

Introduction. Artificial Intelligence (AI) is a field of computer science where hardware and software systems enable machines to think and act like humans. AI utilizes different algorithms and computational resources to perform intelligent tasks autonomously. AI techniques applied in clinical decision support have proven effective across various medical disciplines, including clinical anaesthesia.

Objective. The aim of this review is to explore the areas of anaesthesiology where artificial intelligence is utilized, the benefits of this implementation, and to define ethical dilemmas connected with using AI technology.

Review Methods. PubMed and Google Scholar databases were searched using key words. Original articles in English, published between 2018–2024 were included.

Brief description of the state of knowledge. AI is a rapidly developing field, notable particularly for its increasing application across various domains, including anaesthesiology. The amount of research on AI in anaesthesia is growing.

Summary. AI has shown considerable promise in various aspects of anaesthesiology, from pre-operative to post-operative care. AI-driven systems predict patient risk, manage drug dosages, administer drugs, and monitor vital signs more effectively than traditional methods. Its applications in anaesthesia can enhance patient outcomes through more personalized and precise interventions, optimize resource allocation, and improve overall efficiency in clinical practice. It also facilitates real-time decision-making and pro-active management of potential complications. However, AI cannot entirely replace the nuanced understanding and empathetic care provided by human professionals. As AI technology advances, legal and ethical standards must also evolve.

Key words

anaesthesia, artificial intelligence, machine learning, pain assessment

INTRODUCTION

Artificial Intelligence (AI) is a field of computer science dedicated to the development of hardware and software systems that simulate human intelligence. AI utilizes different algorithms and computational resources to perform intelligent tasks autonomously. These tasks include: making decisions, analyzing data, predicting events, solving problems, and visual perception [1, 2]. Machine learning (ML) and deep learning (DL) are branches of AI that specialize in analyzing extensive datasets to create models for classification or prediction. ML uses data to autonomously train algorithms, encompassing supervised, unsupervised, and reinforcement learning methods. DL represents a more advanced approach within ML, employing deep neural networks (DNNs) with multiple layers to extract complex patterns and relationships from large datasets [1, 3]. AI techniques applied in clinical decision support have proven effective across various medical disciplines, including clinical anaesthesia [1]. Anaesthesia, a pivotal element in medical practice, has undergone substantial evolution, enhancing the safety and sophistication of surgical

and medical procedures [4]. AI in anaesthesia shows potential to enhance patient outcomes, reduce costs, and optimize the delivery of anaesthesia care [3, 5].

STATE OF KNOWLEDGE

AI is a rapidly developing field, particularly notable for its increasing application across various domains, including anaesthesiology. The field of AI has garnered significant interest among medical professionals due to the numerous benefits it offers, such as improved patient outcomes, enhanced decision-making processes, and increased efficiency in clinical practices. The growing amount of research on AI in anaesthesia reflects this interest, with an increasing count of high-quality articles published in prestigious journals, underlining the relevance and impact of AI in this specialty [1].

OBJECTIVE

The aim of this review is to explore the areas of anaesthesiology where AI is utilized, establish the benefits of this implementation, and define ethical dilemmas connected with using AI technology.

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MATERIALS AND METHOD

PubMed and Google Scholar databases were searched using key words: 'artificial intelligence in anaesthesiology', 'artificial intelligence in anaesthesia', 'automated anaesthesia' and 'machine learning in anaesthesia'. Original articles in English, published between 2018–2024 were included.

AI is being efficiently integrated into the preoperative, intraoperative, and postoperative fields of anaesthesia (Tab. 1).

Table 1. Applications of AI in anaesthesia

Preoperative	Intraoperative	Postoperative
<ul style="list-style-type: none"> - preoperative assessment, - evaluation of the airway, - risk stratification 	<ul style="list-style-type: none"> - anaesthesia dose management, - administration of the drugs, - depth of anaesthesia control, - prevention of adverse drug events, - monitoring, - real-time decision making, - ultrasound guidance 	<ul style="list-style-type: none"> - postoperative monitoring, - pain management, - predicting admission to ICU, - predicting patient outcomes

Preoperative assessment. By utilizing extensive patient data and diagnostic images, AI systems help anaesthesiologists craft customized anaesthesia strategies specifically designed to match each patient's unique anatomical and physiological traits [6].

