REVIEW

# Monitoring lung recruitment

*Gianmaria Cammarota[a], Rosanna Vaschetto[a], Luigi Vetrugno[b]*
*and Salvatore M. Maggiore[c]*

**Purpose of review**

This review explores lung recruitment monitoring, covering techniques, challenges, and future perspectives.

**Recent findings**

Various methodologies, including respiratory system mechanics evaluation, arterial bold gases (ABGs) analysis, lung imaging, and esophageal pressure (Pes) measurement are employed to assess lung recruitment. In support to ABGs analysis, the assessment of respiratory mechanics with hysteresis and recruitment-to-inflation ratio has the potential to evaluate lung recruitment and enhance mechanical ventilation setting. Lung imaging tools, such as computed tomography scanning, lung ultrasound, and electrical impedance tomography (EIT) confirm their utility in following lung recruitment with the advantage of radiation-free and repeatable application at the bedside for sonography and EIT. Pes enables the assessment of dorsal lung tendency to collapse through end-expiratory transpulmonary pressure. Despite their value, these methodologies may require an elevated expertise in their application and data interpretation. However, the information obtained by these methods may be conveyed to build machine learning and artificial intelligence algorithms aimed at improving the clinical decision-making process.

**Summary**

Monitoring lung recruitment is a crucial component of managing patients with severe lung conditions, within the framework of a personalized ventilatory strategy. Although challenges persist, emerging technologies offer promise for a personalized approach to care in the future.

**Keywords**

arterial blood gases, artificial intelligence, computed tomography scanning, electrical impedance tomography, esophageal pressure, lung recruitment, lung ultrasound, machine learning, respiratory mechanics

## INTRODUCTION

Monitoring lung recruitment plays a crucial role in the optimization of ventilatory strategy and achievement of lung protection in critically ill patients with severe lung involvement [1]. This is of particular interest for titrating positive end-expiratory pressure (PEEP), a key element in invasive mechanical ventilation (IMV), especially in those conditions characterized by wide variability in lung recruitability as acute respiratory distress syndrome (ARDS) is [2].

Despite practical applications, quantifying lung recruitment remains controversial because of the different assessment methodologies adopted, ranging from quantitative lung imaging, for total volume quantification of previously gasless tissue regaining aeration [3▪▪], to the evaluation of the respiratory system mechanics, based on tidal compliance change in response to PEEP variation [4]. Unfortunately, these approaches intrinsically differ, as improved respiratory system mechanics may arise from an increased number of aerated units or, alternatively, a higher compliance in already open units [5].

This review delves into various aspects of lung recruitment monitoring, encompassing techniques, associated challenges, and future perspectives.

## TECHNIQUES FOR LUNG RECRUITMENT MONITORING

Various methodologies are employed to assess lung recruitment including respiratory system mechanics evaluation, arterial bold gases (ABGs) analysis, lung

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[a]Department of Translational Medicine, Università del Piemonte Orientale, Novara, [b]Department of Medical, Oral and Biotechnological Sciences and [c]Department of Anesthesiology and Intensive Care, Ospedale SS Annunziata & Department of Innovative Technologies in Medicine and Odonto-stomatology, Università Gabriele D’Annunzio di Chieti-Pescara, Chieti, Italy

Correspondence to Professor Gianmaria Cammarota, MD, PhD, Department of Translational Medicine, Università del Piemonte Orientale, Novara, Italy. Tel: +39 3213733406; e-mail: gmcamma@gmail.com

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## KEY POINTS

- Lung recruitment definition is heterogeneous being related to the methodology used in its assessment.
- Various methodologies are employed to assess lung recruitment.
- The tools used in lung recruitment evaluation require expertise in application and data interpretation.
- The perspective of integration between the methodology used to assess lung recruitment and artificial intelligence is of great interest for the implementation of clinical decision-making process at the bedside.

imaging, and esophageal pressure (Pes) measurement (Fig. 1).

## Respiratory system mechanics

Monitoring changes in ventilator parameters, such as tidal volume and driving pressure, which are both components of respiratory system compliance (Crs), theoretically provides valuable information about lung recruitment. Crs is demonstrated to correlate with the amount of spared lung in ARDS [6]. However, changes in lung recruitment assessed through computed tomography (CT) scanning have shown poor correlation with modifications in Crs because of the parenchymal inhomogeneity typical of ARDS [2]. When measuring Crs, gas insufflation may alternatively lead to overdistention in open alveolar units and reaeration in atelectatic alveolar units, with the net effect depending on the balance between these two opposite actions.

