Basic notions of lung ultrasound in neonatology

Silvia Fernández Jonusas^a ⁽⁵⁾, Carolina M. Cribioli^a ⁽⁵⁾, Alejandra S. De Gregorio^a ⁽⁵⁾, Carolina Giudice^a ⁽⁵⁾, Gonzalo Mariani^a ⁽⁵⁾, Cecilia M Acosta^b ⁽⁵⁾

ABSTRACT

Lung ultrasound (LU) has gained ground in the diagnosis of most respiratory conditions present since birth. It is highly sensitive to variations in air content and pulmonary fluids and functions as a true densitometer of the lung parenchyma with a sensitivity superior to that of radiological studies. A LU is a non-invasive, fast and easy tool that can be used at the patient's bedside and, unlike conventional radiology, does not pose risks of radiation. In addition, a LU provides real-time dynamic information in a variety of neonatal settings and, like heart and brain examinations, can be performed by the neonatologist. The objective of this article is to describe the main artifacts and images that can be found in the neonatal LU, as well as the different aeration patterns, and to highlight their usefulness in the study of the most frequent respiratory disorders of neonates

Key words: lung, imaging tests, newborn, respiratory disorders.

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a. Hospital Italiano de Buenos Aires, the City of Buenos Aires, Argentina.

 Hospital Privado de la Comunidad, Mar del Plata, Argentina.

E-mail address: Silvia Fernández Jonusas: silvia.fernandez@hiba. org.ar

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INTRODUCTION

Lung ultrasound (LU) has gained consensus as a safe tool for the diagnosis of different pulmonary conditions in newborn infants (NBIs). The European Society of Paediatric and Neonatal Intensive Care (ESPNIC) recently published the guidelines on point of care ultrasound (POCUS), which mention the usefulness of the LU for the diagnosis of the main respiratory diseases in neonates and pediatric patients.¹

The learning curve for performing LUs is fast and less demanding than for performing ultrasounds on other organs; however, supervised and rigorous training is required to prevent diagnostic errors. The implementation of the LU for the diagnosis and follow-up of different neonatal diseases offers an additional and relevant benefit in this population, who poses an increased risk for cancer when exposed to radiation, compared to the adult population.² In recent years, lung auscultation is being replaced by lung visualization, so that LU is considered the "stethoscope of the new millennium."³

The objective of this review is to describe the basic notions of LU imaging and its use in the differential diagnosis of neonatal respiratory diseases.

STUDY METHODOLOGY

The high-frequency linear probe (6 to 13 MHz) is the probe of choice for the ultrasound exploration of the chest (due to the size of the newborn's rib cage), which allows obtaining a high-resolution image. We suggest setting the image depth at 3–4 cm and positioning the focus at the level of the pleural line. The ultrasound examination of the lung in the neonate is performed by dividing each lung into anterior, lateral, and posterior areas, tracing the following lines: parasternal, anterior axillary, posterior axillary, and paravertebral.⁴ Brat et al., described 3 examination areas for each lung: upper-anterior, lower-anterior, and lateral, to predict the need for surfactant administration in NBIs⁵ (*Figure 1*). It is recommended to use warm ultrasound gel to avoid NBI discomfort. Since the images obtained cannot be differentiated (due to the anatomical characteristics of the lung), it is important to note the area explored and the patient's position.

Main ultrasound modes

- B-mode (two-dimensional mode): the most common; it allows identifying dynamic signs and diagnosing the most important pulmonary diseases.
- M-mode: it allows studying a point over time.
- Color Doppler: it identifies blood flow in consolidations.

ULTRASOUND EXAMINATION OF THE CHEST

Lichtenstein based ultrasound chest examination on 7 simple principles:⁶

- 1. LU requires a B-mode ultrasonograph and a high-frequency linear transducer.
- 2. The main artifacts arise from air and fluids mixing within the thorax; therefore, the

patient's position should be specified for result interpretation.

- 3. It is important to have standardized points of analysis.
- 4. All signs of LU arise from the pleural line, which is below the hyperechoic lines that represent the rib.
- 5. LU is mainly based on artifacts (usually deemed undesirable, here they are useful).
- 6. Most signs are dynamic.
- 7. Almost all chest disorders occur in contact with the surface. This explains the potential of LU.

