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Ultrasound diagnosis of alveolar consolidation in the critically ill

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Abstract *Objective:* Alveolar consolidation is a basic concern in critically ill patients. Radiography is not a precise tool, and referral to CT raises problems (transport, irradiation). The aim of this study was to assess the utility of ultrasound in the diagnosis of alveolar consolidation. *Design:* Prospective clinical study. *Setting:* The medical ICU of a university-affiliated teaching hospital. *Patients:* A total of 65 cases of alveolar consolidation proven on CT were compared to 53 CT controls. *Measurements:* Alveolar consolidation was defined as a tissue-like pattern visible at the chest wall, arising from the pleural line and devoid of centrifugal inspiratory dynamics. *Results:* Feasibility was 99%. In 65 cases of alveolar consolidation, ultrasound was positive in 59 and negative in 6. In 52 analyzable controls, ultrasound was negative in 51 and positive in 1. Sensitivity of ultrasound was 90% and specificity 98%. A concordance test showed a Kappa coefficient of 0.89. Among 62 posterior locations on CT, ultrasound showed posterior consolidation patterns in 56 cases and was negative in 6. Ultrasound showed anterior involvement in all 3 cases of whole lung consolidation. *Conclusions:* Ultrasound provides a reliable non-invasive, bedside method for accurate detection and location of alveolar consolidation in critically ill patients.

Keywords Chest ultrasonography · Ultrasound diagnosis · Lungs · Respiratory failure · Alveolar consolidation · Intensive care unit

Introduction

The assessment of the lungs, a vital organ, is a daily concern in the critically ill. The clinical approach is not precise enough, and bedside radiography, a familiar procedure for more than one century, can be misleading [1, 2, 3, 4, 5, 6]. When a precise evaluation is needed, referral to CT is mandatory [7]. At this stage, the development of a bedside non-invasive method is desirable. Ultrasound could be such a method, but the lungs are traditionally deemed to be inaccessible [8]. However, it has recently been shown that a whole ultrasound semiology is available at the lung level, if one takes care to analyze the artifacts [9]. Although indications for ultrasound of the lungs are increasingly numerous in ICUs, its clinical use is not yet fully developed. Although a few studies have dealt with ultrasound diagnosis of alveolar consolidation [10, 11, 12, 13], to our knowledge no study has been performed in the ICU and with CT as the gold standard.

Patients and methods

Patients

During a 3-year period (part-time observation), 60 consecutive patients were investigated in a prospective study. All patients had chest computerized tomography (CT), which was always required for clinical purposes (exploration of chest pain or severe thoracic disease). The study included 37 men and 23 women with a mean age of 53 years (range 20–84 years) and 30 patients were mechanically ventilated. The alveolar consolidation was unilateral in 15 patients, bilateral in 25 and 20 patients (including 2 with a single lung) were free of consolidation.

In 118 lungs, alveolar consolidation was visible on CT in 65 (study group) and absent in 53 (control group). Of the 65 cases of alveolar consolidation, 62 involved the posterior area and 3 the whole lungs. The volume of the consolidation was arbitrarily separated into small (maximal thickness $\leq$20 mm), average (between 20 and 50 mm) and substantial ($\geq$50 mm). The consolidation was seen in a setting of ARDS (n=30), infectious pneumonia (n=16), pulmonary embolism (n=4), trauma (n=4), cardiogenic pulmonary edema (n=2), surgery (n=2), unknown origin (n=3) and miscellaneous (n=4).

CT

Spiral CT was performed within 6 h after ultrasound, during breath hold, from the apex to the diaphragm with a CT Twin Flash (Elscint Limited, Haifa, Israel) at a window width of 1,600 HU and a level of –600 HU, with iodine injection. Section thickness was 10 or 1.5 mm. Alveolar consolidation was defined as a tissular pattern visible at the mediastinal window.

Ultrasound

A Hitachi Sumi 405 (Hitachi Medical Corporation, Tokyo, Japan) with a 3.5 MHz micro-convex probe was used by two operators trained in emergency ultrasound (operator A, DL and operator B, GM), unaware of the CT findings and of the other results. The sonograph was part of our ICU equipment and was functional at the bedside in less than 1 min. All patients were examined in the supine position with longitudinal scans and with a probe tangential to the chest wall.