A crucial part of the preoperative assessment is evaluating the airway. AI has demonstrated promising results in this field. Various AI techniques employ objective indicators, e.g. body mass index (BMI), thyroid distance, photos and computer-based analysis of the face [7]. It is noteworthy that during the decade from 2010–2020, techniques for predicting difficult airways evolved from advanced mathematical models to employing databases that analyze images and videos of patients' faces [8]. In 2021, Tavolara et al. developed a DL model using frontal facial images that outperformed traditional methods (Mallampati test and thyromental distance) in identifying patients who might be difficult to intubate [9]. In 2021, Kim et al. proposed another AI model that effectively predicts difficult laryngoscopy [10]. Hayasaka et al. created a convolutional neural network (CNN) assessing intubation difficulty from facial photos. The best image position was the supine-side-closed mouth-base [11]. In another study, the Cormack-Lehane classification was predicted using facial and neck features [12].

Patient risk stratification. Preoperative risk evaluation remains a significant challenge, even for experienced anaesthesiologists, involving pinpointing risk factors, offering personalized predictions for patients, delivering comprehensive informed consent, and determining the necessity for intensive care unit (ICU) admission for postoperative care. Machine learning models have demonstrated substantial value in this context. By analyzing patient demographics, medical history, and preoperative assessments, these models can predict individual risks and outcomes, such as the likelihood of complications, duration of hospital stay, or postoperative pain [13, 14]. One of the biggest advantages of machine learning is that it is effective in developing models that predict various outcomes from a single feature [15].

The ASA-PS (American Society of Anesthesiologists – Physical Status) is the most common score to evaluate a patient's risk. However, it is subjective and relies on manual scoring by clinicians. In 2018, Zhang et al. aimed to enhance this by developing an automated system to predict ASA-PS based on a patient's co-occurring diseases and medication with greater precision. The findings indicate that the model used in this research can predict ASA-PS with accuracy comparable to anaesthesiologists [16]. In another study conducted by Hofer et al., the top-performing DNN models outperformed the ASA score across all outcomes, except for mortality [15].

In 2018, Kendale et al. investigated induced hypotension by applying several ML techniques to create predictive models. After optimizing these models, they demonstrated that ML algorithms could effectively forecast the likelihood of hypotension following general anaesthesia [17]. In another study, Hatib et al. proved that an ML algorithm utilizing features from arterial waveforms can predict an intraoperative hypotensive event 15 minutes in advance. This may help clinicians take preventive steps [18]. In 2019, Bihorac et al. developed and validated an automated analytics system called MySurgeryRisk. This system leverages existing electronic health record data to predict individual patient risks for eight significant postoperative complications. MySurgeryRisk demonstrated high accuracy in forecasting these complications and also effectively predicted mortality risk at various intervals [19]. Xue et al. evaluated ML models for forecasting five postoperative complications by using separate and combined pre- and intraoperative data. The study found that models using both preoperative and intraoperative data yielded the best results, while models based only on preoperative or intraoperative data performed slightly worse [20]. Lee et al. explored that DNN could predict in-hospital mortality after surgery. The DNN achieved high prediction accuracy, comparable to other risk assessments [21]. In another study by Fritz et al., the DL model was utilized during surgery to detect patients whose preoperative factors and updated vital signs indicated a heightened risk of mortality [22]. Hill et al. emphasized that an automated model offers the advantage of continuously updating patient risk over time. Patient risk generally fluctuates slightly before and after surgery, but increases notably in those who eventually die. Advanced analytical models can serve as early warning systems, alerting clinicians to sudden risk changes and aiding in the timely deployment of rapid response teams, thus improving patient monitoring in the hospital [23].

Predicting admission to intensive care unit. Chiev et al. created an automated model to predict admission to ICU. This prediction can help clinicians in planning postoperative care in advance, potentially improving outcomes by quick intervention and efficient ICU resource allocation [24]. Several other studies [19, 25] have also shown positive results with models predicting the need for a patient to be admitted to the ICU after surgery.

Anaesthesia dose management. Accurate administration of drug doses is essential for safe and efficient anaesthesia. The incorporation of AI introduces a revolutionary method for predicting appropriate drug dosages. Each patient is unique, therefore the necessary anaesthesia dosage varies significantly based on factors like age, BMI or past and

current health condition. AI can evaluate these factors to determine the most suitable dosage for a patient, reducing the risk of underdosing or overdosing [26]. Machine learning models predict stability, solubility and release kinetics of a drug by examining molecular structures, formulation components, and environmental conditions, facilitating accurate predictions that assist in formulating for the best drug delivery and therapeutic effectiveness [27]. AI holds substantial promise in enhancing the prevention of adverse drug events (ADEs). The capabilities of AI in this field are expansive, offering advanced predictive analytics and early detection systems that can significantly reduce the occurrence and severity of ADEs. By harnessing modern ML techniques and natural language processing, AI can analyze vast amounts of data to identify patterns and predict potential ADEs before they occur [28].