A static pressure–volume curve obtained through a low-flow insufflation–deflation maneuver provides the estimation of lung recruitability and recruitment at the bedside [7–9]. The area enclosed between the inspiratory and expiratory limbs of the pressure–volume loop, known as pulmonary hysteresis, is correlated with lung recruitment [7–9]. Assessment of hysteresis has recently been utilized to enhance the interpretation of PEEP decremental trial in ARDS patients under IMV [10■■].

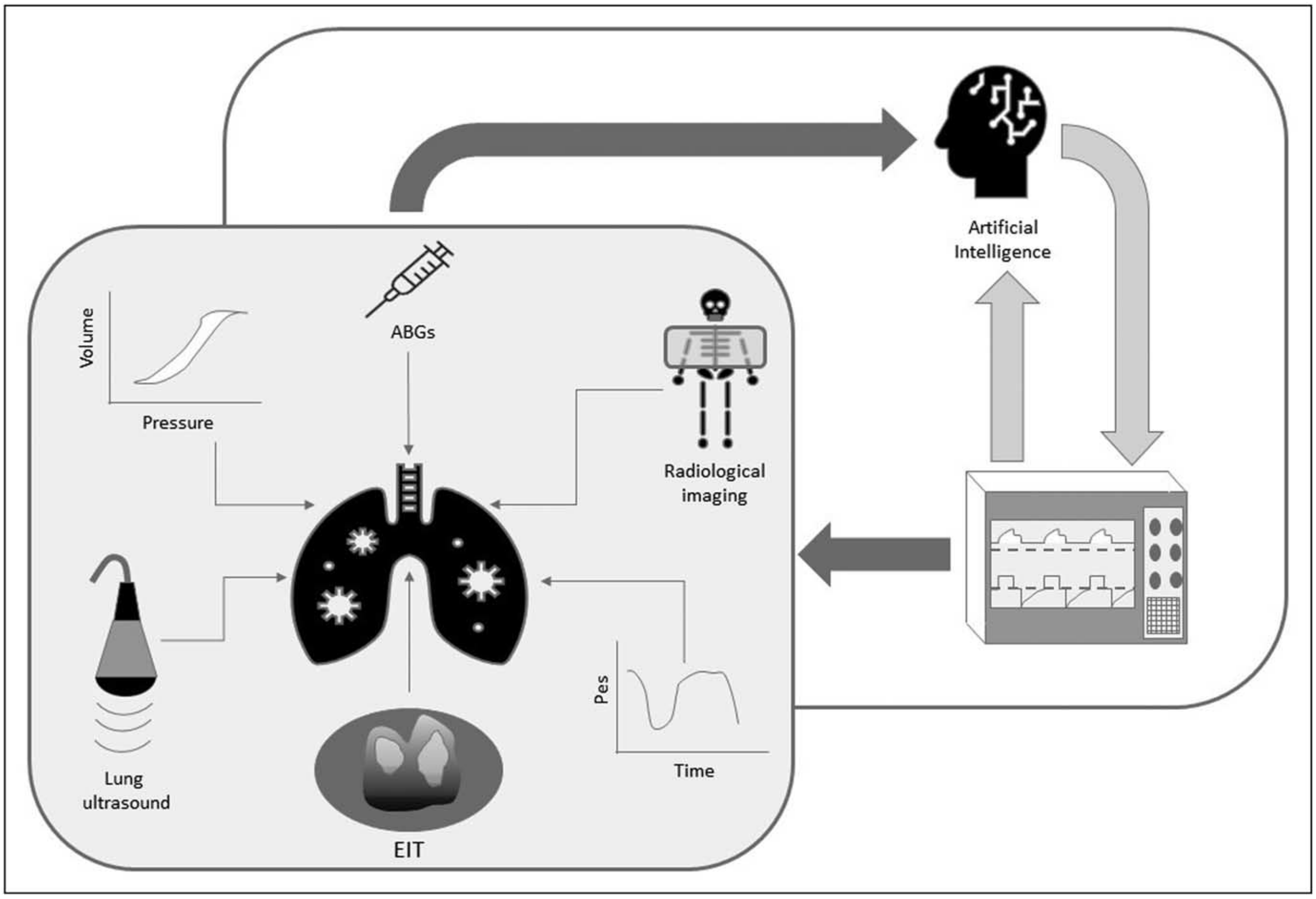

**FIGURE 1.** Methodology used to assess lung recruitment. Methodology employed to evaluate lung recruitment and its implementation with machine learning and artificial intelligence. ABGs, arterial blood gases; EIT, electrical impedance tomography; Pes, esophageal pressure.