When the ultrasound transducer is placed on the chest wall, images are obtained as a result of the interaction of the ultrasound beam with the pleura and the lung parenchyma, which generates horizontal and vertical artifacts of varying echogenicity. The marked difference in acoustic impedance between the soft tissues of the chest wall and the normally-aerated lung parenchyma prevents the formation of a true image and leads to artifacts caused by the reflection of the chest wall on the pleural line.⁶⁷

The A-lines are the main horizontal artifacts (characterized as hyperechoic lines) that are repeated and appear arranged at an equal distance identical to the distance between the skin and the pleura. An A-line is an artifact that is given by the resonance on the pleural surface. In this way, the pleura acts as the "mirror of the lung."⁸

FIGURE 1. A: Examination areas in neonates and infants, anterior, lateral, and posterior, divided into parasternal line (PSL), anterior axillary line (AAL), posterior axillary line (PAL), and paravertebral line (PVL) in both lungs. In older children, these areas are sub-divided into upper and lower; B: Upper-anterior, lower-anterior, and lateral area in each lung



The examination should be started by placing the probe in a longitudinal position with the notch (transducer reference) in the cephalic direction to obtain an image in which the most cephalic structures will be to the left of the screen. Hyperechoic lines corresponding to the rib will be seen on the chest wall; below this, another hyperechoic line representing the parietal and visceral pleura will appear. In neonates, since the ribs are mostly cartilaginous, it is possible to visualize the hyperechoic pleural line below the acoustic shadows of the ribs. During the respiratory cycle, under normal conditions, the movement of the pleura is observed using the B-mode, called the lung sliding sign in both lungs, which indicates the sliding of the parietal pleura over the visceral pleura. Below the pleural line, you can see A-lines, horizontal hyperechoic artifacts. If the M-mode is used, 2 areas can be seen forming the seashore sign: the upper area corresponds to the chest wall formed by parallel horizontal lines and the lower area, arising from the pleura (with a sandy pattern), represents the aerated lung parenchyma.^{6,7} Subsequently, the probe is rotated until it is positioned parallel to 2 ribs, at an angle, so that a complete image of the pleural line and the lung parenchyma is obtained, without visualizing the acoustic shadows of the ribs (Figure 2).^{7,8} If endobronchial intubation occurs: absence of "lung sliding" is observed and "lung pulse sign" appears in this hemithorax, generated by the transmission of the heartbeat in the atelectatic lung.

As the air content in the lung parenchyma decreases and the amount of fluid or the cell deposit in the interlobular septa and interstitium increase, vertical reverberation artifacts called B-lines appear (*Figure 3*).^{6,7,9} These lines indicate an ultrasound sign of loss of lung aeration, and are characterized by being vertical, hyperechoic, and well-defined. They arise from the pleural line and are directed to the lower limit of the image, blur the A-lines, and show a synchronous movement with pleural sliding.¹ It is considered pathologic when 3 or more B-lines are observed in a longitudinal scan. B-lines may be present in different diseases, such as congenital heart disease, heart failure, pneumonia, atelectasis, and neonatal lung conditions.^{7,9} However, isolated or nonconfluent B-lines may be present in healthy NBIs in the first hours of life during the transitional period.⁴

In contrast, when the loss of aeration is complete, the difference in acoustic impedance between both tissues disappears, thus generating a true, high-resolution image that identifies lung consolidation (*Figure 3*). Thus, the LU acts as a true densitometer of the lung parenchyma; as aeration decreases, density increases, and the artifact image becomes a real image.⁷

ULTRASOUND PATTERNS IN THE DIFFERENT RESPIRATORY DISEASES OF NEONATES Pneumothorax

Pneumothorax is defined as the presence of air in the pleural cavity. It may develop in NBIs



FIGURE 2. Images obtained using a linear probe. A: Longitudinal scan showing chest wall, ribs, pleural line, and A-lines; B: Oblique scan: positioning the probe in the intercostal space between the upper and lower rib. The red circle indicates the notch's position in the scan with respiratory distress and is life-threatening. A LU has a higher sensitivity and specificity in the early diagnosis of pneumothorax in neonates—compared to chest X-ray (CXR)— ^{9,10} which also allows for a faster diagnosis than a CXR (5.3 minutes versus 11.7 minutes, respectively [p < 0.001]), with a 100% sensitivity and specificity.¹¹

For diagnosis, the examination should begin with the patient in the supine position, starting with the anterior thoracic areas (with the probe in longitudinal position) and identifying the rib using the B-mode, below the pleural line, and discarding the 3 signs with a high negative predictive value: presence of the lung sliding sign, presence of the pulse sign (synchronous movement of the pleural line and the patient's heartbeat), and presence of B-lines, due to the fact that these arise from the visceral pleura.⁷ Subsequently, moving the probe to the side, the lung point sign is seen, which indicates the extension of the pneumothorax corresponding to the transition between the lung parenchyma –where the visceral pleura is in contact with the

FIGURE 3. A: B-lines. Histological pattern evidencing thickening of alveolar septa and its ultrasound correlation represented by vertical artifacts called B-lines (*). B: Lung consolidation, hypoechoic subpleural area with echotexture similar to the liver, hyperechoic air bronchograms



