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Review Article

REVIEW ARTICLE

# Optimising positive end-expiratory pressure in acute respiratory distress syndrome: a narrative review of approaches to titration

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## Summary

Positive end-expiratory pressure (PEEP) is a fundamental component of mechanical ventilation in patients with acute respiratory distress syndrome (ARDS). However, identifying the optimal PEEP remains a clinical challenge owing to the heterogeneity of lung injury and the resulting regional variability in mechanical properties. A variety of techniques have been proposed to guide individualised PEEP titration, each based on distinct physiological principles and associated with specific advantages and limitations. Among these, oxygenation-based titration remains the most commonly applied method, although its limitations are well recognised. Alternative strategies, including compliance-guided methods, driving pressure (ΔP) minimisation, and oesophageal pressure-guided ventilation, are gaining attention but require further validation. Imaging modalities, ranging from conventional chest radiography to advanced tools such as chest CT, electrical impedance tomography, and lung ultrasound, provide valuable insights into alveolar recruitment and can support more precise PEEP adjustment. This narrative review critically evaluates current approaches to PEEP titration in ARDS, emphasising the integration of physiological and imaging-based strategies to optimise lung recruitment while minimising ventilator-induced lung injury. An integrative strategy that combines physiological assessment, imaging, and continuous monitoring offers the greatest potential to individualise PEEP. Ongoing technological and clinical advances are likely to further improve the feasibility and effectiveness of personalised PEEP titration in critical care.

**Keywords:** acute respiratory distress syndrome; computed tomography; driving pressure; electrical impedance tomography; lung ultrasound; PEEP titration; positive end-expiratory pressure; ventilator-induced lung injury

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### Editor's key points

- Lungs of patients with ARDS are highly heterogeneous, with only a fraction of lung tissue available for ventilation.
- Better oxygenation does not always mean safer lung mechanics, and relying only on $Pa_{O_2}/F_{I_{O_2}}$ tables can result in either under-recruitment or overdistension.
- Approaches based on driving pressure or oesophageal pressure allow a more precise balance between recruitment and overdistension, thereby enhancing lung protection.
- Computed tomography remains the gold standard for assessing recruitability, whereas bedside tools such as electrical impedance tomography and lung ultrasound provide real-time guidance and image regional behaviours.
- Integrating physiological and imaging data enables personalised PEEP titration, reducing driving pressure, improving oxygenation, and potentially enhancing outcomes.

Acute respiratory distress syndrome (ARDS) is characterised by diffuse inflammation, pulmonary oedema, and surfactant dysfunction, leading to lung units that are predisposed to atelectasis and impaired gas exchange.[1] Positive end-expiratory pressure (PEEP) is a cornerstone of mechanical ventilation in ARDS, as it helps maintain alveolar patency at end-expiration, improves oxygenation, and mitigates the injurious effects of repetitive alveolar collapse and reopening—key mechanisms of ventilator-induced lung injury (VILI).[2] The primary objective of PEEP, however, is not merely to maintain patency of already open alveoli but also to recruit previously nonaerated lung regions, thereby increasing the volume of aerated lung available for gas exchange.[3,4]

Three major randomised trials, ALVEOLI, LOVS, and EXPRESS, compared higher *vs* lower PEEP strategies in ARDS using lung-protective tidal volumes ($V_T$). The ALVEOLI trial found that higher PEEP improved oxygenation but did not reduce mortality compared with lower PEEP.[2] Similarly, the LOVS trial used an open-lung strategy combining recruitment manoeuvres and higher PEEP, which enhanced oxygenation and reduced hypoxaemia but showed no survival benefit.[5] In contrast, the EXPRESS trial individualised PEEP to achieve plateau pressures (Pplat) of 28–30 cm $H_2O$ and reported better lung mechanics and oxygenation, although mortality remained unchanged.[6] Collectively, these trials show that the effectiveness of higher PEEP depends largely on lung recruitability, supporting individualised PEEP titration rather than fixed high- or low-PEEP strategies. Meta-analyses consistently show that higher PEEP strategies improve clinical outcomes—particularly mortality—in patients with moderate-to-severe ARDS when combined with lung-protective ventilation. Studies by Santa Cruz and collesgues[7] and Briel and colleagues[8] further demonstrate that higher PEEP improves survival and reduces the need for rescue therapies in patients with highly recruitable lungs, whereas no benefit is seen in mild ARDS. These findings reinforce that the benefits of higher PEEP are not universal but depend largely on lung recruitability and the severity of ARDS.[7,8]

The goal of PEEP titration is to identify a level that stabilises alveoli, enhances oxygenation, and minimises VILI.[9] This is particularly difficult in the context of ARDS heterogeneity, where mechanical properties vary widely between aerated and nonaerated regions. The 'baby lung' concept, referring to the small, functional portion of the lung available for ventilation, underscores the need for individualised PEEP settings tailored to disease severity and distribution.[10]

