Review

# Clinical review: Bedside assessment of alveolar recruitment

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## Abstract

Recruitment is a dynamic physiological process that refers to the reopening of previously gasless lung units. Cumulating evidence has led to a better understanding of the rules that govern both recruitment and derecruitment during mechanical ventilation of patients with acute respiratory distress syndrome. Therefore not only the positive end-expiratory pressure, but also the tidal volume, the inspired oxygen fraction, repeated tracheal suctioning as well as sedation and paralysis may affect recruitment of acute respiratory distress syndrome lungs that are particularly prone to alveolar instability. In the present article, we review the recently reported data concerning the physiological significance of the pressure–volume curve and its use to assess alveolar recruitment. We also describe alternate techniques that have been proposed to assess recruitment at the bedside. Whether recruitment should be optimized remains an ongoing controversy that warrants further clinical investigation.

**Keywords** acute lung injury, acute respiratory distress syndrome, alveolar recruitment, mechanical ventilation, pressure–volume curve, volume history

## Introduction

More than 30 years after the first description of acute respiratory distress syndrome (ARDS), cumulating evidence reinforces the idea that mechanical ventilation, *per se*, can promote ventilator-induced lung injury and may be indirectly implicated in mechanisms leading to multiple organ failure [1–4].

What have we learned from physiological and clinical studies as regards the different pathologic pathways implicated in ventilator-induced lung injury? First, the reduction in lung volume observed in ARDS as well as the heterogeneous distribution of loss of aeration favors overdistension of healthy lung units [5]. This deleterious effect may be prevented by lowering the tidal volume in order to limit the distending lung pressure. Also, a maximal threshold value of 30 $cmH_2O$ for the plateau pressure is currently recommended, although 35 $cmH_2O$ could be acceptable in patients exhibiting very low chest wall compliance [6]. The fact that a large tidal volume, previously proposed to maintain arterial carbon dioxide tension at a normal value, is no longer used today may explain the improvement in ARDS prognosis observed over the past two decades [7]. Second, lung condensation either due to consolidation and alveolar flooding or due to compression and re-absorption atelectasis, which is prone to repetitive opening and cycling collapse, may also play a major role in the lung injury process. Alveolar recruitment is a beneficial process involving a ventilatory approach that permits one to open lung units and to keep them open [8]. By increasing the lung volume, alveolar recruitment may render ventilation more homogeneous, may improve gas exchange and may limit distention of healthy lung units.

Whether a ventilatory approach specifically designed to optimize alveolar recruitment while at the same time limiting end-inspiratory alveolar pressure could be beneficial regarding outcome remains an ongoing issue.

The present article reviews the findings of recent studies that focus on alveolar recruitment. It also summarizes the different

ARDS = acute respiratory distress syndrome; PEEP = positive end-expiratory pressure.

methods currently available for bedside assessment of alveolar recruitment.

## Physiological meaning of alveolar recruitment

Recruitment is a physiological process that refers to the re-aeration of a previously gasless lung region exposed to positive pressure ventilation. The heterogeneous distribution of condensations that predominates in the dependent part of the lung has been attributed to the gravitation forces due to the weight of the edematous lung [9]. This interpretation, according to which lung collapse may be counterbalanced by positive end-expiratory pressure (PEEP), could be considered too simplistic and has been recently challenged [10]. First, because the caudal lung regions are exposed not only to the lung weight, but also to the pressure directly due to the abdominal weight throughout the postero-diaphragmatic region as well as due to the heart and the mediastinal structures [4]. More importantly, the lung may be nonaerated because it is filled with fluid resulting from inflammation and not because it is collapsed.