Three patterns of tidal recruitment have been identified based on hysteresis methodology: high tidal recruitment with a progressive increase in the hysteresis area at decreasing PEEP; low tidal recruitment without modification in hysteresis at PEEP reduction; and a biphasic profile switching from low to high tidal recruitment when PEEP is reduced below a certain threshold. This approach contributes to the identification of PEEP able to mitigate the occurrence of tidal recruitment phenomenon and the energy dissipated on the lung during IMV [10▪▪].

The recruitment-to-inflation ratio (R/I) has been proposed to assess the potential for lung recruitment secondary to PEEP variation in ARDS [11]. In COVID-19-related ARDS [12], R/I variations following the application of the prone position correlated with changes in Crs. In this setting, high recruiters showed a reduction in R/I when switching from supine to prone position, associated with an improvement in Crs, oxygenation, and ventilatory ratio. Conversely, low recruiters undergoing pronation had a consistently low R/I, with only an improvement in oxygenation [12]. A recent secondary analysis of data obtained in ARDS patients under IMV [13▪▪] found a tight correlation between PEEP-induced recruitability (assessed by R/I) and PEEP-induced lung recruitment, as observed on CT scanning, in both prone and supine positions. An increase in R/I during pronation suggested the possibility of further recruitment with high PEEP, whereas a decrease in R/I during pronation indicated no additional improvement with high PEEP. The potential of R/I in discriminating high recruiters and low recruiters following PEEP application was confirmed by Taeneka *et al.* [14▪▪]. R/I allowed the adoption of an individualized ventilatory strategy involving the application of high PEEP in high recruiters and low PEEP in low recruiters during pronation, thereby avoiding deterioration in lung collapse and overdistention [14▪▪]. However, a weak correlation was found between R/I and Crs, the amount of overdistention, and the amount of collapse [14▪▪]. Zhao *et al.* [15▪▪] suggested that R/I might be an index of lung recruitment and overdistention simultaneously. R/I computation relies on the assumption of a linear trend for both Crs at low PEEP during tidal breathing and the compliance of recruited lung within the PEEP variation. However, the parenchymal inhomogeneity characterizing ARDS leads to the development of a nonlinear trend in compliance, especially in the presence of overdistention occurring at high PEEP [16]. The nonuniform behavior of lung recruitment secondary to conventional R/I maneuvers has been confirmed by Grieco *et al.* [17▪▪]. During a decremental PEEP trial, the authors proposed the application of more narrowed PEEP ranges to better follow the granular modifications in lung dynamic strain compared with the standard 5–15 $cmH_2O$ PEEP range of the original R/I procedure [17▪▪].

## Arterial bold gases

The analysis of ABGs, specifically arterial partial pressure of oxygen ($PaO_2$) and carbon dioxide ($PaCO_2$), is commonly employed to assess lung recruitment at the bedside. However, these parameters are strongly influenced by factors not strictly related to lung aeration, such as ventilation, circulation, gas distribution, and diffusion [18]. Additionally, weak correlations have been reported between oxygenation and changes in lung aeration secondary to PEEP modifications [19–21], especially when using peripheral oxygen saturation ($SpO_2$) and the ratio of $PaO_2$ to inspiratory oxygen fraction ($FiO_2$) ($PaO_2/FiO_2$), as these parameters are dependent on $FiO_2$ [22].

