Usefulness of Cardiothoracic Chest Ultrasound in the Management of Acute Respiratory Failure in Critical Care Practice

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Background

This study investigated the clinical relevance of early general chest ultrasonography (ie, heart and lung recordings) in patients in the ICU with acute respiratory failure (ARF).

Methods

We prospectively compared this diagnostic approach (ultrasound) to a routine evaluation established from clinical, radiologic, and biologic data (standard). Subjects were patients consecutively admitted to the ICU of a university teaching hospital during a 1-year period. Inclusion criteria were age = 18 years and the presence of severe ARF criteria to justify ICU admission. We compared the diagnostic approaches and the final diagnosis determined by a panel of experts.

Results

Seventy-eight patients were included (age, 70 ± 18 years; sex ratio, 1). Three patients given two or more simultaneous diagnoses were subsequently excluded. The ultrasound approach was more accurate than the standard approach (83% vs 63%, respectively; P < .02). Receiver operating characteristic curve analysis showed greater diagnostic performance of ultrasound in cases of pneumonia (standard, 0.74 ± 0.12; ultrasound, 0.87 ± 0.14; P < .02), acute hemodynamic pulmonary
edema (standard, 0.79 ± 0.11; ultrasound, 0.93 ± 0.08; P < .007), decompensated COPD (standard, 0.8 ± 0.09; ultrasound, 0.92 ± 0.15; P < .05), and pulmonary embolism (standard, 0.65 ± 0.12; ultrasound, 0.81 ± 0.17; P < .04). Furthermore, we found that the use of ultrasound data could have significantly improved the initial treatment.

**Conclusions**

The use of cardiothoracic ultrasound appears to be an attractive complementary diagnostic tool and seems able to contribute to an early therapeutic decision based on reproducible physiopathologic data.

**Abbreviations**

ARF

acute respiratory failure

Acute respiratory failure (ARF) is frequently encountered in ICUs. ARF cases do not always present in conditions that are ideal for early diagnosis, which sometimes compromises outcomes. Nevertheless, immediate diagnosis and suitable treatment seem to improve prognosis. Traditionally, a physical examination and bedside radiography are considered reference requirements for assessing heart and lung status in this context, but the flaws of these familiar tools are becoming increasingly acknowledged. The low accuracy of clinical evaluations in the critical care context has been highlighted frequently. Additionally, chest radiography has several technical requirements that ensure the quality of images obtained, and these cannot be easily met in the critical care environment. Consequently, a need for sophisticated tests arises, which may delay management.

Cardiac and lung ultrasonography have been independently proposed as useful approaches to patients with acute illness, guiding management and care. For example, the accuracy of lung ultrasound has been established for the diagnoses of pneumothorax, lung consolidation, alveolar-interstitial syndrome, and pleural effusion. In parallel, several studies have demonstrated that cardiac ultrasound can provide accurate information with diagnostic relevance in patients in the ICU. For example, echocardiography may accurately distinguish ARF caused by left-sided heart dysfunction from that resulting from noncardiac causes.

The aim of the current study was to prospectively investigate the clinical relevance of early general chest ultrasonography (ie, heart and lung recordings) in patients with ARF in the ICU. We used the routine evaluation of clinical, radiologic, and biologic data as the standard diagnostic approach against which to test an original integrative ultrasound procedure. The hypothesis was that a significant improvement would be seen in the diagnostic accuracy of this paraclinical tool when both lung and cardiac ultrasonographic data are analyzed together. Finally, we evaluated the extent to which this cardiothoracic ultrasonographic approach could improve therapeutic decision-making during the early management of critically ill patients with ARF.

**Materials and Methods**

**Patients**

We prospectively recruited patients consecutively admitted for ARF to the ICU of a university teaching hospital between September 2010 and September 2011. Inclusion criteria were age = 18 years and the presence of one of the following objective criteria of ARF: a respiratory rate of at least 25/min, a PaO₂ of = 60 mm Hg, an oxygen saturation as measured by pulse oximetry of = 90% while breathing room air, and a PaCO₂ of = 45 mm Hg with an arterial pH = 7.35. The ethics committee of the University Hospital of Toulouse, France (Comité Consultatif pour la Protection des Personnes, CHU Toulouse, France; Ref 2010-A01225-48), approved the therapeutic and investigational procedures and waived the requirement for written informed consent. To simplify this study, patients given several final diagnoses were subsequently excluded.