Computer tomographic analyses obtained in ARDS patients have largely contributed to the better understanding of the physiological mechanisms surrounding recruitment and derecruitment [11,12]. Nevertheless, one should accept that knowledge regarding recruitment and derecruitment remains uncertain. As previously suggested, ARDS is in fact a complex disease. The two mechanisms involved (namely lung collapse and lung consolidations due to fluid-filled alveoli), recently discussed in detail elsewhere, may depend on the origin of ARDS (i.e. pulmonary ARDS versus extrapulmonary ARDS) and may also probably coexist in a given patient [12,13]. Even if the distinction between these two mechanisms required attention and further investigation, this debate does not change the fact that recruitment refers to the part of the lung that is not aerated at low airway pressure and that requires high opening pressure to be re-aerated [10]. The pressure–volume curve technique has been proposed to quantify this alveolar recruitment.

## Physiological approach for alveolar recruitment evaluation

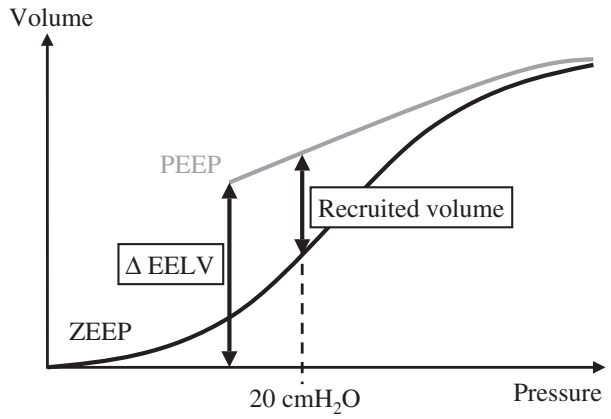
ARDS is a clinical situation resulting from varying etiologies that is characterized by a natural tendency for alveolar instability and a loss of aeration. In addition to currently recommended low peak pressure ventilation, many factors including high fraction of inspired oxygen, sedation, the supine position and repeated tracheal suctioning may favor alveolar derecruitment. In this context, several authors have attempted to evaluate and quantify the influence of different ventilatory settings on recruitment.

By avoiding expiratory lung derecruitment, PEEP remains the cornerstone of the ventilatory approach. This beneficial effect has been widely investigated and is today largely accepted even if its optimal level remains controversial. Katz and colleagues were the first to quantify the amount of recruitment induced by PEEP [14]. To accomplish this goal, they assessed the end-expiratory lung volume change, due to a PEEP increase, by continuously recording the inspired and expired tidal volumes as well as changes in peak pressure. An interesting finding of this study was that PEEP-related recruitment is a time-dependent process requiring roughly 10–15 breaths to be fully accomplished. Nevertheless, in this experiment the change in end-expiratory lung volume analyzed solely does not permit one to differentiate the volume caused by recruitment of previously nonaerated lung units and the volume due to the expected inflation of already open lung units.

In order to differentiate these volumes, one should compare the lung volume measured at a given airway pressure when the patient is ventilated with PEEP with the corresponding volume obtained at the same pressure level during an inflation without PEEP. This approach is based on the assumption that the end-expiratory lung volume measured at zero end-expiratory pressure is not affected by the level of PEEP used before the measurements. This assumption has been adopted by Ranieri and colleagues, who proposed to assess recruitment by superimposing pressure–volume curves recorded from PEEP and zero end-expiratory pressure on a common volume axis [15]. The first volume point of the PEEP pressure–volume curve therefore corresponds to the increase in end-expiratory lung volume induced by PEEP (i.e. the difference in end-expiratory lung volume between PEEP and zero end-expiratory pressure). This volume may be reliably measured during a prolonged expiration from PEEP to zero end-expiratory pressure. For a given airway pressure, the volume difference between the curve recorded from PEEP and the curve recorded from zero end-expiratory pressure corresponds to alveolar recruitment (Fig. 1).

