Bedside Ultrasound Assessment of Positive End-Expiratory Pressure–induced Lung Recruitment

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Rationale: In the critically ill patients, lung ultrasound (LUS) is increasingly being used at the bedside for assessing alveolar-interstitial syndrome, lung consolidation, pneumonia, pneumothorax, and pleural effusion. It could be an easily repeatable noninvasive tool for assessing lung recruitment.

Objectives: Our goal was to compare the pressure–volume (PV) curve method with LUS for assessing positive end-expiratory pressure (PEEP)-induced lung recruitment in patients with acute respiratory distress syndrome/acute lung injury (ARDS/ALI).

Methods: Thirty patients with ARDS and 10 patients with ALI were prospectively studied. PV curves and LUS were performed in PEEP 0 and PEEP 15 cm H2O. PEEP-induced lung recruitment was measured using the PV curve method.

Measurements and Main Results: Four LUS entities were defined: consolidation; multiple, irregularly spaced B lines; multiple coalescent B lines; and normal aeration. For each of the 12 lung regions examined, PEEP-induced ultrasound changes were measured, and an ultrasound reaeration score was calculated. A highly significant correlation was found between PEEP-induced lung recruitment measured by PV curves and ultrasound reaeration score (Rho = 0.88; P < 0.0001). An ultrasound reaeration score of +8 or higher was associated with a PEEP-induced lung recruitment greater than 600 ml. An ultrasound lung reaeration score of +4 or less was associated with a PEEP-induced lung recruitment ranging from 75 to 450 ml. A statistically significant correlation was found between LUS reaeration score and PEEP-induced increase in PaO2 (Rho = 0.63; P < 0.05).

Conclusions: PEEP-induced lung recruitment can be adequately estimated with bedside LUS. Because LUS cannot assess PEEP-induced lung hyperinflation, it should not be the sole method for PEEP titration.

Keywords: lung ultrasound; acute respiratory distress syndrome; acute lung injury; positive end-expiratory pressure; lung recruitment

Ultrasound is increasingly being used at the bedside for assessing cardiovascular (1), neurological (2), and lung status (3) in critically ill patients with shock, multiple trauma, head injury, and acute lung injury/acute respiratory distress syndrome (ALI/ARDS). Ultrasound is noninvasive, easily repeatable, and reproducible and does not require the transportation of patients outside the Intensive Care Unit (ICU). Transthoracic lung ultrasound (LUS) allows the diagnosis of alveolar-interstitial syndrome, lung consolidation, pneumonia, pleural effusion, and pneumothorax and may be more accurate than auscultation and bedside chest radiography (4).

In critically ill patients, lung ultrasound is increasingly being used for assessing lung consolidation, pneumonia, pleural effusion, and pneumothorax, and acute respiratory distress syndrome (ARDS). Ultrasound is noninvasive and easily repeatable at the bedside, it can allow close monitoring of any respiratory maneuvers aimed to improve lung aeration.

AT A GLANCE COMMENTARY

Scientific Knowledge on the Subject

In critically ill patients, lung ultrasound can be used as a diagnostic tool for assessing positive end-expiratory pressure–induced lung recruitment. Because it is noninvasive and easily repeatable at the bedside, it can allow close monitoring of any respiratory maneuvers aimed to improve lung aeration.

What This Study Adds to the Field

We provide evidence that lung ultrasound can be used as a diagnostic tool for assessing positive end-expiratory pressure–induced lung recruitment. Because it is noninvasive and easily repeatable at the bedside, it can allow close monitoring of any respiratory maneuvers aimed to improve lung aeration.

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and fastidious analysis of data, lung CT remains a research tool. At the bedside, a method based on the analysis of static pressure–volume (PV) curves has been proposed (11) and recently validated against CT (12). However, it requires deep sedation and muscle relaxation and cannot be performed in spontaneously breathing patients.

The aim of the present study was to compare the PV curve method with LUS for assessing PEEP-induced lung recruitment. The ultrasound method was based on an ultrasound reaeration score recently used for assessing lung reaeration after the resolution of ventilator-associated pneumonia (5).

