Lung Ultrasound in a Pediatric Intensive Care Unit: a Clinical Review

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Port J Pediatr 2022;53:400-11
DOI: https://doi.org/10.25754/pjp.2022.21846

Abstract

The clinical research conducted in the field of pediatric lung ultrasound has speedily grown over the past few years, with this imaging technique quickly becoming a standard of care in the management of critically ill or injured children. Lung ultrasound is a noninvasive technique that can be routinely performed at the bedside and may provide accurate information on lung status. Based on distinctive sonographic patterns, it has the potential to provide real-time noble information that could alter pulmonary conditions diagnosis, treatment, and management, especially in pediatric intensive care units. The purpose of this article is to review some basic concepts about lung ultrasound and briefly describe its main applications in critically ill or injured children based on previous literature and the specific daily applications in a portuguese pediatric intensive care unit of a tertiary referral center. It aims to create a literature base to help in guiding implementation, development, and training on the use of lung ultrasound in pediatric intensive care units.

Keywords: Child; Intensive Care Units, Pediatric; Lung/diagnostic imaging; Lung Diseases/diagnostic imaging; Point-of-Care Systems; Ultrasonic Therapy; Ultrasonography

Introduction

The pulmonary evaluation of critically ill patients has been traditionally performed by chest radiography (CXR) and thoracic computed tomography scan (CT), as the lung was considered for a long time to be unsuitable for ultrasound imaging. However, for the past 50 years, the paradigm was changed and lung ultrasonography (LUS) has been shown to be a useful diagnostic tool, providing accurate information on the current lung status.[1]

The great advantages of lung ultrasonography compared to the traditional pulmonary imaging techniques have been highlighted, namely its portability, celerity, and ease of use. Technical difficulties of CXR have led to limited accuracy and exposure of the patient to radiation. On the other hand, for CT assessment, there is a need for the mobilization of the patient, higher exposure to radiation and the difficulty in repeatability. In contrast, LUS is a safe, non-invasive and radiation-free imaging technique that can be routinely performed at the bedside, reducing the risk of cumulative radiation and all its inherent risks, especially in the pediatric age.[2-5] Moreover, recent studies have proven that LUS has a better performance compared to chest radiography and it is a reasonable alternative to CT for diagnosing the main pulmonary conditions, namely interstitial syndrome, lung consolidation, pleural effusion, and pneumothorax.[6-9]

Nowadays, it is widely performed in adult intensive care,[10] but its value remains underestimated in the approach of critically ill or injured children. In the past decade, we have observed the rapid increase of literature in this field.[2,3,11,12] Point-of-care lung ultrasound, either alone or combined with other ultrasound techniques - point-of-care ultrasonography (POCUS) - are helpful in children with acute respiratory failure, septic shock, or heart failure, allowing both diagnosis and therapeutic guidance of the critical pediatric patient. It has been emerging as the ideal diagnostic tool in the pediatric intensive care unit (PICU), with increasing applicability and use.

Based on this growing awareness of the value of lung ultrasonography in the medical daily practice, the POCUS working group of the European Society of Paediatric and Neonatal Intensive Care (ESPNIC) is presently establishing practice and educational recommendations, providing specific guidelines for LUS use in neonatal and pediatric intensive care units.

The purpose of this article is to review some basic concepts about lung ultrasonography and describe its main applications on the approach to critically ill or injured children. It aims to create a literature baseline

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Received: 18/12/2020 | Accepted: 04/08/2021 | Published online: 03/01/2022 | Published: 03/01/2022

to help guide the implementation, development, and training on the use of lung ultrasound in a PICU and to provide a basis for further research in this field. Practical applications of LUS in the pediatric intensive care unit of a portuguese tertiary referral center where it has been widely performed since 2011 are also mentioned.

Lung ultrasonography

Principles and technique

The speed of ultrasound wave through tissues is different depending on their coefficient of attenuation. As the air has a high coefficient of attenuation and the lung is an air-rich tissue, the ultrasound wave has great reflection in the lung. It coupled with the reduced lung aeration and compliance by lung injuries creates some artifacts. Accordingly, lung semiotic is made of real images and artifacts, thereby providing significant information. They allow us to identify normal lung patterns, interstitial syndrome/pulmonary edema, lung consolidation and pleural effusion.[13]

When performing lung ultrasonography, many technical issues must be considered. Indeed, the increased application of LUS has led to huge improvements in technology: higher resolution transducers/probes, harmonic imaging, and contrast-enhanced ultrasound.

Some ultrasound platforms may also come with specific software presets that include quick labels and/or diagrams for LUS. However, for general ultrasound equipment, there is no specific preset for lung examination, so the operator can select a small part preset or create a new one to perform the evaluation. There is significant debate as to which is best. Either a lung preset (particularly good for typical artifacts such as A and B-lines) or an abdominal preset (particularly good for pleural effusions) would be generally considered acceptable.

Regardless of the preset used, to obtain a satisfactory acquisition of images, we can adjust and optimize some parameters according to the needs and the patient condition: depth (into which the ultrasound waves will penetrate), gain (which amplifies the signals, making the image lighter or darker), focus (adjustment of image brightness) and zoom (allows to manipulate the ultrasound waves to increase the resolution to a certain depth).

Image resolution is best optimized when a target organ is in the middle of the image and surrounding structures can be visualized. Therefore, the depth of the lung ultrasound image should first be adjusted to visualize the pleural line in the middle of the screen. In pediatrics, the established depth is generally defined as 5-10 cm, despite some authors pointing to a maximum of 8 cm. If there is difficulty in locating the pleural line, the operator should decrease the gain and look carefully between the rib spaces at a depth of 0.5-1 cm below the superficial rib margins. Nevertheless, the depth should always be tailored to the patient, and young children may require less depth once the ribs are more cartilaginous and may allow some penetration of the ultrasound beam through them, as opposed to calcified bone. Depth should then be adjusted to the target of our examination: if we are looking for pneumothorax, it should be lower, to better visualize the pleural line; if we are looking for a free pleural effusion, the depth should be greater, for a better overview of the costophrenic angles. Normally, the focus should be positioned at the pleural line level, but it should be moved deeper when our main target is less superficial.