In ARDS, the modifications of lung aeration in response to PEEP adjustments are heterogeneous and not consistently accompanied by concurrent changes in ventilation and perfusion, as previously described [23]. Indeed, the improvement in lung aeration secondary to PEEP increase is accompanied by three patterns of response in pulmonary shunt and ventilation-to-perfusion ratio ($V/Q$) mismatch encompassing an increase in the amount of normally aerated lung associated with an improvement in pulmonary shunt without overdistention and an increase in high $V/Q$ mismatch associated with worsened shunt, or diminished shunt. In the first condition, the shunt amelioration could be explained as the consequence of lung recruitment or vascular de-recruitment of nonaerated lung zones following PEEP augmentation [24,25]. Conversely, in the case of high $V/Q$ mismatch, the increased intrathoracic pressure secondary to PEEP increase could lead to a worsened shunt because of a blood flow redistribution towards nonaerated lung regions [26]. Moreover, in COVID-19-related ARDS, the accuracy of oxygenation further decreases especially when the phenotypical characterization relies on a significant discrepancy between mechanical properties of the respiratory system and pulmonary shunt [27].

$PaCO_2$ may be more sensitive for monitoring lung recruitment, provided that minute-ventilation is kept constant [28,29]. However, despite demonstrating that metabolically stimulating interventions induce brief variations in $CO_2$ production with a rapid return to baseline [30,31], $PaCO_2$ is deeply affected by the variable metabolic status in critically ill patients. $PaCO_2$, a strong prognostic factor in ARDS [32,33], has been combined with physiological dead space for the computation of ventilatory ratio [34], a useful predictor of adverse outcomes [35].

## Lung imaging

Radiologic imaging provides real-time and instant visualization of lung aeration. Lung CT scanning is the gold standard method for assessing lung involvement in ARDS and monitoring changes in aeration secondary to ventilatory adjustments [36]. Through CT scanning, lung tissue can be classified based on density measured in Hounsfield Units, categorizing it as nonaerated, poorly aerated, normally aerated, or hyperinflated in relation to gas/tissue content [37]. Additionally, CT scanning enables the computation of superimposed pressure, a surrogate for hydrostatic pressure developing across the lung along the ventro-to-dorsal axis [37]. In ARDS, lung CT scanning has gained importance in evaluating modifications in the gas-to-tissue ratio secondary to prone positioning, as confirmed in both conventional ARDS and COVID-19-related ARDS [3▪▪,38▪]. In the context of COVID-19-related ARDS, CT scanning has been used to track changes in lung aeration following recruitment maneuvers and prone positioning [3▪▪]. CT scanning allows the characterization of nonaerated tissue in atelectasis or consolidation, depending on whether reaeration is achieved or not with a recruiting maneuver [3▪▪]. Despite the in-depth analyses, it provides, it is essential to consider the limitations of CT scanning, including risks and complications associated with patient mobilization, organizational challenges, and exposure to radiation, which limit its widespread applicability [39].

Lung ultrasound is a radiation-free tool easily and repeatably applicable at the bedside, gaining prominence for its noninvasive nature [40]. Sonographic examination of the lung can be carried out in emergency/urgency or elective settings and may be oriented towards a qualitative approach to identify the pulmonary condition underlying respiratory compromise or a quantitative approach to describe the global and regional aeration patterns by lung ultrasound score (LUS) [41]. Regional LUS correlates well with tissue density at both low and high PEEP, whereas global LUS is not associated with lung recruitment defined as a reduction in nonaerated lung tissue [42]. To address this limitation, the authors suggest better characterizing severe and complete aeration loss by considering the extent of pleural line involvement (>50%) and the predominance of the aeration pattern [42,43]. Keeping this in mind, Cammarota *et al.* [44▪▪] evaluated the effects of recruiting maneuvers and prone position on lung aeration in intubated patients with COVID-19-related ARDS. Global and regional LUS changed with the recruiting maneuver and pronation, potentially characterizing nonaerated lung regions into consolidation or atelectasis in response to the recruiting maneuver and pronation by ultrasound [44▪▪]. In COVID-19-related ARDS, lung ultrasound was useful for predicting the oxygenation response following pronation [45▪]. Aeration loss, as assessed by a LUS index greater than 50% in the anterior regions, and a $PaCO_2$ elevation in the supine position were predictors of a $PaO_2/FiO_2$ increase less than 20 mmHg [45▪].

Therefore, lung sonography plays a crucial role in defining the degree of aeration impairment secondary to ARDS. In a cohort of adults and newborns undergoing IMV for ARDS, global LUS was inversely correlated with Crs, regardless of the patient's age [46▪]. Recently, the LUS-ARDS score, combining the degree of aeration compromise and pleural line abnormalities in the anterolateral region, has been proposed as a dedicated tool for diagnosing ARDS [47▪▪].