METHODS

Patients

Approval of the local Ethical Committee and written informed consent from patients’ next of kin were obtained. A total of 40 patients with early ARDS/ALI were prospectively included. Exclusion criteria were intracranial hypertension, recurrent pneumothorax, bronchopleural fistula, severe hypoxemia defined as a PaO2/FIO2 ratio of 100 or less at zero end-expiratory pressure, and pregnancy. Lung morphology was assessed on initial frontal chest radiography according to previously described criteria (13, 14). Patients showing a diffuse or patchy pattern at zero end-expiratory pressure, and pregnancy. Lung morphology was classified as having focal lung morphology (15). Were classified as having diffuse lung morphology, and patients showing a lobar pattern were classified as having focal lung morphology (15).

Pressure–Volume Curves and Measurement of PEEP-induced Lung Recruitment

PV curves were measured using a ventilator equipped with specific software. In anesthetized and paralyzed patients, after a prolonged expiratory pause at PEEP 0 or PEEP 15 cm H2O, each patient’s respiratory system was inflated by a constant 8 l/min flow until an inspiratory pressure of 40 cm H2O was reached. Simultaneously, pressures, flows, and volumes were recorded.

Decrease in end-expiratory lung volume (ΔEELV) was defined as the difference in lung volume between PEEP 0 and PEEP 15 cm H2O after a PEEP release maneuver. PEEP-induced lung recruitment was measured according to lung morphology assessed on chest radiography (13, 14). In patients with focal loss of aeration, PEEP-induced lung recruitment was quantified as follows: PV curves in PEEP 0 and PEEP 15 cm H2O were placed on the same pressure and volume axes. PEEP–recruitment was quantified as follows: PV curves in PEEP 0 and PEEP (13, 14). In patients with focal loss of aeration, PEEP-induced lung recruitment was defined as the difference in lung volumes between PEEP 0 and PEEP 15 cm H2O at an airway pressure of 15 cm H2O (16). In patients with diffuse loss of aeration, PEEP-induced lung recruitment was defined as ΔEELV.

Lung Ultrasound

LUS was performed using a 2- to 4-MHz probe. All intercostal spaces of upper and lower parts of anterior, lateral, and posterior regions of left and right chest wall were examined (3, 6). Videos were stored on magneto-optical disks. Each region of interest was extensively examined. The worst ultrasound abnormality detected was considered as characterizing the region examined.

Four ultrasound aeration patterns were defined: (1) normal aeration (N): presence of lung sliding with A lines or fewer than two isolated B lines (17, 18); (2) moderate loss of lung aeration: multiple well-defined B lines (B1 lines); (3) severe loss of lung aeration: multiple coalescent B lines (B2 lines); and (4) lung consolidation (C): the presence of a tissue pattern characterized by dynamic air bronchograms (19). An ultrasound reaeration score was calculated from changes in the ultrasound pattern of each region examined in PEEP 0 and PEEP 15 cm H2O (Table 1).

Protocol

The order of PEEP 0 and PEEP 15 cm H2O was randomized. PV curves and PEEP release maneuvers were performed in each condition (Figure 1), and PEEP-induced lung recruitment was calculated. LUS was analyzed by an independent investigator who was unaware of ventilator settings.

Statistical Analysis

Correlations between ultrasound reaeration score and PEEP-induced lung recruitment were tested using Spearman correlation rank analysis. Statistical analysis was performed using NCSS (Kaysville, UT). Statistical significance was fixed at 0.05.

RESULTS

Patients

Forty consecutive critically ill patients with ALI or ARDS were included in the study. Patients were ventilated using a tidal volume of 6 ml/kg of ideal body weight. PaCO2 was maintained between 35 and 45 mm Hg by increasing the respiratory

### Table 1. Ultrasound Raeaeration Score

<table>
<thead>
<tr>
<th>Quantification of reaeration*</th>
<th>Quantification of loss of aeration</th>
</tr>
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<tbody>
<tr>
<td>1 point</td>
<td>3 points</td>
</tr>
<tr>
<td>B1 → N</td>
<td>B2 → N</td>
</tr>
<tr>
<td>C → B2</td>
<td></td>
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</tbody>
</table>

* The ultrasound reaeration score was calculated as follows: In a first step, ultrasound lung aeration (N, B1, B2, and C) was assessed in each of the 12 lung regions examined before and after application of positive end-expiratory pressure 15 cm H2O. In a second step, ultrasound lung reaeration score was calculated as the sum of each score characterizing each lung region examined according to the scale shown in the table.