FIGURE 4. Proposed algorithm for the ultrasound diagnosis of pneumothorax. B-mode scan showing the lung point sign. The bottom image was obtained using the M-mode and shows the barcode sign and the lung point sign



parietal pleura (presence of lung sliding)– and the area where the visceral pleura has retracted due to the presence of air between the visceral pleura and the parietal pleura (absence of lung sliding).^{4,6,7} The M-mode evidences the absence of the seashore sign (sandy aspect representing the lung) and the appearance of the barcode sign or stratosphere sign, which is observed as parallel lines, due to the presence of air between both pleurae (*Figure 4*).⁶

Pleural effusion

A LU not only allows to diagnose pleural effusion by detecting even small amounts of fluid (5-20 mL), with a high sensitivity and specificity,⁶ but also to monitor its course by estimating pleural effusion volume and determining the area where to perform ultrasound-guided thoracocentesis in order to reduce associated complications.^{6,7} A LU has greater certainty for the differential diagnosis between consolidation and effusion in the presence of opacities detected in the CXR.⁷

Fluid can be seen as an anechoic image between the parietal and visceral pleura; its echogenicity varies depending on effusion characteristics, such that the transudate appears as an anechoic image whereas the exudate may be seen as an anechoic or diffusely echogenic image with internal echoes. The presence of fibrin septa in septated effusion, typical of bacterial pneumonia, are seen with high resolution, both with the LU and the chest computed tomography. The pleural effusion may be examined using a linear probe, or a convex probe in the case of extensive effusion, placing the probe on the costophrenic sinus (*Figure 5*). In his bedside lung ultrasound in emergency protocol (BLUEprotocol), Lichtenstein proposes using a posterolateral alveolar and/or pleural syndrome point (PLAPS-point),⁶ limited by 2 lines: a horizontal line at the level of the nipple that continues to the back until intersecting a vertical line, corresponding to the posterior axillary line. At this point, it is possible to detect pleural effusions and consolidations in 90% of critically ill patients.⁶

Ultrasound signs

- 1. Presence of anechoic/hypoechoic fluid between the parietal and visceral pleurae.
- 2. Quad sign: static sign that appears when the linear probe is placed longitudinally on the chest, where the parietal pleura forms the upper margin, the acoustic shadow of both ribs defines the lateral boundaries, and the lower boundary is formed by a regular line called pulmonary line that represents the visceral pleura.
- 3. Sinusoid sign: using the M-mode, the back and forth movement of the parietal and visceral pleura is observed during the respiratory cycle.⁶
- 4. Jellyfish sign: undulating movement of the consolidated lung surrounded by the effusion.⁶

FIGURE 5. A: Linear probe scan, pleural effusion in B-mode: quad sign. Lower area, M-mode shows the sinusoid sign. B: Image obtained with a linear probe at the postero-lateral alveolar and/or pleural syndrome point (PLAPS-point) described by Lichtenstein,⁶ at the level of the costophrenic sinus, showing extensive pleural effusion in a neonate associated with compressive atelectasis: jellyfish sign. C: Scan using a convex probe at the level of the costophrenic sinus, showing pleural effusion, compressive atelectasis, and presence of the thoracic spine sign



5. Positive spine sign: at the level of the costophrenic sinus, the pleural effusion fluid allows to see the thoracic spine.

Lung consolidations

A consolidation occurs when there is a complete loss of lung aeration. Lung consolidation may be translobar (an echogenicity pattern resembling that of liver with a regular margin) or non-translobar (more common, a hypoechoic subpleural area with an irregular margin known as the shred sign).⁶ Being a surface technique, LU only detects consolidations in contact with the pleural surface.⁷⁸

Ultrasound signs associated with consolidations:⁷

- 1. Hypoechoic subpleural image or liver-like echotexture (tissue pattern).
- 2. Irregular, wedge-shaped or blunt margins.
- 3. B-lines arising from subpleural consolidations.
- 4. Static, dynamic, and fluid air bronchograms. Air bronchograms are evidenced as hyperechoic or lenticular tubular structures depending on whether a longitudinal or transverse section of the bronchus is studied. Dynamic air bronchograms highly suggestive of pneumonia are seen as hyperechoic structures that move on inspiration, while static bronchograms are characteristic of atelectasis.
- 5. A vascular pattern within the consolidation (seen with color Doppler) indicates the existing shunt in the consolidated lung parenchyma.

It is mandatory to identify the diaphragm to make the correct diagnosis of lung consolidations. Different types of consolidations may be observed: pneumonia, obstructive atelectasis, compressive atelectasis, atelectasis induced by general anesthesia (frequent especially in neonates and infants), pulmonary contusion, tumors, and pulmonary embolism. The etiologic diagnosis is established by contextualizing the ultrasound finding with the patient's clinical signs and symptoms and other diagnostic methods (*Figure 6*).