**Experimental Design**

**Routine Clinical Assessment**

For every patient, standard medical care provided by the senior ICU physician in charge (A. M., J. R.) included the following:
medical history; physical examination findings, including signs of ARF (use of accessory respiratory muscles, paradoxical abdominal respiration); arterial blood gas analysis while breathing room air; 12-lead ECG; chest radiograph; and routine blood tests, including plasma levels of cardiac troponin I and B-type natriuretic peptide. Experts were blinded to the ultrasound results. As usual, after the initial presentation in the ICU, all patients were reviewed by a second senior staff member (M. O.). Thus, depending on the suspected diagnosis, initial treatment was decided by these members of the medical staff in accordance with normal practice and recommendations. [20] [21]

Cardiothoracic Ultrasound

All patients underwent a cardiothoracic ultrasound test by investigators who did not participate in the patient’s management (S. S., B. R.). The ultrasound test was performed without interrupting management at the time of ICU admission (ie, within 20 ± 6 min) and lasted 12 ± 4 min. Investigators used standardized criteria (Table 1) and followed a strict pattern analysis. Data were recorded for further interobserver variability assessment and then discussed to obtain an ultrasound diagnosis based on consensus of the two scanners. Transthoracic echocardiography and lung ultrasound assessment were performed with an HP Sonos 5500 (Hewlett-Packard Development Company, LP) and 2- to 4-MHz probes. All patients were studied in the semirecumbent position.

Table 1  -- Ultrasound Profiles Used in the Bedside General Chest Ultrasound Evaluation

<table>
<thead>
<tr>
<th>Condition</th>
<th>Lung</th>
<th>Heart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary embolism</td>
<td>A profile with DVT</td>
<td>RV failure (acute)</td>
</tr>
<tr>
<td>Acute hemodynamic pulmonary edema</td>
<td>B profile</td>
<td>High end-diastolic LV pressure</td>
</tr>
<tr>
<td>Decompensated COPD</td>
<td>A profile</td>
<td>RV failure (chronic)</td>
</tr>
<tr>
<td>Pneumothorax</td>
<td>A' profile</td>
<td>Nonspecific</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>C profile</td>
<td>Nonspecific</td>
</tr>
<tr>
<td></td>
<td>A profile plus PLAPS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A/B profile</td>
<td></td>
</tr>
</tbody>
</table>

LV = left ventricular; PLAPS = posterolateral alveolar and/or pleural syndrome [22]; RV = right ventricular.

The echocardiographic examination included left ventricular systolic function (visual estimation of the left ventricular ejection fraction at < 30%, 30%-50%, and > 50%), [23] left ventricular end-diastolic pressure estimation (pulsed Doppler echocardiography-recorded mitral inflow and Doppler tissue imaging with the sample cursor placed in the lateral mitral annulus to record the following: E-wave velocity, A-wave velocity, Ea velocity, and E/A and E/Ea ratios), [24] right ventricular function (assessment of the interventricular septal configuration and dynamic M-mode measurement of the inferior vena cava diameter, including paradoxical septal motion, right ventricular dilatation, and central venous pressure estimation), [25] and pericardial evaluation (detection of pericardial effusion as either present or absent). [12] For the lung ultrasound examination, the anterior chest wall was delineated from the clavicles to the diaphragm and from the sternum to the anterior axillary line. The lateral chest was delineated from the axillary zone to the diaphragm and from the anterior to the posterior axillary line. The anterior and lateral chest walls were divided into three lung regions. Lung ultrasonograms were contemporaneously classified in a few categories according to previously described criteria. [17] The pleural line was defined as a horizontal hyperechoic line visible 0.5 cm below the rib line. A normal pattern was defined as the presence, in every lung region, of lung sliding with A lines (A profile). [26] Pleural effusion was defined as a dependent collection limited by the diaphragm and the pleura with an inspiratory movement of the visceral pleura from depth to superficial. [27] With the use of TM mode, pneumothorax was defined by the loss of pleural sliding (A’ profile). [28] Alveolar consolidation was defined as the presence of poorly defined, wedge-shaped hypoechoic tissue structures (C profile). [29] Within the consolidation, hyperechoic punctiform images can be seen that correspond to air-filled bronchi (ie, bronchograms). [15] Pleural effusion can also be associated with the patterns of alveolar consolidation (ie, posterolateral alveolar consolidation and/or pleural effusion syndrome). [19] Alveolar-interstitial syndrome was defined as the presence of more than two B lines in a given lung region (B profile). [30] Each of the 12 lung regions examined per patient was classified in one or more of these profiles and associated with cardiac ultrasonographic data to establish a diagnosis (Table 1). Finally, a simplified DVT study was performed on all patients with the same probe. [19]

