How to monitor a recruitment maneuver at the bedside

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Purpose of review
To provide an overview on most recent knowledge on methods currently available for monitoring of recruitment maneuvers at the bedside.

Recent findings
The effects of recruitment maneuvers on clinical outcomes in patients with moderate to severe acute respiratory distress syndrome and in patients with healthy lungs undergoing major surgery were recently assessed. Despite being part of a multifaceted approach of protective ventilation, recruitment maneuvers are supposed to decrease mortality and improve postoperative outcomes. However, the role of recruitment maneuver remains controversial in routine practice owing to concerns regarding complications, especially its effects on hemodynamics. In addition, although recruitment maneuvers are being increasingly used, there remains a great deal of uncertainty regarding the precise way to evaluate the effect of recruitment. An effective recruitment maneuver is expected to reinflate nonaerated lung units. End-expiratory lung volume, compliance, dead space, volumetric capnography, and bedside imaging techniques such as lung ultrasound and electrical impedance tomography have all different strengths and weaknesses. A multimodal and multiparametric approach could be a valuable option for bedside monitoring of recruitment maneuvers both in the ICU and in the operative room.

Summary
Several methods offer evaluation of lung recruitability and allow the monitoring of positive and negative effects of recruitment maneuvers. More than the type of method used, a multifaceted approach of monitoring of recruitment maneuvers should be regarded.

Keywords
bedside monitoring, lung volume, lung-protective ventilation, mechanical ventilation, oxygenation, recruitment maneuver

INTRODUCTION
The recognition of the importance of ventilator-induced lung injury (VILI) in the last decades has led to a significant change in the provision of mechanical ventilation and the acceptance of a lung-protective ventilation approach. Although the emphasis of lung protection was mainly placed on patients with established acute respiratory distress syndrome (ARDS), much attention is now paid to patients with healthy lungs. The prevention of VILI involves a multifaceted approach including the use of lower tidal volume (VT) to limit alveolar overdistension and positive end-expiratory pressure (PEEP) to prevent injury from repetitive opening and closing of lung units and atelectrauma \cite{1}. However, as low VT ventilation can be responsible for alveolar instability, lung-protective ventilation remains characterized by a potential for lung derecruitment, especially if sufficient PEEP is not applied. Recruitment maneuvers (i.e., transient increase in transpulmonary pressure by an

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intentional application of high airway pressures to fully reinflate collapsed lung units) should theoretically reduce VILI by minimizing lung heterogeneity [2–4] and have become a component of some ventilatory strategies. A recent meta-analysis of randomized controlled trials assessed the effects of recruitment maneuver on clinical outcomes in patients with moderate to severe ARDS and concluded that the use of recruitment maneuver was associated with a 6% reduction in mortality, although most of the included trials did not use recruitment maneuver as an isolated intervention but as part of a ventilatory package [5]. Two recent randomized controlled trials also found that a multifaceted approach of protective ventilation including repeated recruitment maneuvers improved postoperative outcomes in patients with healthy lungs undergoing major abdominal surgery [6, 7].

The role of recruitment maneuver remains controversial in routine practice owing to concerns regarding complications, especially its effects on hemodynamics [8, 9]. In addition, although recruitment maneuvers are being increasingly used, there remains a great deal of uncertainty regarding the precise way to evaluate the effect of recruitment. In this review, we provide an overview on recent knowledge on methods currently available for bedside monitoring of the positive and negative effects of recruitment maneuver in the ICU or in the operating room.

**WHAT SHOULD BE EXPECTED FROM RECRUITMENT?**

From a physiological perspective, alveolar recruitment refers to the reaeration of previously poorly aerated and/or nonaerated (rather than collapsed) lung areas. It is worth reminding that anatomic recruitment, defined as restored aeration (the primary objective of the procedure) documented by computed tomography (CT) often fails to coincide with functional recruitment, usually defined as improved gas exchange [10]. In this context, the most relevant information has been obtained from the quantitative analysis of CT images [11, 12]. CT scan provides morphological (focal and nonfocal distribution of lung injury) and functional information, allows the estimation of potentially recruitable lung (i.e., the amount of lung tissue in which aeration can be restored) and to differentiate between recruitment (an increase in gas volume in previously poorly aerated and nonaerated lung regions) and inflation. Nevertheless, although CT has become faster with reduced radiation exposure, it is clear that CT does not meet the prerequisites for use in everyday practice, especially at the patient bedside, and should be reserved for clinical research.

The rationale for the use of recruitment maneuver is to promote alveolar recruitment leading to increased end-expiratory lung volume (EELV) and to a reduced mechanical stress on the boundary between nonaerated and aerated areas, with the results being an increase in oxygenation and improved lung mechanics [13, 14].

