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Review Article

Integrating Artificial Intelligence and Digital Health Tools for Early Prediction of Pulmonology Disorder in Critical Care Unit

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Abstract

Background: Mortality prediction in ICU patients remains a critical unmet need. Clinical prediction is integral to modern healthcare, leveraging current and historical medical data to forecast health outcomes. The integration of Artificial Intelligence (AI) in this field significantly enhances diagnostic accuracy, treatment planning, disease prevention, and personalized care leading to better patient outcomes and healthcare efficiency.

Objectives: This minireview objective was to illustrate the role of artificial intelligence and digital health tools for early prediction of pulmonology disorder in critical care units.

Methods: We used a variety of research sources, including Google Scholar, Web of Science, PubMed, Springer, Frontiers, ELSEVIER, and Scopus. In our research we used key words including artificial intelligence, digital health, pulmonology, respiratory diseases, and intensive care unit. Up until 2026, studies published in English were included in the search. Articles with no full text available, conference abstracts, and publications written in languages other than English were excluded. To find further pertinent studies, the reference lists of chosen publications were also examined.

Results: The reviewed evidence demonstrates that the integration of artificial intelligence and digital health tools significantly enhances early prediction and risk stratification of pulmonary disorders in critical care settings. AI-based models showed high predictive accuracy for adverse respiratory outcomes, including acute respiratory failure, ARDS development, mechanical ventilation dependency, and weaning success, with reported AUROC values ranging from good to excellent across multiple studies. Machine learning algorithms utilizing clinical, ventilator-derived, imaging, and physiological data enabled earlier detection of clinical deterioration compared to conventional scoring systems. Additionally, digital health interventions, including telemonitoring and remote follow-up models, improved patient surveillance, continuity of care, and early identification of post-ICU respiratory complications.

Conclusions: Artificial intelligence and digital health tools represent powerful adjuncts in the early prediction and management of pulmonary disorders in critical care units. By enabling timely risk assessment, personalized ventilation strategies, and improved post-ICU monitoring, these technologies have the potential to reduce complications, ICU readmissions, and healthcare burden.

Keywords: Yam, Landraces, Yield and Post-harvest, Pest.

Introduction

Patients may become vulnerable to medical errors and adverse events during the transition from the intensive care unit (ICU) to general wards [1]. This transitional period is considered one of the most critical phases of hospitalization. The ICU provides continuous monitoring and multidisciplinary care, whereas such resources are more limited on general wards. Moreover, the healthcare team responsible for the patient's care changes during this transition. For these reasons, post-ICU care demands rigorous monitoring and standardized [2].

Among hospital wards, pulmonary medicine units hold a distinctive position. These wards commonly manage patients with acute or chronic respiratory conditions and are equipped to provide close respiratory monitoring such as continuous oxygen saturation monitoring and Noninvasive ventilation support. This makes them particularly well-suited for post-ICU patients with ongoing respiratory needs. Patients transferred from the ICU to the ward often include individuals who have received treatment for severe infections, respiratory failure, sepsis, or multiple organ dysfunction. Even after discharge from the ICU, these patients remain at risk of complications and clinical deterioration. This may lead to unfavorable outcomes such as ICU readmission or mortality [3]. Therefore, close monitoring of patients in the post-ICU period and early identification of high-risk individuals are essential. Several clinical parameters have been identified as being associated with in-hospital mortality during the post-ICU period. These include advanced age, altered mental status, hypoxia, need for mechanical ventilation, and elevated blood urea levels. Early assessment of prognosis in patients transferred to pulmonary medicine is crucial for optimizing clinical management [4].

With the large volume of data coming from implemented technologies and monitoring systems, intensive care units (ICUs) represent a key area for leveraging artificial intelligence (AI) to enhance patient care and outcomes through personalization and optimization of clinical decisions [5]. While recent advances in digital health have shown promise, predicting disease progression in patients with ILD and exacerbation in patients with COPD remains challenging. By enabling digital health and data collection, digital health tools can potentially improve self-management and deliver timely clinical insights [6]. So, our study aimed to evaluate the role of artificial intelligence and digital health in prediction of pulmonary diseases in intensive care units.

Understanding Pulmonology

Pulmonology is a vital field dedicated to improving respiratory health and addressing the diverse challenges associated with lung diseases [7]. This field encompasses a wide range of conditions, from common issues like asthma and Chronic Obstructive Pulmonary Disease (COPD) to more complex

disorders such as interstitial lung disease and pulmonary hypertension. As the world grapples with increasing respiratory illnesses and the ongoing impacts of air pollution, the role of pulmonologists medical professionals who specialize in this area has never been more critical. Pulmonology covers various respiratory disorders that impact the airways, lungs, and other structures involved in breathing. A chronic condition characterized by airway inflammation and hyper reactivity, leading to episodes of wheezing, shortness of breath, and coughing [8].

Asthma can be managed with medications and lifestyle changes, but it requires ongoing monitoring. A progressive disease primarily caused by long-term exposure to irritants such as tobacco smoke [9]. COPD includes chronic bronchitis and emphysema, both of which cause breathing difficulties and a significant decline in lung function over time [10]. A group of disorders characterized by inflammation and scarring of lung tissue. Interstitial Lung Disease (ILD) can be idiopathic or associated with other conditions like autoimmune diseases or occupational exposures. Managing ILD often involves immunosuppressive therapies and careful monitoring [11].

