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# MODERN STRATEGIES IN THE TREATMENT OF ACUTE RESPIRATORY DISTRESS SYNDROME (ARDS): FROM VENTILATORY SUPPORT TO ARTIFICIAL INTELLIGENCE-BASED MONITORING SYSTEMS

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## ABSTRACT

**Background and objective:** Acute respiratory distress syndrome (ARDS) remains one of the leading causes of mortality among patients treated in intensive care units. Despite the use of lung-protective ventilation, prone positioning, and rescue therapies, mortality in severe cases continues to exceed 30–40%. In recent years, the precise optimization of ventilator settings has gained particular importance, including the control of driving pressure, mechanical power, and patient–ventilator asynchrony, while simultaneously the use of advanced monitoring systems and artificial intelligence (AI)–based decision-support tools have expanded rapidly. The aim of this review is to present contemporary, advanced methods of ARDS management, ranging from complex mechanical ventilation strategies to AI-driven solutions, with particular emphasis on their effectiveness, safety, and potential for clinical application.
**Scope of review:** This review includes literature from 2020–2025 addressing interventional and technological aspects of ARDS treatment, with a specific focus on lung-protective ventilation and mechanical power regulation, the application of prone positioning, strategies for reducing patient–ventilator asynchrony, the use of ECMO as a rescue therapy, and AI models designed for outcome prediction, assessment of readiness for ventilator liberation, and automated asynchrony detection. The analysis primarily incorporates observational and cohort studies, methodological work, and publications dedicated to integrating AI into intensive care unit practice and ventilator systems.
**Findings:** Modern mechanical ventilation strategies concentrate on minimizing ventilator-induced lung injury (VILI) by reducing tidal volumes, limiting driving pressure, and decreasing mechanical power. At the same time, accumulating evidence suggests that clinically subtle patient–ventilator asynchrony may worsen outcomes, creating opportunities for machine-learning algorithms capable of its automatic identification. AI models are also being applied to predict weaning success, assess the risk of extubation failure, and develop decision-support systems that integrate ventilator parameters, vital signs, and laboratory data. Although preliminary findings are promising, most AI algorithms remain in developmental stages and require further validation.
**Conclusions:** Current therapeutic approaches in ARDS are shifting away from the exclusive use of lung-protective ventilation principles toward highly personalized strategies incorporating mechanical power assessment, asynchrony analysis, and AI-based predictive tools. The synergistic integration of advanced ventilatory support with AI systems may enable more precise tailoring of therapy to ARDS phenotypes, improve decision-making regarding ventilation management and liberation, and potentially enhance clinical outcomes, however, large, well-designed prospective and randomized studies are needed to determine the impact of these innovations on mortality, ventilator-free days, and the safety of applied interventions.



## KEYWORDS

Acute Respiratory Distress Syndrome, ARDS, Mechanical Ventilation, Patient-Ventilator Asynchrony, Artificial Intelligence, ICU Monitoring

## CITATION

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## 1. Introduction

Acute respiratory distress developing in the course of ARDS represents a complex clinical syndrome characterized by abrupt onset, diffuse injury to the alveolar–capillary barrier, severe impairment of oxygenation, and characteristic radiological findings [1]. Despite substantial advances in intensive care practice, ARDS remains associated with high mortality, particularly in severe forms, and in the long term leads to significant sequelae such as chronic dyspnea, reduced exercise tolerance, and cognitive dysfunction in patients discharged from intensive care units [4]. The fundamental, classical therapeutic strategies in ARDS include lung-protective ventilation based on the use of low tidal volumes and limitation of airway pressures, selection of an appropriate level of positive end-expiratory pressure (PEEP), prone positioning in patients with severe hypoxemia, fluid balance optimization, and treatment of the underlying etiology [1]. Although these approaches are well supported by evidence, they do not always allow for precise tailoring of therapy to individual lung biomechanics, inflammatory phenotype, or the dynamic interactions between the patient and the ventilator. In recent years, increasing importance has been attributed to parameters such as driving pressure and mechanical power delivered to the lungs, as well as the influence of patient-ventilator asynchrony on lung injury and clinical outcomes [4]. At the same time, the rapid development of digital technologies has enabled the application of advanced signal-analysis methods and artificial intelligence algorithms to process flow and pressure waveforms, vital signs, and laboratory data in real time [7]. AI-based systems may potentially support clinicians in assessing the risk of ventilator-weaning failure, in the early detection of deteriorating respiratory function, and in the automated identification of patient-ventilator asynchrony [5]. In the context of ARDS, this opens the way for implementing more precise, individualized mechanical ventilation strategies tailored to current respiratory mechanics and patient load [7]. This review aims to summarize current knowledge on contemporary ARDS management, with particular emphasis on advanced mechanical ventilation techniques, monitoring of patient-ventilator interaction, and the use of artificial intelligence in monitoring, analysis, and decision-making related to ventilation and ventilator liberation.