In patients with ARDS, PEEP can also influence the phenomenon of *pendelluft*—an intrapulmonary gas redistribution between regions with differing time constants. In theory, *pendelluft* may exacerbate lung injury by promoting regional overdistension, cyclic alveolar collapse, and increased mechanical heterogeneity. Appropriate PEEP levels may reduce *pendelluft* by homogenising regional mechanics and minimising alveolar instability, whereas insufficient or excessive PEEP can aggravate these harmful patterns.[11]

Traditionally, PEEP has been titrated based on improvements in oxygenation, typically assessed via the $Pa_{O_2}/F_{I_{O_2}}$ ratio.[12] Early protocols adopted stepwise PEEP increments under the assumption that enhanced oxygenation reflected successful recruitment.[13] However, oxygenation is an imperfect surrogate for lung mechanics: PEEP may improve gas exchange while simultaneously overdistending non-recruitable lung regions, thereby increasing the risk of VILI.[14]

In response to these limitations, alternative PEEP titration strategies have emerged, incorporating physiological and mechanical parameters, such as compliance, driving pressure ($\Delta P$), and transpulmonary pressure (PL) via oesophageal manometry. Additionally, imaging techniques, including chest CT, electrical impedance tomography (EIT), and lung ultrasound (LUS), enhance real-time assessment of lung recruitability and regional PEEP responses.[15]

This narrative review critically evaluates current strategies for PEEP titration, examining their physiological foundations, clinical applications, and potential to optimise lung recruitment while minimising VILI.

## PEEP titration techniques

### Oxygenation-based PEEP titration

Oxygenation-based PEEP titration is among the earliest and most widely used methods for setting PEEP in mechanically ventilated patients with ARDS.[16] This strategy relies on improvements in arterial oxygenation, typically assessed by the $Pa_{O_2}$ or $Pa_{O_2}/F_{I_{O_2}}$ ratio, to guide incremental adjustments in PEEP.[17]

Despite widespread adoption, oxygenation-based approaches to PEEP titration have important limitations. Improvements in oxygenation do not necessarily indicate better lung mechanics or protection against VILI.[18,19] In heterogeneous ARDS, higher PEEP may appear beneficial by improving oxygenation owing to recruitment occurring in already well-aerated regions, whereas severely affected areas remain collapsed. Moreover, excessive PEEP can cause overdistension and ventilation–perfusion mismatch, leading to seemingly improved gas exchange without mechanical benefit.[20] Changes in arterial oxygenation after PEEP adjustments are influenced not only by alveolar recruitment but also by factors such as intrapulmonary shunt and cardiac output.[21,22] For example, an increase in

cardiac output can reduce pulmonary shunt by improving perfusion of ventilated but previously underperfused alveoli, thereby enhancing the ventilation–perfusion ratio.[23,24] This effect does not reflect structural alveolar recruitment; instead, it results from a redistribution of blood flow that may produce an apparent increase in $Pa_{O_2}/F_{I_{O_2}}$.[24] Conversely, although higher PEEP can lower shunt by reopening collapsed alveoli, it may also reduce cardiac output and impair systemic oxygen delivery, illustrating the complex interplay between PEEP, haemodynamics, and oxygenation.[25]

Interpatient variability in lung mechanics further challenges the generalisability of fixed PEEP/$F_{I_{O_2}}$ tables. Although some patients may achieve recruitment with lower PEEP, others may require higher levels, risking under-recruitment or overdistension when uniform protocols are applied.[26] To address these limitations, oxygenation-guided titration is often combined with additional physiological parameters such as compliance, Pplat, or ΔP. This integrated approach allows a more nuanced balance between oxygenation and mechanical protection. For instance, after achieving satisfactory gas exchange, PEEP may be further adjusted to minimise lung stress and strain using metrics such as Pplat or estimated PL.[27]

A practical bedside approach to evaluate lung recruitability and detect overdistension is the recruitment-to-inflation (R/I) ratio.[28] This method helps estimate how much of the lung can be reopened with higher PEEP using only standard ventilator data. It involves a single-step reduction in PEEP, typically from 15 to 5 cm $H_2O$ while measuring the corresponding changes in end-expiratory lung volume (EELV) and ΔP.

The change in EELV is derived from a standardised single-breath release manoeuvre. When PEEP is abruptly reduced, the ventilator measures the exhaled volume required to reach the new equilibrium at the lower PEEP level. This exhaled volume represents the lung volume that had been maintained by the higher PEEP and is therefore taken as the recruited volume. The accompanying change in ΔP is assessed at the lower PEEP level. An increase in ΔP reflects the additional elastic load imposed after derecruitment; a marked increase indicates that many units have collapsed, whereas little or no change suggests preserved mechanics and limited loss of aeration.