Elevated blood pressure in the pulmonary arteries can lead to heart failure and reduced exercise capacity. This condition can be primary (idiopathic) or secondary to other diseases such as left heart disease or chronic lung conditions. Pulmonologists often work closely with oncologists to diagnose and manage lung cancer, which can be primary or metastatic [12]. Early detection and treatment are crucial for improving outcomes. Pulmonologists utilize a range of diagnostic tools to assess respiratory conditions. A fundamental test that measures lung function by assessing the volume and flow of air during inhalation and exhalation. It's crucial for diagnosing conditions like asthma and COPD [13,14]

Imaging techniques provide detailed views of the lungs, helping in diagnosing and monitoring various respiratory conditions, including infections and tumors [15]. A procedure that involves inserting a flexible tube with a camera into the airways to directly visualize the lungs. It is useful for diagnosing infections, obtaining biopsies, and managing certain conditions. These tests measure various aspects of lung function, including lung volumes, capacities, and gas exchange efficiency. They are essential for assessing the severity of diseases and monitoring treatment progress [16].

Treatment in pulmonology is often multifaceted and tailored to the specific condition and patient needs. Approaches include. These may include bronchodilators, corticosteroids, and other drugs to manage inflammation, open airways, and control symptoms [17]. Used for patients with severe respiratory conditions or low blood oxygen levels, this therapy helps improve oxygenation and quality of life. In some cases, surgery may be necessary to treat conditions like lung cancer or

severe emphysema. Procedures can range from minimally invasive techniques to more extensive surgeries. Advancements in pulmonology are driven by ongoing research and technological innovations. Emerging treatments, such as targeted therapies and biologics, offer new hope for managing complex respiratory diseases [18].

Artificial Intelligence

Artificial intelligence (AI) refers to the simulation of human intelligence, including critical thinking, perception, reasoning, learning, planning, and predicting, using systems or machines [19]. AI is classified into three categories: First, artificial narrow intelligence (narrow or weak AI) is goal-oriented and designed for specific tasks. While these systems are considered intelligent, they do not mimic human intelligence. These systems simulate human behavior based on predefined parameters, for example, virtual assistants on smartphones and email spam filters. Second, artificial general intelligence (strong or deep AI) are machines that mimic human intelligence, potentially solving problems similarly to humans. Last, artificial super intelligence is a hypothetical concept where machines surpass human capabilities and become self-aware, as depicted in various science fiction [20].

Learning is the most crucial property of AI, reflecting the machine's ability to acquire or memorise knowledge with-

out explicit programming. Machines learn using various approaches, such as machine learning (ML) as the broad subset of AI, with deep learning (DL) and reinforcement learning (RL) as the subsets of ML, and natural language processing (NLP) as an application area with the ML (Figure 1) [21]. ML enhances performance over time by obtaining more data, empowering computer systems to “learn” independently by processing data through algorithms, detecting patterns, and making accurate predictions. Some methods include forward reasoning, backward derivation, regression, clustering, and categorisation [22].

DL, the subset of ML, involves artificial neural networks (ANNs) to solve problems. ANNs, composed of interconnected “neurons,” mimic the human brain's decision-making processes. DL algorithms process data through ANNs, with each layer progressively extracting information. Some commonly used DL networks include convolutional neural networks (CNNs) for image recognition, recurrent neural networks (RNNs) for sequential data, autoencoders for unsupervised learning, and generative adversarial networks for generative tasks [23]. RL, a subset of ML, shares the characteristics of both supervised and unsupervised processes and enables machines to learn through trial-and-error using their own experiences. In RL, agents receive rewards or penalties based on outcomes, facilitating learning [24].

