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Review article

The basics of application of medical ultrasonography in the diagnosis of acute respiratory failure

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ABSTRACT

Introduction: Medical ultrasonography (USG) is a cheap, accessible, reproducible, and radiation-free diagnostic tool. However, medical USG for the imaging of lungs and the pleural cavity as a diagnostic tool remains underutilized, despite its proven effectiveness, especially for life-threatening conditions such as acute respiratory failure.
Aim: The aim of this work is to describe actual techniques of medical USG for acute respiratory failure.
Material and methods: A literature review was conducted.
Results and discussion: We presented how to identify with USG the most common respiratory system diseases at intensive care unit patients.
Conclusions: Medical USG is a simple, fast, cheap, and reproducible method of evaluating the respiratory system and seems to be one of the most promising imaging techniques for the diagnosis of lung diseases and monitoring of respiratory functions by intensive care unit physicians.

1. Introduction

Respiratory failure is a condition in which respiratory system disorders impair gas exchange in the lungs, leading to hypoxemia and/or hypercapnia.[1–5] Identifying the cause of respiratory failure is often difficult. In the case of patients with serious conditions, diagnosis should be rapid in order to deliver the appropriate treatment. The chest radiograph (CXR) is the most basic imaging technique used in the intensive care unit (ICU). Despite its advantages, the CXR is often not sufficient for making the diagnosis. For this reason, reports

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on medical ultrasonography (USG) for the diagnosis of acute respiratory failure have drawn recent attention.

2. Aim

The aim of this paper is to present data from literature on the current use of medical USG as a diagnostic tool for identifying lung and/or pleural cavity pathology that can progress to acute respiratory failure.

3. Material and methods

In the our study we focused on a review of actual literature for identifying with USG the most common respiratory system diseases at ICU patients.

Micro-convex, convex, linear, and sector transducers are used for a lung USG.[3] The selected transducer moves along each intercostal space, evaluating the entire chest wall. Scanning in the longitudinal and transverse planes has also been recommended.[4,5] Lichtenstein developed Bedside Lung Ultrasound in Emergency (BLUE), a protocol which streamlines the exam for patients in critical condition. It involves the assessment of the lungs in three points on both sides of the chest. Points 1 and 2 are the upper- and lower-BLUE points determined by two hands (without thumbs) that are juxtaposed below the lower edge of the clavicle. Point 3, which has been designated the posterolateral alveolar and/or pleural syndrome (PLAPS) point, is at the junction of the posterior axillary line and a line extending from the lower-BLUE point. Lichtenstein has shown that his BLUE protocol has correctly confirmed the diagnosis of acute respiratory failure in 90.5% of cases.[6–8]

4. Results and discussion

4.1. *Normal appearance of the lung*

A typical USG image of the chest using the transducer in the longitudinal place includes subcutaneous tissue, muscles and pleural cavity that are visible starting from the top of the screen. In this type of image, identifying the ribs is the first step toward correctly localizing the pleural cavity. In adult patients, ribs appear as hyperechogenic structures with an acoustic shadow. Two adjacent ribs will form a so-called rib line. At a distance of approximately 5 mm below the rib line is a thin (generally less than 2 mm) hyperechogenic line which consists of parietal and visceral pleura, which make up the pleural line. Therefore the pleural line forms the border between the two centers with different water content: the components of chest with a high water content and the lung parenchyma – a low water content. Under non-pathological conditions the pleural line cannot be distinguished by means of ultrasound, however, it becomes visible in diseased states. Together, the pleural and rib line form an image called the 'bat sign.' This is a fixed point that allows for locating the surface of the lung (Fig. 1).

On the boundary of the pleural cavity and aerated lung tissue, the A-line, B-line, Z-line, and lung sliding artifacts are visible.