Figure 1. Time course of the protocol. In each patient, the order of positive end-expiratory pressure (PEEP) 0 and PEEP 15 cm H2O was randomized. After a stabilization period of 15 minutes of ventilation in PEEP 0 or PEEP 15 cm H2O, a complete lung ultrasound (LUS) examination was performed, arterial blood gas (ABG) was withdrawn for analysis, and a pressure-volume (PV) curve was performed. At the end of the PEEP 15 cm H2O period, a PEEP release maneuver was performed to measure change in end-expiratory lung volume.
frequency in zero end-expiratory pressure conditions as previously described (20, 21). Ventilator settings other than PEEP were kept constant throughout the experiments, and FiO2 was maintained at 1. Clinical and physiological characteristics are summarized in Table 2. Compared with patients with focal loss of aeration, patients with diffuse loss of aeration had a higher lung injury severity score, were ventilated with a higher respiratory rate, and had a higher level of PEEP-induced lung recruitment (Table 2).

Diagnostic Accuracy of LUS for Quantifying PEEP-induced Lung Recruitment

A highly statistically significant correlation was found between PEEP-induced lung recruitment measured by the PV curve method and the ultrasound reaeration score (Figure 2A). The ultrasound reaeration score was accurate for detecting a significant increase in lung aeration (Figure 2B). PEEP-induced lung recruitment greater than 600 ml was detected by an ultrasound lung reaeration score of 18 or greater. An ultrasound lung reaeration score of 14 or greater was associated with PEEP-induced lung recruitment ranging from 75 to 450 ml. Therefore, the ultrasound reaeration score was less accurate for detecting smaller changes of lung aeration. A statistically significant correlation was found between the LUS reaeration score and a PEEP-induced increase in PaO2 (Figure 2C). The correlation was tighter in patients with diffuse loss of lung aeration than in patients with focal loss of lung aeration.

Ultrasound Analysis of Regional Lung Reaeration after PEEP

Among 480 regions of interest, 469 could be examined before and after application of PEEP (11 regions of interest could not be examined because of the presence of a chest tube). Ultrasound reaeration after PEEP was predominantly made of the

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**TABLE 2. PATIENT CHARACTERISTICS**

<table>
<thead>
<tr>
<th></th>
<th>All Patients (n = 40)</th>
<th>Patients with Focal Loss of Aeration (n = 27)</th>
<th>Patients with Diffuse Loss of Aeration (n = 13)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>61 ± 16*</td>
<td>62 ± 18</td>
<td>57 ± 14</td>
<td>0.52</td>
</tr>
<tr>
<td>Mortality, n (%)</td>
<td>30</td>
<td>8/26 (30)</td>
<td>3/13 (27)</td>
<td>0.19</td>
</tr>
<tr>
<td>Initial etiology</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major vascular surgery</td>
<td>20</td>
<td>15</td>
<td>5</td>
<td>0.31</td>
</tr>
<tr>
<td>Multiple trauma</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>0.30</td>
</tr>
<tr>
<td>Digestive or gynecological surgery</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>0.22</td>
</tr>
<tr>
<td>Cardiac surgery</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0.24</td>
</tr>
<tr>
<td>Community-acquired pneumonia</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0.24</td>
</tr>
<tr>
<td>ALI/ARDS</td>
<td>30/10</td>
<td>8/19</td>
<td>2/11</td>
<td>0.45</td>
</tr>
<tr>
<td>Cause of ALI/ARDS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early-onset bronchopneumonia</td>
<td>19</td>
<td>11</td>
<td>8</td>
<td>0.22</td>
</tr>
<tr>
<td>Late-onset bronchopneumonia</td>
<td>18</td>
<td>13</td>
<td>5</td>
<td>0.56</td>
</tr>
<tr>
<td>Abdominal sepsis</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0.53</td>
</tr>
<tr>
<td>Severity acute physiological score</td>
<td>35 ± 14</td>
<td>36 ± 14</td>
<td>34 ± 13</td>
<td>0.87</td>
</tr>
<tr>
<td>Lung injury severity score</td>
<td>2.4 ± 0.6</td>
<td>2.3 ± 0.5</td>
<td>3.0 ± 0.5</td>
<td>0.002</td>
</tr>
<tr>
<td>PaCO2/FiO2 ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEEP 0 cm H2O</td>
<td>181 ± 100</td>
<td>205 ± 105</td>
<td>146 ± 60</td>
<td>0.08</td>
</tr>
<tr>
<td>PEEP 15 cm H2O</td>
<td>261 ± 105</td>
<td>282 ± 106*</td>
<td>241 ± 92*</td>
<td>0.26</td>
</tr>
<tr>
<td>PaCO2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEEP 0 cm H2O</td>
<td>39 ± 7</td>
<td>38 ± 7</td>
<td>40 ± 7</td>
<td>0.43</td>
</tr>
<tr>
<td>PEEP 15 cm H2O</td>
<td>38 ± 7</td>
<td>38 ± 7</td>
<td>38 ± 7</td>
<td>0.98</td>
</tr>
<tr>
<td>Respiratory rate, cycles/min</td>
<td>21 ± 5</td>
<td>16 ± 4</td>
<td>23 ± 5</td>
<td>0.002</td>
</tr>
<tr>
<td>PEEP-induced lung recruitment measured with the PV curve, ml</td>
<td>502 ± 304</td>
<td>347 ± 190</td>
<td>834 ± 226</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* Data are given as mean ± SD or as number. Comparisons between groups were made using a nonpaired t test or a Chi-squared test (or a Fisher’s exact test when needed).