The physiological effects of recruitment maneuver have been primarily evaluated based on changes in respiratory mechanics, with the ultimate goal being an improvement in the ventilation–perfusion ratio and better oxygenation. However, previous studies have shown that the measurement of oxygenation is of limited value for assessing functional recruitment as several factors other than recruitment can influence oxygenation [15,16]. In other words, although improvement in oxygenation is usually associated with the reexpansion of nonaerated lung areas and has been used in several studies to discriminate between responders and nonresponders to recruitment, the absence of change in arterial partial pressure of oxygen does not necessarily mean absence of anatomical recruitment. In a prospective study of 16 mechanically ventilated patients with ARDS, Di Marco et al. [17] suggested that the measurement of the diffusing capacity of the lung for carbon monoxide, using a bag-in-box system between the circuit Y-piece and the endotracheal tube that allows a rebreathing maneuver without patient disconnection, may supply further information about functional recruitment, which cannot be predicted by changes in oxygenation. As established byGattinoni et al. [10], the anatomical and the functional lung recruitment can coincide only if the restoration of aeration of pulmonary units occurs in association with the absence of a change in perfusion of the same units, which is a critical determinant of oxygenation.
Also investigated was the extent to which changes of either dynamic or static respiratory system compliance may be related to changes in lung aeration following alveolar recruitment. In fact, respiratory compliance was found not to be related to the amount of poorly or nonaerated lung tissue but, rather, closely associated with the amount of normally aerated tissue, as detected by CT scan [18]. Interestingly, in their seminal 2006 article,Gattinoni et al. [10] found that patients with ARDS who had the higher percentage of potentially recruitable lung (defined as the proportion of the total lung weight accounted for by nonaerated lung tissue in which aeration was restored by the recruitment maneuver) also had poorer oxygenation and respiratory system compliance in addition to higher levels of dead space compared with those having a lower percentage of potentially recruitable lung. Although an increase in static lung compliance could intuitively be reflective of improved lung aeration, after recruitment maneuver application, this parameter lacks sensitivity and specificity to precisely assess lung status and should therefore be used in conjunction with other parameters. Moreover, assessment of static lung compliance (i.e., the difference between the total compliance of the respiratory system and the chest wall compliance) that should be preferred to the static compliance of the respiratory system requires the measurement of inspiratory airway plateau pressure during 3 s of an end-inspiratory occlusion, which is technically possible with an ICU ventilator but not with an anesthesia machine, and the measurement of esophageal pressure that is not widely spread in clinical settings [19].

ALVEOLAR RECRUITMENT AND DEAD SPACE

Dead space represents the portion of ventilation that is not participating in gas exchange as it does not come in contact with the pulmonary capillary blood flow. Dead space (VD) variables can reflect changes in lung condition such as collapse and recruitment. Since 1975, Suter et al. [20] suggested that alveolar dead space (VD_{alv}) measurement, computed as the difference between anatomical and physiological dead space, could be useful to individualized PEEP setting in patients suffering from pulmonary failure. The decrease in VD_{alv} with PEEP was assumed to reflect the reexpansion of atelectatic areas, with some of the inspired volume being shifted from overdistended and unperfused (VD_{alv} changes in inverse proportion to changes in cardiac output) low compliance alveoli toward newly expanded perfused lung areas. Interestingly, lung overdistension can also be characterized by an increase in VD_{alv}. The hypothesis that VD variables, analyzed by the single breath test of carbon dioxide using a mainstream sensor, may be useful to evaluate the collapse-recruitment phenomena has been explored in an experimental study by Tusman et al. [21] in which VD was compared with CT images of the lungs. The alveolar dead space to alveolar tidal volume ratio (VD_{alv}/VT_{alv}) was obtained dividing VD_{alv} by alveolar VT (i.e., the difference between VT and airway dead space). They found that VD_{alv} and VD_{alv}/VT_{alv} were closely correlated with atelectatic lung areas on CT scan and had a high sensitivity and specificity for detecting early lung collapse during a PEEP trial following a recruitment maneuver. As lung closing and opening is not easy to evaluate at the bedside, monitoring of dead space may be useful for detecting lung collapse and for establishing open lung PEEP after a recruitment maneuver. Some publications support the value of volumetric capnography (VCap) for assessing dead space at the bedside. The main difference between VCap and common capnography is that CO_2 data are related to expiratory flow (instead of being plotted against time) to obtain volume, with the area under the curve of the capnogram representing the elimination of CO_2 per breath [22]. The VCap capnogram is divided into three phases, with phase 3 representing the pure alveolar gas allowing the evaluation of the VD_{alv}. The same study group recently evaluated whether Cap might be useful to define the lungs’ opening and closing pressures in 20 morbidly obese patients undergoing laparoscopic bariatric surgery [23]. They found that VCap could help identify the optimal level of PEEP (defined as the point of PEEP associated with the lowest dead space value during the descending limb of the recruitment maneuver) that keeps the lung open after a recruitment maneuver has been applied.

MONITORING CHANGES IN LUNG VOLUME AT THE BEDSIDE

The multiple pressure–volume curves method has long been proposed to provide an acceptable bedside assessment of recruitment [24]. Nevertheless, performing multiple pressure–volume curves is difficult to introduce into clinical practice, and possible underestimation of alveolar recruitment must be considered [25].