Final Diagnosis

The final diagnosis of ARF was determined by two independent senior experts (T. G, O. F.) from an examination of the complete medical chart, including all initial clinical findings; emergency laboratory tests, including plasma levels of cardiac troponin I and B-type natriuretic peptide; chest radiograph data; and the results of thoracic high-resolution CT scans.
(performed in 75% of the patients). Additionally, transthoracic Doppler echocardiography was performed in 68% of the patients by a senior cardiologist (C. B.) who was blinded to the ultrasound data to allow an independent comparison between the different diagnostic methods. In a few cases (5% of the patients), a pulmonary function test (peak expiratory flow or bedside spirometry) was conducted to assess the severity of a suspected airflow obstruction in accordance with current recommendations.[31] In case of disagreement between the two experts, a consensus was reached with the help of a third expert (M. G.). The main diagnoses finally proposed were cardiogenic pulmonary edema, including left-sided heart failure; community-acquired pneumonia; acute exacerbation of chronic respiratory disease; acute asthma; pulmonary embolism; and pneumothorax. Validated criteria were used (ie, response to diuretic or vasodilator, results of cardiac troponin I[32] and B-type natriuretic peptide tests performed at admission to the ED), and other cardiac tests were specifically analyzed for cardiogenic pulmonary edema.[33] Response to bronchodilators, steroids, or antibiotics; results from the pulmonary function test; and thoracic high-resolution CT scans were analyzed specifically for respiratory disorders.[34] Results of echocardiography and a contrast-enhanced helical CT scan were analyzed specifically for pulmonary embolism,[35] as recommended.

Initial Treatment

The initial treatment of ARF was decided by two physicians on the ICU staff (A. M., J. R., M. O.) and was established from the standard data. It must be pointed out that an inaccurate initial treatment was recorded when (1) pulmonary embolism was diagnosed by the experts (ie, final diagnosis) without initial anticoagulation, (2) cardiogenic pulmonary edema was diagnosed without initial administration of vasodilators or diuretics, (3) community-acquired pneumonia was diagnosed without initial antibiotics, (4) asthma was diagnosed without initial β2-agonist administration, and (5) pneumothorax/pleural effusion was diagnosed without initial thoracentesis.

Statistical Analysis

Continuous data are expressed as mean ± SD and categorical variables as numbers and percentages. McNemar test was used to compare the diagnostic approaches (standard vs ultrasound) and the final diagnosis determined by the panel of experts. Two means were compared with a Student test and two proportions with Fisher exact method. The diagnostic performance of each approach was assessed by calculating the sensitivity, specificity, and diagnostic accuracy with standard formulas.[36] A receiver operating characteristic curve depicting the relationship between the proportion of true-positive findings and the proportion of false-positive findings was drawn.[37] The level of agreement among observers for the ultrasound finding was evaluated by means of the 900 lung regions analyzed (12 per patient) and the 300 echocardiographic data analyzed (four criteria per patient) with the ? reliability test[38]; ? values < 0.40 indicated low agreement, values between 0.40 and 0.75 indicated medium agreement, and values > 0.75 indicated high agreement between the two raters. All statistical tests were two-sided, and P < .05 was required to reject the null hypothesis. Statistical analysis was performed with Statistica 7.0 (StatSoft, Inc) software.

Results

Patients

Seventy-eight patients with ARF admitted to the ICU were prospectively included in the study. The mean age of the patients was 70 ± 18 years, and the sex ratio was 1. At inclusion in the study, patients had a mean PaO2 of 58 ± 19 mm Hg (spontaneous ventilation and FiO2 of 0.21), and mean PaCO2 was 44 ± 9 mm Hg. Within the first 8 h of initial treatment, 26 patients (34.6%) were intubated, and 34 patients (45.3%) were treated with noninvasive mechanical ventilation. The mortality rate was 18%. The final diagnoses established by the panel of experts were pneumonia (n = 33), acute hemodynamic pulmonary edema (n = 19), decompensated COPD (n = 12), pulmonary embolism (n = 8), and pneumothorax (n = 3). It must be highlighted that CT scan was used as the reference criterion to confirm a suspected pneumothorax. In the absence of a clinical and standard chest radiographic sign of compressive pneumothorax, CT scan and thoracic ultrasonography were performed before pleural exsufflation in all three cases. All the pneumothoraces identified by the gold standard procedure were also diagnosed with use of the ultrasound approach. Three patients had several final diagnoses. To simplify the analysis, these patients were subsequently excluded.

