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Review article

The role of artificial intelligence in airway management: current applications and future perspectives

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Abbreviations

AI	– artificial intelligence
ANN	– artificial neural networks
AUC	– area under the curve
CNN	– convolutional neural networks
DL	– deep learning
FOB	– fibreoptic bronchoscopy
ML	– machine learning
RNN	– recurrent neural networks
ROC	– receiver operating characteristic

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Abstract

Background and purpose: *Artificial intelligence (AI) is a diverse field within computer science that focuses on creating and enhancing technologies, principles, methods, and application systems designed to replicate and enhance human intelligence. Over the past few decades, AI applications have significantly expanded across various medical fields. Despite the upgraded guidelines, challenges in managing difficult airways persist. Even with advancements in anaesthesia techniques and equipment, serious complications can still arise during the management of difficult airways. A consensus on the most effective method for assessing a difficult airway has not yet been established. Consequently, researchers are increasingly implementing AI and developing algorithms to assist anaesthesiologists and other healthcare professionals. This review aims to provide an overview and analysis of the current applications of AI in anaesthesiology, with a particular focus on difficult airways.*

Conclusions: *The development of AI has the potential to bring significant changes to this field, enabling more accurate and faster assessment of airway conditions, as well as improved monitoring during the intubation process. AI should serve as a supportive tool for physicians, simplifying their work and helping them make more informed decisions.*

INTRODUCTION

Artificial intelligence (AI) is a diverse field within computer science that focuses on creating and enhancing technologies, principles, methods, and application systems designed to replicate and enhance human intelligence. It often employs algorithms to reason through challenges and conducts analytical tasks *(1,2).*

Today, AI is involved in many scientific disciplines. The applications of AI have expanded greatly across various medical fields over the past few decades. Given the rapid advancements in AI, healthcare providers must grasp the current state of AI technologies and how these innovations can enhance the efficiency, safety, and accessibility of health services, ultimately leading to value-based care. AI in anaesthesiology focuses on improving patient safety, optimising resource utilisation, and elevating the quality of anaesthesia management throughout all stages of perioperative care (*2).*

This review aims to provide an overview and analysis of the current application of artificial intelligence in anaesthesiology, with a primary focus on managing difficult airways.

THE DEVELOPMENT OF ARTIFICIAL INTELLIGENCE

The concept of AI began to develop in the 20th century. The notion that machines could mimic human behaviour and potentially think like humans was first introduced by Alan Turing, who created the Turing test to distinguish between humans and machines. Since then, advancements in computing power have significantly increased, enabling instantaneous calculations and the ability to evaluate new information in real time based on previously processed data *(3).* The foundation for AI as a formal field was established in the 1950s, primarily based on the hypothesis proposed by John McCarthy. At the Dartmouth Conference, McCarthy introduced the term "artificial intelligence" for the first time *(4).* This conference marked the official inception of AI as an academic discipline, where researchers aimed to develop machines capable of human-like reasoning.

By the late 1970s, the first expert systems emerged, utilising databases and rule-based approaches for decision-making. Over the following decades, AI experienced periods of significant progress as well as setbacks, often referred to as "AI winters." During the 1970s and late 1980s, funding and interest in AI research declined due to unmet expectations and technological limitations *(5).* In the early 1990s, improvements in computational power sparked a resurgence in AI research, which led to the development of more sophisticated algorithms and enhanced computing hardware. Subsequently, advancements in computing power, algorithms, and data availability in the 21st century have contributed to the renewed prominence of AI applications across various domains.

The initial breakthrough of artificial intelligence in healthcare occurred in 1950. Subsequently, in 1975, the first research resource focused on the application of computers in medicine was developed. The advent of deep learning in the 2000s, along with the introduction of Deep Question Answering in 2007, significantly expanded the scope of AI applications within healthcare. In 2010, computer-aided diagnosis was first applied to endoscopy, and by 2015, the first Pharmbot had been developed. In 2017, the introduction of the first Food and Drug Administration-approved cloud-based deep learning application marked a crucial moment in the integration of AI into healthcare *(6).*

CONCEPT OF AI

Artificial intelligence involves machine learning (ML), deep learning, language processing, speech and image recognition, as well as expert systems *(2,7).* ML is an area of AI that centres on the development of algorithms designed to represent a given set of data optimally. In the field of machine learning, four primary learning approaches are frequently utilized, each serving distinct purposes: supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning *(8,9).* DL represents a branch of ML that utilizes neural networks, including convolutional neural networks (CNN), artificial neural networks (ANN), and recurrent neural networks (RNN). DL is commonly employed for image recognition and the identification of atypical patterns. ANN are DL algorithms modelled after the structure and function of biological neural networks. CNN represents a class of DL algorithms that are primarily used for image processing. They are recognised for their superior performance in handling inputs such as images, speech, and audio signals, setting them apart from other neural networks *(2,9).* RNN are a category of DL algorithms developed to process sequential data. They are primarily applied in areas such as natural language processing, speech recognition, robot control, sequential forecasting, and brain-computer interfaces (*2,9,10).*