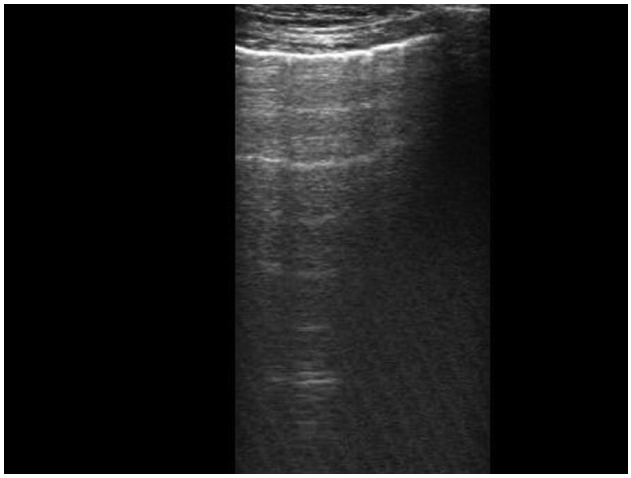

Fig. 1 – Normal appearance of the lung.

A-lines are hyperechogenic lines parallel to the pleural cavity, repeated at the same distance. It is equal to the distance between the pleural line and the skin surface. These artifacts were named after the English word 'air' since they are produced by a reflection of the ultrasound on air contained in the lungs. In other words, these are multiple reflections of the pleural cavity.

The lung sliding sign is produced on the pleural line when the visceral pleura slides against the parietal pleura. In M-mode, the movement of the pleural cavity is visible as a homogenous granular structure, which resembles a grainy seashore (seashore sign). The A-line and lung sliding artifacts are major artifacts seen in normal interstitial syndrome.

B-lines are vertical, hyperechogenic lines spreading from the pleural line to the edge of the screen. They belong to the group of artifacts called comet tail artifacts, named for their characteristic appearance. They are dynamic findings that are synchronized with the movement of the pleural cavity, erase A-lines, and their echogenicity increases during inspiration.[5,7,8] They form due to the high gradient of acoustic impedance between the air and the fluid accumulated in subpleural interalveolar septa. In healthy lungs, they are not permanent, occur in only 28% of examinations, and are most often seen in the last two intercostal spaces above the diaphragm.[5] With the transducer in the longitudinal plane, the presence of B-lines or bb-lines between two ribs is typical in normal interstitial syndrome. However, the presence of three or more B-lines is seen when there is thickening or edema of the interalveolar septa and is not a typical normal finding.

Z-lines are similar to B-lines, but are poorly echogenic (gray), they do not reach the end of the screen, do not erase A-lines, and do not move with the pleural line. They are observed in about 80% of the tests performed on healthy individuals.[6,9] In normal interstitial syndrome, they can be more common than B-line artifacts.

4.2. *Pathological lung imaging*

4.2.1. *USG diagnosis of pneumonia*

Pneumonia is characterized by the accumulation of exudates and cellular elements in the lumen of pulmonary alveoli.[1–5] In

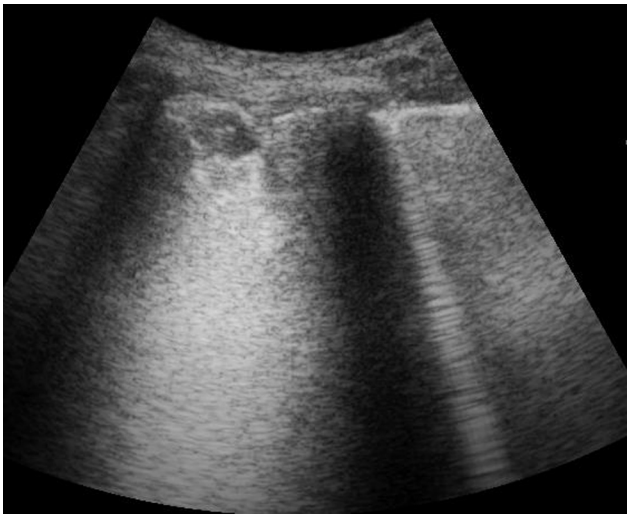

Fig. 2 – Pneumonia.

order to diagnose pneumonia with an USG, it is helpful to use the 3 criteria presented by Ressig et al.[10] – parenchymal, pleural and parenchymal (Fig. 2).