The R/I ratio, calculated as the recruited volume divided by the inflation volume during tidal ventilation at lower PEEP, captures the balance between recruitment and distension. Current evidence supports interpreting the R/I ratio as a continuous measure of recruitability rather than a binary classifier. Low ratios indicate limited potential for recruitment and a greater risk of overdistension with higher PEEP, whereas intermediate or high values suggest increased potential for beneficial recruitment. This continuous approach better reflects the underlying physiology and aligns with data showing a spectrum of recruitability across patients. Because it relies solely on standard ventilator measurements, the R/I ratio provides a simple, reproducible, and noninvasive tool for individualising PEEP at the bedside.

Clinical perspectives recommend assessing recruitability soon after intubation by increasing PEEP from ~5 to 15 cm $H_2O$ in a single step and observing changes in compliance, oxygenation, and $CO_2$.[29] Patients demonstrating improved compliance and oxygenation without worsening $CO_2$ likely have moderate-to-high recruitability and may safely benefit from higher PEEP, whereas nonresponders are at risk of overdistension and adverse effects.

## Compliance- and driving pressure-based PEEP titration

Compliance- and ΔP-guided PEEP titration provides a physiology-based framework for individualising ventilatory settings in patients with ARDS. The fundamental goal is to identify the PEEP level that maximises respiratory system compliance or, equivalently, minimises ΔP when $V_T$ remains unaltered, thereby optimising alveolar recruitment while limiting overdistension and mechanical stress.

In recruitable lungs, incremental increases in PEEP at the same $V_T$ act to reopen collapsed alveoli, improving compliance of the respiratory system (Crs) and reducing ΔP until recruitment is complete. Beyond this point, additional PEEP causes overdistension of already open units, leading to reduced compliance and increased ΔP. The PEEP associated with the highest compliance or the lowest ΔP when $V_T$ is constant is considered physiologically 'optimal', as it reflects maximal recruitment with minimal dynamic strain. Crs is calculated as $V_T/\Delta P$, where ΔP equals the difference between Pplat and total PEEP.[30]

In practice, PEEP is adjusted in small increments while monitoring compliance, ΔP, and gas exchange. When compliance ceases to increase or ΔP begins to increase, the preceding PEEP level is considered optimal. Unlike fixed PEEP/$F_{I_{O_2}}$ tables, compliance- and ΔP-guided titration adapts to individual and temporal variations in lung mechanics. By relying on mechanical rather than oxygenation parameters, it more accurately captures the interaction between applied pressures and lung stress. As ARDS evolves, reassessment of PEEP may be necessary to account for dynamic changes in lung recruitability.[31] Compliance- and ΔP-based titration has been associated with improved oxygenation, reduced physiological dead space,[27] and lower risk of VILI.[20]

The ΔP reflects the cyclic stress applied to the 'baby lung', the aerated portion of parenchyma available for ventilation, and has emerged as a strong predictor of survival in ARDS.[32,33] The physiological rationale for targeting a lower ΔP lies in the stress–strain relationship of the lung; stress corresponds to the pressure applied to the lung tissue, whereas strain represents the change in volume relative to functional residual capacity or EELV. Higher ΔP increases both stress and strain, predisposing to VILI through alveolar overdistension, barotrauma, and cyclic recruitment–derecruitment.[26] Each 1 cm $H_2O$ reduction in ΔP has been linked to lower mortality, underscoring its clinical relevance. Reducing ΔP promotes more homogeneous ventilation and limits regional mechanical injury.

In clinical practice, ΔP can be reduced by either decreasing $V_T$ or adjusting PEEP. As $V_T$ is generally fixed at a value approximating 6 ml $kg^{-1}$ predicted body weight in lung-protective ventilation, PEEP becomes the main variable. The optimal PEEP is the level that achieves the lowest ΔP without compromising oxygenation or haemodynamics. Minimising ΔP may also provide cardiovascular benefits by reducing intrathoracic pressure, preserving venous return, and supporting cardiac output.[4,10,34]

Despite these benefits, compliance- and ΔP-guided PEEP titration has limitations. Measurements can be influenced by spontaneous breathing efforts, patient movement, or

variations in sedation, which may reduce reliability.[26] Accurate ΔP measurement requires both an end-inspiratory and an end-expiratory pause and absence of spontaneous effort. Both compliance and ΔP are global indices that cannot resolve regional heterogeneity; some lung units may remain collapsed, whereas others are overdistended. In patients with altered chest wall mechanics or elevated pleural pressure (Ppl), ΔP might not adequately reflect PL; in such cases, oesophageal manometry provides a more precise estimate.[35,36] Moreover, a decrease in ΔP after PEEP reduction might result from tidal recruitment rather than improved mechanics, meaning that a lower ΔP does not invariably indicate safer ventilation.