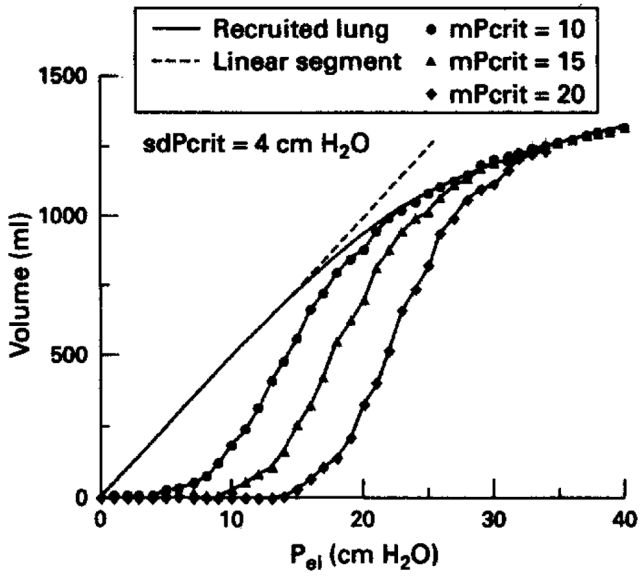
The lack of any alveolar recruitment is indicated by the superposition of PEEP and zero end-expiratory pressure volume curves. Using this technique, Jonson and colleagues quantified recruitment in a series of ARDS patients ventilated with a PEEP level set approximately above the lower inflexion point [16]. PEEP induced an upward shift of the PEEP pressure–volume curve in all patients, indicating recruitment. Interestingly, recruitment was associated with a significant decrease in the slope of the PEEP pressure–volume curve, namely the cord compliance, compared with the curve performed from zero end-expiratory pressure. Jonson and colleagues suggested that the chord compliance read on the zero end-expiratory pressure–volume curve reflects the continuous recruitment that roughly starts at the lower inflexion point and continues far above it. Based on this interpretation, the upper inflexion point could be viewed as the end of this continuous recruitment rather than as the beginning of alveolar distension even if both mechanisms are in fact associated at a high level of transpulmonary pressure.

**Figure 1**




Measurement of positive end-expiratory pressure (PEEP)-induced alveolar recruitment using the pressure–volume (PV) curve. The PV curves of the respiratory system recorded from zero end-expiratory pressure (ZEEP) and from PEEP are superimposed on a common volume axis. '0' volume corresponds to the end-expiratory lung volume (EELV) on ZEEP. The first point of the PEEP PV curve corresponds to the increase in EELV induced by PEEP (ΔEELV). On this example, the recruitment induced by PEEP is measured at a pressure of 20 $cmH_2O$.

**Figure 2**




Mathematical model of the pressure–volume (PV) curve. PV curves obtained with a mathematical model simulating a multicompartmental lung model. The continuous PV curve reflects elastic properties of a completely recruited lung. The other curves represent the behavior of the simulated models according to a different mean opening pressure (10 $cmH_2O$, 15 $cmH_2O$ and 20 $cmH_2O$). Modified from [17]. $P_{el}$, elastic pressure; mPcrit = 10, mean opening pressure of 10 $cmH_2O$; sdPcrit = 4 $cmH_2O$, standard deviation of mPcrit.

These findings have been corroborated using a mathematical lung model recently proposed by Hickling, who simulated the behavior of the respiratory system submitted to a different level and distribution of alveolar opening pressure (Fig. 2) [17]. The shape of the different zero end-expiratory pressure–volume curves obtained with the simulation is very close to those curves obtained in patients. Interestingly, the author suggested that the absence of an upper inflexion point did not necessary indicate the lack of overdistension since continuous recruitment may mask the flattening upper part of the curve.

Maggiore and colleagues proposed an original automatic technique to assess recruitment obtained at different PEEP levels without modifying baseline ventilation [18]. A low flow inflation maneuver is programed to occur after a prolonged expiration automatically performed at 15 $cmH_2O$, at 10 $cmH_2O$, at 5 $cmH_2O$ and at zero end-expiratory pressure. The most important finding of this study was to demonstrate that the increase of PEEP above the lower inflexion point resulted in a significant further recruitment that was correlated with the linear compliance of the zero end-expiratory pressure–volume curve. These results show that the lower inflexion point is definitively not a 'magic' point reflecting the opening pressure of the lung. Moreover, the clinical relevance of the study is high since the lower inflexion point of the zero end-expiratory pressure–volume curve is widely proposed to set PEEP. For the reasons discussed, this approach may be misleading.