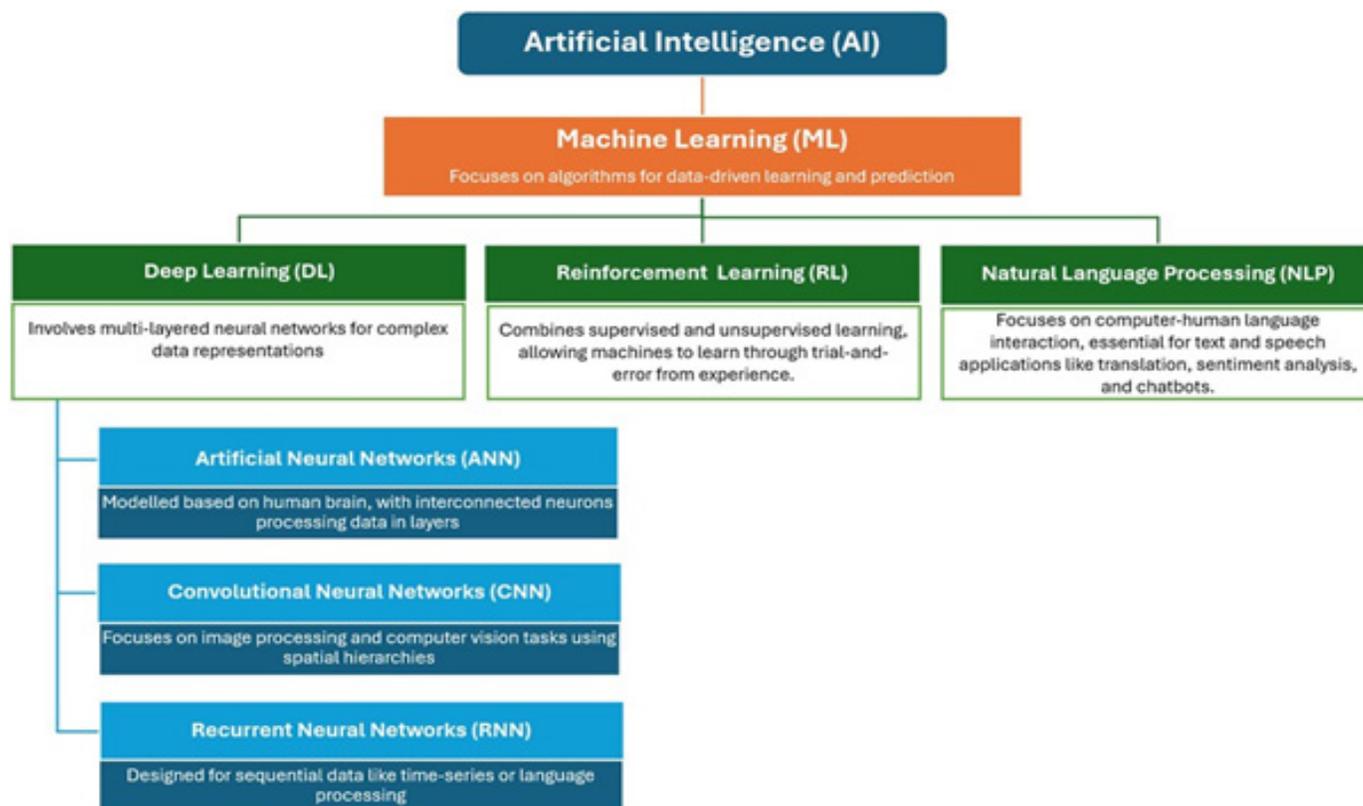


Figure 1. An overview of artificial intelligence [20].

Applications of AI in ICU

Early disease identification, prediction of patients' clinical evolution, personalized treatment strategies and optimization of healthcare resources allocation are to be considered the future promises of AI application in critical care [25]. Despite the use of AI in ICU is still taking its first steps, several studies have so far revealed the potentials of this technology in the management of critically ill patients. Some of these used big data sets in order to predict length of stay and mortality, while others applied AI for early detection of sepsis and septic shock, cardiocirculatory failure, and acute respiratory conditions [26-28].

In their recent validation study, Persson et al tested the NAVOY sepsis algorithm demonstrating its ability to detect patients at high risk to develop sepsis within 3 h. This algorithm revealed a prediction performance superior to existing sepsis early warning scoring systems (eg, SOFA, qSOFA, MEWS, NEWS2), showing its usefulness if integrated into routine clinical practice [29]. The Feasible Artificial Intelligence with Simple Trajectories for Predicting Adverse Catastrophic Events model can predict the onset of cardiac arrest or acute respiratory failure from 1 h to 6 h prior to its occurrence (AUROC 0.886 and 0.869, for the 2 respective outcomes), [30]. The use of AI in ICU environments is mainly limited to machine learning which combines statistical analysis techniques with computer science to produce algorithms aimed at generating knowledge from available data, but with no actual intervention on events. Even if this application of AI technology would be of great assistance for intensivists dealing with information overload and the need to make quick decisions, the "predictive" AI approach should be complemented by an "actionable" AI approach [31]. This refers to casual inference, or the ability to predict outcomes and events that would result from alternative decisions/treatments. Hence, the comparison of different future potential outcomes deriving from different decisions/treatments should lead AI to identify "the best possible predicted outcome," and therefore choose the optimal decision/treatment [32].

The Use of AI for Mechanical Ventilation Management

More than any other device in ICU, mechanical ventilators offer a large amount of data as settings, waveforms, alarms, and measured parameters [33]. When integrated with clinical variables and patient characteristics, it is reasonable to expect that the implementation of AI might improve efficiency, efficacy, and safety in critical care. Most studies involve the use of AI to predict outcomes for mechanically ventilated patients, including the need for mechanical ventilation, the complications, and the weaning success [34].

Timely identification of patients developing ARDS and risk stratification through AI implementation has been explored in different studies [35]. Interestingly, by combining structured (monitor and laboratory data) and unstructured data (clinical notes), Apostolova et al. applied a deep learning approach to

build context vectors containing information on patients' conditions, which were then combined together and analyzed by a prediction model in order to successfully identify early development of ARDS [36].

Another potential advantage of AI implementation for mechanical ventilation practice is its ability to identify specific phenotypes and personalize treatments accordingly: hypo- and hyperinflammatory ARDS phenotypes might in fact benefit from different therapeutic approaches. With regard to ventilation, AI may indicate the most correct strategy which may be beneficial for the considered ARDS subphenotype in real time and modify ventilator parameters accordingly [37]. Mechanical ventilation is admittedly an "open-loop" system, where the input (the set ventilation mode) is not influenced by the output (the adequacy of the ventilation settings): an ideal model should adjust the ventilator settings while analyzing respiratory mechanics and considering potential clinical improvements [32]. Thus, "closed-loop" newer ventilation modes could target complex purposes such as prevention of ventilator-induced lung injury, continuously adapting to lung mechanics and patient conditions, while even testing weaning success and extubation readiness [38]. In this respect, it should be noted that the currently commercially available mode INTELLiVENT-Adaptive Support Ventilation (INTELLiVENT-ASV®, Hamilton Medical) has thus far proven to be clinically safe and to effectively reduce healthcare team workload by reducing manual setting adjustments [39].

Patient-ventilator asynchronies too have been extensively explored, given how lack of adequate patient-ventilator coupling is known to be associated with higher mortality and delayed extubation [40]. Sottile et al. applied a number of machine learning algorithms on data from 62 ventilated patients at risk for, or affected by ARDS. In their study, they were able to identify synchronous breathing and presence of asynchronies (double triggering, flow limitation, and ineffective triggering) with high sensitivity and specificity [41]. In their pilot study, Gholami et al. used a machine learning framework to automatically and continuously detect cycling asynchronies based on waveform analysis: this model detected the presence of cycling asynchronies with a sensitivity and specificity of 89% and 99%, respectively. The results of these and other studies may represent a turning point in mechanical ventilation, enabling clinicians to adequately respond to alerts while ameliorating ventilation management [42].