Combining compliance- and ΔP-guided titration with regional monitoring tools, such as EIT, can refine PEEP selection by confirming homogenous ventilation and minimising local mechanical stress. This integrative approach translates bedside physiology into patient-specific lung protection.[37]

## Oesophageal pressure-guided PEEP titration

Oesophageal pressure (Poes) monitoring provides a valuable method for individualised PEEP titration in patients with ARDS, particularly those with altered or heterogeneous chest wall mechanics. By estimating Ppl through a balloon catheter positioned in the distal oesophagus, clinicians can calculate PL, defined as the difference between airway pressure (Paw) and Ppl (Fig. 1).[37] This technique is especially relevant in patients with compromised thoracoabdominal mechanics, such as those with intra-abdominal hypertension or significant fluid overload, where Paw alone may not reflect true lung stress. Although obese patients often exhibit elevated Ppl and reduced functional residual capacity, their tidal chest wall compliance may not be modified.[38,39] This is because the excess thoracoabdominal mass primarily increases baseline Ppl rather than alters the elastic properties of the chest wall. Within the $V_T$ range used during protective ventilation, the pressure–volume relationship of the chest wall remains nearly linear. Consequently, the reduction in measured Crs in obesity is largely as a result of reduced lung volume and the additional pressure needed to reopen lung units that collapse at end-expiration, rather than to any true stiffening of the chest wall, whose elastic behaviour remains near normal within the $V_T$ range. By directly estimating Ppl, Poes monitoring enables more precise discrimination between the mechanical contributions of the lung and the chest wall, allowing for a physiologically guided ventilatory strategy.[40]

Key metrics derived from Poes include end-expiratory transpulmonary pressure (PLexp) and end-inspiratory transpulmonary pressure (PLinsp). Clinically, PEEP is adjusted to