Artificial intelligence has been utilized across multiple areas of medicine, spanning from predominantly diagnostic roles in radiology and pathology to more therapeutic and interventional functions in fields like cardiology and surgery. Anaesthesiology is uniquely positioned to benefit from advancements in artificial intelligence due to its involvement in various aspects of clinical care, such as perioperative and intensive care, pain management, and drug administration and development *(7).* The notable advancements in AI applications may provide solutions to the challenges faced during airway management *(11).*

AI in the assessment and management of difficult airways

A "difficult airway" is typically described as a clinical condition in which an anaesthesiologist with more than five years of experience faces significant difficulty in performing facemask ventilation or in intubating an artificial airway *(12).*

Despite upgraded guidelines, unanticipated problems with difficult airway management persist. Additionally, even with significant advancements in anaesthesia techniques and equipment, the occurrence of a difficult airway during intubation continues to lead to severe anaesthesia-related complications. The development of a difficult airway may cause damage to the trachea or oesophagus, aspiration, and severe hypoxemia, which can result in irreversible brain damage and, in some cases, lead to fatality *(2,13).* The anaesthesiologist needs to conduct a thorough preoperative assessment of the potential for a difficult airway. Proper perioperative evaluation can help minimise the occurrence of adverse events. However, a consensus on the most effective method for assessing a difficult airway has not yet been established *(14,15).* An ideal method for assessing difficult airways has yet to be established. Therefore, many researchers have attempted to implement artificial intelligence and develop various algorithms to assist anaesthesiologists and other healthcare professionals in their practices.

AI in facial image identification of difficult airways

In 2016, Cuendet et al. published their research findings, which focused on the use of AI in evaluating difficult airways. They utilized an automated facial analysis approach to detect morphological traits associated with difficult intubation and enhance its prediction. The study included a database of 970 patients, including photos, videos, and ground truth data. This AI model, based on facial scanning, achieved an area under the curve (AUC) of 0.779, demonstrating a level of precision comparable to that of conventional methods for predicting difficult airways (16). Hayasaka et al. utilised a CNN to develop an AI model that associates facial images with the actual difficulty of intubation, enabling the classification of intubation difficulties. The best AI model for classifying intubation difficulty was based on images taken in the supine, side-facing, closed-mouth position, with an AUC of 0.864, an accuracy of 80.5%, a sensitivity of 81.8%, and specificity of 83.3%. This study represented the initial effort to utilize deep learning (CNN) for distinguishing intubation difficulty. Tavolara et al. applied AI to this analytical system and developed a DL model using frontal images of faces. The model showed an AUC of 0.7105, demonstrating high sensitivity but low specificity *(17).* This study represents the initial step in developing a method for the clinical application of AI at the patient's bedside (18).

The results of a prospective cohort study were published in 2024 and conducted on a sample of 623 patients who underwent tracheal intubation. A three-step approach was utilized, which involved identifying 2D orofacial landmarks in preoperative photographs, extracting new 3D airway morphology measurements to predict intubation difficulty, and training specialized ML models to assess risk based on these features along with patient demographics. The median AUCs were between 0.746 and 0.766. This study proposed five ML and DL algorithms designed to classify difficult airways for tracheal intubation. The algorithms used preoperative photographs of each patient, one from a frontal view and one from a lateral view, as well as seven demographic variables: sex, age, height, weight, BMI, ASA status, and MMS score *(19).*

Predictive facial analysis models can be effectively utilized during preoperative assessments, enabling the anaesthesiologist to obtain additional information about the airway. However, these algorithms necessitate a substantial number of images of the patient's face from different angles. Thus, programs and algorithms will be needed to facilitate a more streamlined collection of perioperative images in the future *(18*).

Utilizing AI for speech feature analysis in difficult airways

Anatomical features that are recognised to contribute to difficult intubation include limited mouth opening, protruding teeth, a receding chin, a large tongue, and a narrow palate *(12,20).* Acoustic parameters examined during speech can indicate the anatomy of the upper airway. Structural changes in these anatomical features may also alter pronunciation, making speech a valuable indicator for predicting difficult airways. Several studies have investigated the potential role of acoustic features in evaluating a difficult airway.