The VentAI is a reinforcement learning algorithm which is able to suggest a dynamically optimized mechanical ventilation regime for critically ill patients. Authors used a Markov decision process, including a reward system and a Q-learning approach, to find the optimized settings for positive end-expiratory pressure, fraction of inspired oxygen, and ideal body weight-adjusted tidal volume (Vt). They observed that VentAI would adjust settings more frequently when compared to human decisions, indicating a continuous reevaluation of

the ventilation strategy to find the best fit for the individual patient [43].

Identifying the right time for weaning initiation from mechanical ventilation is essential, given the associated risks and the lack of standardized protocols. An exponentially growing body of AI-related literature has been focused on the predic-

tion of weaning timing and extubation success, demonstrating promising outcomes, including increased ventilator-free days and shorter ICU length of stay. These results highlight the potential of AI-guided weaning strategies and prediction models for helping clinicians in their decisions (Figure 2), [44].

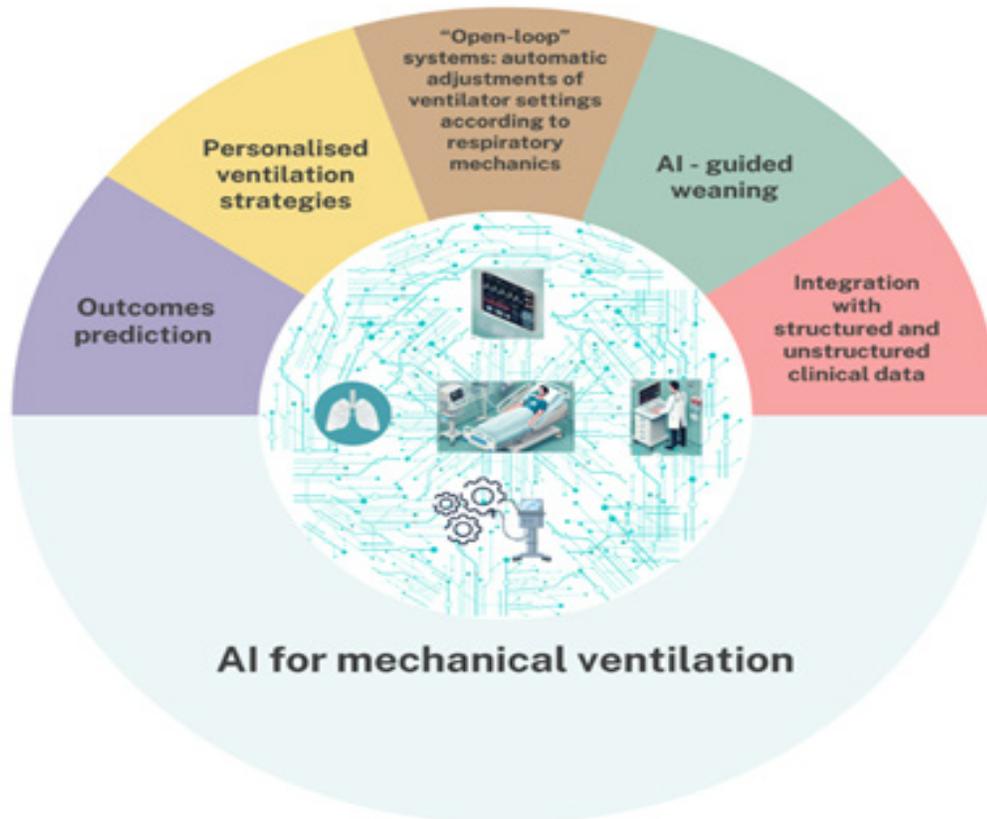


Figure 2. Infographic on artificial intelligence use for mechanical ventilation [32].

Artificial intelligence (AI) and machine learning (ML) in MV Weaning Prediction

The process of weaning patients from mechanical ventilation is complex, with multiple stages from the initiation of ventilation to liberation and extubation. Delayed or failed weaning leads to increased complications and mortality [45]. In recent years, several studies have been performed in order to generate ML/AI-based MV weaning prediction models. Neural networks (NNs) model, designed by Kim, used a novel DL model called FT-GAT in order to predict a successful SBT and, eventually, extubation. The AUROC of this model was 0.8, with a similar AUROC being found upon temporal validation [46].

Menguy et al. used a data-mining process and AI on a prospective database of 108 medical ICU patients in order to find predictors of a successful SBT and weaning from MV for at least 72 h after extubation. In their analysis, cardiovascular parameters (reflected in heart rate variability) had a substantial impact on SBT success in addition to respiratory and

systemic parameters (respiratory drive and BMI, respectively). Although the association between heart rate variability and ventilation weaning outcome is established, not many AI modals use this parameter in their algorithms [47,48].

The support vector machine model developed by Fabreget attempts to predict the likeliness of extubation failure, advising ICU physicians to reconsider their decision to extubate. This model, based on data reflecting the state of the patient 2 h before a planned extubation, showed excellent predictive capabilities, with an AUROC of 98.3% [49]. Hung et al. developed a real-time AI model for predicting successful extubation using only six ventilator-derived features. This random forest model exhibited a strong predictive performance, with an AUROC of 0.976. This model enables the prediction of MV weaning success every 3 min and is easily applicable in clinical practice in the ICU [50].