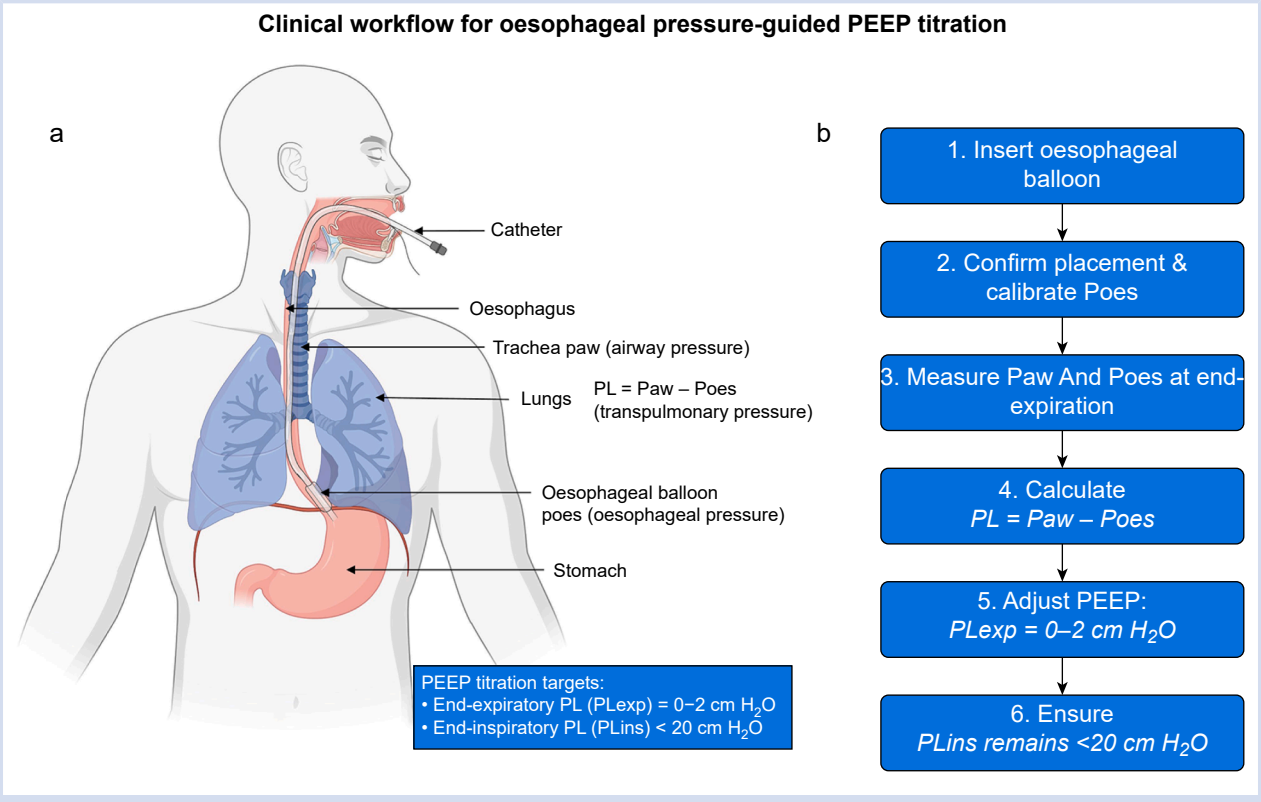


Fig 1. Oesophageal pressure (Poes)-guided PEEP titration in acute respiratory distress syndrome (ARDS): anatomical basis and clinical workflow. (a) Schematic illustration of a nasogastric catheter equipped with an oesophageal balloon, used to measure Poes, a validated surrogate for pleural pressure. Transpulmonary pressure (PL) is calculated as the difference between airway pressure (Paw) and Poes. (b) Stepwise clinical workflow for Poes-guided PEEP titration. The process involves insertion and calibration of the oesophageal balloon catheter, measurement of Paw and Poes at end-expiration, and PEEP adjustment to achieve physiologically safe transpulmonary pressures. Clinical targets include maintaining end-expiratory transpulmonary pressure (PLexp) between 0 and 2 cm $H_2O$ to prevent alveolar derecruitment, and end-inspiratory transpulmonary pressure (PLins) below 20 cm $H_2O$ to minimise ventilator-induced lung injury.

maintain PLexp between 0 and 5 cm $H_2O$ to prevent alveolar collapse while ensuring that PLinsp remains below 20 cm $H_2O$ to avoid overdistension. Recent data suggest that a narrower target of PLexp between 0 and 2 cm $H_2O$ may be more appropriate.[41,42] Additionally, PLinsp calculated via elastance ratios may provide a more reliable estimate of PL than direct Poes measurements.[41,42] These thresholds can be further individualised based on patient-specific factors such as compliance, body habitus, and disease severity.[35] A major advantage of Poes-guided PEEP titration is its ability to disentangle lung mechanics from the effects of the chest wall. For example, when Ppl is elevated owing to chest wall stiffness, a low Pplat can give the false impression of safe ventilation even though many alveolar units may remain collapsed because the resulting PL is too low to keep them open. Poes monitoring helps identify the need for higher PEEP to achieve a positive PL and maintain alveolar recruitment.[35,40]

Randomised trials such as EPVent[23] and EPVent2[40] evaluated Poes-guided strategies *vs* empirical high PEEP, showing improved oxygenation and compliance and suggesting potential mortality benefit in moderate-to-severe ARDS. Despite these advantages, Poes monitoring has technical and practical limitations. Accurate interpretation requires correct balloon placement, calibration, and ongoing validation of signal quality. Measurement errors caused by malpositioning, under- or over-inflation, or external factors such as coughing, swallowing, or patient movement can compromise accuracy and lead to inappropriate PEEP adjustments. Consequently, clinician training and experience are essential.[27]

Poes-guided titration is particularly useful in patients with abnormal chest wall mechanics, but its utility may be limited in those with relatively preserved thoracopulmonary compliance. Additional barriers include equipment cost, availability, and the need for trained personnel, which may challenge implementation in resource-limited settings.[43] Poes-based titration is most effective when integrated with complementary strategies such as compliance monitoring and ΔP minimisation. Although compliance reflects global respiratory mechanics, Poes provides insight into regional Ppl, enhancing the understanding of lung–chest wall interactions. Imaging modalities such as EIT can further augment Poes-guided titration by offering real-time visualisation of regional ventilation, recruitment, and overdistension.[26]

Although technical and logistical challenges persist, this approach improves physiological understanding and precision in lung-protective strategies. As clinician expertise and access to advanced monitoring evolve, integration of Poes into routine care is likely to expand.[4] Table 1 summarises key PEEP titration techniques, including physiological basis, main advantages, and limitations.

## Adjunctive tools for PEEP titration in acute respiratory distress syndrome: role of imaging modalities in assessing lung recruitment

Given the heterogeneous nature of ARDS, individualising PEEP requires tools capable of assessing regional lung mechanics and recruitment potential. Advanced imaging modalities, such as chest CT, EIT, and LUS, provide detailed information on aeration and recruitability, whereas chest X-ray offers only limited insights and is primarily useful for serial monitoring in resource-constrained settings.[31,44] The overarching clinical goal remains the optimisation of PEEP to balance alveolar recruitment while minimising overdistension. Figure 2 depicts an integrated physiology- and imaging-guided algorithm for personalised PEEP titration in ARDS.

### Chest computed tomography

Chest CT remains the reference standard for assessing lung morphology and recruitability in ARDS, providing high-resolution and three-dimensional visualisation, and radiation exposure.

