REVIEW

Chest ultrasound in acute respiratory distress syndrome

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Purpose of review

This review discusses the role of chest ultrasound in diagnosis and management of acute respiratory distress syndrome (ARDS) and the most recent technical progresses in this field.

Recent findings

Clinically, suspected ARDS can be easily confirmed by lung ultrasonography through the recognition of a typical pattern characterized by B-lines, spared areas, pleural line thickening, and subpleural consolidations. A visual score based on number and thickness of B-lines permits a semiquantitative evaluation of the amount of extravascular lung water and lung density. Recently, a quantitative lung ultrasound method has been proposed. The heart may be also involved in ARDS either primarily or by the application of positive pressure ventilation. The incidence of acute cor pulmonale during ARDS is, even if under protective ventilation, not negligible. The use of echocardiography combined with lung ultrasound is important for early detection of cor pulmonale, identification of the best ventilator strategy to preserve heart-to-lung interaction, and prediction of weaning success.

Summary

An ultrasound-integrated approach combining lung ultrasound and echocardiography should be recommended as a suitable technique to manage ARDS during diagnosis, mechanical ventilation setting, and weaning.

Keywords

extravascular lung water, pulmonary edema, pulmonary hypertension and mechanical ventilation, right heart dysfunction

INTRODUCTION

Lung ultrasound is a diagnostic technique becoming very common in critically ill patients [1]. Until 1967, it was thought that ultrasound was not applicable to lungs because they are organs containing mostly air. Joyner *et al.* [2] first described the possibility of visualizing pathological lung conditions by ultrasound artefactual images. Since then, knowledge in this field has increased exponentially, leading ultrasound to become a highly sensitive and specific technique for a large number of lung diseases. In the intensive care unit (ICU), daily evaluation of pulmonary conditions is extremely important not only for primary lung diseases requiring ventilatory support but also for lung disorders secondary to mechanical ventilation. Although, nowadays, radiologists offer very accurate and specific techniques for lung evaluation such as computed tomography (CT) and magnetic resonance imaging (MRI), the anterior-to-posterior chest X-ray remains the one most widely used in ICU. This is because of risks and difficulties related to transportation of critically ill patients, radiation exposure, and costs. It is well known that anterior-to-posterior supine chest X-ray has low specificity and sensitivity for most lung diseases and is still not void of radiation risks for both patient and staff [3]. Lung ultrasound is a method with higher sensitivity and specificity than chest X-ray in most lung diseases and has also a good diagnostic efficacy when compared with more

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KEY POINTS

- Lung ultrasound can provide an early diagnostic tool to detect ARDS by showing B-lines with inhomogeneous and gravity-independent distribution, spared areas, pleural line thickening, and subpleural consolidations.
- Lung ultrasound can allow a quantification of extravascular lung water and lung density, an important tool for the evaluation and clinical management of ARDS.
- In ARDS, heart–lung interactions should be accurately assessed by echocardiography because the occurrence of acute cor pulmonale is not negligible and represents an independent risk factor for outcome.
- An ultrasound-integrated approach combining lung and heart is important to set up a mechanical ventilation setting protective for right heart and appropriate for treatment of ARDS, to evaluate the effects of positive intrathoracic pressure on the heart and to predict weaning failure.

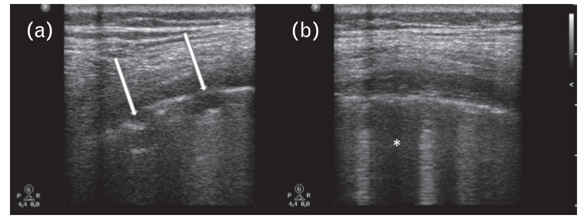

FIGURE 1. Lung ultrasound with high-frequency linear probe in anterior upper lung region of an ARDS patient. Panel (a) shows the presence of thickened irregular pleural line with subpleural antidecubitus consolidations (arrow); panel (b) shows the presence of B-lines with spared areas (star).

sophisticated techniques such as CT and MRI [4]. Moreover, lung ultrasound is rapid, repeatable, inexpensive, radiation-free, noninvasive, and viable at bedside for the managing ICU physician. In addition, it has been described that lung ultrasound can differentiate acute respiratory distress syndrome (ARDS) from other pathological conditions, like cardiogenic pulmonary oedema [5]. In view of all these considerations, lung ultrasound can be regarded as a future progress in the daily management of critically ill patients. The main aims of current scientific research are to identify differences in sonographic artefactual images, to develop integrated ultrasound methods for increasing specificity in the recognition of different lung diseases, and to reduce the most important limitation of this technique, namely, of being operator-dependent, subjective, and nonquantitative.