Parenchymal criteria include subpleural consolidations of lung parenchyma, air bronchograms, fluid bronchograms, and superficial fluid alveogram. Consolidations are common features of pneumonia. Sonomorphology of consolidations are diverse and depend on the etiology and duration of the disease. Changes are most often hypoechogenic and heterogeneous with different sizes and shapes. In an USG image, the characteristic changes of lobar pneumonia, such as pneumococcal pneumonia, are known as the tissue-like and shred signs. The consolidation has major hypoechogenic changes that make the lung parenchyma appear similar to hepatic echostructure, which stays fixed when the patient breaths. This is known as the tissue-like sign. The properly aerated tissue in the lung creates an irregular edge adjacent to the diseased tissue called the shred sign. When these two signs coexist, USG has a better sensitivity (90%) and specificity (98%), than computed tomography (CT), which is the gold standard, for the diagnosis of alveolar consolidations.[11] It should be noted that an USG is limited to only visualizing consolidations that are in contact with the pleural cavity. However, this is not a major limitation since 98.5% of the lesions are located under the pleural cavity.[11]

Other sonographic findings in the parenchyma include dynamic and static air bronchograms. Dynamic air bronchograms are characteristic features of consolidations in pneumonia[12] that occur when air moves through the bronchioles. This proves that the respiratory tract remains patent in the consolidated area of the lungs. When visualized in M-mode imaging, bronchograms appears as sinusoidal lines that exhibit a centrifuge-like motion during inspiration. In the diagnosis of pneumonia, the presence of dynamic air bronchograms on an USG has a specificity of 94% and a positive predictive value of 97%. USG analysis of bronchograms within a consolidation also allows for distinguishing pneumonia from resorption atelectasis.

Pleural criteria include fluid in the pleural cavity or at the base of the lung. During the course of pneumonia, the pleural cavity may also be involved and will appear hyperechogenic and fragmented at the sight of the infection.[13] Inflammation of the pleura adjacent to the affected lung parenchyma creates fluid accumulation within the pleural cavity. Initially, the accumulation occurs around the affected region and eventually it accumulates at the base of the lung. The frequency of local fluid accumulation and fluid at the base of the lung are 9% and 60%, respectively.[10]

Vascular criteria include evaluation of blood vessels within the consolidation, which is possible by using the color-coded Doppler mode. This can help distinguish pneumonia from inflammation that arises during a pulmonary embolism. However, one should keep in mind that a flash artifact can also exist. This is when the burst of color signal is caused by moving the transducer or movement of the patient's chest. Therefore, certain authors claim that vascular criterion is not a reliable sign of pneumonia.[14]

In cases where pneumonia is accompanied by parenchymal necrosis, abscesses may occur. USG visualization of parenchymal abscesses is possible only if they are located within the consolidation. Typically, they are seen as an area of hypoechogenicity within the surrounding consolidation that appear as round or oval lesions with a smooth and echogenic edge (Fig. 3).[13] Small pleural effusions can accompany abscesses. If the patient is scanned through the intercostal spaces while in an upright position, an air-fluid level can be visible within the abscess. In this image, the air will appear hyperechogenic with a posterior acoustic shadow. If the fluid is under the atmospheric air pressure, a swirl sign can be observed.[15]

The ability to detect necrosis or abscess in the course of pneumonia by medical ultrasound is comparable to CT.[16] However, in certain cases of visualization of the internal components within the pleural fluid, including fibrin strands, USG has been shown to be more accurate than CT.[17]

4.2.2. *USG diagnosis of atelectasis*

Atelectasis is a common condition in the ICU, which requires early diagnosis and immediate treatment. By definition, it is

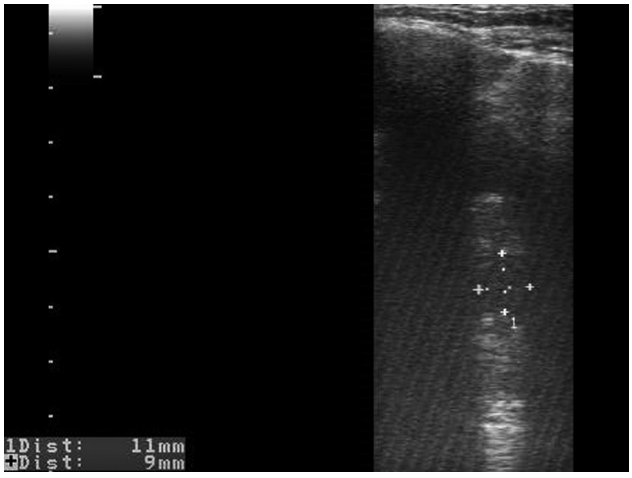

Fig. 3 – Lung abscess.