Quantitative CT allows estimation of recruitable lung volume. Research indicates that patients with non-focal ARDS typically display higher recruitability and may benefit from higher PEEP levels, whereas focal ARDS is often less recruitable and more responsive to conservative ventilatory strategies.[45,46]

**Table 1** Summary of PEEP titration techniques. Summary of commonly used PEEP titration strategies in acute respiratory distress syndrome (ARDS), highlighting key benefits and limitations. Methods range from simple bedside approaches based on oxygenation or respiratory mechanics to advanced imaging- and physiology-guided techniques that enable individualised optimisation of alveolar recruitment while minimising overdistension and ventilator-induced lung injury.

| Technique | Main benefit(s) | Main limitation(s) |
|---|---|---|
| **Oxygenation-based PEEP titration** | Simple and widely available; useful for early management of severe hypoxaemia | Poor correlation with lung mechanics; may cause overdistention in non-recruitable lung regions |
| **Compliance-based PEEP titration** | Individualised and physiologically informed; adapts to dynamic lung mechanics | Influenced by spontaneous breathing; reflects global rather than regional mechanics |
| **Driving pressure-based PEEP titration** | Strongly associated with survival; targets lung stress and strain | Requires accurate plateau pressure; may not detect regional overdistention or collapse |
| **Oesophageal pressure-guided PEEP titration** | Accounts for chest wall mechanics; targets transpulmonary pressures; improves precision of PEEP titration | Technically demanding; invasive; requires equipment and trained personnel |
| **Chest computed tomography** | Gold standard for assessing lung morphology and recruitability; provides high-resolution anatomical detail | Radiation exposure; limited bedside applicability owing to logistical and safety constraints |
| **Electrical impedance tomography** | Real-time, bedside, regional monitoring of ventilation and recruitment | Limited spatial resolution; reduced accuracy in patients with obesity or oedema; requires expert interpretation |
| **Lung ultrasound** | Bedside, repeatable, radiation-free; detects consolidation, aeration loss, and recruitment | Operator-dependent; limited assessment of deep lung regions |