A high frequency (7.5-10 MHz) linear transducer allows an appropriate evaluation of surface structures such as pleura, while a lower frequency (3.5-5 MHz) convex transducer is preferred for the evaluation of deeper lesions. For scanning the lungs in neonates and infants, a high-frequency linear transducer is recommended, whereas in older children, a curvilinear probe is preferred. The exam is executed in the supine position for critical patients and the scan can be performed on a longitudinal plane (the transducer marker pointed to the patient head) or in a transverse plane (the transducer runs along the intercostal space), providing this last position a better visualization of a determined pulmonary region.

There are several methods described for scanning the lungs.[10,12,14] In all of them, chest scanning should be performed in areas defined by anatomical landmarks using an intercostal approach.[15] Therefore, in infants and older children, each side of the chest is divided into six areas: upper and lower anterior, upper and basal lateral, and upper and lower posterior chest. The anterior and lateral areas are separated by the anterior axillary line, whereas the posterior axillary line delimitates the lateral and posterior ones. In critically ill children, often ventilated and with multiple vascular accesses, minimal manipulation is essential. Therefore, for the approach of posterior fields, child reposition with a safe slight rotation is needed, allowing a quick and effective evaluation.

There are two types of sonographic modes used for lung and pleura imaging: real-time B-mode (brightness mode) and time-motion (M-mode). The pleura, described in ultrasound as a horizontal hyperechoic line (pleural line) created by the surface of the visceral pleura against that of the air-filled lung, represents the basic monographic anatomical landmark for lung examination. Ribs are the most suitable anatomical reference for pleural recognition, which can be found 0.5-1 cm deep of the hyperechoic surface of the ribs in an intercostal acoustic window. This is typically called “the bat sign”, with the periosteum of the ribs representing the wings and the bright hyperechoic pleural line in between them representing the bats body (Fig. 1A). It is through the initial identification of the pleural line that we will be able to identify and interpret all the other characteristic LUS findings and patterns, namely A and B-lines.

The change in acoustic impedance at the pleura-lung interface results in horizontal artifacts named A-lines (Fig. 1B). They are seen as multiple hyperechoic parallel lines equidistant from one another. The B-lines (previously called ultrasound lung comets/comet tail artefacts) are long vertical well-defined lines, moving with lung sliding, hyperechoic and erasing A-lines (Fig. 1B). They project from the pleural line to the edge of the screen without fading, consisting in artifacts produced when the ultrasound wave encounters the alveolar gas-liquid interface. The presence of B-lines mostly indicates an abnormality in the interstitial or alveolar compartment and correlate with lung interstitial fluid content. Nevertheless, they can also be seen in normal pulmonary parenchyma.

Lung ultrasound normal findings

The normal pattern of lung ultrasonography on B-mode is defined by the presence of lung sliding and A-lines. On M-mode it is represented as “the seashore sign”.[15,16]