Another noninvasive lung imaging tool applicable at the bedside is electrical impedance tomography (EIT). EIT provides dynamic, real-time images of ventilation and perfusion of the entire lung or specific zones technically known as regions of interest (ROI) [40]. EIT allows for a comprehensive analysis of the degree of ventilation inhomogeneity and end-expiratory lung impedance, a surrogate for functional residual capacity or end-expiratory lung volume. It also provides information on regional Crs and regional lower and upper inflection points during a low-flow insufflation maneuver [48]. Various PEEP titration approaches relying on EIT analysis have been proposed, as previously highlighted [40]. An EIT-based optimal PEEP, defined as the crossing point of the collapse and overdistention curves obtained with a decremental PEEP trial, was investigated in patients undergoing extracorporeal membrane oxygenation [49] and, more recently, in COVID-19-related ARDS [50▪▪]. EIT was also used to identify low, medium, and high recruiters based on the extent of modifiable collapse following a 6–24 $cmH_2O$ PEEP increase. Lung recruitability varied from 0.3 to 66.9% regardless of ARDS severity, and EIT-based PEEP ranged from 10 $cmH_2O$ in low recruiters to 15.5 $cmH_2O$ in high recruiters. The EIT-based PEEP approach, as the best compromise between the lowest collapse and atelectasis, was shown to ensure lower de-recruitment, inhomogeneity of ventilation, and better oxygenation in a semi-recumbent position (40° head-of-the-bed) compared with a supine-flat position [51▪].

EIT and ultrasound are contemporarily employed during weaning from IMV. Extubation failure was associated with higher LUS and lower surface available for ventilation compared with extubation success. After extubation, whereas LUS remained persistently higher, early modifications of the global inhomogeneity index and surface available were detected in extubation failure. No correlation was found between LUS and EIT-derived indices, possibly because of the score definitions adopted during quantitative lung sonography [52■].

## Esophageal pressure assessment

Among advanced respiratory monitoring tools, Pes is used as surrogate of pleural pressure to estimate the pressure surrounding the lung surface [40]. Pes signal is acquired through a dedicated catheter equipped with an air-filled balloon positioned midway between the apex and the base of the lung [53]. Several factors affect Pes measurement depending on the device employed for its acquisition and the patient. To overcome artifacts from esophageal balloon inflation, a specific procedure has been proposed to identify the optimal filling volume that maximizes Pes swing and corrects for the response generated by esophageal wall contraction [54–59].

Pes is utilized for the computation of transpulmonary pressure (Pl), the actual pressure distending the lung. In experimental settings of human cadavers and pigs under IMV and subjected to simultaneous acquisition of pleural pressure and Pes, Pl computed according to the direct method [60] approximated the pressure distending the mid-to-dorsal lung during end-inspiration and end-expiration [61]. Pressure across the nondependent lung at end-inspiration corresponded to Pl computed through the elastance-derived approach [61,62]. Thus, end-inspiratory elastance-derived Pl enables the assessment of overdistention, whereas end-expiratory direct Pl allows the evaluation of the lung tendency towards collapse [40]. Recent findings show that critically ill obese patients with and without ARDS have higher end-expiratory Pes compared with nonobese patients [63■]. In obese ARDS patients undergoing IMV, a positive end-expiratory direct Pl was associated with a higher probability of survival compared with a negative end-expiratory direct Pl [64■]. These results support the hypothesis that, during IMV, higher PEEP is required to counterbalance the fat load and enhance dependent lung recruitment in obese patients compared to nonobese patients.

## Emerging technologies

Advancements in medical technology continue to shape the landscape of lung recruitment monitoring. Artificial intelligence and machine learning algorithms are being explored to assist in real-time data analysis and decision support. In this context, a machine learning methodology that relies on data obtained through CT scanning has enabled the stratification of ARDS patients into recruiters and nonrecruiters within the first 48 h as the onset of IMV [65■].

Furthermore, wearable devices and remote monitoring systems are on the horizon, potentially allowing for continuous monitoring of lung recruitment even outside the ICU.

# CONCLUSION

Monitoring lung recruitment is a crucial component of managing patients with severe lung conditions, within the framework of a personalized ventilatory strategy. Although challenges persist, emerging technologies offer promise for a personalized approach to care in the future.

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