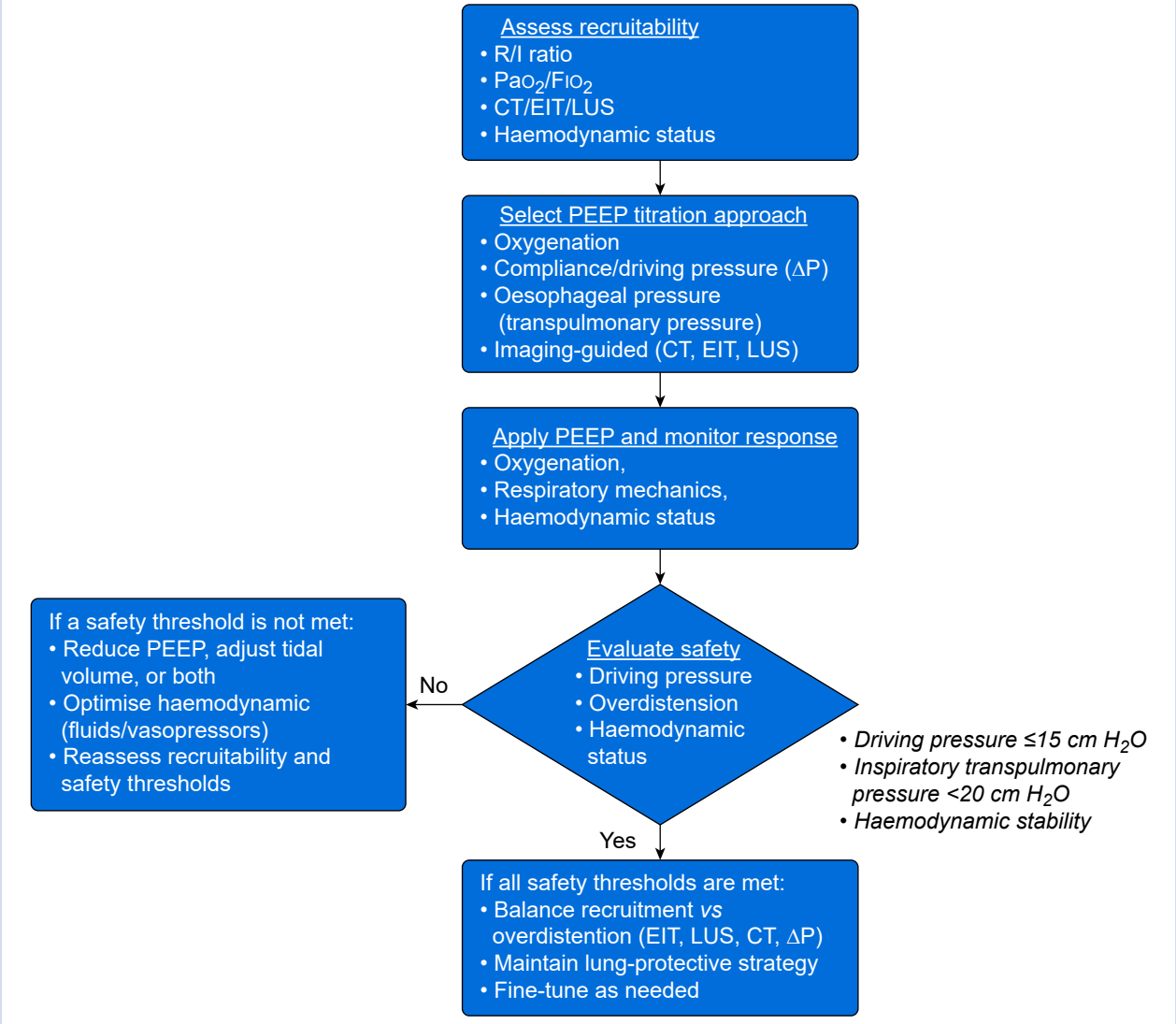


Fig 2. Algorithm for physiology- and imaging-guided PEEP titration in acute respiratory distress syndrome (ARDS). The process starts with a general assessment of recruitability, followed by selection of a PEEP titration approach. PEEP is then applied and the response monitored through changes in oxygenation, respiratory mechanics, and haemodynamics. Safety is subsequently evaluated by assessing driving pressure, overdistension, and haemodynamic stability. If safety thresholds are not met, PEEP, tidal volume, or both should be reduced, haemodynamics optimised (fluids or vasopressors), and recruitability reassessed. This stepwise process ensures an individualised balance between alveolar recruitment and lung protection. EIT, electrical impedance tomography; LUS, lung ultrasound; R/I, recruitment-to-inflation ratio.

At PEEP 5 cm $H_2O$, patients with non-focal ARDS exhibit higher ΔP and Crs than those with focal ARDS. In non-focal ARDS, increasing PEEP to 15 cm $H_2O$ significantly decreases both ΔP and elastance when the lung parenchyma is recruitable; such improvement is not observed in focal ARDS.[10]

Despite its diagnostic value, chest CT use in the ICU is limited by logistical and safety concerns. Transporting critically ill patients carries inherent risks, repeated imaging raises concerns about radiation exposure, and quantitative analysis requires time-consuming processing, confining its use largely to research. Semiquantitative or visual CT assessments, however, are more practical and can provide useful bedside guidance by classifying lung regions into well-aerated, poorly aerated, or consolidated compartments.[47]

## Chest radiography

Chest radiographic imaging remains accessible and portable but has major limitations for PEEP titration. Its low spatial resolution and two-dimensional projection hinder accurate distinction between atelectasis, pleural effusion, and consolidation, while preventing assessment of regional recruitment

or overdistension. Subtle changes in lung aeration at different PEEP levels are often undetectable, as radiographic density lacks sensitivity and specificity for recruitment assessment. Serial radiographs provide only static, indirect information and are influenced by patient positioning, exposure parameters, and interobserver variability. In current practice, its use in monitoring should be restricted to identifying complications, such as lobar collapse, pneumothorax, or pleural effusion, rather than guiding individualised PEEP titration.[47]

### Electrical impedance tomography

EIT is a noninvasive, radiation-free imaging modality that provides real-time bedside assessment of ventilation distribution. Electrodes placed around the thorax detect impedance changes, which correspond to variations in regional lung aeration. Unlike static modalities, EIT provides breath-by-breath information on the effects of PEEP on recruitment and overdistension.[48,49]

The global inhomogeneity (GI) index[50] quantifies ventilation distribution by comparing pixel-level with global impedance changes. High GI values reflect ventilation heterogeneity, often caused by regional collapse or overdistension. Adjusting ventilator settings to minimise GI may promote more homogeneous ventilation, though targeting the lowest GI can increase Paw in patients with low recruitability, potentially aggravating VILI.[51,52]

Clinical studies indicate that EIT-guided PEEP titration improves oxygenation, compliance, and weaning success compared with conventional strategies.[53–55] Although mortality benefits remain unproven, reductions in ΔP and mechanical power have been observed. For example, in moderate-to-severe ARDS, EIT-guided PEEP was associated with improved survival and lower elastic dynamic power.[55] A recent prospective study confirmed that EIT-guided titration enhances regional recruitment and reduces overdistension compared with traditional methods.[56] EIT-guided PEEP titration enhanced lung recruitment, reduced overdistension, and improved oxygenation and compliance compared with conventional methods, suggesting its potential for individualised PEEP despite the need for larger trials to confirm long-term benefits.[56]

Limitations of EIT include the absence of standardised interpretation protocols and by its restricted signal penetration, which may be affected by increased chest wall thickness or oedema. Nevertheless, its safety, bedside applicability, and ability to provide continuous regional information support its increasing adoption in ARDS management.[49]