Chen et al. developed a simplified AI model using only 7 parameters (expiratory minute ventilation, expiratory tidal volume, ventilation rate set, heart rate, peak pressure, pH,

and age), reporting an AUROC comparable to a previously built 28-parameter AI model that predicts the success in MV weaning in the coming 24 h among cardiac care unit patients (AUROCs: 0.86 vs. 0.88, respectively), [51]. Jia et al. developed a convolutional NN (CNN) explainable prediction model that can assist clinicians in deciding the feasibility of MV weaning within the next hour. This model incorporates an advanced DL approach in addition to classic AI models (e.g., CNN). This aims to provide physicians with an importance assessment of the relevant clinical factors that can assist them in understanding which treatable factors can lead an individual patient to successful MV weaning [52].

Liu et al. developed a model that predicts the success and timing of MV weaning in two stages: from intubation to the change in the ventilator mode, and from assist control to support mode and the following stage that includes the weaning itself. Each stage was divided into 11 time frames, and the AI system provides the probability of weaning success in the nearest time frames. The implementation of this system in clinical practice led to a shortening of the MV duration by 21 h and a shortening of ICU length of stay (LOS) by 0.5 days compared to previous data, although the weaning success rates were similar [53].

In conclusion, it was emphasized that the need for AI- and ML-based models as a reliable tool to assist the physician in decision making for weaning from mechanical ventilation, particularly in the challenging-to-wean ARDS population. Clinical studies employing ML as a tool have demonstrated promising outcomes, including reduced ML durations and shorter LOSs in critical care units in diverse populations [54,44].

The Role of Artificial Intelligence in Pulmonary Medicine

AI has significantly enhanced the diagnostic accuracy of pulmonary conditions through advanced medical imaging analysis. AI algorithms, such as convolutional neural networks, have demonstrated remarkable proficiency in interpreting chest X-rays and computed tomography (CT) scans to detect diseases such as pneumonia, tuberculosis, and lung cancer. AI models have shown high accuracy in identifying lung nodules and predicting their malignancy, facilitating early detection and treatment of lung cancer [55]. In the case of idiopathic pulmonary fibrosis (IPF), AI has been instrumental in improving diagnostic accuracy. AI algorithms can analyze high-resolution CT scans to identify specific patterns indicative of IPF, enabling earlier and more accurate diagnoses. This advancement is crucial as early diagnosis can significantly impact disease management and patient outcomes [56,57].

AI's predictive capabilities are transforming the management of chronic respiratory diseases such as chronic obstructive pulmonary disease and asthma. ML models can predict exacerbations by analyzing patient data, including medical history, medication use, and environmental factors

[58]. This allows for timely interventions that can prevent hospitalizations and improve quality of life. AI-driven mobile applications monitor asthma symptoms and environmental triggers, providing personalized recommendations and alerting health-care providers about potential exacerbations. In COPD management, AI algorithms predict the risk of acute exacerbations by analyzing pulmonary function test results and other clinical data. This enables early intervention and personalized treatment plans, reducing the frequency and severity of exacerbations [59].

AI aids in developing personalized treatment plans by integrating data from various sources, including genomics, imaging, and electronic health records. In pulmonary embolism (PE) care, AI can track patient scans and monitor therapeutic responses, enabling clinicians to tailor treatments more precisely and adjust them in real time based on the patient's progress [60]. AI algorithms also predict patient responses to specific medications based on genetic profiles, optimizing drug efficacy and minimizing adverse effects. In cystic fibrosis management, AI-driven precision medicine approaches analyze genetic and clinical data to provide personalized treatment recommendations, improving patient outcomes and quality of life [61].

AI has made significant strides in pulmonary imaging, particularly in the interpretation of chest CT scans and X-rays. AI-powered tools can detect lung nodules, classify lung textures, and quantify the extent of diseases such as COVID-19 and interstitial lung disease. During the COVID-19 pandemic, AI algorithms identified characteristic patterns of COVID-19 pneumonia on CT scans, aiding in swift and accurate diagnosis [62]. Dynamic Digital Radiography, an AI-powered X-ray imaging technique, provides additional quantitative data by visualizing lung function and diaphragm motion during normal breathing patterns. This technology offers a comprehensive assessment of respiratory function, aiding in the differentiation of pulmonary disorders and guiding treatment decisions [61].

AI is accelerating research and clinical trials in pulmonary medicine by improving patient recruitment and data analysis. AI-driven patient recruitment enhances the efficiency and accuracy of identifying eligible participants in studies on PE, expediting the research process, and contributing to faster clinical advancements. In addition, AI can analyze vast amounts of clinical trial data to identify trends and outcomes that might not be immediately apparent, leading to new insights and more effective treatments [63].

In critical care settings, AI is utilized to monitor and manage patients with severe respiratory conditions. For example, AI algorithms analyze data from ventilators and other monitoring devices to predict respiratory failure or other complications, allowing for timely interventions. These systems assist in adjusting ventilator settings to optimize patient outcomes, reduce the incidence of ventilator-associated complications, and support weaning processes. Furthermore, AI can inte-

grate data from multiple sources, including laboratory results, imaging, and clinical notes, to provide a comprehensive overview of a patient's condition and support decision-making in intensive care units [31].

The future of AI in pulmonary medicine looks promising, with ongoing research focused on developing more sophisticated algorithms and expanding AI applications. Innovations such as AI-driven three-dimensional reconstruction for lung volume measurement in transplantation and predictive models for ventilator-associated complications are just the beginning [64]. As AI continues to evolve, it will undoubtedly play a crucial role in shaping the future of pulmonary care. Future developments might include the use of AI in telemedicine to remotely monitor patients with chronic respiratory diseases, providing continuous care and reducing the need for frequent hospital visits. Pavithra et al. discuss the assessment of lung health status by analyzing cough sound using "Swaasa AI Technology." Embracing these technological advancements is essential for improving patient outcomes and advancing the field of pulmonary medicine [65].