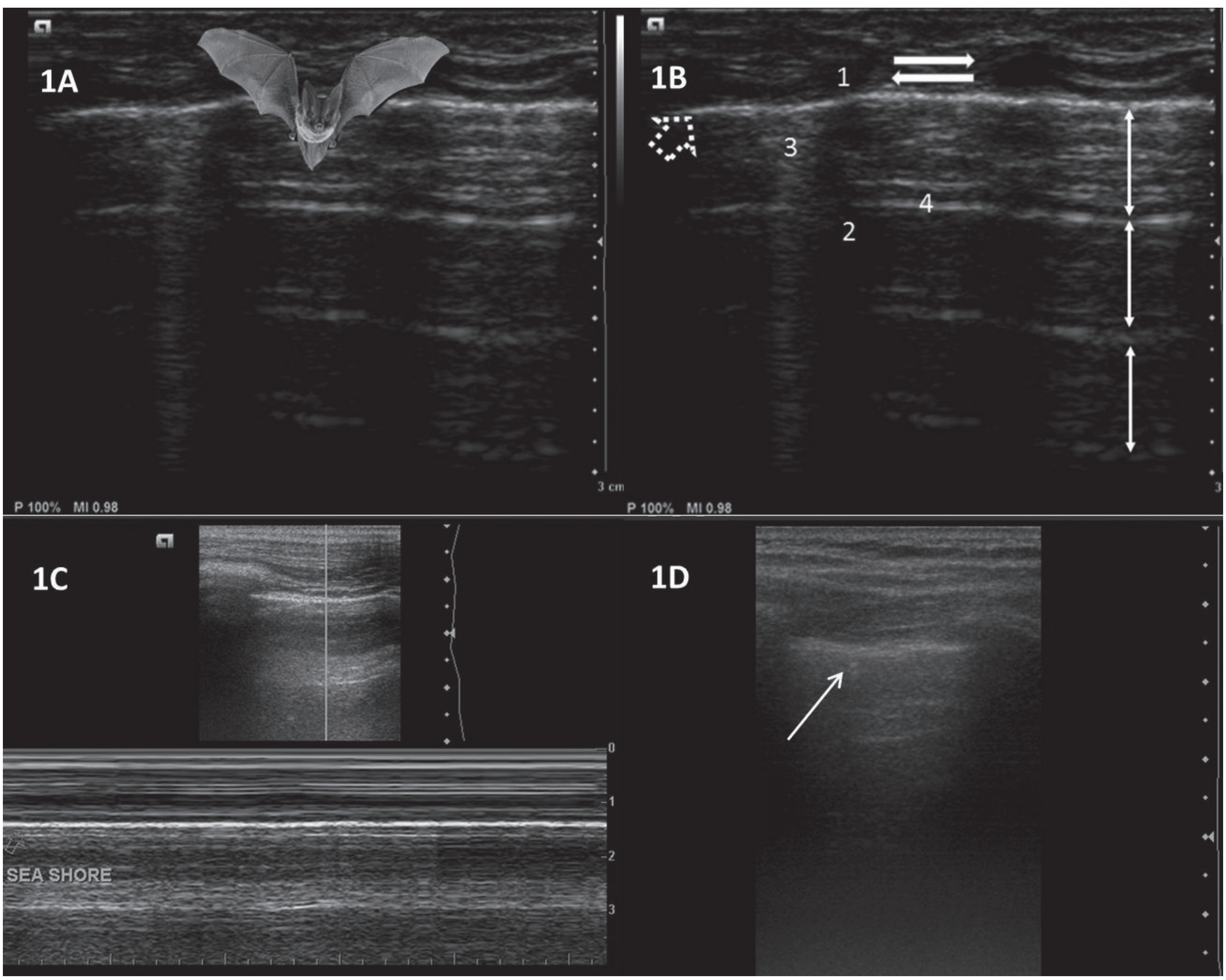

Figure 1. A. Ultrasound image of “bat sign”. The pleural line can be found 0.5-1 cm deep of the hyperechoic surface of the ribs in an intercostal acoustic window. B. Ultrasound pattern of normal lung. The pleural line (dashed arrow) is a roughly horizontal hyperechoic line below the upper and lower ribs (1) identified by acoustic shadow (2). A-lines represented by horizontal artefacts (4) equidistant from each other (vertical full arrows). A vertical B-line arising from the pleural line and spreading up to the edge of the screen can be seen in dependent regions in normally aerated lungs (3). Lung sliding (two parallel horizontal arrows) portrays the normal movement of the lung relative to the chest wall, where the visceral and the parietal layers of the pleura are sliding over each other. C. Ultrasound M-mode image of “seashore sign”, a complex image of multiple parallel horizontal lines with a sandy granular pattern below the pleural line (representing normal parenchyma). D. Ultrasound image of a Z-line in a healthy lung.

Lung sliding portray the normal movement of the lung relative to the chest wall, where the visceral and the parietal layers of the pleura are sliding over each other (Fig. 1B). It can be recognizable in B-mode by the hyperechoic line moving forward and backward from the probe during respiration. M-mode allows visualization of a complex image of multiple parallel horizontal lines representing the static thoracic wall and, below the pleural line, a sandy granulous pattern - "seashore sign" -, created by the movement of the two layers of the pleura, which represents the normal pulmonary parenchyma (Fig. 1C). Actually, pleura is one of the main structures to be evaluated in LUS, namely its thickness since it may be affected in many pulmonary pathological conditions. The normal thickness of pleura, with the parietal and visceral layers, is 0.2-0.4 mm, and it is generally not possible to distinguish between the two layers on a healthy lung ultrasound.

A few (less than three) isolated B-lines in an examined region may also be present in healthy patients, with no pathological meaning.[15,16] A similar comet tail artifact called Z-line (Fig. 1D) can also be found in lung ultrasonography. It is a vertical line that also arises from the pleural line but, unlike B-lines, it does not efface A-lines[16] and quickly vanishes after a few centimeters. It has unknown clinical use.

Lung ultrasound pathological pattern

Some LUS patterns suggest specific pathological conditions that can be grouped according to both ultrasound characteristics and pathophysiology of the disease. Thereby, there are four major patterns on lung ultrasonography: interstitial pattern, lung consolidation, pleural effusion, and pneumothorax.

Interstitial pattern

In interstitial syndrome, the pulmonary interstitium is affected by increased extravascular water, causing loss of aeration. The presence of B-lines and, consequently, the loss of A-lines, are highly suggestive of interstitial lung disease of cardiogenic and/or inflammatory etiologies. They can be single or multiple and be localized or disseminated to the whole chest wall. Therefore, separated B-lines are consistent with the presence of a moderate interstitial edema, while confluent B-lines indicate a more severe one.

A region positive for interstitial syndrome is classically defined by the presence of three or more B-lines in a longitudinal plane between two ribs (Fig. 2). When multiple B-lines are observed only in one pulmonary region, it is defined as focal interstitial syndrome. This is the first sonographic sign of the perilesional interstitial edema around a consolidation that is being formed. It may be the result of many pathological conditions, including pneumonia, lung contusion, atelectasis, pulmonary embolism, or lung tumor infiltration. The correlation with the clinical picture is crucial and the presence of symptoms helps to interpret these imaging findings.[10]

Lung consolidation

Lung consolidation appears at LUS as a subpleural hypoechoic region or tissue-like echotexture (lung tissue hepatization), which differs from the surrounding aerated pattern.[10] This area is poorly defined and wedge shaped, with a shredded boundary separating the consolidated and aerated lung - "shred sign" - that is specific of non-translobar consolidations (Fig. 3).

Lung consolidation may also be associated with air bronchograms, which consist in a significant lung artifact that is helpful for discrimination between pneumonia and atelectasis as the etiology of the consolidation.[15,16]

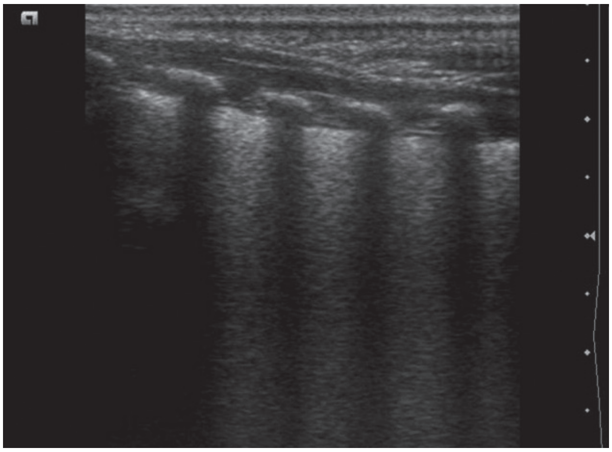

Figure 2. Ultrasound aspects of interstitial syndrome. Vertical B-lines arising from the pleural line and spreading up to the edge of the screen can be seen.

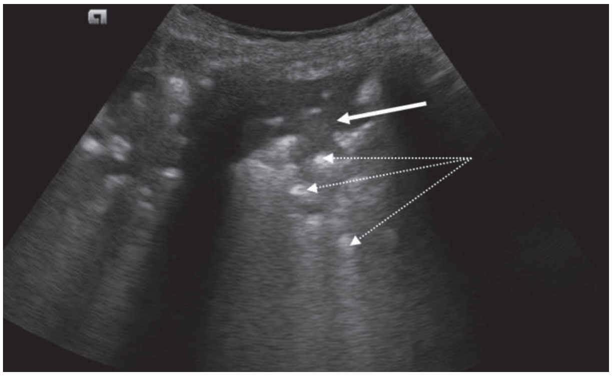

Figure 3. Ultrasound image of lung consolidation. The "shred sign" (full arrow), representing a poorly defined and wedge shaped, with a shredded boundary separating the consolidated and aerated lung can be identified. Hyperechoic punctiform elements (dashed arrows) inside the tissue-like pattern of the pulmonary consolidation representing dynamic bronchogram are also present.