### Lung ultrasound

LUS has become an increasingly valuable bedside tool for evaluating lung aeration in ARDS.[57] Compared with chest CT and chest X-ray, LUS provides real-time imaging without radiation exposure and allows repeated assessments, making it particularly suitable for critically ill patients.[58] In addition, echocardiographic evaluation of right ventricular function can be performed simultaneously to monitor the haemodynamic effects of PEEP.[59]

LUS findings are based on characteristic artifacts: A-lines indicate normal aeration, B-lines suggest interstitial or alveolar fluid, and consolidations appear as tissue-like patterns, often with air bronchograms. Pleural effusions are seen as anechoic or hypoechoic areas above the diaphragm.[59,60]

For PEEP titration, LUS enables semiquantitative assessment of regional lung aeration and recruitment.[61] By scanning multiple thoracic regions before and after PEEP changes, clinicians can identify collapsed areas that re-aerate with higher pressures, and zones at risk of overdistension.[62] Recruitment is typically evidenced by conversion of coalescent B-lines or consolidations into normal or partially aerated patterns.[62]

Several LUS scoring systems quantify aeration across predefined lung zones.[61,63] These scores track the effects of recruitment manoeuvres or incremental PEEP changes, providing a dynamic, bedside measure of lung response. Studies have demonstrated good correlation between LUS findings and chest CT–based aeration, supporting LUS as a practical alternative where CT is not feasible.[64]

The main limitations of LUS are operator dependency, limited assessment of deeper lung regions, and reduced accuracy in patients with obesity or oedema.[65] Accurate interpretation also requires specific training to differentiate pathological patterns from normal variants or artifacts.[66]

Despite these limitations, LUS is increasingly incorporated into multimodal ventilatory strategies.[67] It is particularly valuable when access to CT or EIT is limited or when rapid, repeated imaging is required.[68] When combined with physiological monitoring (e.g. compliance, ΔP), LUS can guide PEEP titration to optimise recruitment while minimising overdistension.[69]

## Comparative advantages and integrated approaches

Each imaging modality provides unique and complementary insights into lung recruitment: (1) chest CT offers precise morphological and volumetric analysis and is best suited for baseline phenotyping and early recruitment assessment; (2) EIT enables dynamic, real-time monitoring of ventilation distribution and is ideal for continuous assessment of ventilatory strategies; and (3) LUS provides portable, radiation-free bedside imaging of lung aeration, allowing dynamic evaluation of recruitment and overdistension through artifact patterns and semiquantitative scoring systems. It is especially valuable for serial assessments and in resource-limited settings.

The choice of imaging modality depends on patient stability, available resources, and clinical objectives. In practice, a multimodal approach is often advantageous. For example, an initial chest CT can establish lung morphology and guide early ventilatory strategies, whereas serial EIT can monitor responses to PEEP titration over time.

Clinical and physiological studies support combining regional imaging with mechanical targets during PEEP titration.[70] At the bedside, the integration of helium dilution (EELV/mechanics) with EIT has shown that setting PEEP to minimise both overdistension and collapse improves inflation homogeneity and recruitment.[37] Randomised trials of EIT-guided PEEP have reported superior oxygenation, compliance, lower ΔP, and improved organ function compared with conventional methods.[71] CT-based studies further link lung morphology and recruitability to mechanical responses. Even low-resource imaging tools can be combined with mechanics for individualised titration.[47] Translational studies also demonstrate that imaging-derived recruitability metrics can be mapped to bedside mechanical targets.[64] Collectively, these findings provide a strong rationale for an integrated imaging-plus-mechanics approach to PEEP individualisation.

## Conclusions

Effective PEEP titration is a cornerstone of lung-protective ventilation in ARDS, aiming to maintain alveolar stability while minimising overdistension and VILI. Oxygenation-based approaches remain widely used because of their simplicity and accessibility but often fail to capture the complexity of lung mechanics. More physiologically informed methods, such as compliance-guided titration, ΔP minimisation, and Poes monitoring, offer greater personalisation but are constrained by technical challenges and monitoring requirements. Radiological techniques, including chest CT and EIT, provide visual insights into lung recruitment and often allow more refined ventilatory adjustments. A multimodal approach that integrates physiological measurements, imaging, and continuous monitoring holds the greatest promise for individualising PEEP. Advances in bedside technology and clinical research may further improve the feasibility and effectiveness of personalised PEEP titration in critical care.

## Authors' contributions

Conception: AS, DB, JM, PRMR
Manuscript drafting: AS, DB, NP, SS, BJ, LA-H, JM, PRMR
Critical revision for important intellectual content: DB, JM, PRMR
Final approval of the submitted version: all authors

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## Declaration of interest

The authors declare that they have no conflicts of interest.

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