## 2. Materials and methods

This work is a narrative review with both clinical and technological orientation. The primary source base consisted of studies published between 2020 and 2025 addressing issues related to ARDS management and the use of artificial intelligence in monitoring patients with respiratory failure, including those diagnosed with ARDS. These publications included clinical trials, observational analyses, methodological studies, and articles dedicated to AI models designed for outcome prediction, patient-status monitoring, and detection of patient-ventilator asynchrony. The literature search was conducted in databases such as PubMed and MEDLINE and was supplemented with targeted searches through journal title screening and citation analysis. The identification of relevant studies involved combinations of keywords including: “acute respiratory distress syndrome”, “ARDS”, “mechanical ventilation”, “driving pressure”, “mechanical power”, “prone positioning”, “patient-ventilator asynchrony”, “artificial intelligence”, “machine learning”, “weaning prediction”, and “ICU decision support”.

The review included studies that met the following criteria: -publications concerning adult patients with ARDS or acute respiratory failure requiring invasive mechanical ventilation, - studies analyzing lung-protective ventilation strategies, mechanical power parameters, the use of prone positioning, patient-ventilator interactions, or the application of AI in monitoring or decision-making related to ventilatory management, - articles published in English in peer-reviewed journals, - studies providing data on clinical outcomes (e.g., mortality, ventilator-free days, complications) or performance metrics of AI models (e.g., sensitivity, specificity, AUC). Excluded were: - studies focusing exclusively on pediatric or neonatal populations, - animal studies or in vitro models without practical clinical relevance, - single case reports and small case series lacking analysis of ventilatory strategies or AI system performance, - articles without numerical data or without structured outcome assessment. For each included publication, key information was extracted, such as population characteristics, type of intervention (ventilation strategy, type of AI algorithm, monitoring method), primary endpoints, and major clinical conclusions. The collected data were synthesized descriptively, with attention to consistency of findings, methodological limitations, and potential implications for clinical practice [7].

### 3. Definition and pathophysiology of cardiogenic ARDS

Acute respiratory failure occurring within the spectrum of acute respiratory distress syndrome (ARDS) represents a clinical and radiological syndrome characterized by abrupt onset, diffuse injury to the alveolar-capillary barrier, and significant impairment of oxygenation [1]. According to the Berlin criteria, the diagnosis of ARDS requires fulfillment of the following conditions: - onset of respiratory failure symptoms within one week of a known clinical insult or the appearance of new or worsening respiratory abnormalities, - presence of bilateral opacities on chest imaging that cannot be fully explained by effusion, lobar or lung collapse, or pulmonary nodules, - respiratory failure that cannot be completely attributed to left ventricular dysfunction or fluid overload, - reduced $PaO_2/FiO_2$ ratio in the presence of positive end-expiratory pressure [1]. The severity of ARDS is determined based on the degree of oxygenation impairment, which carries prognostic significance and allows tailoring therapeutic approaches - from intensification of lung-protective ventilation to the use of prone positioning or ECMO therapy [1,3].