LUNG MORPHOLOGY IN ACUTE RESPIRATORY DISTRESS SYNDROME

In ARDS, the distribution of lung injury is extremely inhomogeneous and not gravity dependent, with some lung areas being preserved and others affected to varying degrees. Inhomogeneous distribution is the radiological pattern that permits a differential diagnosis between ARDS and acute cardiogenic pulmonary oedema [6]. Lung ultrasound provides a regional assessment of lung to distinguish healthy from unhealthy lung areas. The presence of B-lines [7], also called 'comet-tail artefact', with spared-areas and pleural line abnormalities can confirm a suspected ARDS (Fig. 1). B-lines are vertical artefacts from the pleural line to the edge of the screen, moving synchronously with breath and hiding A-lines (horizontal artefacts, typical of healthy lungs). Many and thick B-lines generate an image of 'white lung', which is regarded as a typical pattern of wet lung. Spared regions are areas of sonographic healthy lung (A-lines and 'black lung') between two areas of sonographic diseased lung (B-lines or 'white lung'). These areas are more frequent in anterior fields because of the patient's supine position and gravitational forces, which make the affected pulmonary parenchyma more compact and homogeneous in the posterior regions. Pleural line abnormalities can be visualized by ultrasound as thickening, irregular or with presence of small subpleural consolidations, leading also to a reduction of 'lung sliding'. Finally, consolidations are frequently present in ARDS, specially, at basal and posterior lung regions (Fig. 2). Consolidations are visualized by ultrasound as hyperechoic punctiform or hepatization areas with the presence of static or dynamic air bronchograms. Sometimes, pleural effusion may be also present in ARDS and can be easily diagnosed and quantified by ultrasound showing an anechoic homogeneous area limited by diaphragm and pleura.

LUNG ULTRASOUND AND EXTRAVASCULAR LUNG WATER

Quantification of extravascular lung water (EVLW) represents an important tool for the evaluation of lung disease, specially, ARDS in which the amount of EVLW independently correlates with the outcome [8]. Furthermore, a conservative and restrictive fluid management in ARDS patients proved to be successful in improving oxygenation and ventilatory parameters, reducing lung injury score and promoting early extubation [9]. EVLW can be quantified accurately by CT densitometry [10,11] and

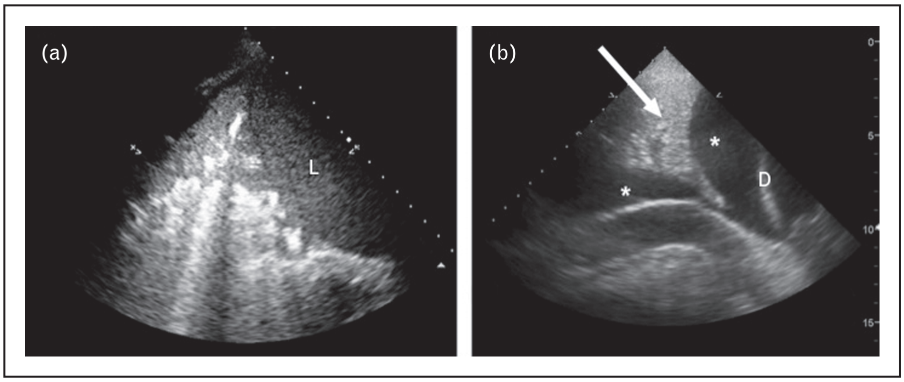

FIGURE 2. Lung ultrasound with phased-array probe in posterior-basal lung region of two ARDS patients. Presence of basal posterior consolidation (arrow) without (panel a) and with (panel b) pleural effusion (stars). L: liver. D: diaphragm.