Air bronchograms can be static or dynamic. Dynamic air bronchograms are more likely to occur in pneumonia, often in a tree-like or linear shape, whereas static air bronchograms are more likely to occur in atelectasis.[15,16] Therefore, a dynamic bronchogram is defined in lung ultrasonography by the presence of air inside the bronchi moving within the tissue, consisting in hyperechoic linear or punctiform elements inside the tissue-like pattern of the pulmonary consolidation (Fig. 3), while the static air bronchogram is characterized by the motionless air trapping inside the atelectatic region of the lung.

Pneumothorax pattern

The international evidence-based recommendations define four LUS signs to reliably diagnose pneumothorax: the presence of lung point and the absence of lung sliding, B-lines, and lung pulse.[1] Longitudinal reverberation artifacts of motionless pleural line - horizontal A-lines - can also be observed and indicate the presence of subpleural air.[17] Concerning the device settings, it is important to turn off the harmonic imaging because the presentation of pneumothorax depends on the evaluation of artifacts.

The lung point can be detected in both B and M-mode, and it has a 100% specificity for the diagnosis of pneumothorax.[16] It represents the exact point of transition between pneumothorax and normal lung patterns. Consequently, it is possible to observe both normal lung and pneumothorax patterns in the same ultrasound image (Fig. 4A). Its location may provide important information on the extent of pneumothorax: an anterior lung point indicates that the pneumothorax is probably radio-occult, whereas a lateral one indicates an extensive pneumothorax. Massive pneumothorax will have absent or posterior lung point.[15] “Stratosphere sign” (Fig. 4B), which is only visualized in M-mode, is another sign of pneumothorax and it consists of the replacement of the diffuse granular pattern below the pleural line by horizontal lines.[18]

In normal conditions, the ultrasound perception of heart activity vibrations at the pleural line is hindered by the sliding of the two layers of the pleura during respiration. However, in cases of pneumothorax, there is the abolishment of lung sliding.[16] Therefore, heart beats emerge at the pleural line and can be recorded in M-mode. It is called lung pulse to the sign of absence of lung sliding in B-mode with the simultaneous presence of a cardiac pulse in the pleural line in M-mode.

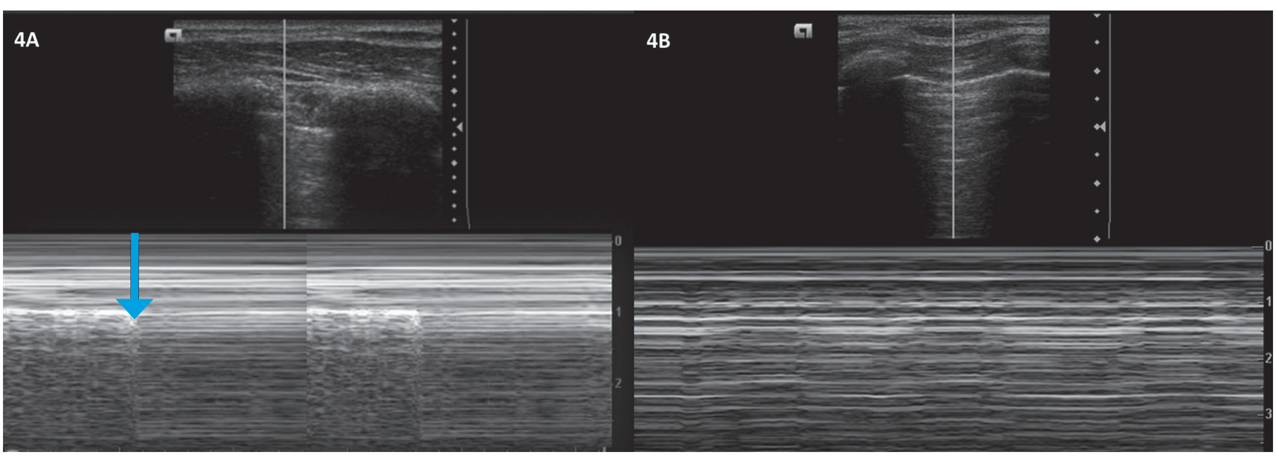

Figure 4. A. Lung point on motion mode (M-mode). The arrow indicates the transition between a “seashore sign” (normal lung) and “stratosphere sign” (pneumothorax). B. Ultrasound image of “stratosphere sign”, representing the replacement of the normal diffuse granular pattern below the pleural line by horizontal lines.

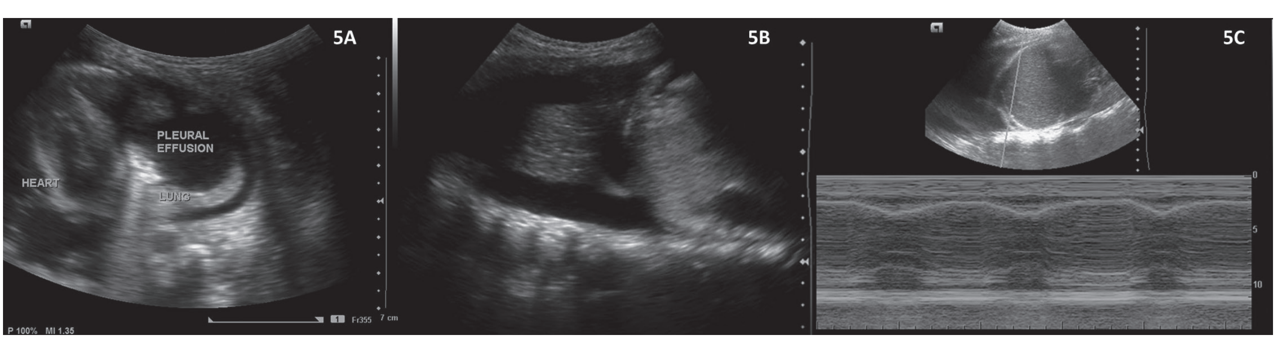

Figure 5. A. Ultrasound image of lung collapsed by a large pleural effusion. B. Ultrasound image of “jellyfish sign”, with lung flapping. C. Ultrasound image of “sinusoid sign”, created by the movement of lung surface line toward the pleural line with each respiratory cycle.