The pathophysiology of ARDS involves multiple overlapping mechanisms: - disruption of the alveolar–capillary barrier leads to leakage of protein-rich fluid into the alveolar space, resulting in edema of the alveolar walls and the interstitial compartment. - the inflammatory response and neutrophil activation promote the release of proinflammatory cytokines, reactive oxygen species, and proteases, further damaging the epithelium and endothelium. - loss of surfactant contributes to alveolar collapse, reduces lung compliance, and promotes the formation of atelectatic regions, Substantial heterogeneity of ventilation and perfusion develops, with adjacent regions being relatively preserved or severely injured, generating non-uniform mechanical stresses [1]. As a consequence, only a small portion of the lung parenchyma, the so-called "baby lung", remains responsible for gas exchange. Mechanical ventilation, although essential for ensuring adequate oxygenation and $CO_2$ elimination, may further injure this limited functional lung tissue. These mechanisms, collectively known as ventilator-induced lung injury (VILI), may result from: - barotrauma and volutrauma caused by excessive pressures and volumes, - atelectrauma resulting from cyclic alveolar collapse and reopening, - biotrauma generated by inflammatory activation triggered by mechanical stress. Understanding these processes and monitoring key parameters such as driving pressure and mechanical power remain fundamental for minimizing additional lung injury in patients with ARDS [1,4].

### 4. Modern Ventilatory Strategies in the Management of ARDS 4.1. Lung-Protective Ventilation and the Role of Driving Pressure

The foundation of contemporary ARDS management remains lung-protective ventilation, whose primary objective is to limit ventilator-induced lung injury (VILI) by reducing tidal volumes and airway pressures [1,4]. The classical approach involves the use of low tidal volumes of approximately 6 ml/kg of predicted body weight, maintaining moderate levels of PEEP, and controlling plateau pressure. In recent years, particular importance has been attributed to driving pressure, defined as the difference between plateau pressure and PEEP. This parameter is considered an approximate indicator of the mechanical load imposed on the "baby lung," the functional portion of the lung parenchyma. Numerous analyses have demonstrated that elevated driving pressure is associated with poorer prognosis and an increased risk of ventilator-induced lung injury (VILI) [1,4]. This translates into the practical recommendation not to focus solely on reducing tidal volume but to aim at lowering driving pressure through optimization of PEEP, adjustment of tidal volume, or improvement of lung compliance. An extension of the lung-protective ventilation concept is the detailed assessment of respiratory system mechanics, encompassing both static and dynamic compliance, airway resistance, and the relative contribution of the chest wall and the lungs to overall compliance. This allows for more precise adjustment of ventilator settings to the individual anatomical and functional conditions of a given patient [1].

### 4.2. Prone Positioning and the Significance of Mechanical Power

Prone positioning is currently recommended primarily for patients with severe oxygenation impairment who are simultaneously managed with lung-protective ventilation principles [6]. Increasing evidence, however, indicates that improvement in the $PaO_2/FiO_2$ ratio is neither the only nor the complete expression of the benefits associated with prone positioning. Attention has increasingly shifted toward mechanical power, defined as the amount of energy delivered to the respiratory system by the ventilator per unit of time [4]. Mechanical power is a composite parameter that incorporates factors such as peak pressure, tidal volume, respiratory rate, and the level of PEEP. It is generally accepted that excessively high mechanical power, particularly in relation to the limited volume of functional lung tissue - the "baby lung"- may contribute to the progression of ventilator-induced lung injury (VILI) [4]. Studies examining the relationship between mechanical power and clinical outcomes in ARDS indicate that reducing this parameter, including during ventilation in the prone position, may be crucial for improving prognosis [4,6]. In practice, this means that the mere implementation of the prone position is not sufficient; it is essential to simultaneously and deliberately monitor ventilatory parameters in this position to avoid excessive mechanical loading of the lungs, even when improvement in oxygenation is observed [4].