† Significant difference between PEEP 0 and PEEP 15 cm H2O (P < 0.01).

‡ Significant difference between PEEP 0 and PEEP 15 cm H2O (P < 0.001).
disappearance of B lines and of transformation of ultrasound consolidation into B lines in anterior and lateral parts of the chest wall (Figure 3). Consolidations present in the posterior parts of the chest wall were only slightly modified by PEEP. Figure 4 illustrates the different types of PEEP-induced lung recruitment as assessed by bedside LUS.

**DISCUSSION**

This study demonstrates that LUS is as reliable as the PV curve method for assessing PEEP-induced lung recruitment at the bedside. LUS has two main advantages over the PV curve method: (1) It is easily repeatable and does not require deep sedation and paralysis, and (2) it allows a regional analysis of lung recruitment in dependent and nondependent lung regions.

Lung CT is the gold standard for evaluating lung morphology and assessing the effects of different therapies on lung reaeration (5, 22). However, to perform a lung CT scan requires transportation to the department of radiology and a risky procedure necessitating the presence of trained physicians and sophisticated cardiorespiratory monitoring (23). Helical multidetector row CT also exposes the patient to a substantial risk of radiation-induced cancer associated with cumulative radiation dose, which limits its repeatability because of the need for radiation protection (6). In these studies, the ability of LUS to monitor lung aeration changes was based on number and type of B lines. The interstitial syndrome (expanded lung) is characterized by separated B lines, whereas the involvement of the alveolar spaces (fluid-filled lung) leads to the coalescence of B lines (34). The extension of pulmonary edema, the amount of extravascular lung water, and the corresponding decrease in lung aeration are linearly correlated to the number of B lines (35). Therefore, ultrasound scores exclusively based on the number of B lines have been proposed to quantify pulmonary aeration (36). Such scores are not adapted to ALI/ARDS, where lung consolidation predominates over alveolar interstitial syndrome. In addition, numbering B lines throughout the entire lung is fastidious and time-consuming. Therefore, we propose a new aeration score that is defined by four stages of aeration, including normal aeration, decreased lung aeration (number and type of B lines), and consolidation.

Several studies support the concept that an improvement in lung aeration may be detected by corresponding changes in lung ultrasound patterns. Changes in pulmonary aeration have been accurately detected by LUS during various pathologic situations, such as community-acquired or ventilator-associated pneumonia (5, 28), acute respiratory distress syndrome (29), high altitude pulmonary edema (30), and cardiogenic pulmonary edema (31–33). In these studies, the ability of LUS to monitor lung aeration changes was based on number and type of B lines. The interstitial syndrome (expanded lung) is characterized by separated B lines, whereas the involvement of the alveolar spaces (fluid-filled lung) leads to the coalescence of B lines (34). The extension of pulmonary edema, the amount of extravascular lung water, and the corresponding decrease in lung aeration are linearly correlated to the number of B lines (35). Therefore, ultrasound scores exclusively based on the number of B lines have been proposed to quantify pulmonary aeration and to monitor its resolution and the resulting increase in lung aeration (30–33, 36–38). Such scores are not adapted to ALI/ARDS, where lung consolidation predominates over alveolar interstitial syndrome. In addition, numbering B lines throughout the entire lung is fastidious and time-consuming. Therefore, we propose a new aeration score that is defined by four stages of aeration, including normal aeration, decreased lung aeration (number and type of B lines), and consolidation.