single thermodilution techniques [11,12], the latter being considered a gold standard in the evaluation of EVLW even if they are based on mathematical calculations potentially susceptible to error. In daily clinical practice, a widespread use of this thermodilution is difficult because invasive, expensive, and needing frequent calibrations. Lichtenstein *et al.* [7] first described lung ultrasound as a technique able to detect increased EVLW by the appearance of B-lines (Fig. 3). Subsequently, number and thickness of B-lines quantified by visual scoring were reported to be highly correlated with chest X-ray visual score [13], with wedge pressure and with EVLW determined invasively respectively by pulmonary artery catheterization and by indicator diluition methods [14], and with lung weight determined by gravimetry in experimental animals [15]. Recently, Baldi *et al.* [16■■] found strong correlations between a semi-quantitative ultrasound assessment of EVLW (ultrasound B-line score) and lung weight or density determined by quantitative CT analysis. Interestingly, the correlation with lung density was better than with lung weight. A limitation of that study was the small number of patients ($n = 13$) with only 10 having pathological EVLW (five ARDS and five pneumonia). Using an ex-vivo model, Soldati *et al.* [17] confirmed the adequacy of lung ultrasound for semiquantitative assessment of lung density, by showing in healthy rabbit lungs that B-lines appearance varied with lung inflation. These results have been confirmed by Bilotta *et al.* [18], who found in 45 patients a linear relationship between B-lines and PaO_2/FiO_2 ratio. These results should be validated in ARDS patients because the study was conducted in neurocritical-care patients with a high PaO_2/FiO_2 ratio (from 346 to 251), suggestive of mild secondary lung disease very different from ARDS conditions. In a model of pulmonary oedema using isolated bovine lungs, we have recently introduced a method of ultrasound quantitative analysis based on a video grey-scale analysis [19■]. Quantitative lung ultrasound intensity was correlated with EVLW density more closely than quantitative CT and provided an estimate of EVLW that was independent of physical density.

HEART-TO-LUNG INTERACTIONS AND TITRATION OF MECHANICAL VENTILATION

ARDS is a syndrome characterized by both alveolar and pulmonary circulation damage. The abnormal

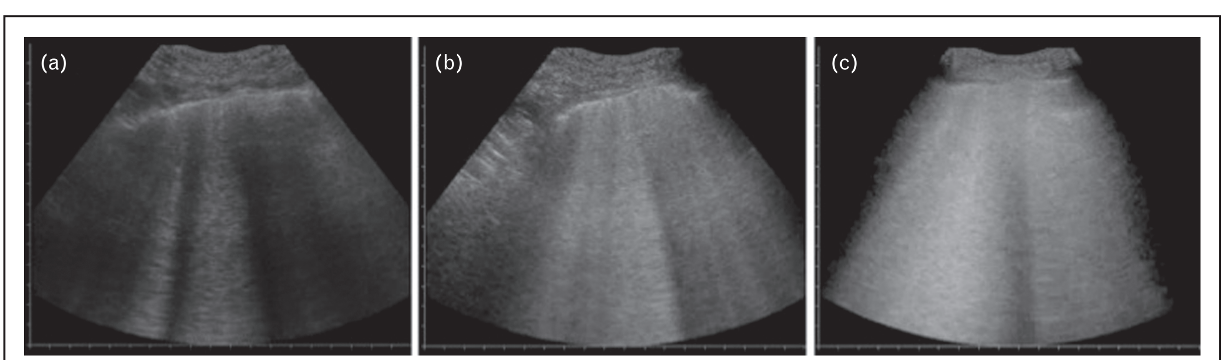

FIGURE 3. Increasing amounts of extravascular lung water from mild with scattered B-lines (panel a) to severe with the typical, so-called, 'white lung' (panel c).

increase in pulmonary vascular resistance leading to pulmonary hypertension causes an increase in right ventricle stroke-work index. An increasing degree of right ventricle dysfunction from mild to severe ARDS, defined according to alterations in respiratory mechanics, is described in 22–27% of ARDS [20]. Acute cor pulmonale is the end stage of right ventricular dysfunction, characterized by right ventricle dilatation and septal dyskinesia because of volume and pressure overload [21]. Moreover, a coexisting patency of foramen ovale with shunting may be responsible for an increased number of ventilator-dependent days and worse outcome [22]. Boissier *et al.* [23■■] found in an observational study of 226 ARDS patients under protective ventilation a 22% prevalence of acute cor pulmonale being an independent risk factor for 28-day mortality. In addition, right ventricular function may be heavily affected by ventilator strategies, as suggested by strong negative correlations found between right ventricular dysfunction and airway plateau pressure [24], or positive end-expiratory pressure (PEEP) [25], or hypercapnia [24,25], and positive correlation with prone position [26,27]. For these reasons, a so-called 'right ventricle protective ventilation approach' has been recently proposed, recommending to perform at least one echocardiographic examination per day during the first 3 days to evaluate right ventricle function and identify the best ventilator settings [28].

In this context, an ultrasound-integrated approach combining echocardiography and lung ultrasound might be useful for a comprehensive assessment of ARDS severity and hemodynamic response to ventilator settings.