Digital Health

Digital health is transforming medical and health practices.

The field has seen rapid growth; the development of new technologies facilitates medical research as well as personalized medicine [66]. Digital health has revolutionized the delivery of healthcare; it is changing the way in which we diagnose, treat, manage and prevent health conditions. The term digital health has expanded to encompass a much broader set of scientific concepts and technologies, including genomics, artificial intelligence, analytics, wearables, mobile applications, and telemedicine. Digital technology is also a major factor in shifting the focus of healthcare from healthcare professionals to patient-centric. Many digital health tools, particularly wearables and mHealth apps, now place patients in the front seat [67].

The development of requirements will vary across types of digital health solutions based on functionality (diagnostics, monitoring, care coordination, etc.), which can also be modeled from other industry approaches. It is critical to incorporate the preferences of the clinicians and patients impacted by the digital health solution into the requirement development process. Once requirements are established, the proposed framework that could form the basis for evaluation includes the following domains: technical, clinical, usability, and cost (Figure 3), [68].

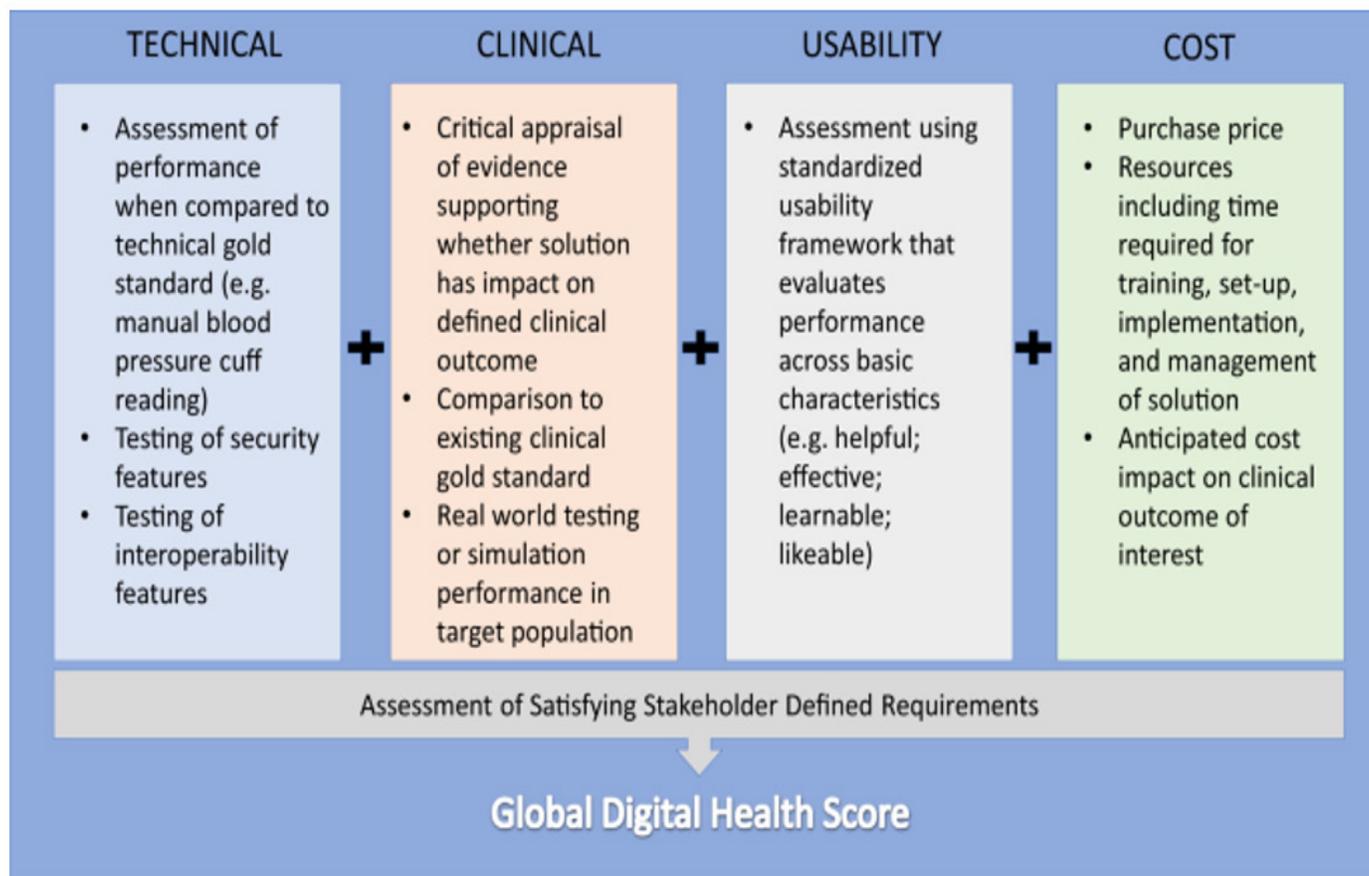


Figure 3. Components of Digital Health Scorecard. The four domains of a digital health scorecard with example considerations are detailed in this figure. Their relationship to an assessment of stakeholder requirements is also presented [68].