One of the first studies to examine the association between acoustic characteristics and patients with difficult laryngoscopy, conducted within the Chinese population, was carried out in 2021. The study found that patients who experienced difficult laryngoscopy during orthognathic surgery exhibited distinct phonetic characteristics, supporting the notion that acoustic features can be used to predict difficult laryngoscopy accurately. Phonetic traits, including formant frequencies (f1–f4) and bandwidths (bw1–bw4), were effective in predicting difficult intubation and mask ventilation, with AUC values of 0.709 and 0.779, respectively. However, the study had several limitations, including a small sample size and its focus on the Chinese population and one specific type of surgery *(21).*

Another similar study investigated the predictive value of voice parameters for difficult mask ventilation. This study was conducted on patients undergoing general anaesthesia. The results suggest that voice parameters may be considered alternative predictors of difficult mask ventilation, although further studies are required to validate these preliminary findings *(22).*

AI innovations in video laryngoscopes and flexible bronchoscopes

In clinical practice, a video laryngoscope is frequently used in cases of difficult airways. Despite the many advantages of video laryngoscopes, two potential areas in the video laryngoscopy technique could be improved. Firstly, the 2D screen visualisation lacks depth perception, which can cause delayed or failed intubations. Secondly, the person performing the intubation must handle multiple tools at once. Several researchers have attempted to incorporate AI-based algorithms into existing video laryngoscopes to improve the visualisation of upper airway structures with real-time feedback *(2).*

Adamian et al. proposed a user-friendly software tool for the automated quantification of vocal fold movements from previously recorded video laryngoscopy examinations, referred to as automated glottic action tracking using artificial intelligence. The potential of this software could prove valuable in difficult airway cases *(18, 23).*

Wang et al. created a deep convolutional neural network capable of automatically identifying laryngeal adductor reflex events in laryngeal endoscopy videos. The experimental findings demonstrated promising results for the automated, objective, and quantitative analysis of these videos *(24).*

Few researchers have proposed a fully automated video segmentation system based on deep learning, designed to segment the vocal cords in laryngeal endoscopy videos *(25).* In a 2020 study, researchers aimed to develop a machine learning algorithm capable of real-time classification of vocal cords and tracheal airway anatomy during video laryngoscopy or bronchoscopy. They also assessed the performance of three innovative convolutional networks for detecting vocal cords and tracheal rings. A clinical dataset comprising 775 video recordings of laryngoscopy and bronchoscopy was used. The results demonstrated that the CNN, capable of identifying and classifying airway anatomy in real-time, achieved high performance *(26).*

AI algorithms are capable of automatically identifying blood vessels and the trachea based on fibreoptic bronchoscopy (FOB), providing valuable assistance to clinicians during intubation and positioning. This precise localization can lead to improved patient outcomes *(27).*

DISCUSSION

Airway management is a fundamental responsibility of anaesthesiologists, and ensuring adequate ventilation during the perioperative period is crucial for patient safety. Difficult airway management presents a notable challenge in clinical practice, especially in cases that demand immediate intubation or when there is a substantial risk of complications. Several studies on the incidence of intubation difficulties indicate a range of 5% to 27% *(28, 29).*

A variety of methods are employed to anticipate a difficult airway, including the modified Mallampati test, inter-incisor gap, thyromental distance, sternomental distance, upper lip bite test, and composite scores. Nevertheless, the commonly used clinical screening tests exhibit low sensitivity and specificity, as well as limited predictive value *(21).* Of the various methods, the upper lip bite test is the most precise when applied individually. Nonetheless, the AUC for the receiver operating characteristic (ROC) curve is approximately 0.70 *(30).* Additionally, all methods rely on the subjective assessment of the evaluator. From this perspective, an objective method for assessing difficult airways is crucial to minimise complications. The development of AI has the potential to bring significant changes to this field, enabling more accurate and faster assessment of airway conditions, as well as improved monitoring during the intubation process.

The use of AI in anaesthesiology is growing rapidly. A 2024 study assessed global research trends in AI for anaesthesiology using bibliometric software. The results showed that a total of 48 countries published research on AI and anaesthesiology. The top 10 countries in terms of the number of publications were the United States, China, the United Kingdom, South Korea, Canada, Germany, Italy, the Netherlands, France, and Spain. The strongest collaborations were between the USA, China, and England. A total of 715 institutions published research on AI and anaesthesiology, among which 43 institutions published more than 5 papers. The significant rise in the number of publications since 2018 indicates that research on AI in anaesthesiology is gaining growing attention *(31).* Research on AI in airway management primarily focuses on detecting airway structures, predicting difficult airways, and determining the appropriate size and depth for tracheal tube intubation *(32).* The focus of some studies has been on AI models based on facial and voice analysis, while other research has investigated innovations in video laryngoscopy and bronchoscopy.