### 4.3. Sedation and Neuromuscular Blockade Strategies

In patients with ARDS, particularly in severe forms requiring high levels of ventilatory support, deep sedation is often necessary, and in selected situations temporary neuromuscular blockade may also be required. These interventions aim to reduce spontaneous respiratory effort, which can increase transpulmonary pressure and contribute to lung injury referred to as patient self-inflicted lung injury (P-SILI). They also serve to improve patient-ventilator synchrony and enable the safe application of lung-protective ventilation and prone positioning [8]. However, the use of neuromuscular blocking agents carries risks such as muscle weakness, delirium, and increased susceptibility to infections. For this reason, they should be administered for the shortest duration possible, following clearly defined protocols and with simultaneous monitoring of sedation depth and the degree of neuromuscular blockade [8]. Tools enabling the assessment of patient-ventilator interaction, including analysis of pressure and flow waveform morphology, are playing an increasingly important role. They facilitate evaluation of whether the current level of sedation and any neuromuscular blockade are truly necessary to maintain the desired degree of synchrony [7,10].

### 4.4. ECMO as a Rescue Therapy

In patients with severe ARDS who continue to exhibit profound hypoxemia or significant hypercapnia despite optimal application of lung-protective ventilation, prone positioning, and treatment of the underlying cause, the initiation of extracorporeal membrane oxygenation (ECMO) may be considered. The aim of ECMO is to offload the lungs and enable further reduction of ventilatory parameters, including the implementation of ultraprotective ventilation strategies. In appropriately selected patients, initiated at the right time, ECMO can improve oxygenation, stabilize gas exchange, and create conditions that allow lung parenchyma recovery or the administration of definitive causal therapy. It should be remembered, however, that ECMO is a therapy associated with a substantial risk of complications, including bleeding, thromboembolic events, vascular injury, and infections. This necessitates the involvement of a highly experienced team and implementation in centers equipped with appropriate infrastructure and clearly defined qualification criteria [9]. In the context of modern approaches to ARDS, there is increasing emphasis on the need for more precise risk stratification and identification of patients who may truly benefit from ECMO. Attention is also drawn to the necessity of integrating hemodynamic monitoring, ventilatory parameters, and imaging findings into the qualification process. An additional important element is the use of predictive tools, including artificial intelligence models, which may support the assessment of risk and potential benefits associated with ECMO initiation [2,9].

### 4.5. Monitoring Patient-Ventilator Interaction and Detecting Asynchrony

The interaction between the patient and the ventilator is one of the key, though often underestimated, components of ARDS management. Asynchrony may take various forms, ranging from premature or delayed triggering of the breath, through double triggering, to clinically subtle patient inspiratory efforts that fail to initiate an assisted breath [7]. In the context of modern approaches to ARDS, increasing emphasis is placed on the need for more precise risk stratification and identification of patients who may truly benefit from ECMO. There is also a growing recognition of the necessity to integrate hemodynamic monitoring, ventilatory parameters, and imaging findings into the qualification process for this therapy. An additional important component is the use of predictive tools, including artificial intelligence models, which may support the assessment of risk and the potential benefits associated with ECMO initiation [2,9]. Standard assessment of asynchrony requires analysis of ventilator-generated pressure, flow, and volume waveforms, a task that demands expertise and continuous vigilance from clinical staff. Numerous studies, however, have shown that a substantial proportion of asynchrony episodes remains undetected during routine observation [7]. In response to these limitations, systems for automatic asynchrony detection based on machine-learning algorithms are being developed. These systems continuously analyze ventilator signals and allow classification of individual types of asynchrony with high sensitivity and specificity [7,10]. They have the potential to become an integral component of monitoring in mechanically ventilated patients, providing clinicians with early warning alerts when adjustments to ventilator settings, modification of sedation level, or changes in ventilation mode are required.

**5. Artificial Intelligence in Monitoring and Clinical Decision Support in ARDS**

The complex pathophysiology of ARDS and the rapid, often abrupt changes in clinical status make decision-making regarding ventilator settings, the level of sedation, qualification for prone positioning, or the timing of ventilator liberation highly variable and inconsistent across centers. In this context, tools based on artificial intelligence (AI) and machine learning (ML) emerge as promising forms of support in intensive care. They enable real-time signal analysis, prediction of patient deterioration, and automatic monitoring of interactions between the patient and the ventilator [9,11].