Overall, the physiological principle of the multiple pressure–volume method initially proposed by Ranieri and colleagues seems to allow a reliable assessment of alveolar recruitment, whereas indications provided by this technique regarding overdistension should be cautiously interpreted. Nevertheless, one should note that the pressure–volume curve technique has not been compared with an independent method as regards recruitment assessment. Caution is therefore required concerning the exact interpretation of PEEP-related recruitment quantified using this technique even if the clinical relevance of recruitment is currently widely accepted.

## Effect of different ventilatory settings on alveolar recruitment

Although the effect of PEEP on alveolar recruitment has been widely investigated, the influence of the tidal volume has remained unknown until recently. Lung alveolar derecruitment associated with a low tidal volume is now documented and may represent an undesirable effect of the 'low-stretch' ventilatory strategy. Supine patients exposed to repetitive tracheal suctioning, to high fraction of inspired oxygen and to paralysis are particularly prone to this deleterious effect, which is related to volume history.

Ranieri and colleagues were the first to specifically investigate the effect of tidal volume reduction on alveolar recruitment measured by the pressure–volume curve technique [19]. These authors observed that PEEP led to a greater alveolar recruitment with low tidal volume compared with high

tidal volume. Their interpretation was that low plateau pressure ventilation renders the lungs more recruitable. These results slightly differ from those obtained by Richard and colleagues, who compared the effect on alveolar recruitment of 10 ml/kg tidal volume with 6 ml/kg tidal volume for a similar PEEP level set at the lower inflexion point [20]. Recruitment calculated as the volume difference between the PEEP pressure–volume curve and the corresponding zero end-expiratory pressure–volume curve was significantly reduced when patients were ventilated with the low tidal volume, demonstrating that a reduction in plateau pressure promotes alveolar instability. This derecruitment was fully regained by the application of two consecutive sighs. Significantly, recruitment obtained after the increase of the PEEP level 4 $cmH_2O$ above the lower inflexion point largely exceed those obtained after the recruitment maneuver, suggesting that PEEP remains the main determinant of recruitment.

Both studies demonstrate that the tidal volume, namely volume history, may affect recruitment. Nevertheless, Ranieri and colleagues observed a higher recruitment with low tidal volume while recruitment measured in the study reported by Richard and colleagues was significantly less with low tidal volume ventilation. This apparent discrepancy is probably due to the fact that zero end-expiratory pressure–volume curves were performed immediately after a single expiration at zero end-expiratory pressure in the latter study, while prolonged ventilation at zero end-expiratory pressure preceding zero end-expiratory pressure–volume curve recording may have affected end-expiratory lung volumes in Ranieri and colleagues' study. These results emphasize that the volume history preceding measurement may significantly affect recruitment evaluation.

Also investigated was the extent to which a similar plateau pressure obtained with the combination of a low tidal volume with a high PEEP compared with a pressure obtained with the combination of a low PEEP with a high tidal volume may differently affect recruitment [21]. In this experiment, the recruitment obtained with the high PEEP level and the low tidal volume largely exceeded the recruitment obtained with the low PEEP and high tidal volume despite a similar plateau pressure. These findings show that the magnitude of derecruitment due to the reduction in tidal volume remains significantly lower compared with the recruitment that results from the PEEP increase. These data corroborated a computed tomography physiological experimental study reported by Pelosi and colleagues, in which the authors elegantly and clearly demonstrated that both end-inspiratory pressure and PEEP could affect lung recruitment [22].

## Currently available methods to assess alveolar recruitment in the routine practice

### Pressure–volume curve at the bedside

Several techniques have been proposed to assess the static mechanical properties of the respiratory system (chest wall and lung) by recording the zero end-expiratory pressure–volume curve. In an extended review, Lu and Rouby discuss the limits and advantages of the different methods (static versus quasi-static technique) and detail the procedure that should be performed to record the pressure–volume curve using the low flow inflation technique with currently available ventilators [23].