the lack of ventilation of a portion of or the entire lung and can be classified as passive or active.[18]

Passive atelectasis occurs as a result of compression from an extensive pleural effusion. It appears as a consolidation, which is most often apneumatic and has the appearance of hepatic echostructure. It is usually accompanied by a pleural effusion, which is greater than that found in the active atelectasis. This consolidation, when floating in exudate, has the appearance of a waving hand.[18]

Active atelectasis, also known as obstructive or resorption atelectasis, is caused by an obstruction that prohibits air from entering the bronchi. It is more heterogeneous and diversiform than passive atelectasis, has the appearance of hepatic echostructure, and contains fluid bronchograms. The air visualized within the consolidation typically does not change during inspiration. There are early and late USG signs of active atelectasis. Early signs include the loss of the lung sliding sign in the presence of a 'lung pulse,' which is the visualization of the activity of the heart due to immobility of the diaphragm. In the cases of patients with one lung ventilation without prior respiratory disorders, this artifact has a sensitivity of 93% and specificity of 100% for the diagnosis of this kind of atelectasis.[19] Late signs include a static air bronchogram, which does not demonstrate the same dynamics in M-mode imaging.

4.2.3. *USG diagnosis of pneumothorax*

Pneumothorax (PTX) is a common, life-threatening complication of chest injury, acute respiratory distress syndrome (ARDS), mechanical ventilation, and thoracentesis. The imaging technique most commonly used for the diagnosis of PTX is radiography, which, in the ICU patients, is acquired while the patient is in the recumbent position. The specificity of X-ray is 100%, and its sensitivity is only 52%, compared to 92% of sensitivity and 99.4% of specificity for medical USG.[7,8,20] Literature reports the percentage of undiagnosed PTX using X-ray ranging 2%–17% in patients in the recumbent position with chest injury. The diagnosis was made by a subsequent CT.[21]

Medical USG is a valuable diagnostic tool for PTX. USG has a higher level of sensitivity and specificity when compared to X-ray or CT. It is well documented that it is effective for the diagnosis of PTX in patients with chest injury, after invasive procedures, and for lung biopsy.[21,22]

The protocol for evaluation by lung USG has been simplified and streamlined for urgent cases. In this protocol, the site for application of the transducer is at only one point, called the lower-BLUE point for patients who are recumbent or at the upper-BLUE point when the patient in the half-lying position. The diagnosis of PTX is based on the analysis of four findings. The first is the absence of lung sliding sign. Pleural immobility is seen in M-mode imaging as numerous horizontal lines. This image, which is similar to the phenomenon of stratosphere condensation arising from the flight of B-17 aerial fleet, is called the stratosphere sign (Fig. 4). The second finding is the absence of B-line artifacts and the third one is the absence of the lung pulse. The fourth finding, which confirms the diagnosis, while verifying the other findings, is known as the 'lung point.' It is formed at the border between the air in the pleural cavity and properly aerated lungs. The search for the lung point starts from the site of disappearance of the lung sliding sign and proceeds toward the posterior axillary line until the moment the lung sliding sign or B-line appears. The specificity of the lung point is 100%, while its sensitivity is 66%. In the case of an occult traumatic PTX, the sensitivity increases to 79%.

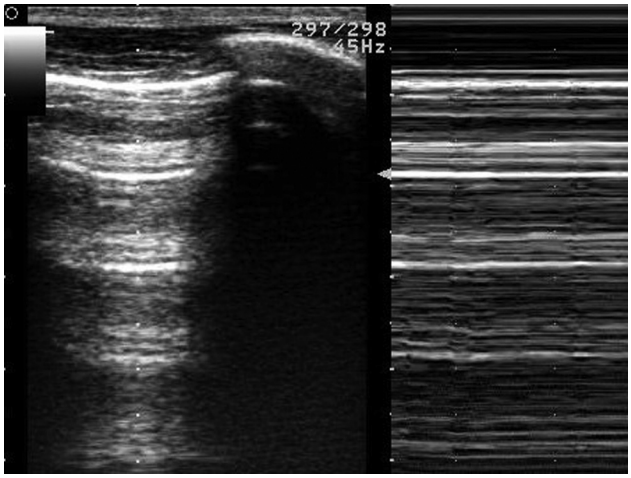

Fig. 4 – Pneumothorax.