By lung ultrasound, the balance between lung recruitment and over-distension can be assessed, thus allowing a better ventilator setting in ARDS patients. Bouhemad *et al.* [29] compared the pressure–volume curve method with the ultrasound reaeration score to assess PEEP-induced lung recruitment in 30 ARDS patients and found that lung ultrasound adequately estimated lung recruitment but not lung hyperinflation. Constantin *et al.* [30] described lung morphology assessed by ultrasound as a good predictor of lung recruitment; in particular, by assessing regional aeration loss they identified focal or homogeneous interstitial patterns. Patients with focal lung pattern were at higher risk of hyperinflation during recruitment manoeuvres.

By echocardiography, either with transthoracic (TTE) or transoesophageal approach, hemodynamic monitoring on heart–lung interactions is possible. Because cardiac preload and afterload are influenced by intrathoracic pressure, echocardiography may permit monitoring effectiveness and impact of PEEP or recruitment manoeuvres on cardiac size and function [31]. By B-mode TTE it is possible to describe both right ventricular dilatation and septal dyskinesia. An apical four-chamber view allows to visualize right ventricular enlargement, whereas a parasternal short axis view permits to recognize right septal flattening usually called 'paradoxical septal motion' (Fig. 4). The degree of flattening is directly proportional to the elevation of right ventricular systolic pressure. By measuring tricuspid annular plane systolic excursion with M-mode ultrasonography (Fig. 5), systolic dysfunction of the right ventricle can be detected. Ultrasound continuous wave Doppler of tricuspid regurgitation jet (Fig. 6) permits to evaluate right ventricular-to-atrial pressure gradient and calculate pulmonary pressures adding a central venous pressure value (invasively measured or derived from inferior vena cava diameter). In addition, variation of specific parameters such as vena cava diameter or left ventricle stroke volume may be evaluated in response to various stimuli, such as volume infusion, inotropics or intrathoracic pressures yielding valuable information on preload responsiveness [32,33]. Finally, the great vessel view by Doppler analysis of pulmonary artery flow can quantify strength and ability of the right ventricle to counterbalance the afterload.

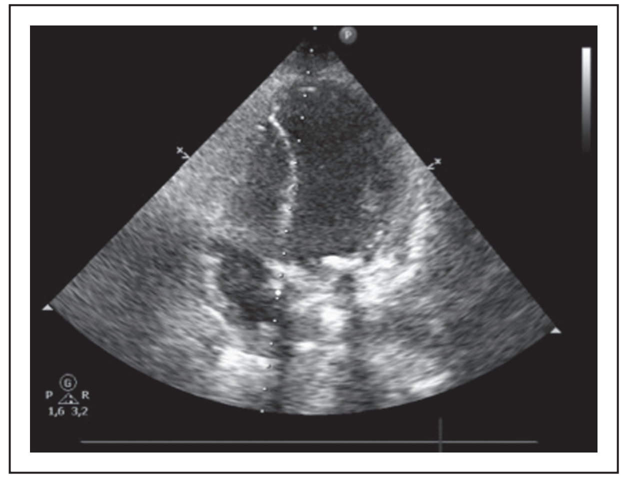

FIGURE 4. A four-chamber apical view to assess interventricular septal wall motion abnormality showing diastolic septal shift.

ULTRASOUND AND WEANING

Weaning from mechanical ventilation represents an on-going challenge for the intensivist because of the high incidence (31%) of weaning failure, i.e., failed spontaneous breathing trial or need for reintubation [34]. The cessation of pressure support provided by mechanical ventilation creates abrupt

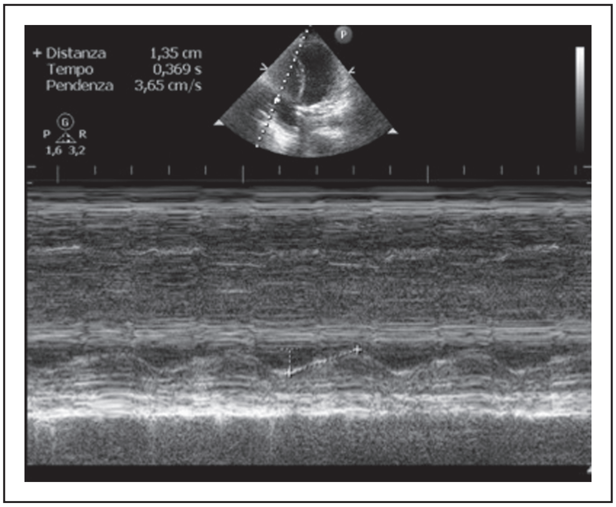

FIGURE 5. A four-chamber apical view to assess tricuspid annular plane systolic excursion (TAPSE). A straight line (M mode) is drawn through the lateral tricuspid valve annulus. The level of excursion of the tricuspid valvular plane (TAPSE, in mm) corresponds to right ventricle ejection fraction.

