Neonatologist Performed Lung Ultrasound

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v4 english
September 28, 2023

MEDIZINISCHE UNIVERSITÄT WIEN

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Contents

Acknowledgements

We would like to thank Stefan Reithmayr, whose help, experience and expertise contributed significantly to the preparation of this document, as well as Ulrike Salzer-Muhar, who initiated the implementation of lung ultrasound in neonates at the Department for Neonatology, Paediatric Intensive Care and Neuropediatrics of the Medical University of Vienna.

Chapter 1

Methods

This document defines a standard for lung ultrasound as a point-of-care ultrasound in neonatology - a "Neonatologist Performed Lung Ultrasound - NPLUS". On regular basis the new publications are screened and evaluated in context with clinical practice as well as experience.
This is an integrative review of the literature published until 26.7.2022 including posters, discussions and presentations from relevant meetings and congresses as well as experiences of experts in the field. For this purpose the platform pubmed.ncbi.nlm.nih.gov was searched with the query "(lung OR thoracic) AND ultrasound AND (neonate OR infant)". Titles and abstracts were independently reviewed for relevance by two experts in the field (experience in lung ultrasound over 2 years) for their relevance. In case of discrepancies, a third author decided.
Clinical experience and practical comments are added to the content after critical review by the authors.

1.1 Screened Literature

Table 1.1: Screened and included number (n) of papers for each version starting with v4.

Version	Screened	Included
4	580	79

Chapter 2

Introduction

Neonatologist performed lung ultrasound (NPLUS) is a tool for dynamic assessment of lung diseases and diseases with lung involvement and can be used for visualization during various procedures and interventions. The interpretation of findings in lung ultrasound can only be made taking into account the current clinical situation and patient history. Only then, appropriate treatment can be initiated or continued.
It is a simple examination technique that, when used correctly and with knowledge of its limitations, can provide rapid answers to specific questions.
Implementation of lung ultrasound at a neonatal intensive care unit reduces [3] or even halves [4] the number of chest X-rays with significant reduction of radiation dose per patient [3, 4]. A systematic review performed during the SARS-CoV-2 pandemic showed that the use of lung ultrasound can be seen complementary to clinical and laboratory assessment and is a corner stone in the care of respiratory infections [5].
At the University of Manitoba, Canada, lung ultrasound is the first-line diagnostic in neonates with suspected pulmonary diseases since 2016 [6]; at a large Chinese NICU since 2017 [7].

2.1 Indications

- Suspected respiratory distress syndrome [8]
- Acute deterioration [8]
- Assessment after acute deterioration [8]
- Suspected pneumothorax
- Assessment during mechanical ventilation [8]
- Suspected atelectasis or dystelectasis / loss of aeration

- Assessment in patient with increased oxygen requirement
- Persistent pulmonary hypertension of the newborn [9]
- Assessment after cardiac surgery
- Suspected congenital pulmonary airway malformation [8, 10]
- Assessment after placement of central venous line
- Assessment before transfer [11]
- Assessment of ventilation during extracorporal membrane oxygenation (ECMO) [12]
- Assessment in situations without further imaging
- Suspected pneumonia / bronchiolitis [5]

2.2 Users

In neonatology, a theoretical course and 20-25 supervised [6, 13] with a total of 30 lung ultrasounds [13] is sufficient for an adequate inter-rater reliability with chest-X-ray [13]. Especially in paediatric critical care adequate training is essential: it was shown that a 2-day course only achieves agreement with experts in 56 % of cases [14].
Theoretical training for 12 h followed by practice for 45 h was successfully used to train nurses in recognition of intrathoracic structures (i.e. aortic arch, right pulmonary artery, trachea, lung sliding and esophagus) with an accuracy of 80-100 % [15].
Overall, inter-rater reliability is high [13, 16]; between novices (6 months experience), users (1 year experience) and experienced (5 year experience) [16]. The use of a non-linear probe causes lower inter-rater reliability [16].

2.3 Instructors

There is no definition or certification process for a lung ultrasound instructor.
At the university of Manitoba, Canada, the instructor status is achieved after one year of application and 50 performed lung ultrasound scans of good quality. [6]

Chapter 3

Technique

3.1 Safety

Mechanical index should be below 0,3 and neither contrast agents nor shear wave elastography is recommended [17].

3.2 Probe

Every probe can be used for lung ultrasound [18]. The use of a linear probe [19] with a frequency of at least 7.5 MHz [20], 9 MHz [8], 10 MHz [19, 21, 22], but mostly with 12-14 MHz [22, 23] is recommended.
If there is no linear probe available, a high frequency convex probe with at least 8 MHz can be used [8], but using a non-linear probe in neonates causes lower inter-rater reliability, especially in inexperienced users [16]. In children, a convex probe may have advantages over a linear probe [19, 24].
The probe must be disinfected before and after every examination as defined by the local guidelines [8, 22].
Many ultrasound machines now have a lung preset; if this is not available small parts or a similar program used to display muscles are good alternatives. Additional software filters should not be used, because they can reduce or change artifacts you are looking for.

3.2.1 Wireless Probe

The recent development of wireless probes allows for easy examination of isolated patients and live assessment of ultrasound images by a supervisor [25].