Comparative Diagnostic Accuracy

With respect to the final diagnosis, the ultrasound diagnostic approach was more accurate than the standard approach (83% vs 63%, respectively, P < .02) (Fig 1). Furthermore, receiver operating characteristic analysis showed a significantly greater area under the curves when the diagnosis was made with the ultrasound rather than with the standard approach (Fig 2) in cases of pneumonia (standard, 0.74 ± 0.12; ultrasound, 0.87 ± 0.14; P < .02), acute hemodynamic pulmonary edema (standard, 0.79 ± 0.11; ultrasound, 0.93 ± 0.08; P < .007), decompensated COPD (standard, 0.8 ± 0.09; ultrasound, 0.92 ± 0.15; P < .05), and pulmonary embolism (standard, 0.65 ± 0.12; ultrasound, 0.81 ± 0.17; P < .04).
Figure 1  Comparative diagnostic accuracy. Each diagnostic approach (standard and ultrasound) was compared against the final diagnosis determined by a panel of experts (*P < .05).

Figure 2  A-D, Receiver operating characteristic curves depicting the relationship between the proportion of true-positive findings and the proportion of false-positive findings. The standard and ultrasound approaches are represented for each diagnosis as follows: hemodynamic pulmonary edema (A), pneumonia (B), decompensated COPD (C), and pulmonary embolism (D).

Interobserver Variability

For the 900 lung regions analyzed by two independent investigators, \( \kappa \) values for assessing normal lung ultrasonography pattern (Table 1), B profile, A profile, A profile with DVT, A' profile, C profile, and A profile plus posterolateral alveolar and/or pleural syndrome were 0.81, 0.78, 0.69, 0.78, 0.72, 0.79, and 0.88 respectively. For the 300 echocardiography data, \( \kappa \) values for assessing normal cardiac patterns, left ventricular systolic failure, left ventricular diastolic failure, right ventricular failure, and the presence of pericardial effusion were 0.82, 0.77, 0.82, 0.69, and 0.77, respectively. Finally, when the 200 echocardiographic data provided by a senior cardiologist (C. B.) were compared with that obtained by intensivists, \( \kappa \) values for assessing normal cardiac patterns, left ventricular systolic failure, left ventricular diastolic failure, right ventricular failure, and the presence of pericardial effusion were 0.88, 0.81, 0.82, 0.72, and 0.79, respectively, for the first investigator (B. R.) and 0.79, 0.88, 0.79, 0.80, and 0.81, respectively, for the second (S.S.).

Potential Therapeutic Improvement

The accuracy of the initial treatment, established with use of the standard approach, was compared with the therapeutic decisions that could have been made from the ultrasound data. The use of general ultrasound chest data, already available at
the time of the first therapeutic decisions, could have significantly improved the initial treatment (Fig 3) in cases of pneumonia ($P < .05$), acute hemodynamic pulmonary edema ($P < .04$), decompensated COPD ($P < .009$), and pulmonary embolism ($P < .05$).

![Figure 3](image)

**Figure 3** Potential therapeutic improvement related to the use of the ultrasound approach. The accuracy of the initial treatment, established with standard data, was compared with the therapeutic decisions that could have been made with the ultrasound approach. The use of general ultrasound chest data could have significantly improved the initial treatment in cases of pneumonia ($P < .05$), acute HPE ($P < .04$), decompensated COPD ($P < .009$), and pulmonary embolism ($P < .05$). *$P < .05$. HPE = hemodynamic pulmonary edema.

**Discussion**

Lung and heart ultrasound generates standardized patterns, which have been independently proposed to help bedside diagnosis in patients admitted to the ICU. Previous studies have focused on assessing the sensitivity and specificity of these profiles, comparing ultrasonography data to gold standard methods, such as thoracic CT scan [39] or pulmonary artery catheter [40]. To our knowledge, this study is the first to evaluate the diagnostic value and potential therapeutic impact of an approach that combines lung and heart ultrasound scans in the early management of critically ill patients with ARF. The main result was a significant improvement in the initial diagnostic accuracy with general chest ultrasound compared with a standard approach that encompassed clinical, radiologic, and biologic data. Furthermore, greater diagnostic ability of the ultrasound approach was identified when each main etiologic entity was analyzed independently.