Anaesthetic administration. The precise way in which general anaesthetics cause a reversible sedation remains a significant challenge in anaesthesia research. Since the 1950s, scientists have utilized pharmacokinetic and pharmacodynamic models to regulate anaesthetic infusion rates, control anaesthesia depth, and develop automated infusion systems that maintain stable drug concentrations. Currently, the target-controlled infusion (TCI) method has gained widespread use in clinical anaesthesiology. AI can calculate the dose-effect relationship based on pharmacodynamics and other drug features, and optimize drug infusion using real-time monitoring data [7].

Examples of pharmacological models that use AI are:

- Diprifusor (target controlled infusion pump utilizing pharmacological model);
- CLAD (drug administration systems designed to dispense medications with precision to achieve specific levels of anaesthesia);
- McSleepy (an independent system that concurrently manages sedation, pain relief, and muscle relaxation using propofol, remifentanyl, and rocuronium);
- SEDASYS (an AI system created to deliver propofol by doctors that are not anesthesiologists);
- goal-directed fluid therapy models (AI models administering fluid boluses based on patients' parameters), models for vasopressor titration (AI models adjusting vasopressor administration based on non-invasive blood pressure, stroke volume, and stroke volume variation) [26].

In 2018, Lee et al. proved that the bispectral index (BIS) predicted by DL models during TCI of propofol and remifentanyl is more precise than that predicted by traditional models [29]. Miyaguchi et al. focused on employing various ML models to predict the appropriate timing for administering remifentanyl, reflecting decisions made by anaesthesiologists [30]. Syed et al. developed a model that predicts the necessary sedation level for colonoscopy, taking into account factors such as patient demographics, current medical conditions, and prescribed drugs [31]. Wei et al. developed a model to forecast the ideal dose of 0.5% hyperbaric bupivacaine administered intrathecally for caesarean section [32]. In 2018, Mendez et al. demonstrated that automated delivery of propofol has better results than manual administration methods [33]. Xu et al. developed a computer-assisted diagnostic system that allows anaesthesiologists to dynamically make decisions on the delivery of a drug. This system reduced the time of

emergence and recovery, leading to higher satisfaction scores among patients [34].

Controlling anaesthesia depth. The depth of anaesthesia (DoA) relies on maintaining a balance between the administered anaesthetic dosage and the level of surgical stimulation [8]. ML encompasses numerous algorithms that can be employed to create a robust index for evaluating the DoA [35]. In several studies [36, 37, 38, 39, 40] assessment of DoA was performed with artificial neural networks using EEG features. Automated methods used in these studies outperformed the use of BIS.

Monitoring. AI-driven systems utilize complex algorithms to analyze real-time data, such as vital signs and drug levels, thereby enabling anaesthesiologists to make more informed and timely decisions. This approach surpasses traditional monitoring techniques by offering a dynamic, individualized assessment of a patient's condition, allowing for early detection of potential issues and facilitating proactive interventions. As a result, AI-enhanced systems not only improve the accuracy of patient monitoring, but also foster a more personalized and predictive model of anaesthesia management, significantly improving patient safety during surgeries [4, 14].

Pain management. Proper pain assessment is essential for determining effective treatment, but traditional self-reported methods have notable limitations. Techniques using AI offer a promising avenue for developing objective and standardized tools for pain assessment across diverse clinical settings. Behavioural-based methods in pain assessment include analyzing spontaneous facial expressions through image classification [41], as well as utilizing natural language processing, body posture analysis, and respiratory patterns. Neurophysiological approaches rely on biosignals, such as electroencephalography (EEG), electromyography (EMG), and electrodermal activity (EDA), to detect pain. Recent advancements combine these behavioural and neurophysiological data for a more comprehensive evaluation [42]. An ML algorithm is able to estimate the probability of a patient's post-surgical pain by analyzing patients and surgical features. This predictive model could be applied to anticipate pain more effectively, allowing for better pain management and enhancing patient recovery outcomes [14]. Patient-controlled analgesia (PCA) allows individuals to manage their pain by self-administering additional doses based on their pain levels, although it has limitations such as incomplete feedback and high rates of inadequate analgesia. To address these issues, AI patient-controlled analgesia (Ai-PCA) integrates AI and Internet of Things (IoT) technologies, improving the efficiency of acute pain services by identifying and alerting medical staff to adverse events, e.g. insufficient analgesia and excessive sedation. Studies indicate that Ai-PCA enhances postoperative pain management, reduces adverse reactions, and increases patient satisfaction, compared to traditional PCA [7].