As the lungs are the most voluminous organ of the body, a methodical analysis was mandatory, with three basic steps. First the thorax had to be located, then the lung surface, then areas had to be defined. The thorax was distinguished from the abdomen by locating the diaphragm, usually at the mamillary line or one or two intercostal spaces below in a supine patient (see Fig. 2). In order to locate the lung surface, the probe was applied over an intercostal space to identify the upper and lower ribs, which gave a frank posterior shadow. Between two ribs and slightly deeper (0.5 cm), a hyperechoic, horizontal line was visible: the pleural line (i.e. the lung surface in the absence of pneumothorax). The ribs and the pleural line outlined a characteristic pattern (Fig. 1). "Lung sliding" is normally visible at the pleural line [14]. Air artifacts normally arise from the pleural line [9]. Areas of interest were defined using clinical landmarks. The anterior and posterior axillary lines are practical landmarks which delineate anterior, lateral and posterior areas (Fig. 2). Four clinical stages of investigation had to be defined, as they were of clinical value. "Stage 1" related to the anterior chest wall in a supine patient ("area 1"), and was immediately informative regarding pneumothorax or interstitial syndrome. "Stage 2" included the lateral chest wall in a supine patient until the bed prevented further progression of the probe towards the posterior zones ("area 2") and gave information on substantial pleural effusions or substantial alveolar consolidations. "Stage 3" was defined by slightly raising the ipsilateral back of the supine patient, in order to position the probe as posterior as possible and to gain more room for exploration ("area 3"). Small probes were mandatory for this approach. In "stage 4", the patient was positioned in frank lateral decubitus, or seated, in order to fully study the posterior chest wall. In addition, the apex was investigated. In the present study, only stages 1–3 were used.

Six items were required to define alveolar consolidation (Fig. 3). (1) Pattern located at the thoracic level, (2) pattern arising

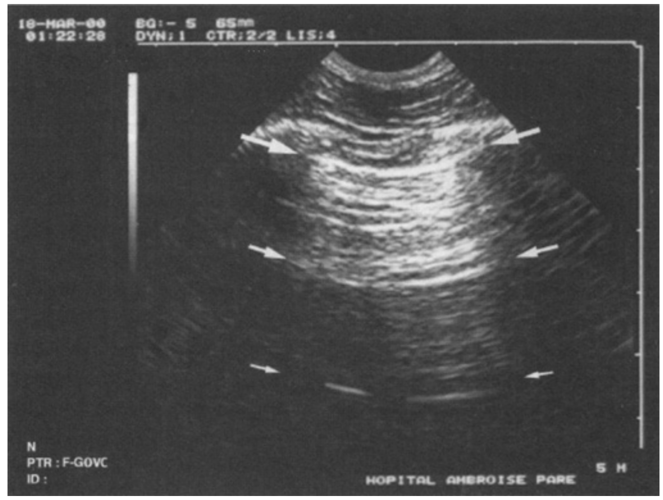

Fig. 1 Normal subject (ultrasound, longitudinal scan, anterior chest wall). The ribs generate posterior shadows on both sides (where arrows are located). The pleural line *(large arrows)* is visible slightly (0.5 cm) below the ribs. The succession upper rib-pleural line-lower rib designates a characteristic landmark: the "bat sign". One or two roughly horizontal, parallel lines, called "A lines", are visible at regular intervals below the pleural line *(fine arrows)*. The lung sliding, a basic sign of normality, will be objectified using TM mode

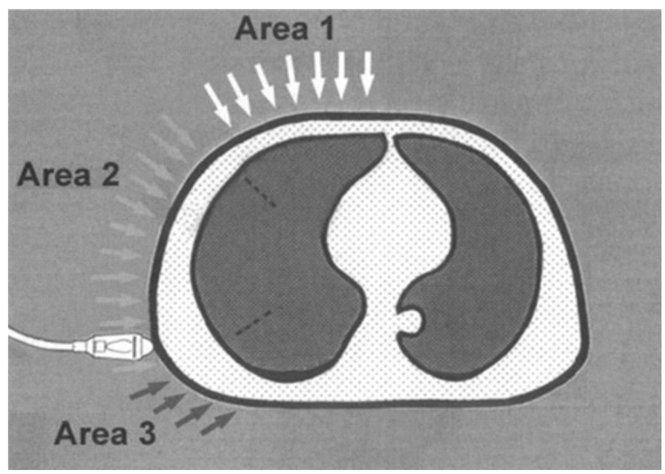

Fig. 2 Lung areas of investigation. Diagram showing clinical areas of investigation 1, 2 and 3 of the chest wall, in relation to the anterior and posterior axillary lines