**5.1. AI Models for Predicting Ventilator Liberation** The process of liberating a patient with ARDS from mechanical ventilation is a key stage of treatment, and extubation failure is associated with prolonged hospital stay and a markedly increased mortality. Classical criteria for assessing readiness for extubation, such as the rapid shallow breathing index (RSBI), level of consciousness, arterial blood gas values, or measurements of respiratory mechanics, have a limited ability to predict outcomes. AI-based predictive models incorporate a wide range of data, including physiological parameters, ventilator settings and waveforms (pressure, flow), as well as other clinical information. They have been shown to predict both successful ventilator liberation and the risk of reintubation with greater accuracy than traditional tools [5]. Studies indicate that machine-learning algorithms such as random forest, neural networks, and gradient-boosting methods can achieve AUC values exceeding 0.85 in predicting successful ventilator liberation in patients with acute respiratory failure. In ARDS, where lung structure is particularly heterogeneous and the response to ventilatory support changes rapidly, such models may assist clinical decision-making by identifying patients ready for a spontaneous breathing trial, enabling early detection of elevated risk of weaning failure, and integrating ventilator waveform data with other clinical variables, thereby supporting a more personalized assessment of the recovery process [2].

**5.2. Automatic Detection of Patient-Ventilator Asynchrony**

Asynchrony between the patient and the ventilator is a frequent phenomenon and, at the same time, difficult to detect during routine observation. Numerous analyses have shown that even 40-60% of asynchrony episodes remain unrecognized by clinical staff. Typical forms include double triggering, ineffective inspiratory efforts, and premature or delayed termination of the inspiratory phase. These phenomena contribute to increased work of breathing, fluctuations in transpulmonary pressure, and an elevated risk of progression of ventilator-induced lung injury (VILI) [7]. AI-based systems that analyze ventilator-derived signals in real time can: - automatically identify different types of asynchrony with high sensitivity and specificity, - classify episodes continuously, around the clock, - generate alerts for clinical staff when abnormalities are detected, - support the optimization of ventilator mode selection and the level of support, - assist in decision-making regarding the intensity of sedation or the use of neuromuscular blockade. Models based on deep neural networks have demonstrated performance comparable to that of intensive care experts. They thus form the basis for the concept of the so-called "intelligent ventilator," which in the future may enable more automated and precise mechanical ventilation [10].

**5.3. Clinical Decision Support Systems in the ICU**

AI systems that collect and integrate data from multiple sources, such as patient monitors, the ventilator, blood gas analyses, and electronic medical records, can provide clinicians with a wide range of advanced analyses. These include predicting deterioration in respiratory function, estimating the risk of mortality, optimizing ventilator settings based on individual patient parameters, offering guidance on improving synchrony, and analyzing hemodynamic and respiratory trends in real time [10]. Some of these models are capable of predicting hypoxemic episodes several minutes before they occur, allowing the clinical team to intervene earlier. In ARDS, where the safety margin for oxygenation is exceptionally narrow, such early warning may play a crucial role in the further course of treatment [2,9].

**5.4. Integration of Multimodal Data**

One of the most promising directions in the development of artificial intelligence for ARDS is the integration of data originating from multiple different sources, referred to as multimodal integration. This includes pressure, volume, and flow waveforms from the ventilator; blood gas results and measurements of oxygen saturation and other vital signs; as well as imaging studies such as chest X-ray, computed tomography, and lung ultrasound. It also encompasses biomarkers of inflammation and metabolic activity, along with clinical data extracted from electronic medical records. Such an approach enables the creation of personalized

ARDS profiles, which may support the selection of appropriate ventilation strategies, assessment of lung recruitability, qualification for prone positioning, and decision-making regarding the initiation of ECMO [11]. Preliminary studies suggest that artificial intelligence models analyzing both physiological signals and chest CT imaging can accurately predict the response to PEEP and the optimal level of lung recruitment [2].