AI has demonstrated significant advantages in image recognition, data analysis, and the construction of predictive models, helping to improve the safety, accuracy, and efficiency of anaesthesia *(31).* The facial analysis technique is a non-invasive method that allows for quick and objective assessments of facial features associated with airway difficulties, thereby enhancing predictive accuracy. This technology can be seamlessly integrated into existing AI systems and scaled to analyse large patient populations, improving overall workflow efficiency for healthcare providers. Additionally, the data collected can be used to refine algorithms and contribute to further research in the field, making it a valuable tool in airway management.

Voice production is a complex physiological process that involves the interaction of the vocal cords, larynx, pharynx, tongue, epiglottis, palate, hyoid bone, mandible, teeth, and lips, all of which play crucial roles in endotracheal intubation *(21,33).* Structural changes in the vocal tract can result in alterations to the acoustic properties of the voice. De Carvalho et al. reported that vowel formants exhibited a significant association with difficult laryngoscopy *(34)* and difficult facemask ventilation *(21).* AI models based on voice analysis require the patient to be awake and cooperative. Therefore, such models cannot be used to predict difficult airways in critically ill patients or in emergency surgery cases *(22).* The advantages of this approach include its non-invasive nature, allowing for easy integration into routine clinical practice without the need for additional procedural interventions. Furthermore, voice parameter-based methods offer the potential for automation and objectivity, enabling the simultaneous analysis of multiple voice characteristics. This could significantly enhance the accuracy and efficiency of airway assessments. Studies that focused on voice analysis as a predictor of difficult intubation were conducted on a small sample and within a specific population. Larger patient groups are necessary to investigate better the potential uses of acoustic parameters in patients with difficult intubation. It is also essential to include different age groups in future studies.

AI technology for assisting physicians with video laryngoscopy and flexible bronchoscopy (FOB) has been proposed relatively recently. It has not been widely implemented in clinical practice, with relevant studies and data still being scarce. As technology progresses, the visualization of tracheal intubation continues to improve. This not only minimises risks for patients but also alleviates stress for physicians. It can significantly enhance the success rate of the first attempt and reduce patient harm during procedures. The integration of AI has the potential to further elevate the performance of intubation devices to a new standard *(25).*

Challenges and limitations of AI

Research on AI in anaesthesiology is actively progressing, yet its limitations are becoming more evident. One primary concern is that AI relies on the analysis of large datasets, making the authenticity and accuracy of this data crucial. However, assessing the accuracy of the data can be challenging, highlighting the need for the establishment of regulatory bodies. Acquiring large datasets presents a considerable challenge, necessitating substantial human resources, financial investment, and collaboration among various institutions *(31).* AI models have primarily been developed in specific and predefined scenarios, which likely differ from those encountered in clinical practice, especially in emergency cases. As such, they do not account for all the unpredictable factors that can affect airway management *(30).* In certain studies, only patients from specific ethnic groups (such as Asian or European) were included, which limits the ability to generalise the findings to a broader population. This lack of diversity in research subjects not only affects the reliability of AI models but also underscores the need for inclusive research practices that reflect the diverse patient populations that clinicians serve.

Integration of AI tools into existing clinical workflows may also pose significant challenges that require careful consideration. Healthcare professionals may require additional training to effectively use these technologies, as the nuances of AI applications can differ from traditional methods. This training is critical not only for proficient use but also for maximising the potential benefits of AI in enhancing patient care. Moreover, there may be resistance to adopting new practices, stemming from concerns about the reliability of AI systems, the disruption of established routines, and the fear of obsolescence among healthcare staff.

Furthermore, the interpretability of AI models is essential; clinicians must understand the reasoning behind AI recommendations to trust their guidance and make informed decisions. Without clear explanations of how AI arrives at its conclusions, clinicians may hesitate to rely on these tools in high-stakes situations. This lack of transparency can lead to scepticism and hinder the integration process. Therefore, developers must focus on creating AI systems that provide clear and understandable insights and rationales, fostering a collaborative relationship between technology and healthcare providers. Ensuring that AI tools are user-friendly and effectively integrated into clinical workflows will be crucial for their successful implementation and widespread adoption in everyday medical practice.

CONCLUSION

The potential of AI in managing difficult airways is significant, especially with the rapid advancement of technologies. Innovations such as facial recognition and analysis, as well as voice analysis, can facilitate the prediction of difficult airways, thereby enhancing patient safety. Such methods are essential because they are non-invasive, easy to implement, and provide objective information. Therefore, they could play a promising role in managing difficult airways, but further development is necessary. Detection and anticipation of difficult intubation during the preoperative period are crucial, as unexpected difficult intubation can be associated with significant morbidity and mortality.

As AI continues to evolve, sustained research will be essential to fully harness its potential in improving both safety and efficiency in airway management. AI should serve as a supportive tool for physicians, simplifying their work and helping them make more informed decisions.

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