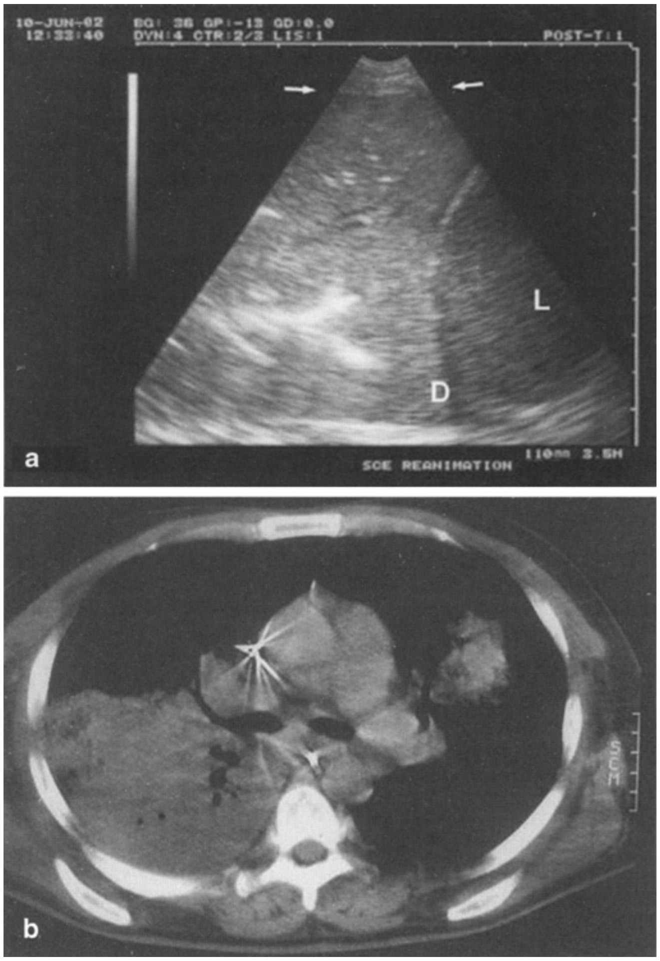

Fig. 3a Substantial alveolar consolidation of the right lower lobe. Tissue-like pattern clearly located in the lung, i.e. above the diaphragm *(D)* and the liver *(L)* and located behind the pleural line *(arrows)*. Air bronchograms are visible. Note here the absence of pleural effusion. In real time, this mass does not change along the core-to-surface axis (bottom to top of the screen) during breathing. Note also that the thickness of the visible alveolar consolidation, in this view, is 91 mm. **b** Corresponding tomodensitometric view showing a massive right lower lobe consolidation with air bronchograms

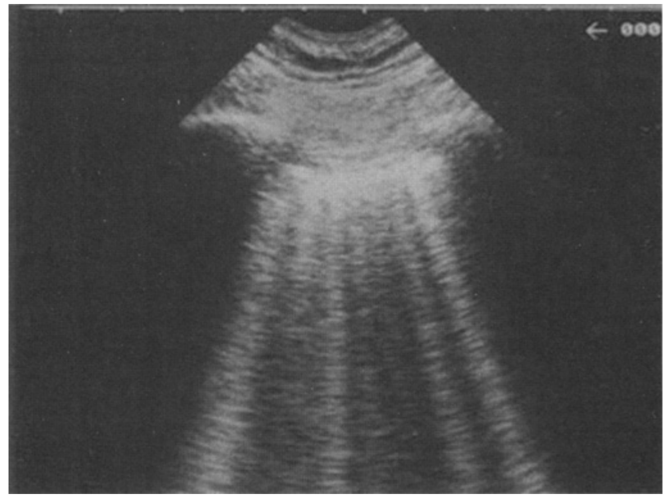

Fig. 4 A common type of air artifact found at the surface of aerated lungs in the ICU. These vertical comet-tail artifacts (called "lung rockets") indicate interstitial syndrome. However, the observed pattern is artifactual (as in Fig. 1), and no anatomic structure is visible below the pleural line