Role of Digital Health in Intensive Care Unit

Post-intensive care unit (ICU) models of follow-up are limited in availability, accessibility, and efficacy [69]. The optimal mode of delivery is unclear. Digital health models of follow-up care may be a promising mode of delivery. A recent systematic review identified that models without in-person hospital attendance, including digital health models, had higher rates of patient recruitment, intervention delivery, and participant retention than hospital-based models [70,71]. The nexus of post-ICU follow-up care and digital health has the potential to yield improvements in recovery from the ICU and warrants a specific review. Digital health is a rapidly expanding area of healthcare [72].

There is significant potential for digital health interventions to provide cost-effective and scalable interventions to improve health outcomes and health system efficiencies while overcoming some of the barriers related to accessing in-person models of care. Digital health interventions use technologies such as smartphones, websites, and text messaging to provide health care and are often complex interventions, with multiple intervention components and aims. Digital health interventions have been demonstrated to improve outcomes in other chronic diseases including diabetes, cardiac rehabilitations, mental health, and other chronic diseases [73,74]. Within the field of critical care, digital health interventions have been implemented in the ICU predominantly to support remote monitoring and delivery of tele-ICU to provide access to specialist input in non-metropolitan settings and family engagement, particularly during the COVID-19 pandemic visitation restrictions [75]. Digital health interventions in ICU recovery is a nascent field but has the potential to address the known physical, psychological, time, and financial barriers to attending hospital-based ICU recovery programs. Studies predominantly delivered digital health interventions focused on psychological and physical rehabilitation. Digital health interventions included telehealth ICU follow-up clinics, cognitive and physical telerehabilitation, telephone coping skills training, phone cognitive skills training, mindfulness training program via a self-directed software program application (app), app-based cognitive behavioural therapy, virtual reality education on the ICU, and a web-based cognitive-behavioural writing therapy [76-79].

The role of Digital Health in Respiratory Diseases

As one of the best recognised examples of digital medicine, telemedicine serves as an alternative to traditional in-person clinic visits [80]. There are many cases in respiratory medicine where telemedicine has developed into a sustained and practical way of delivering healthcare. For example, telemedicine is well-suited to manage patients with sleep and ventilation disorders. Using remotely monitored data from ventilation devices and connecting virtually with patients most in need of care rather than routine in-person clinic visits makes for a more efficient delivery of care. Similarly, pulmonary re-

habilitation can be successfully delivered online, leading to a wider participation by patients who might otherwise not be able to travel to in-person classes [81].

These examples address some challenges associated with traditional in-person clinics, notably time constraints and patient convenience. The approach also leads to enhanced patient retention and reduced carbon emissions by minimising travel requirements [82]. Patients have high rates of reported satisfaction with telemedicine delivered care, demonstrating that they are not only practical but well-received. However, clinician enthusiasm for telemedicine has significantly declined since the coronavirus 2019 (COVID-19) pandemic, when its use flourished. Some of this waning enthusiasm may reflect the difficulty in financial reimbursement, as well as a return to the “old ways”, wherein clinicians feel that they deliver better care in person providing the “human touch” [83].

Digital therapeutics (DTx) deliver medical interventions directly to patients using evidence-based, clinically evaluated software aimed at treating and preventing a broad spectrum of diseases and disorders [84]. DTx are increasingly being used in respiratory medicine for conditions such as smoking cessation. Virtual cognitive behavioural therapy platforms, accessible online or via app-based programmes, are now recommended by National Institute for Health and Care Excellence guidelines for the treatment of insomnia. Digital therapeutics for dysfunctional breathing, a common yet debilitating condition, are also in development [85].

AI-Assisted Microwave Based Dual Sensor System for Digital Pulmonology

Electrical impedance distribution in the human body is different as conductivity in each tissue is different. Conductivity also changes with pathology. This principle has been used in electrical impedance tomography (EIT) imaging systems to diagnose various diseases. EIT is a new technology with clinical applications in specific lung pathology diagnosis, tumor detection and real-time monitoring of lung volume changes [86]. The electrical properties of normal and diseased tissue in the human body are different. Bioimpedance studies help diagnose pathological tissues, including cancer. Yang et al. conducted a multicenter study using electrical impedance analysis (EIA) as a diagnostic tool for pulmonary lesions. The study showed that EIA is an excellent diagnostic tool for lung cancers with high accuracy and can be adjunctively used with other diagnostic methods [87].

Similarly, microwave imaging (MWI) techniques are based on the dielectric properties of biological tissues. MWI uses electromagnetic waves at frequencies ranging from 0.5 GHz to 9.0 GHz to detect dielectric contrast that scatters from the tissue of the imaging domain [88]. Microwave (MW) technology can potentially help diagnose malignant tumors and other pathologies using the evaluation of complex permittivity of the tissue [89]. MW are safe diagnostic tools that generate

images based on differences in dielectric properties. Recently, MWI has been gaining attention for diagnoses of various diseases such as breast cancer, bone tumors, stroke and lung cancer. Multiple studies have shown the difference in dielectric properties of ground glass opacities in lung lesions and the potential of MWI to detect these lesions [90].

Khalesi et al. successfully experimented with Huygens principle-based MWI to see lung lesions in phantoms. The aim was to investigate elliptical, asymmetric and multilayer torsos. They suggested further research for a better MWI device that can be used in clinical trials for lung imaging [91]. Another study used a human torso to detect pulmonary edema and hemorrhage using MWI. They used a contrast source inversion method based on MWI and used the Cole–Cole model to determine the dielectric properties of human tissues. They simulated the scattered field via the method of moments [92].

There is an excellent development of electro-acoustic sensors based on electro-acoustic transduction in industrial, scientific and healthcare applications. Recently there have been tremendous advancements in acoustic biosensors, which are widely used to detect various diseases [93].