Regional anaesthesia. The integration of AI into ultrasound-guided regional anaesthesia is a rapidly evolving field. According to Bowness et al. (2024), there are seven AI systems that are commercially used: cNerve, Nerveblox, NerveTrack, ScanNav Anatomy Peripheral Nerve Block, Smart Nerve

(used in peripheral nerve blockade), Accuro and uSine (used in central neuraxial blockade). These systems play a crucial role in detecting and tracking nerves and other structures, improving speed, efficiency and safety. This helps to reduce the costs of procedures [43].

Mechanical robots. AI has created robotic systems designed for such mechanical tasks as intubation, ventilation, and performing nerve blocks. Although these systems are currently used predominantly in simulated settings with mannequins, their future applications show considerable potential. The DaVinci surgical system has been used experimentally for fiberoptic intubations. Several robots have been developed for intubation: Kepler intubation system or REALITI. SAFIRA offers a safe method of injection for regional anaesthesia by aspirating and stopping the flow when the injection pressure goes beyond the limit. Magellan, operated via joystick, facilitated needle insertion during training for ultrasound-guided regional anaesthesia (UGRA). There is also a robot designed for positive-pressure bag-mask ventilation [26].

Issues. Integrating AI into anaesthesia and medical practice raises several ethical challenges, with the key concerns being data privacy and security. AI technologies rely on vast datasets comprising sensitive patient details, making it crucial to implement strong protections to maintain their confidentiality and integrity. To prevent data breaches and unauthorized access, it is essential to establish comprehensive data security measures, including advanced encryption methods, rigorous access controls, and clear policies on data usage [4, 5]. Another major issue is algorithmic bias. Bias in AI algorithms often arises from flawed or non-diverse training datasets, leading to discriminatory behaviour and unequal treatment outcomes. This disproportionately affects certain demographic groups, making continuous examination and adjustment of datasets crucial to uphold fairness and equity in patient care [4, 5, 44, 45].

The transparency and explainability of AI systems also present ethical challenges. Often, AI models function as 'black boxes', which complicates their application in clinical settings. To address this, AI systems need to produce outputs that are understandable and transparent, enabling healthcare professionals to grasp and trust how decisions are made by the AI. This transparency enhances collaborative decision-making and facilitates the seamless integration of AI into patient care [4, 7, 44]. The rise of AI in clinical decision-making may alter the patient-doctor relationship. It's essential to sustain empathy, clear communication, and human touch in patient care to balance the efficiency and objectivity offered by AI. AI should serve to augment, not substitute, human judgment to maintain trust and ensure patient involvement [4].

Finally, there are significant concerns regarding legal and ethical oversight. As AI technology evolves, legal standards surrounding negligence and physician responsibility must adapt. Clinicians must continuously update their knowledge and understand the strengths and limitations of AI systems to make informed decisions during patient care. These ethical considerations underline the need for ongoing dialogue between technologists, healthcare professionals and government, to ensure that AI advancements align with patient-centred values and ethical standards in medicine [12].

SUMMARY

AI has shown considerable promise in transforming various aspects of anaesthesiology, from preoperative to postoperative care. AI-driven systems leverage vast datasets and sophisticated algorithms to predict patient risk, manage drug dosages, administer drugs, and monitor vital signs more effectively than traditional methods. Its applications in anaesthesia can enhance patient outcomes through more personalized and precise interventions, optimize resource allocation in critical care, and improve overall efficiency in clinical practice. This capability not only helps in tailoring anaesthesia care to individual patient needs, but also facilitates real-time decision-making and proactive management of potential complications. The rapid development and high quality of AI research in anaesthesia underlines the substantial interest and potential this technology holds in the medical field. However, AI cannot entirely replace the nuanced understanding and empathetic care provided by human professionals. The integration of AI into clinical practice must be carefully managed to preserve the human aspects of medical care, such as empathy and patient communication. As AI technology advances, legal and ethical standards must evolve to address issues such as negligence and physician responsibility. Healthcare professionals must stay informed about the capabilities and limitations of AI to make well-informed decisions in patient care.

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