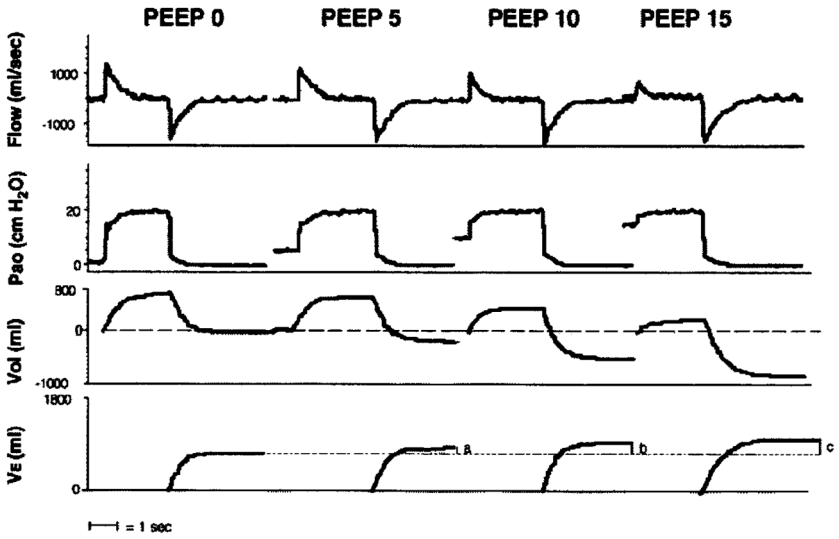
Only two manufacturers, Taema and Hamilton, have at present commercialized an automatic tool specifically designed to automatically record the pressure–volume curve on their ventilator: Horus (Taema, Antony, France) and Gallileo (Hamilton, Rhäzúns, Switzerland). The technique proposed by Taema is a low flow inflation (8 l/min) that allows one to record the zero end-expiratory pressure–volume curve from the zero end-expiratory pressure after a prolonged expiration from the set PEEP level, taking into account the intrinsic PEEP (the expiratory pause preceding the inflation). A cursor permits one to measure linear compliance and the lower inflexion point. A maximal pressure and tidal volume alarm renders the technique relatively safe and easy to perform.

The working principle on the Hamilton ventilator is significantly different since the variable that is controlled during the inflation is the pressure and not the flow. This original approach allows one to record the pressure–volume curve from the zero end-expiratory pressure to a predefined maximal pressure. The inspiratory flow therefore decelerates along inflation. Interestingly, the system automatically records the volume expired during the expiration from the set PEEP to the zero end-expiratory pressure (i.e. end-expiratory lung volume variation related to PEEP) and indicates this point on the graph illustrating the pressure–volume curve. A cursor is also available to compute linear compliance. According to the multiple pressure–volume curve technique discussed earlier, this ventilator is the first to directly assess PEEP-related recruitment by simply calculating the volume difference between the first point of the PEEP pressure–volume curve and the volume read on the zero end-expiratory pressure–volume curve at the corresponding pressure. This method was compared with the multiple occlusion technique on a bench model mimicking different compliance and resistance combinations [24]. The results obtained with the Gallileo method were closed to those obtained with the multiple occlusion technique except for a very low compliance value (10 ml/$cmH_2O$) where inspiratory flow could not be accurately measured by the flow sensor. In this situation, the pressure ramp could be increased at the higher value to maximize inspiratory flow.