There is a growing body of evidence suggesting that direct measurement and monitoring of EELV could be used to assess both alveolar recruitment and derecruitment at the bedside. In an experimental study, Chiumello et al. [26] demonstrated that,
alveolar recruitment has been evaluated in a study by Dellamonica et al. [28]. In an elegant study of 30 patients receiving mechanical ventilation for acute lung injury, Dellamonica et al. [28] have shown that measuring EELV with the nitrogen washout technique may be useful to assess alveolar recruitment and strain (i.e., lung deformation owing to the stress induced by volume inflation) without the need for multiple pressure–volume curves or CT scan. The ratio of changes of EELV to functional residual capacity (ΔEELV/FRC) also showed satisfactory accuracy to discriminate between high and low recruiters, with an optimal cut off value of 73% (sensitivity and specificity of 80%). In previous studies from our group, EELV has also been found to be an interesting tool in combination with elastance to evaluate the effect of recruitment in both obese and nonobese surgical patients undergoing laparoscopic surgery [29]. Changes in EELV analyzed solely should however be interpreted with caution as EELV does not permit one to differentiate the volume caused by recruitment of previously nonaerated lung units and the volume as a result of the inflation of already open alveoli.

**LUNG ULTRASONOGRAPHY AND ALVEOLAR RECRUITMENT**

Lung ultrasonography (LUS) has gained increased interest in recent years both in the ICU and in the operating room largely thanks to its innocuity and availability at the bedside. Several studies support the concept that an improvement in lung aeration can be assessed and detected by LUS [30,31]. The capacity of LUS to assess the extent of alveolar recruitment has been evaluated in a study by Bouhemad et al. [32]. A statistically significant correlation was found between PEEP-induced lung recruitment, evaluated by the pressure–volume curves method, and the ultrasound reaeration score calculated from changes in the ultrasound pattern of each of the 12 lung regions [31]. However, although LUS is an easily repeatable technique, it nevertheless remains time-consuming, unsuitable for continuous monitoring and obviously inappropriate to detect lung hyperinflation.

**BEDSIDE ASSESSMENT OF LUNG DERECRUITMENT**

Several conditions such as endotracheal suctioning and disconnection from the ventilator (for example, during intrahospital transfer or nursing) can develop during the time course of mechanical ventilation, which can all lead to atelectasis formation and alveolar derecruitment (i.e., a decrease in lung aeration). As alveolar derecruitment may promote arterial hypoxemia but, above all, aggravate or even induce ventilator-associated lung injury, repeated recruitment maneuvers may need to be applied. In a study of 59 mechanically ventilated surgical patients, Heinzé et al. [33] demonstrated that the measurement of EELV could be useful for early identification of patients exhibiting a decrease in lung volume induced by an open suctioning procedure and for which recruitment maneuver was beneficial as evidenced by significant lung reaeration. Interestingly, using electrical impedance tomography (EIT; Dräger Medical, Lubeck, Germany), they also found that open suctioning was associated with a ventral shift in distribution of ventilation (suggesting loss of aeration in the most dependent part of the lungs), allowing therefore for bedside assessment of several ventilatory units of different lung regions that differ in their mechanical behavior. EIT, which confers the major benefit of allowing real-time rather than intermittent monitoring, measures relative impedance changes in lung tissue during tidal breathing and provides images of the lungs divided into regions of interest. Among other EIT-based indices that were evaluated in recent years, the regional ventilation delay index describing the scatter of impedance time courses has been found to correlate well with the relative amount of recruited voxels (regional recruitment) measured by CT scan [34].

**HEMODYNAMIC TOLERANCE**

Previous studies have clearly shown that increased intrathoracic pressure resulting from recruitment maneuvers transiently compromises hemodynamic function by impeding venous return with an increase in right atrial pressure, thus promoting a decrease in cardiac output and arterial pressure, and that recruitment maneuver should therefore be used with caution in patients with hemodynamic instability [8,35]. It is worth noting that the hemodynamic effects of recruitment maneuver are widely influenced by the method of recruitment, the applied level of alveolar pressure, the lung and chest wall mechanics and, obviously, by the properties of the underlying cardiovascular system. In addition, Lim et al. [8] found that the
CONCLUSION

Although further studies are needed to better identify the patients who could benefit the most from alveolar recruitment, recruitment maneuver will undoubtedly become more extensively used in the multifaceted approach of lung-protective ventilation. Monitoring the effects of recruitment maneuver at the bedside should therefore become an integral part of the strategy.

As there is no one one-size-fits-all solution, on the basis of our interpretation of the literature and our experience, we believe that a multimodal approach should be considered for the monitoring of recruitment at the bedside both in the ICU and in the operating room. There is however no need to reinvent the wheel as most solutions to this problem have been given in the landmark article by Suter et al. [20].

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REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

* of special interest
** of outstanding interest


A must read review. Clear and concise presentation of deleterious effects of mechanical ventilation by two ARDS experts. Any practitioner dealing in or using mechanical ventilation should have read this literature.


Large multicentric randomized controlled trial on the application of the concept of open lung ventilation to patients undergoing major abdominal surgery. The study shows drastic decrease in postoperative complications with a ventilation bundle (low VT, recruitment maneuver and high PEEP) and suggests huge benefits in closer monitoring of peroperative mechanical ventilation.