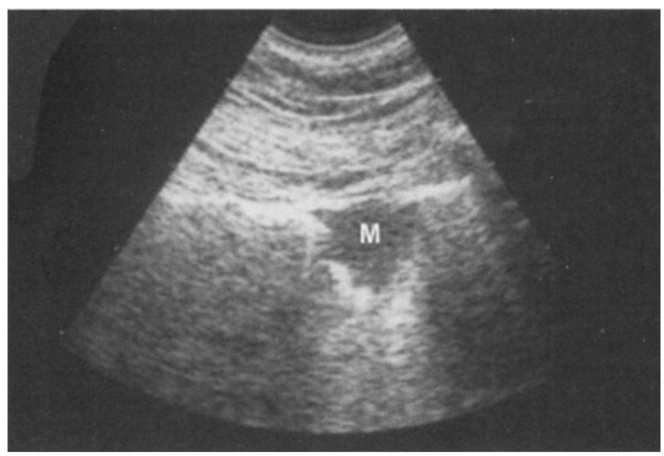

Fig. 5 Small, centimetric alveolar lesion, surrounded by aerated lung tissue. Patient with systemic staphyloccal infection

from the pleural line, (3) real image, i.e. not artifactual, as an aerated lung would give (Figs. 1 and 4), (4) tissue-like pattern reminiscent of the liver (hence the term "hepatization"), (5) anatomic boundaries, with superficial boundary at the level of the pleural line or the deep boundary of a pleural effusion if present, and a deep boundary usually irregular with the aerated lung, or regular in case of whole lobe involvement and lastly (6) the search for the absence of the "sinusoid sign" was mandatory for distinguishing alveolar consolidation from potentially associated pleural effusion. This sign, which consists of inspiratory centrifugal shifting of the visceral pleura with decrease in apparent thickness, is specific to pleural effusion [15]. In the case of alveolar consolidation, caudal inspiratory movement (from left to right of the screen) was either present or impaired, but no inspiratory centrifugal shift (i.e. from the bottom to the top of the screen, an axis called "core-to-surface axis") had to be observed. Other distinctive signs were not taken into account in this study: internal hyperechoic punctiform or linear elements, which were considered as air bronchograms [10], and intrinsic dynamics of these bronchograms, a pattern called "dynamic air bronchogram" [16]. Different patterns were possible (Figs 5 and 6).

Less than 2 min were necessary to assess the presence or absence of alveolar consolidation.

Results

In 118 ultrasound attempts, 117 were successful (1 extensive dressing). In 65 cases of alveolar consolidation, ultrasound was positive in 59 and negative in 6. In 52

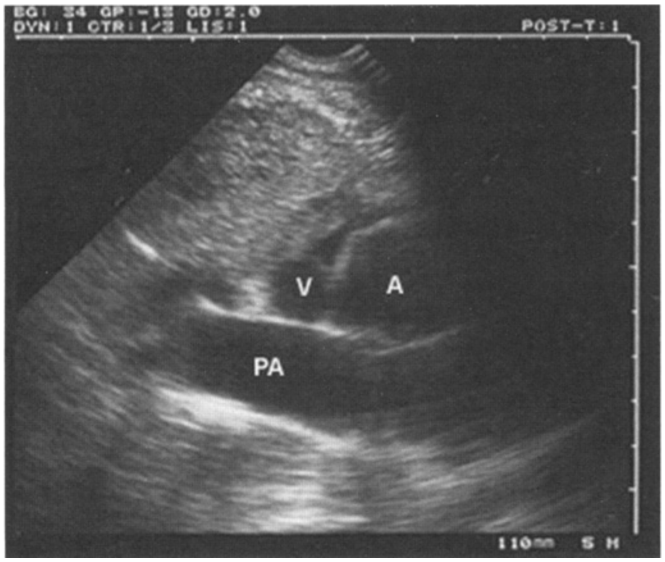

Fig. 6 Example of compact consolidation (with a thickness measured as 40 mm at this level). There are no air bronchograms. Heart structures are visible in depth *(A, V, PA)*. Yet the probe is applied to the right anterior wall, which means that the heart is shifted to the right. In real time, lung sliding and craniocaudal dynamics are also impaired. Case of massive right lung atelectasis

analyzable controls, ultrasound was negative in 51, and positive in 1 (Table 1). Alveolar consolidation was diagnosed using ultrasound with a sensitivity of 90% and a specificity of 98%. A concordance test between operators A and B showed a Kappa coefficient of 0.89 (Table 2).