The value of LUS for assessing PEEP-induced pulmonary reaeration has been reported qualitatively in a case report (39) and semiquantitatively in one study using transesophageal echocardiography (7). In the latter study, which was performed in patients with ARDS, the ultrasound tissue pattern characteristic of lung consolidation was replaced by coalescent B lines after PEEP, indicating partial reaeration of the left lower lobe (7). In another study from the same group performed in patients with ALI/ARDS, time-dependent lung reaeration was monitored daily by measuring the decrease in the area of consolidated regions within left lower lobe (8). An increase in lung aeration resulting from prone positioning was detected using...
the same method (9). Although these studies were limited to left dependant lung regions, significant correlations were found between decrease in consolidated areas and improvement of oxygenation (7–9).

Observed changes in LUS patterns after PEEP implementation are consistent with the CT changes in lung aeration previously reported in patients with ARDS/ALI (13, 15, 40). In accordance with these studies, we found that distribution of LUS aeration loss (lung consolidation and B lines) was predominant in the most dependant lung regions (posterior parts of lower lobes). PEEP-induced lung reaeration was predominantly made of the disappearance of B lines in the anterior and lateral parts of the chest wall, whereas consolidation present in posterior lung regions was marginally modified by PEEP. PEEP-induced lung recruitment was dependant on lung morphology. In patients with diffuse loss of aeration (initial radiological aspect of “white lungs”), multiple coalescent B lines or consolidation were found in all anterior, lateral, and posterior lung regions at PEEP 0. The beneficial effect of PEEP on lung aeration was observed in all but posterior and caudal lung regions (Figures 3A–3D) and was associated with a significant increase in arterial oxygenation. In patients with focal loss of lung aeration (initial radiological aspect of bilateral inferior consolidations), normal lung sliding and horizontal A lines (normal aeration) were found in upper anterior and lateral lung regions, whereas consolidation or multiple B lines were found in lower posterior and lateral lung regions. The beneficial effect of PEEP on lung aeration was predominantly observed in the lower parts of anterior and lateral lung regions and in the upper parts of posterior lung regions.

LUS is a unique tool for understanding PEEP-induced lung reaeration. The essential of recruitment results from the reaeration of poorly aerated lung regions (Figure 3): B2 lines are transformed into B1 or A lines, and B1 lines are transformed into A lines (normal aeration). The reaeration of nonaerated lung regions remains marginal: Ultrasound consolidations transformed into B2, B1, or A lines is a rarely observed event, occurring mostly in the lower parts of anterior, lateral, and posterior lung regions. This critical information questions recent studies on “potentially recruitable lung,” defined as the proportion of nonaerated lung tissue whose aeration is restored after PEEP (41, 42). It is likely that by confining recruitment to the reaeration of nonaerated lung regions, PEEP-induced lung recruitability was underestimated.

Limitations

Ultrasound assessment of lung recruitment was performed during mechanical ventilation (dynamic conditions), whereas assessment of lung recruitment using the PV curve method was performed without mechanical ventilation (static conditions), including the measurement of static intrinsic PEEP–induced lung recruitment. Therefore, the possibility exists that ultrasound assessment of lung recruitment was underestimated. We think that this methodological limitation had a limited impact on the validity of the results presented. The ventilatory strategy applied to each patient was standardized and included an optimization of respiratory frequency, according to previous studies (20, 21). At the bedside and in zero end-expiratory pressure conditions, the clinician increased the ventilator respiratory rate while looking at the expiratory flow displayed on the screen of the ventilator and the highest “safe respiratory rate” was the rate at which the end of the expiratory flow coincided with the beginning of the inspiratory phase. Therefore, it can be assumed that, in the vast majority of patients, static intrinsic PEEP was null or minimum during dynamic ventilatory conditions. In addition, according to the American European