It is evident that microwave-based sensors for a dual acoustic sensing for PPG and dielectric properties imaging are feasible with significant advancements in the AI-assisted microwave sensing and image reconstruction. Figure 4 depicts an implementation example of digital phonopulmography using dual microwave sensing systems and its potential impact. Novel microwave-based acoustic PPG sensors will open new avenues for technologies suitable for the accurate capture and recording of lung sounds. Digital phonopulmography using AI-assisted dual microwave sensing can positively impact pulmonology clinical practice operations as well as enhance patient care [90].

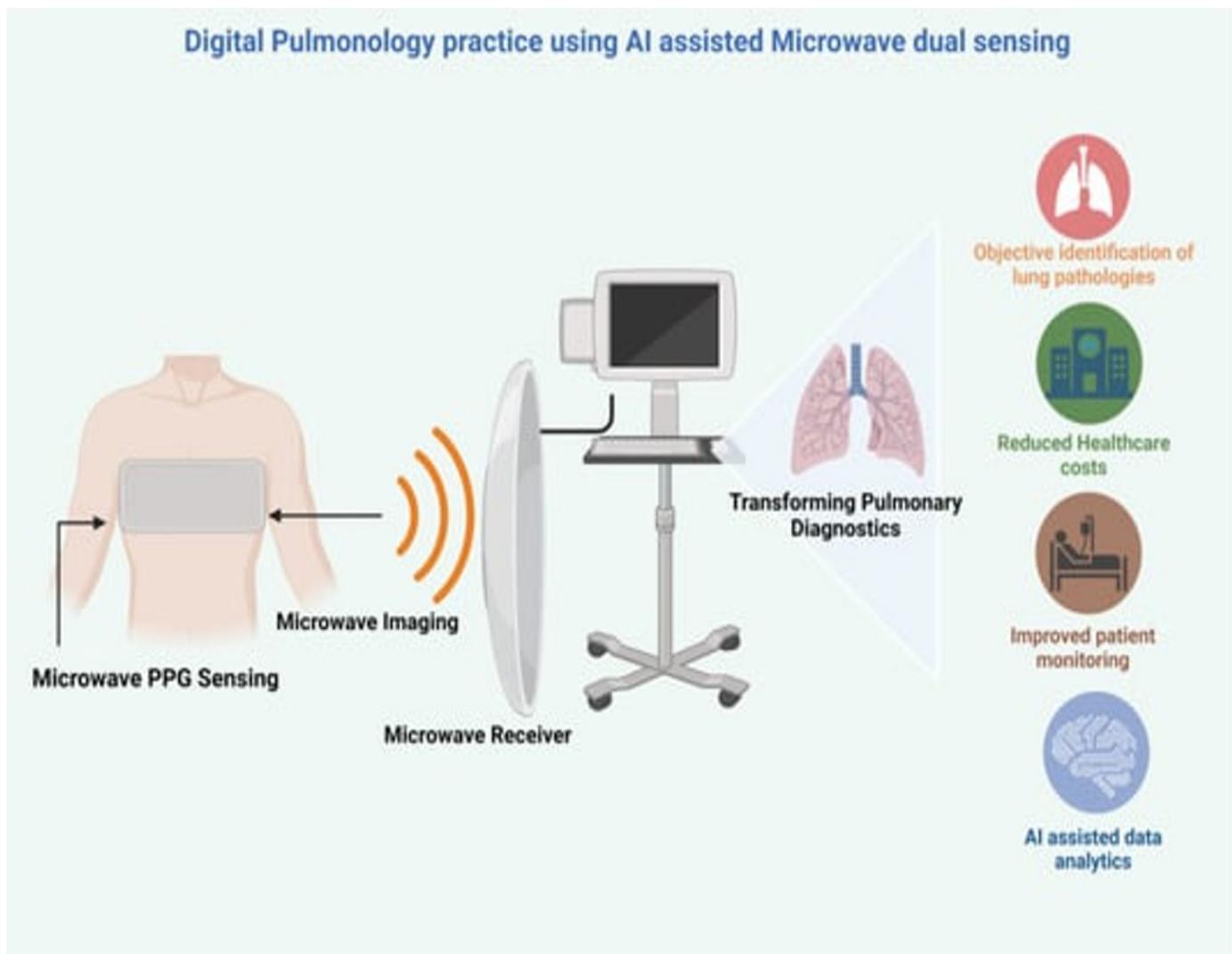


Figure 4. Pictorial representation of digital phonopulmography using AI-assisted dual microwave sensing systems [90].

Conclusion

In conclusion, the integration of artificial intelligence and digital health tools has emerged as a transformative approach in the early prediction and management of pulmonary disorders within critical care units. Evidence from recent studies highlights the ability of AI-driven models to analyze complex, high-dimensional data derived from clinical variables, ventilator parameters, imaging, and physiological monitoring, enabling early detection of respiratory deterioration, personalized treatment strategies, and optimized mechanical ventilation management. In parallel, digital health interventions, including telemonitoring, telemedicine, and digital therapeutics, have demonstrated potential in enhancing post-ICU follow-up, continuity of care, and early identification of high-risk patients. Despite these promising advances, the implementation of AI and digital health in routine critical care practice remains challenged by issues related to data quality, model interpretability, clinical integration, and ethical considerations. Embracing these technologies holds substantial promise for improving patient outcomes, reducing ICU-related morbidity, and shaping the future of pulmonary care in critical care settings.

Declaration

Consent for Publication: All authors have read and revised the manuscript and agreed to its publication.

Availability of Data and Material: All data supporting the study are presented in the manuscript or available upon request.

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Authors' Information (optional): Not applicable

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