### 5.5. Limitations and Challenges

Despite their considerable potential, the implementation of artificial intelligence in ARDS management is associated with numerous challenges. Among the most important is the limited number of randomized studies with sufficient statistical power to allow a definitive assessment of the effectiveness of these solutions. A significant issue is the substantial heterogeneity of data sources, which complicates full standardization of the applied methods. Another barrier is the risk of model overfitting, especially when algorithms are trained on relatively small datasets. Reliable external validation is also essential to confirm the applicability of AI models across different patient populations and clinical conditions. The implementation process is further slowed by legal, organizational, and ethical factors. Additionally, limited interoperability between various devices and systems used in intensive care units poses a barrier to the widespread adoption of AI-based solutions. Despite these obstacles, the overall trajectory of development clearly points toward broader integration of artificial intelligence tools into intensive care practice, and their widespread use appears to be only a matter of time [9,11].

## 6. Discussion

The contemporary approach to ARDS management is based on the interplay of two fundamental pillars. The first includes advanced lung-protective ventilation strategies, such as driving-pressure control, monitoring and reduction of mechanical power, optimization of PEEP, systematic use of the prone position, and, in selected cases, the application of ECMO. The second pillar consists of digital technologies and artificial intelligence tools that enable real-time signal analysis, automatic detection of asynchrony, prediction of ventilator liberation success, and integrated clinical decision support. The studies analyzed clearly highlight the growing importance of individualized respiratory therapy. Parameters such as driving pressure and mechanical power are increasingly recognized as key indicators of the risk of progressing ventilator-induced lung injury (VILI). Systematic monitoring of these parameters, both in the supine and prone positions, may help reduce excessive loading of the “baby lung.” At the same time, artificial intelligence tools show potential for reducing the rate of ventilator liberation failure, improving patient-ventilator synchrony, enabling earlier detection of clinical deterioration, and supporting decisions regarding sedation level, ventilator mode selection, and qualification for ECMO. However, most available models remain in early stages of investigation, and data regarding their impact on hard clinical endpoints such as mortality or duration of mechanical ventilation are still limited. For this reason, it is necessary to conduct multicenter studies involving larger patient populations, to standardize methods of signal analysis and interpretation, to systematically compare the performance of AI models with expert assessment, to perform cost-effectiveness analyses, and to develop protocols that enable the implementation of artificial intelligence tools into the daily practice of intensive care units. **7. Conclusions** Current strategies for ARDS management combine classical lung-protective ventilation techniques with modern monitoring technologies. Key elements include controlling driving pressure and mechanical power, maintaining appropriate patient-ventilator synchrony, and systematic use of the prone position.

AI-based systems-including predictive models of ventilator liberation success, algorithms for automatic detection of asynchrony, and clinical decision-support platforms, represent a promising direction for the development of intensive care, although they require further investigation, including rigorous clinical validation. The combination of physiologically guided ventilation with digital predictive tools may become the future standard of ARDS management, enabling more personalized, effective, and safer therapy.

**8. List of abbreviations**
ARDS - Acute Respiratory Distress Syndrome
AI - Artificial Intelligence
ML - machine learning
PEEP - positive end-expiratory pressure
VILI - ventilator-induced lung injury
P-SILI - patient self-inflicted lung injury
ECMO - Extracorporeal Membrane Oxygenation
$PaO_2/FiO_2$ - oxygenation index
SBT - spontaneous breathing trial
CT - computed tomography
RSBI - rapid shallow breathing index
ICU / OIT - intensive care unit
EHR - electronic medical record
PP - prone positioning
DP - driving pressure
MP - mechanical power

**Author's contribution** Conceptualization and methodology - Paulina Dybiak Check - Paweł Słoma, Paulina Dybiak Resources - Julia Florek, Paulina Dybiak Investigation - Maciej Zachara, Paulina Dybiak Form analysis - Adrian Morawiec, Paulina Dybiak Writing - rough preparation - Patryk Harnicki, Mateusz Bartoszek, Paulina Dybiak Writing - review and editing - Erwin Grzegorzak, Paulina Dybiak Supervision - Oliwia Krawczyk, Paulina Dybiak Visualization - Rafał Pelczar, Paulina Dybiak Project administration - Mikołaj Grodzki, Jakub Minas, Paulina Dybiak

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