Pleural effusion pattern

Pleural effusion should be sought in dependent lung regions delineated by the chest wall and the diaphragm. It classically appears in ultrasound as a homogeneous hypoechoic structure with no gas inside.[16,17] If the lung remains aerated it can be seen as a bright pleural line, once pleural effusion acts as an acoustic window. However, if the lung is being compressed by a large amount of fluid (Fig. 5A), there will be seen a lung flapping in ultrasound, known as "the jellyfish sign" (Fig. 5B). In M-mode, the lung surface line will move toward the pleural line with each respiratory cycle creating a specific "sinusoid sign" (Fig. 5C).

Nevertheless, pleural effusions may differ from the classical aspect and so they can be sonographic classified into four major patterns: anechoic, complex non-septated, complex septated, and homogeneously echogenic. The first one is determined if no echogenic density is present within the effusion. The second one if there is a heterogeneous density within the effusion but without evidence of fibrinous septations. The third one if fibrinous septations are present within the anechoic pleural effusion, and the last one if echogenic density is homogeneously distributed within the effusion.[16]

Lung ultrasonography clinical applications: diagnostic and therapeutic value

Although lung ultrasonography is currently established as a gold standard technique for early use in the initial evaluation of the severely ill or injured child,[15] it remains underestimated for point-of-care diagnostic and therapeutic interventions. The role of LUS in the diagnosis and approach of some pulmonary conditions is described below. Other practical applications used in the daily clinical practice of our pediatric intensive care unit are also designed.

Community-acquired and ventilator-associated pneumonia

Pneumonia is characterized in lung ultrasonography by a lung consolidation diffusely demarcated by the aerated surrounding lung by a shredded boundary - "shred sign" (Fig. 3). Often in pneumonia, the consolidation is associated with dynamic tree-like or linear bronchograms and lung pulse.[17,19]

All LUS patterns originate from the pleural line, so ultrasound is not able to detect consolidation in the deep lung far from the surface. Nevertheless, in the pediatric population, the in-depth analysis of the lung parenchyma and so the identification of profound abnormal images may be possible. Previous studies found a high sensitivity of lung ultrasonography for pneumonia diagnosis in the pediatric population, which may be explained by its smaller thoracic diameter and lung volume combined with the usual peripheral location of lung consolidation.[4,9,20]

A meta-analysis comparing the use of LUS to chest radiography for the diagnosis of pediatric community-acquired pneumonia presented a sensitivity of 95.5% and specificity of 95.3% for lung ultrasonography, concluding that lung ultrasound had meaningly better sensitivity with similar specificity for the diagnosis of pneumonia when compared to CRX[9] Current evidence supports LUS as an imaging alternative for the diagnosis of pneumonia in pediatrics.[9,17,21-24] Nevertheless, LUS allows antibiotic monitoring, reducing the number of chest radiography needed.

On the concern of specific pediatric ventilator-associated pneumonia, studies assessing the diagnostic and treatment monitoring performance of LUS are nonexistent. On the other hand, studies in adults demonstrate that lobar or hemilobar consolidations, when associated with clinical diagnostic criteria, are useful to ventilator-associated pneumonia diagnosis. [25,26] Exact measurement methods of the consolidations and thresholds for their size still need to be defined.

Lung abscess

Lung ultrasound is also able to detect peripheral lung abscesses with pleural contact or included inside a lung consolidation.[17] They appear in ultrasound as roundish hypoechoic lesions with outer margins, without traversing vascular flow in the consolidated lung, and if there is a cavity present it will generate an interface gas/tissue that in its turn will generate additional non-dependent hyperechoic signals.[12,17]

Several studies have been performed on the value of ultrasound as a method of intervention, including ultrasound guidance for biopsy or aspiration of lung and mediastinal lesions.[12,27,28] For lung abscesses ultrasound-guided percutaneous drainage has proven to be as safe and effective as CT-guided drainage.

Lung contusion

Lung contusion is one of the most common injuries of pediatric thoracic trauma and its severity can range from an isolated asymptomatic image finding to significant respiratory failure requiring mechanical ventilation.[29] Lung contusion may be diagnosed by lung ultrasonography in the presence of areas with an interstitial pattern, characterized by multiple focal B-lines, and/or areas with peripheral parenchymal lesions, with confluent lung consolidations or a parenchymal disruption with localized pleural effusion.[1,30]

Therefore, many studies have been conducted to evaluate the capability of LUS to detect lung contusions at an earlier stage than chest radiography, and a recent one found an overall sensitivity of 97.5% for ultrasound and of 40% for initial CRX, suggesting that the assumption that LUS may reach a higher sensitivity is true.[30]

Atelectasis

Atelectasis is one of the major complications of lung diseases and represents a frequent reason for difficulty in weaning mechanical ventilation, being its diagnosis a priority in critical care.[16,31,32] Lung collapse can have different patterns in LUS depending on the extension of atelectasis.[15] Atelectasis by itself is typically identified as a hyperechoic branching, roughly parallel to the lung surface. If there is only slight to moderate loss of lung aeration, it will also be manifest by isolated to coalescent B-lines in the dependent lung area. On the other hand, if the atelectasis is complete, a sub-pleural consolidation with static air bronchograms will be observed. Compressive atelectasis is often presented with large associated pleural effusion.

Lung pulse represents a specific sign of atelectasis that can also typically be found in LUS.[33]

Acute viral bronchiolitis

Acute viral bronchiolitis is characterized in ultrasound by a panoply of patterns, including alveolar consolidations, interstitial infiltrate and peribronchial thickening, atelectasis, and a more regular pattern of multiple B-lines that tend to coalesce in the most severe cases. Atelectatic areas may be seen mainly in the upper lobes, usually in the right side.

Several articles have emphasized the role that ultrasound may play in the diagnosis and monitoring of this condition.[3,15,34,35] The major aim of its use in bronchiolitis is to rule out pneumonia, having a significant impact on the therapeutic approach.