USG analysis of the lung point may be helpful in determining the size of PTX. It has been demonstrated that the location of this artifact on the anterior chest wall correlates with an occult or small PTX, while its location on the lateral or posterior wall correlates with a clinically significant PTX. In the case of a large PTX, the lung point can either be absent or located on the posterior chest wall.[15]

The loss of the lung sliding sign is not sufficient for the diagnosis of a PTX. Pleurisy complicated with adhesions, complete atelectasis, massive pulmonary fibrosis, apnea, or one lung intubation may cause a reduction or loss of pleural movement. Occasionally, it also occurs in patients with chronic obstructive pulmonary disease (COPD), particularly over the top of the lungs. This is most likely due to a reduction in lung expansion.[23]

The incidence of PTX as a complication of thoracentesis is 6.0%.[24] The use of medical USG to determine the point of introduction of the needle for thoracentesis significantly reduces the risk of PTX[25,26] as demonstrated by Mayo et al., who reduced the incidence of PTX associated with a thoracentesis to 1.3% in patients requiring mechanical ventilation.

4.2.4. *Ultrasound diagnosis of fluid in the pleural cavity*

The incidence of pleural fluid in ICU patients is estimated to be at 62%.[27] Convex transducers are widely used for imaging the pleural cavities (Fig. 5). The approach when using this probe is typically by a subcostal approach, however, data from recent literature has reported that the intercostal approach is more accurate.[15] A microconvex transducer is applied at the PLAPS point, where the free pleural fluid is most common. During scanning, the fluid produces an image that has four

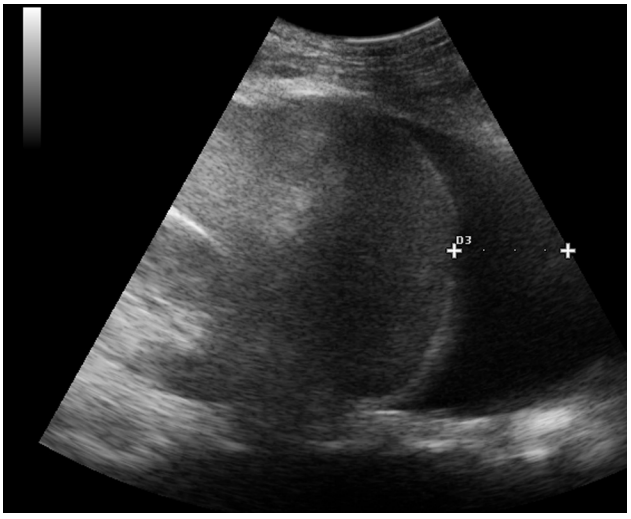

Fig. 5 – Fluid in the pleural cavity.

boundaries. The upper boundary is the pleural line. There are two lateral boundaries formed by the acoustic shadows of the ribs. The lower boundary is the lung line. Lichtenstein coined this entire image as the 'quad sign.' Furthermore, the inspiratory dynamics of the lung line (inspiratory expansion of the lung in the pleural fluid) produces a sinusoidal line visible in M-mode imaging. This is known as the 'sinusoid sign.' The presence of both these signs are highly specific (93%) and sensitive (93%) for the diagnosis of pleural fluid when compared to CT, which is the current gold standard.[28] Grimberg et al. confirmed this by conducting a meta-analysis that evaluated the effectiveness of medical USG compared to radiography. In this study, the average sensitivity of USG was 93%, the average specificity was 96%, while radiography had reported sensitivities and specificities ranging 24–100% and 85–100%, respectively.[28]

5. Conclusions

Medical USG is a simple, fast, cheap, and reproducible method of evaluating the respiratory system. Modern USG scanners are light and portable, which facilitates a bedside exam and dispenses the need for transport to a diagnostic laboratory. It is particularly important for ICU patients who are critically ill and hemodynamically unstable. Furthermore, the development of the BLUE protocol reduces the examination time to 1 min, which allows for a quicker investigation into the initial cause of acute respiratory failure.

Medical USG seems to be one of the most promising imaging techniques for the diagnosis of lung diseases and monitoring of respiratory functions by ICU physicians. Its use should develop rapidly in the near future.

Conflict of interest

None declared.

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