### Alternative techniques

Mergoni and colleagues have reported an original method for bedside measurement of PEEP-related alveolar recruitment [25]. This method is based on the ability of modern ventilators to set the inspiratory pressure very accurately and indepen-

**Figure 3**




An alternative technique to assess recruitment: the equal pressure technique. Illustration of the technique proposed by Mergoni and colleagues who measured recruitment without performing pressure–volume curves. Recruitment is computed by comparing the volume expired after pressure breaths performed with the same distending pressure but at different positive end-expiratory pressure (PEEP) levels (5–15 $cmH_2O$). (a–c) Difference corresponding to the recruitment related to the different PEEP levels studied. Modified from [25]. $P_{ao}$, airway pressure; Vol, volume; $V_E$, expired volume.

dently from the expiratory pressure. Using pressure-controlled ventilation, these authors measured the volume expired during a prolonged expiration from 20 $cmH_2O$ inspiratory pressure to zero end-expiratory pressure. This volume represents the increase in volume induced by 20 $cmH_2O$ alveolar pressure. The expiratory pressure used, before this test cycle, can be set from 0 to 20 $cmH_2O$. Alveolar recruitment induced by PEEP is defined as the difference in expired volumes recorded during two test cycles preceded by ventilation in zero end-expiratory pressure and in PEEP (Fig. 3). Mergoni and colleagues reported a good agreement between the results obtained with this method and with the pressure–volume curve method.

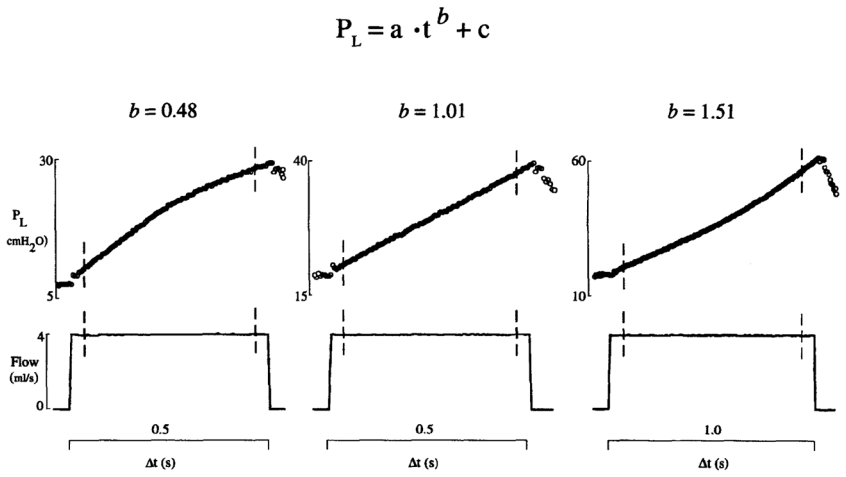
Ranieri and colleagues have reported a method that allows a qualitative assessment of recruitment and overdistension during tidal ventilation [26]. This method is based on the analysis of the airway pressure trace during volume-controlled ventilation with constant inspiratory flow. Assuming that resistances are constant during inspiration, the shape of the airway pressure–time curve indicates the change in compliance during inflation. A concave downward shape indicates that compliance increases during tidal inflation, suggesting the occurrence of recruitment, while a convex downward shape indicates that compliance decreases during tidal inflation, suggesting the occurrence of overdistension (Fig. 4). Ranieri and colleagues recently demonstrated that this analysis could predict the risk of ventilator-induced lung injury associated with various ventilatory strategies in an isolated rat lung model [27].

Thoracic computed tomography was proposed in the 1990s to evaluate the effect of different levels of PEEP on alveolar recruitment. Initially, a single computed tomographic section was used to assess recruitment defined as the decrease in nonaerated lung units. This experimental technique has largely contributed to better understand the influence of respiratory parameters on alveolar recruitment and ventilation distribution [11,12]. Nevertheless, this technique may be flawed because it ignores the recruitment that occurs in poorly aerated lung units and therefore does not reflect the recruitment that may occur in the entire lung. Malbouisson and colleagues recently proposed a new computed tomographic method whereby recruitment was defined as the volume of gas penetrating in poorly and nonaerating lung units when PEEP is applied [28]. Data obtained with this technique differed significantly from those obtained with the approach proposed by Gattinoni and colleagues; the positive correlation found with this new computed tomographic technique with the effect of PEEP on oxygenation indirectly suggests that this approach may, in fact, be more accurate [12]. Nevertheless, computed tomographic assessment of alveolar recruitment remains a technique not currently available in the majority of intensive care units. An interesting review of this computed tomographic approach has recently been published [11].