Acute respiratory distress syndrome

In adult studies,[36] the LUS pattern of acute respiratory distress syndrome (ARDS) characteristically has a heterogeneous distribution, including bilateral well detached or coalescent B-lines, pleural thickening, and spared areas of normal lung. A posterior subpleural consolidation associated with dynamic bronchograms is also often described.[36,37]

Despite the still sparse data from pediatric studies, similar findings are described mainly by pediatric intensivists, presenting LUS as a promissory tool in this field. In fact, the most recent example of its value and increasing importance is its use both in the triage of patients suspected of having severe ARDS by a coronavirus 2 (SARS-CoV-2) infection and in monitoring patients with coronavirus disease 2019 (COVID-19).[38] COVID-19 causes typical LUS patterns (Fig. 6A). The appearance of B-lines could vary from focal to confluent. On the other hand, consolidations could be represented by multifocal small subpleural consolidations up to a non-translobar or translobar consolidation with occasional air

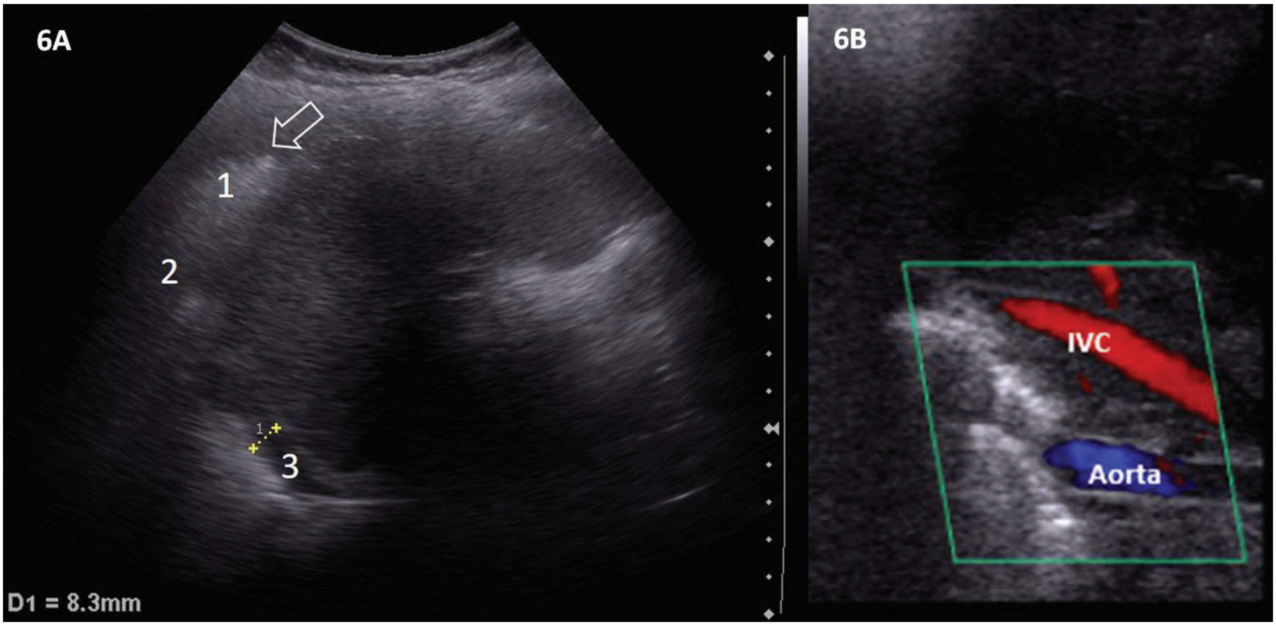

Figure 6. A. Ultrasound image of COVID-19. Pleural thickening (arrow), air bronchogram (1), confluent B-lines (2) and small pleural effusion (3) are seen. D1 - represents the measurement of interpleural distance, in millimeters, which allows to estimate the extent of pleural effusion. B. Ultrasound image showing normal vascular filling: inferior vena cava (IVC) has the same dimension than aorta.

bronchograms. Thickening and irregularity of the pleural line and small pleural effusion can also be seen.[38,39]

Cardiogenic pulmonary edema and congenital heart diseases

Cardiogenic pulmonary edema (CPE) can be a significant cause of acute respiratory failure, particularly in pediatric intensive care units. In contrast with ARDS, the classical LUS pattern of CDE is characterized by a homogeneous bilateral distribution of B-lines, with regular pleural line and normal lung sliding, characteristically without lung consolidations associated. Although pleural effusions are present more frequently in CPE than in ARDS, their presence cannot be relied on for differential diagnosis.[36,40] Nevertheless, the diagnostic accuracy of LUS is dependent on the clinical context considerations and it is enhanced when used in association with echocardiography.

B-lines are one of the most useful LUS signs for the identification of the cardiogenic origin of dyspnea, yielding a high sensitivity and excellent specificity in differentiating acute heart failure syndrome from non-cardiac causes of acute dyspnoea.[41,42]

Infants and young children with congenital heart disease most of the time represent a complex and vulnerable population, being at increased risk for developing cardiac dysfunction and respiratory insufficiency.[43] The use in the association of lung ultrasonography and echocardiography may be of great value in cardiac postoperative care, once they can provide a practical and noninvasive monitoring of the time course of lung water changes after interventions, thereby allowing to achieve timely management and prevent complications.[2]

In our clinical activity, we also use lung ultrasonography in the process of determining the vascular filling in non-ventilated children, predicting the need of fluid therapy (Fig. 6B). Moreover, in heart failure, the routine performance of LUS in our PICU allows the management of anti-congestive therapy, namely diuretics.

Pneumothorax

Pneumothorax is a life-threatening condition that sometimes is difficult to diagnose in useful time. It is often a complication of trauma, ARDS, thoracentesis, and mechanical ventilation, being its diagnosis a priority in the emergency department and PICU settings.

Lung ultrasonography is a proven reliable and feasible imaging technique for pneumothorax diagnosis[6,44,45] that may be essential in some clinical scenarios, including cardiorespiratory arrest secondary to hypertensive pneumothorax and in unstable patients.[1,15,24] A recent prospective multicenter study found sensitivity, specificity, positive and negative predictive values of 100% for LUS in the diagnosis of pneumothorax in critically ill neonates.[18]

As described before, the main ultrasound signs of pneumothorax are the presence of the lung point and the absence of lung sliding, B-lines, and lung pulse. The presence of lung sliding implies contact of both layers of pleura and, therefore, excludes the existence of pneumothorax. However, in some circumstances, lung sliding can be abolished in the absence of pneumothorax, such as in the presence of a thoracic tube, bullous emphysema, pleural adherence, and in critically ill patients, especially those with ARDS.[15,19]

Although the decision to place a thoracic drain is based on the clinic, LUS may help to identify small and anterior pneumothorax that cannot be seen on chest radiography. Furthermore, it allows the clinicians to read the image exam at the time of clinical evaluation, helping make faster decisions that may be lifesaving. In our clinical experience, we also use LUS in the process of thoracic drain removal: if ultrasound signs of pneumothorax are still present during clamping, its removal will not be possible.