Figure 4. Illustration of positive end-expiratory pressure (PEEP)-induced lung recruitment detected by ultrasound. (A) Left: Transversal view of consolidated lower lobe. Lung consolidation appears as a tissue structure (C), and hyperechoic tubular images (*) can be seen, corresponding to dynamic air bronchograms (air-filled bronchi). Right: After PEEP 15 cm H2O, the same lung region appears normally aerated. The pleural line (white arrow) can be seen with multiple horizontal A lines (thin arrows). (B) Left: Transversal view of consolidated lower lobe. Lung consolidation appears as a tissue structure (C), and hyperechoic punctiform images (*) can be seen, corresponding to static air bronchograms (air-filled bronchi). Right: After PEEP 15 cm H2O, the same lung region is characterized by multiple coalescent B lines (B2 lines), attesting to the penetration of gas within the consolidation. The pleural line is visible (white arrow), as well as coalescent B lines (*) arising from the pleural line and spreading up to the edge of the screen. These artifacts correspond to ground-glass areas on chest computed tomography (18). (C) Left: Transversal view of a lung region with alveolar syndrome. Coalescent B lines (B2 lines) arising from the pleural line (white arrow) are present. Right: After PEEP 15 cm H2O, the same lung region appears normally aerated. The pleural line (white arrow) can be seen with an isolated B line (*). (D) Left: Transversal view of a lung region with pneumonia. Coalescent B lines (B2 lines) arising from the pleural line (white arrow and *) or from a juxtapleural consolidation (*) are present. Right: After PEEP 15 cm H2O, the same lung region is characterized by multiple well-defined and irregularly spaced B lines (B1 lines), attesting of the penetration of additional gas within the lung region. B1 lines (*) arise from juxtapleural consolidations, suggesting the presence of small foci of pneumonia (>).
Consensus Conference ARDS criteria, patients with a past history of chronic obstructive pulmonary disease were excluded.

The ultrasound reaeration score has been recently validated against CT, the reference method (10), for assessing lung reaeration after antimicrobial therapy in patients with ventilator-associated pneumonia (5). In the present study, LUS was compared with the PV curve method, a technique that is tightly correlated to lung CT for measuring PEEP-induced lung recruitment (12). The ultrasound method for measuring lung reaeration resulting from antimicrobial therapy or PEEP relies on the same principles. Therefore, the ultrasound reaeration score could be appropriate for measuring recruitment resulting from any treatment aimed at increasing lung aeration, such as PEEP, negative fluid balance, positioning (9), or recruitment maneuvers. In addition, the statistically significant correlation existing between the LUS reaeration score and the PEEP-induced increase in PaO₂ indirectly confirms that LUS accurately detects PEEP-induced lung recruitment. The correlation was tighter in patients with diffuse loss of lung aeration than in patients with focal loss of lung aeration. Such a result is in accordance with previous studies demonstrating that lung recruitability is higher in patients with diffuse loss of aeration than in patients with focal loss of aeration (22, 43, 44).

LUS has intrinsic limitations that are patient dependent. Obese patients are frequently difficult to examine using LUS because of the thickness of subcutaneous tissue around the rib cage. The presence of subcutaneous emphysema or large thoracic dressings precludes the propagation of ultrasound beams to the lung periphery and makes LUS examination difficult.

There are also operator-dependent limitations to LUS. In the present study, ultrasound examinations were performed by experienced physicians in LUS, and the results might not be extrapolated to all ICU physicians. Recently, we demonstrated that the learning curve of residents in general LUS is short (<3 wk). After a 6-h focused training period and the practice of 6 ultrasonic examinations, the performance of “naive” residents for diagnosing pleural effusion, alveolar interstitial syndrome, and consolidation was similar to the performance of experts in LUS (45). Similar results have been reported concerning general ultrasound applied to critically ill patients (46). Therefore, with a relatively short focused training period, any physician working in the ICU can acquire the skills required to assess lung recruitment using LUS.

LUS cannot detect PEEP-induced lung hyperinflation. CT data of the whole lung have shown that PEEP produces not only end-expiratory reaeration of nonaerated parts of the lung (recruitment) but also simultaneous end-expiratory hyperinflation of aerated pulmonary areas in patients with focal ARDS (15, 22, 44). As a consequence, ultrasound evidence of PEEP-induced recruitment is insufficient to consider the applied PEEP as optimum (43, 47).

Conclusions

Bedside LUS is equivalent to the PV curve method for quantitative assessment of PEEP-induced lung recruitment. It can be considered accurate enough in clinical practice and has the advantage of being noninvasive and easily feasible at the bedside. In addition, it allows regional assessment of lung recruitment and close monitoring of treatments and maneuvers aimed at improving lung aeration. However, it does not allow an accurate assessment of PEEP-induced lung hyperinflation, and it should not be the sole method for PEEP titration. Further studies are needed to evaluate the benefit of ultrasound monitoring in patients with ARDS/ALI in terms of morbidity and mortality.

Author Disclosure: None of the authors has a financial relationship with a commercial entity that has an interest in the subject of this manuscript.