In mechanically ventilated patients LU should be considered as it is more accurate than CXR in the detection of consolidation.⁷ A study in neonates reported a sensitivity of 100% for LUs in the diagnosis of atelectasis, while the sensitivity of CXR was 75%.¹²

Interstitial syndrome

B-lines may be present in neonatal lung diseases, such as bronchopulmonary dysplasia, meconium aspiration syndrome, transient tachypnea of the newborn, and respiratory distress syndrome (RDS). Depending on the pathology, they may be present in one or both lungs.

Transient tachypnea of the newborn

Transient tachypnea of the newborn (TTN) is characterized by a delay in clearance of lung fluid. Copetti and Cattarossi described an ultrasound sign called the double lung point sign, pathognomonic of TTN (with a 100% sensitivity and specificity),¹³ characterized by a pattern of A-lines in the upper chest and coalescent B-lines in the basal areas. However, subsequent studies showed that this sign is present in only 38.4% of cases in the first 24 hours of life.¹⁴ The ultrasound

FIGURE 6. Lung consolidation images. A: Subpleural consolidations; the shred sign is observed. B: Lung consolidation in a neonate, presence of air bronchograms (white arrows) and fluids (yellow arrows). C: Color Doppler, consolidated pulmonary parenchymal shunt is observed



signs typical of TTN include the presence of an usually normal or thickened pleural line, the double lung point sign (which is not an essential criterion), and numerous, non-coalescent B-lines in one or both lungs (*Figure 7*).

Meconium aspiration syndrome

This is a lung disease caused by the aspiration of meconium. The ultrasound pattern is characterized by subpleural consolidations, coalescent B-lines, and consolidations with air bronchograms, with irregular margins alternating with respected areas, with a varying distribution in both lungs.¹⁵

Respiratory distress syndrome

This is one of the most common neonatal respiratory diseases. Typical ultrasound findings include the presence of pleural irregularity with subpleural consolidations, coalescent

FIGURE 7. A: CXR and LU in a NBI with TTN. On the left, double lung point sign characterized by the presence of A-lines in upper regions and coalescent B-lines in lower areas. On the right, scan with numerous non-coalescent B-lines. B: CXR and LU in a preterm NBI with RDS. The LU shows, on the left, a pattern of coalescent B-lines with "white lung" appearance associated with subpleural consolidations and, on the right, extensive consolidation with air bronchograms



FIGURE 8. Images obtained using a linear probe. Lung aeration patterns. A: score = 0 normal aeration; B: score = 1 moderate loss of aeration; C: score = 2 severe loss of aeration; D: score = 3 complete loss of aeration



B-lines with "white lung" appearance, bilateral involvement, and absence of respected areas (*Figure 7*). Numerous studies have highlighted the usefulness of LU in the diagnosis and follow-up of neonates with RDS. In a recent review, Corsini reported that the LU has a sensitivity of 96.7% and a specificity of 100% for the diagnosis of RDS in NBIs, so that, when considering the CXR as the gold standard, agreement was 96.7%.⁴

CLINICAL IMPLEMENTATION

The LU allows a semi-quantitative assessment of lung aeration using the aeration score previously described in adults.^{7,16} Each lung should be examined by dividing it into 3 regions (anterior, lateral, and posterior) or following the scanning areas described by Brat,⁴ as shown in *Figure 1*. One of the following ultrasound patterns should be identified in each of these regions to establish the final score (*Figure 8*):^{47,16}

- 1. *Normally aerated lung (aeration score = 0):* presence of A-lines, bilateral lung sliding.
- Moderate loss of lung aeration (aeration score = 1): emergence of B-lines, 3 or more B-lines occupying less than 50% of the scanning area.
- 3. Severe loss of lung aeration (aeration score = 2): presence of coalescent B-lines occupying more than 50% of the scanning area, "white lung." They may be associated with an irregular pleural line and small subpleural consolidations.
- 4. *Complete loss of aeration (aeration score = 3)*: lung consolidation.

Recently, Raimondi has defined the LU as a "functional tool", since it allows monitoring the progression of a disease and decide on a therapeutic approach.¹⁷ In this way, the LU makes it possible to obtain a semi-quantitative aeration score that allows predicting the need for ventilatory support in neonatology,^{1,18,19} as well as guiding surfactant therapy,^{5,20} assessing the response to fluid restriction, and the implementation of alveolar recruitment maneuvers.¹

CONCLUSIONS

LU has gained consensus as a safe, noninvasive, and radiation-free tool that allows neonatologists not only to perform a rapid bedside examination of the respiratory status, but also to interpret findings and repeat the examination by monitoring the response to different therapeutic strategies. The implementation of LU in daily practice allows the diagnosis of the most important respiratory disorders in NBIs with high accuracy, thus enabling a reduced exposure to the ionizing radiation from CXR in neonates.

Ultrasound findings should always be integrated with the patient's clinical signs and symptoms, as well as with other diagnostic methods. ■

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