Pleural effusion

Lung ultrasonography can report with precision even small effusions at costophrenic angles, particularly in children, due to the thinner adipose subcutaneous tissue plus the high spatial resolution obtained by high-frequency probes.[15] In the emergency department and PICU settings, it can add valuable information and allow clinicians to both readily make the decision to perform thoracocentesis and safely guide the procedure. In addition, LUS is an imaging technique that allows a dynamic assessment of the lung and, therefore, it can directly be used to observe how an effusion affects the patient ventilation. It also allows a more detailed characterization of the pleura itself, such as the existence of pleural thickening (Fig. 7A). Pleural thickening describes any form of thickening - diffuse, circumscribed or even nodular - involving either the parietal or visceral pleura. It can diversify between hyperechoic and hypoechoic with complex internal architecture.

Lung ultrasonography cannot replace diagnostic thoracentesis. Nevertheless, it can provide valuable information of the cause of the effusion, namely transudate/exudate, parapneumonic effusion/empyema, effusion related to cardiogenic pulmonary edema, hemothorax, and chylothorax.

Although LUS performed alone is not able to accurately assess the nature of pleural effusion - transudate or exudate -, some ultrasound patterns are suggestive.

Whereas transudates often appear anechoic and homogeneous, exudates usually are hyperechoic and loculated.[17] Hemothorax (Fig. 7B) is the paradigm of exudates, but its sonographic appearance often depends on whether LUS is performed shortly after chest trauma/bleeding in the pleural cavity occurred or performed several hours or days later, ranging from hypoechoic (if performed early) to hyperechoic (if performed later after the injury). Another specific condition is chylothorax, in which LUS allows the diagnosis showing the differences in the effusion sonographic characteristics before and after enteral feeding (Fig. 7C).

The volume of a pleural effusion can be quantified using various techniques.[46,47] It can be estimated by lung ultrasonography based on the evaluation of the interpleural distance, which is defined as the maximal distance between the two layers of the pleura - visceral and parietal -, measured at the posterior axillary line and in the supine position (Figs. 6A and 7B).[16,46] Afterward, the amount of pleural fluid can be estimated by the following formula[16]:

V (mL)= 20 X Id (mm), where V is the volume of pleural fluid and Id is the interpleural distance.

As for its therapeutic value, lung ultrasonography is increasingly used for guiding thoracocentesis at the bedside, providing the possibility of detecting pleural adherences and enabling safe thoracic drainage of small and loculated pleural effusions. In our PICU, the number of adhesions plays a role in the decision on whether to use or to repeat intrapleural fibrinolytic therapy. It can also be of great value to monitor residual collections post drainage.[1,15,17]