It must be highlighted that we observed similar levels of sensitivity and specificity to those described in previous studies that used lung ultrasonography alone. [19], [27], [39] We believe that combining echocardiography with lung ultrasonography in this context probably does not improve the diagnostic value of lung ultrasound alone but could have fundamental importance in therapeutic decisions. Actually, the present data suggest that general chest ultrasonography provide accurate online assessment of lung and heart status and dynamic interactions, which are specifically disrupted in pathologic states. For example, it has been shown that the diagnosis of acute pulmonary edema is accurate with lung ultrasound (sensitivity near 100%), [27] but with heart ultrasound, we can obtain crucial information about the etiology and underlying mechanism (acute lung injury vs cardiogenic edema). Further investigations are needed to evaluate the impact of such integrative ultrasound procedures for the correct initial treatment of ARF in this context. [41] , [42]. [43] Furthermore, we describe how the use of general chest ultrasonography, easily performed at the patient's bedside, could have improved initial treatment in cases of pneumonia, decompensated COPD, and pulmonary embolism. Altogether, these results confirm the present hypothesis of a direct diagnostic and potential therapeutic impact when general chest ultrasonography is used in critically ill patients with ARF.

In agreement with previous studies, [11], [39] we observed a high concordance between chest ultrasonography and CT scan data. We speculate that in the present cohort, where 75% of patients underwent thoracic CT scanning, these tests could have been avoided by thoughtful use of ultrasound in more than one-half of the cases. Future studies are needed to assess the time savings and cost-effectiveness of combined cardiothoracic ultrasonography compared with CT scan in this context.
This study has several limitations. First, the intensivists who performed the ultrasonography could not be blinded to obvious clues of diagnosis that might be readily apparent to an experienced observer while performing an ultrasound examination. Second, in a few cases, the echocardiography performed by the senior cardiologist was probably recorded past the initial management of the patient, so it had limited value in determining the diagnosis at the time of presentation. For the purposes of this study, a general chest ultrasound team was set up and comprised two noncardiologist intensivists (B. R., S. S.) with advanced-level training and competence in lung, pleural, and cardiac ultrasonography according to La Société de Réanimation de Langue Française and American College of Chest Physicians criteria. These investigators followed a training tailored to critical care practice (2 years) and have > 3 years of experience in using and teaching ultrasonography in their daily practice. In the present work, we concentrated on comparing a standard approach and an independent general chest ultrasound analysis because we wanted to assess the diagnostic and therapeutic impact of this novel procedure against a gold standard approach. Finally, patients who were given several final diagnoses were subsequently excluded from this study. Future studies will need to focus on evaluating the utility of combining standard and ultrasound data to obtain better diagnostic accuracy, particularly when several simultaneous causes contribute to the ARF.

Conclusions

Cardiothoracic ultrasonography appears to be an attractive complementary diagnostic tool and one of the most promising techniques for the management of critically ill patients with ARF. Ultrasound is noninvasive, easily repeatable at the bedside, and provides an accurate online assessment of lung and heart status and dynamic interactions, which are specifically disrupted in pathologic states. Furthermore, this new tool seems to contribute to an early ICU therapeutic decision based on more accurate and reproducible data. Benefits to be evaluated in future studies include a reduced need for CT scans and, thus, shorter delays; lower irradiation levels and cost; and above all, improved prognosis for the patient.

Acknowledgments

**Author contributions:** Dr Silva had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

*Dr Silva:* contributed to the study design; data acquisition, analysis, and interpretation; critical revision of the manuscript for important intellectual content; and approval of the final version of the manuscript.

*Dr Biendel:* contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Ruiz:* contributed to the study design, data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Olivier:* contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Bataille:* contributed to the study conception, data analysis, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Geeraerts:* contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Mari:* contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

*Dr Riu:* contributed to the study design, data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.
Dr Fourcade: contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

Dr Genestal: contributed to the data acquisition, critical revision of the manuscript for important intellectual content, and approval of the final version of the manuscript.

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