### Alveolar recruitment and arterial oxygenation

Arterial oxygenation is probably the most widely used criteria for PEEP titration in daily clinical practice. Since recruitment is the main mechanism by which the PEEP improves oxygena-

**Figure 4**




An alternative technique to assess recruitment: automatic analysis of the pressure–time curve. Illustration of the concept proposed by Ranieri and colleagues to monitor recruitment and overdistension during tidal normal breaths. A mathematical equation allows one to analyze the aspect of the inspiratory part of the airway pressure tracing during a breath obtained with a constant inspiratory flow. A concave downward shape of the pressure–time curve reflects continuous recruitment (left panel) while a convex downward shape indicates overdistension (right panel) The straight shape in the middle panel indicates the lack of recruitment and alveolar overdistension. Modified from [27]. $P_L$, airway pressure.

tion, it could be proposed to use arterial oxygenation as an index of alveolar recruitment. Two recent studies showed a significant positive correlation between PEEP-related recruitment and arterial oxygenation [18,28]. The correlations found in these two studies are unfortunately relatively weak, suggesting that arterial oxygenation cannot reliably predict the amount of recruitment induced by a given level of PEEP in an individual patient.

## Clinical implication

Ventilator-induced lung injury that results from both end-inspiratory overdistension and end-expiratory cycling collapse is recognized as a key feature implicated in the multiple organ failure process. This statement, mainly based on experimental findings, is now supported by the results of a recent randomized controlled trial clearly demonstrating that acute lung injury mortality and inflammatory response can be significantly affected by ventilator settings [29]. As a result, the use of a low tidal volume to limit the end-inspiratory pressure is now widely recommended. However, controversies remain regarding the accepted optimal level of PEEP even if keeping the lung aerated may be viewed as an important goal of the lung protective ventilatory approach. How and to what extent PEEP should be increased continues to be debated.

In this context, Rouby and colleagues recently proposed an algorithm to determine the optimal PEEP level [30]. The strategy they proposed not only takes into account the chest radiographic distribution of lung condensations, but also considers the characteristics of the pressure–volume curve. According to their recommendations, a high PEEP level should be tested in patients exhibiting a marked inflexion point on the zero end-expiratory pressure–volume curve associated with a homogeneous distribution of lung densities. In fact, in this situation the probability of alveolar recruitment largely predominates the risk of overdistension. In contrast, an uneven distribution of lung consolidations associated with the lack of lower inflexion point suggests that PEEP could promote overdistension.

Finally, the most important question is to determine whether a strategy aimed to improve alveolar recruitment is able to improve outcome when a low tidal volume is used. Unfortunately, this issue remains an ongoing question.

## Conclusion

Alveolar recruitment is a key feature in the ventilatory management of patients with ARDS. However, this approach should be cautiously balanced with the risk associated with overdistention. In this context, the pressure–volume curve represents an interesting tool that may be used at the bedside to help the caregiver in determining the optimal PEEP level. Nevertheless, the classical interpretation of the sigmoidal shape of the curve by which critical opening pressure and overdistension may be reflected by the lower inflection point and the upper inflexion point, respectively, has been widely discussed. The influence of volume history on recruitment, which considers not only PEEP, but also the tidal volume and the respiratory rate, should be taken into consideration in order to better understand and interpret information reflected by the pressure–volume curve recorded from zero end-expiratory pressure. Limits of the different techniques currently available

to assess recruitment are also important to consider so that a useful physiological tool can be transposed into routine practice. Whether recruitment should be considered as a therapeutic goal remains controversial and warrants further clinical investigation.

## Competing interests

None declared.

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