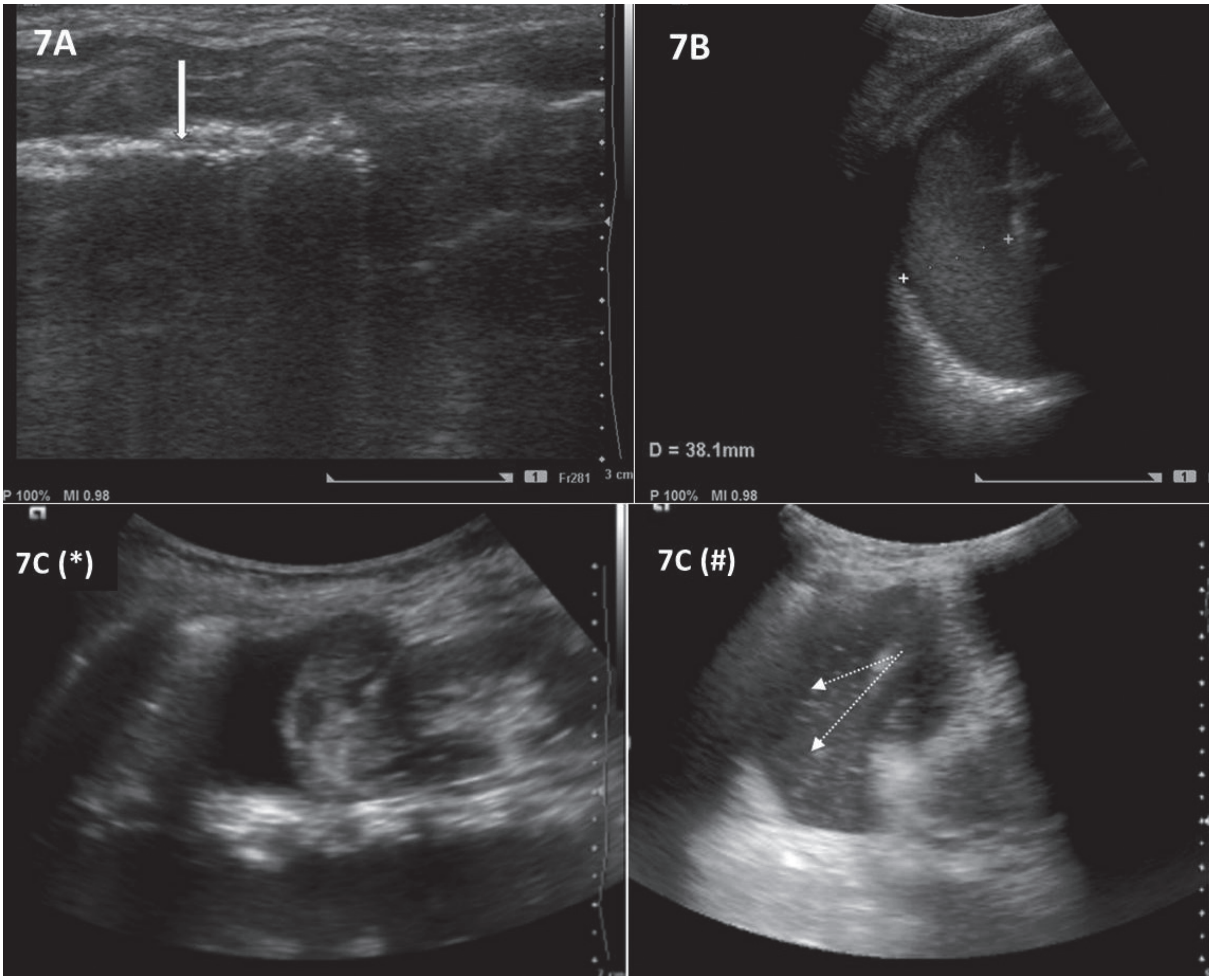

Figure 7. A. Ultrasound B-mode image of pleural thickening in a child with pleurisy due to pleuritis. B. Ultrasound pattern of a hemothorax secondary to inadvertent internal carotid puncture during attempted right internal jugular vein cannulation. D is the interpleural distance measured between the lung and the dorsolateral chest wall in the posterior axillary line, allowing to estimate the volume of pleural effusion. C. Ultrasound pattern of a chylothorax secondary injury to the thoracic canal after surgical intervention for the total correction of the tetralogy of Fallot. Lung ultrasound allows the diagnosis of this condition showing the differences in the effusion sonographic characteristics before (*) and after enteral feeding with expressed breast milk (#): seven days after starting enteral feeding, the previously anechoic pleural effusion became hyperechoic (dashed arrows). Thoracentesis allowed diagnostic confirmation.

Invasive mechanical ventilation, diaphragm assessment, and endotracheal tube position

Invasive mechanical ventilation is a crucial technique in PICU, and multiple studies have shown that mechanical ventilation, even if used for short periods of time, has deleterious effects on respiratory muscles, conditioning diaphragmatic atrophy, and progressive loss of its function.[48-51] This process is called ventilator-induced diaphragmatic dysfunction. Consequently, diaphragm ultrasound has emerged as a promising technique for assessing both morphology and contractile activity of diaphragm, through evaluation of diaphragmatic thickness (T_D) and thickening fraction (TF_D), respectively.[49] Systematic assessment of these parameters allows the identification of diaphragmatic dysfunction/paralysis and the prediction of extubation success or failure.[5]

Atelectasis and lung collapse are major complications of positive pressure mechanical ventilation that led to ventilatory and lung mechanical impairment - ventilator-induced lung injury.[52,53] These negative effects of lung collapse can be reversed by a lung recruitment maneuver. Although it is not routinely used in our clinical practice, lung ultrasonography has been described as a promising technique in this process.[53,54]

In the process of mechanical ventilation, the accurate assessment of the endotracheal tube position is crucial to preventing wrong-placement-associated complications and morbidities.[12] Some studies used the lung sliding or direct visualization of the endotracheal tube tip as a surrogate marker of proper endotracheal tube depth and placement in PICU.[55,56] Nevertheless, a more recent prospective study proved that LUS is a more feasible, safer and faster alternative technique when using a saline-filled endotracheal tube cuff.[57]

Limitations of lung ultrasound

Despite its many advantages and usefulness, lung ultrasound has some limitations.

One of the limitations often cited regarding to any ultrasound imaging technique is the operator dependence, directly related with its experience in performing the technique.

The use of LUS is also limited in cases where structures that contribute to the acoustic window are altered, such as in some liver and/or splenic pathological conditions and in the existence of overlying thoracic dressings or subcutaneous emphysema. Soft tissue edema, anasarca, and obesity may also preclude the examination of subjacent lung areas.

In some cases, LUS may also miss small consolidations or consolidations localized in the central of lungs and mechanical ventilation-induced pulmonary hyperinflation, a common issue in PICU, also cannot be detected by lung ultrasonography.

Future perspectives

Lung ultrasonography has a promising future in pediatric critical care. Nevertheless, no guidelines for LUS training or competency standards exist in pediatric critical care. Therefore, no certification process has been formally recognized by professional groups or societies so far.

Future challenges include the requirement of establishing specific norms intended to identify best practices for clinical effectiveness and efficiency as well as the need for institutions to train and credential pediatric intensivists in the use of lung ultrasonography. The future of LUS also remains to be expanded into other pediatric areas.

Final remarks

Lung ultrasound has been proven to be a radiation-free technique to assess and manage pulmonary disorders in critical care. It is changing the way of examining, diagnosing, treating, and managing patients, while allowing saving from radiation exposure and delaying or even avoiding transportation to the radiology department. Nevertheless, its usefulness has yet to be proven or better established in the routine practice of PICU.

The aim of this article is to create a literature basis in order to help in guiding the implementation, development, and training on the use of lung ultrasound in PICU. It also serves as the basis for further research in the field.

Conflicts of Interest

The authors declare that there were no conflicts of interest in conducting this work.

Funding Sources

This work has not received any contribution grant or scholarship.

Provenance and peer review

Not commissioned; externally peer reviewed

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Ecografia Pulmonar numa Unidade de Cuidados Intensivos Pediátricos: Revisão Clínica

Resumo:
Os estudos no campo da ecografia pulmonar pediátrica cresceram rapidamente nos últimos anos, tendo-se revelado esta técnica de imagem uma ferramenta extremamente útil na abordagem de crianças gravemente doentes ou feridas. A ecografia pulmonar é uma técnica não invasiva que pode ser realizada rotineiramente no leito e pode fornecer informações precisas sobre as características pulmonares. Baseada em padrões ultrassonográficos distintos, ela tem o potencial de fornecer informações nobres em tempo real que podem alterar o diagnóstico, o tratamento e o manejo das doenças pulmonares, especialmente em unidades de cuidados intensivos pediátricos. O objetivo deste artigo é rever alguns conceitos básicos sobre a técnica de ecografia pulmonar e descrever brevemente as suas principais aplicações na abordagem de crianças gravemente doentes, com base na literatura existente até à data e nas aplicações específicas diárias numa unidade de cuidados intensivos pediátricos de um centro de referência terciário português. O propósito é criar uma base de literatura para ajudar a orientar a implementação, desenvolvimento e treino no uso da ecografia pulmonar em unidades de cuidados intensivos pediátricos.

Palavras-Chave: Criança; Pneumopatias/diagnóstico por imagem; Pulmão/diagnóstico por imagem; Sistemas Automatizados de Assistência Junto ao Leito; Ultrassonografia; Terapia por Ultrassom; Unidades de Cuidados Intensivos Pediátricos