modifications of both lung and heart functions. Soummer *et al.* [35] found lung ultrasound determination of aeration changes during spontaneous breathing trial an accurate predictor of weaning failure. In their study, they detected loss of lung aeration by lung ultrasound score calculation only in the group developing postextubation distress. The reduction of positive intrathoracic pressure creates a sudden increase in venous return and left ventricle afterload. All these factors lead to an increase of left ventricle filling pressure resulting in possible development of cardiogenic pulmonary oedema or even cardiac ischemia. Lamia *et al.* [36] described the need of echocardiography during spontaneous breathing trial to evaluate the development of weaning-induced pulmonary artery occlusion pressure leading to pulmonary oedema. In that study, TTE was used to calculate E/A and E/Ea ratio by measuring pulsed wave Doppler maximal flow velocity during diastole (E wave) and atrial systole (A wave) and tissue Doppler imaging mitral annular early peak diastolic velocity (Ea). These two measurements accurately depicted hemodynamic changes induced by spontaneous breathing trial screening patients at high risk of cardiac weaning failure. Also, the measurement of left ventricle stroke volume and deceleration time of E wave are important to predict weaning success and outcome [37]. Recently, the need of an ultrasound-integrated approach was highlighted by Mongodi *et al.* [38]. In a single case report, they described how combined use of lung ultrasound and echocardiography during a spontaneous breathing trial revealed an unexpected cause of weaning failure by identifying an increased extravascular lung water pattern and a concurrent left ventricular diastolic failure. Unfortunately, this was only a case report but it represents an example of the usefulness of ultrasound in ICU, which needs to be confirmed in large number of patients.

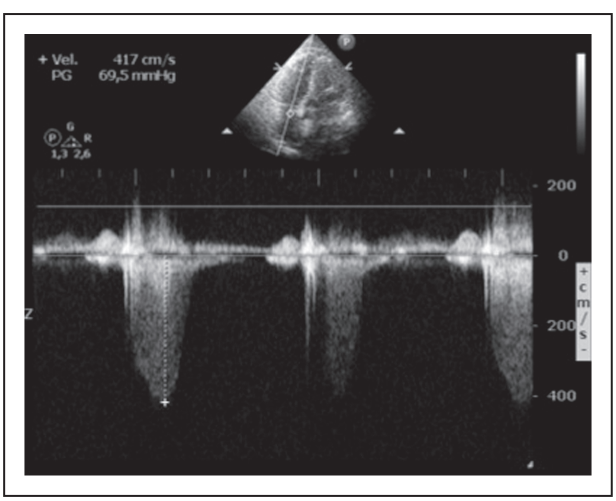

FIGURE 6. Tricuspid continuous wave Doppler indicating increased right ventricular-to-atrial pressure gradient to calculate pulmonary pressures by adding a central venous pressure value.

Lately, ultrasonography of the diaphragm has had a remarkable development because useful in identifying patients at high risk of weaning failure. Kim *et al.* [39] found a correlation between diaphragmatic dysfunction, assessed by M-mode ultrasonography, and weaning time, total ventilation time and rate of weaning failure. Indeed, it is possible by sonography to assess and follow diaphragmatic weakness or paralysis providing a semiquantitative evaluation of diaphragmatic thickness, force, and velocity of contraction [40]. However, the role of diaphragmatic excursion as a predictor of extubation outcome in the weaning process remains to be further evaluated.

CONCLUSION

In daily clinical management of ARDS patients an integrated heart–lung ultrasound approach is advisable. Lung ultrasound can provide a regional evaluation of lung disease to confirm a suspected ARDS by showing typical patterns. Echocardiography can give important information on heart response to pathological ARDS modifications and to intrathoracic pressures induced by ventilator strategies. An ultrasound-integrated approach can be useful to optimize lung recruitment, thus avoiding lung hyperinflation and right heart dysfunction. Future research in this field should try to move lung ultrasonography toward a more quantitative approach.

Acknowledgements

None.

Conflicts of interest

None of the authors have any financial interest in the manufactures cited in this manuscript.

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■ of special interest

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