The location and volume of the alveolar consolidation were roughly correlated with the location of the ultrasound signs. In three cases where ultrasound signs of consolidation were visible at the anterior wall, they were also visible in the lateral and subposterior areas, and CT always showed whole lung involvement. In 62 posterior locations on CT, ultrasound showed signs of consolidation in zones 2 (lateral) or 3 (posterior) in 56 cases and was negative in 6. When ultrasound signs appeared only in area 2 (n=22), the consolidation was posterior in 21 cases, with substantial volume in 18 cases, and was absent

Table 1 Global correlation between ultrasound and CT

	Positive Ultrasound	Negative Ultrasound	Not feasible Ultrasound
Consolidation on CT	59	6	
No consolidation on CT	1	51	1 (drain)

Table 2 Concordance test

	Operator A		
Operator B		Positive test	Negative test
	Positive test	56	2
	Negative test	4	56

in 1 case. When ultrasound signs of consolidation appeared only from area 3 (n=35), the consolidation was always posterior, and the volume was small in 18 out of 35 cases, average in 11 and substantial in 6 (Table 3).

Among the 6 false negatives of ultrasound, location was posterior and volume small in 5, and 1 was substantial on CT but did not reach the posterior surface. In this series, alveolar consolidation did not reach the lung surface in 1.5% of the cases. In the only case in this study where ultrasound showed alveolar consolidation not confirmed by CT, the ultrasound image was small (estimated <2 ml).

Discussion

The capacity of ultrasound to detect alveolar consolidation is logical. First, acute alveolar consolidation usually reaches the lung surface. Second, water is a good transmitter of ultrasound, yet a consolidated lung is water-rich and therefore easily crossed by ultrasound. Chest radiography data are known to be imprecise [1, 2, 3, 4, 5, 6]. A comparison with CT, the gold standard, highlighted a close correlation.

This approach has diagnostic applications (acute dyspnea, fever, pain), therapeutic (setting of the optimal PEEP, indication for ventral decubitus) and monitoring purposes (follow-up of an ARDS). Ultrasound provides

Table 3 Rough correlation with location and volume

	No visible consolidation on ultrasound	Ultrasound consolidation visible only in area 3 (subposterior)	Ultrasound consolidation visible in area 2 (lateral)	Ultrasound consolidation visible in area 1 (anterior)	Ultrasound not feasible
No consolidation on CT	51		1		1
Posterior location <20 mm	5	18	2		
Posterior location between 20 and 50 mm		11	1		
Posterior location >50 mm	1	6	18		
Whole lung involvement on CT				3	

additional information, not dealt with in this study. The thickness of the consolidation can be measured (see Fig. 3). This requires some experience and has limitations: ultrasound will underestimate the real volume if massive air bronchograms yield an acoustic barrier, or when a large consolidation has a small parietal contact. Fine analysis distinguishes retractile from non-retractile consolidation, i.e. atelectasis vs pneumonia [16]. Signs suggestive of pulmonary infarction are accessible [17, 18]. Abscesses can be detected within consolidations [19]. The craniocaudal dynamics of the consolidation provides information on lung compliance. Lung puncture for bacteriological purposes can be envisaged as an alternative to puncture based on radiography alone which is a hazardous procedure [20].

Lung ultrasound is not limited to alveolar consolidation. Interstitial changes can be distinguished from alveolar ones, with clinical applications [21]. Pneumothorax and pleural effusion are accessible to ultrasound. Information obtained from lung, cardiac, venous and abdominal analysis provide a bedside visual approach to the critically ill [22]. A simple device without Doppler is suitable. The skill needed is easily learned if the training is rigorous [23]. Information can be obtained using a simple protocol, provided precise definitions are adopted at the outset. In particular, a limited analysis of the posterior chest wall yields sufficient information. Ultrasound will complement or sometimes replace bedside radiography or even CT in such situations: prompt information needed, limitation of irradiation required (pregnant woman, child); non-diagnostic radiography; need for repeated measurements; cost-cutting. The need for bedside radiographs and CTs (and consequently the irradiation level) should decrease.

Limitations of ultrasound should be considered. In this series, the number of patients and investigators is small. The imperfect sensitivity can be explained by small consolidations, if care is not taken to scan the entire lung surface, or by consolidations which do not reach the surface, a rare finding, or by a poor echogenicity of the patient. Parietal emphysema, pleural calcifications or dressings will prevent analysis. In rare instances, it is possible to observe a dark image with homogeneous anechoic echostructure without any sinusoid sign or "dynamic air bronchogram". Such a pattern, which was called the "black ultrasound lung", calls for a careful approach and should, in a simplified approach, be considered non-diagnostic.

The possibility of analyzing the lungs in critical situations should be added to the potential of ultrasound, and turn this user-friendly method into a genuine stethoscope, as predicted long ago [24]. In conclusion, ultrasound appears to be a reliable bedside method for assessing alveolar consolidation.

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