3.3 Recommended Settings

- Lung; otherwise: small parts
- 4-5 cm depth [22, 23]
- Set focus zone to pleural line.
- Activate CRI (Crossbeam) at level 2 to increase contrast and resolution.
- Deactivate Harmonics, speckle reduction, sono-CT and XRES.

Chapter 4

Exam

The entire examination can be performed in the supine position [8, 19, 20, 22, 23]. The posterior areas can also be evaluated this way with slight tilting up or the patient can be brought in lateral position. The examination is also possible in prone position [6, 22, 23] or lateral position [22, 23]. Immediately after position change, false high scores occur which level off after 1 h [6, 26].
The examination is possible during ECMO [12, 27, 28].
The examination takes approximately 2 minutes [1].

4.1 Views

The views are performed in sagittal plane orthogonal to the thorax and ribs (vertical) in at least six anatomical areas [22]. Apart from the standard views it is essential that every area of the lung was examined for at least one breathing cycle; some conditions are only visible in inspiration or expiration.
Particularly in the lateral and posterior areas, attention should be given to place the transducer exactly orthogonal to the pleural line. If there is a tilt, the pleura seems thickened and the number of B-lines is increased and debris sign might be visible.
In the case of abnormalities, the transducer is rotated 90° to visualize and verify them in the transverse plane (horizontal) or in the intercostal space parallel to the ribs [22].
Abnormalities are documented in at least two planes

4.1.1 Thoracic Views

6-region Method [8, 20, 22, 23]

- Right posterior: right paravertebral to posterior axillary line
- Right lateral: right posterior to anterior axillary line

- Right anterior: right anterior axillary to parasternal line
- Left anterior: left parasternal to anterior axillary line
- Left lateral: left anterior to posterior axillary line
- Left posterior: left posterior axillary to paravertebral line

12-region Method [8, 19, 22, 23]

Each region from the 6-region method is divided into a cranial and a caudal view by the mammillary plane [8].

4.1.2 Transabdominal views

The lung bases can be visualized via transabdominal views in the sagittal or transverse plane. The liver or spleen are used as ultrasound windows to assess the *Pars diaphragmatica* [19].

Chapter 5

Documentation

5.1 Medical History and Clinical Information

Lung ultrasound is a tool to address clinical questions. Accordingly, information relevant to a diagnosis or clinical condition should be documented: age, postmenstrual age, weight, mode of ventilation (HFNC, nCPAP, NIV, CV, HFOV), previous intervention (LISA, INSURE, cardiac catheterization, ductal ligation, cardiac surgery, abdominal surgery, drain placement, intubation, position change, physical therapy, taping, change in ventilatory parameters, etc.) and the indication for the examination.

5.2 Minimal Documentation of Lung Ultrasound

At least 6 areas are documented, each with at least one B-scan and corresponding labeling. If the child's thorax is too large for the transducer, the area must be divided into 2 cross-sectional images (cranial and caudal) according to the 12-region method (see chapter 4.1.1) and labeled accordingly.

5.3 Documentation

To ensure transparency and reproducibility, all features specific to a diagnosis are documented in addition to the minimum documentation. Abnormalities are documented in two planes (see section 4.1). If the size of an abnormality is relevant, it is measured and documented in two planes at its maximum extent.
The best way to document are video loops of at least 3 s duration.

Chapter 6

Elements of Lung Ultrasound

6.1 Anatomy

The thorax consists of skin, subcutaneous tissue, and muscles above and between the ribs. Beneath the ribs is the parietal and visceral pleura, which slide together with each breath. Many interlobular septa lie within the visceral pleura and separate the individual lobes, which consist of many air-filled acini. [21]

6.2 Signs

Lung ultrasound signs vary little by age [29].

6.2.1 Pleural Line

The pleural line is a slightly bent, echogenic, smooth and thin line [8, 19, 20, 21, 23, 30] (Figure 6.1). It is caused by reflection due to the different acustic impedances of pleura and lung tissue [8]. The ribs are two anechoic round areas if they are not ossified; or a shadowing area if they are ossified [31] with the pleural line between them: the bat sign. The bat sign guarantees correct positioning of the probe. In neonates this sign is

Figure 6.1: Picture of a pleural line.

Figure 6.2: Picture of lung sliding.

not visible in the anterior parts of the lung, because the ribs are not yet ossified and therefore no shadow is visible [21, 30].
The pleural line is typically established after 4 breaths. Initially the lung is collapsed and is becoming more inflated with each breath. The lung is collapsed at the beginning and fills with air with each breath [32]. After this initial ventilation, there continues to be increased interstitial fluid, visible as increased B-lines or even a white lung. This increased interstitial fluid is typically reabsorbed and vanishes after 4 hours [33].

Interpretation

The condition of the pleural line is assessed: regular (thin and smooth), thickened, irregular (rough).

Pleural Thickness

The exact thickness of the pleura depends on the fat content of the tissue (body mass index), as this has an influence on the acustic impedance [34]. In addition, it depends on the frequency of the transducer [34]. In healthy newborns and preterm infants without respiratory distress syndrome, pleural thickness is <1 mm in the first 24 h [35]. In children <5 mm [19]. In clinical practice, pleural thickness is highly variable and depends in particular on the angle of the transducer to the pleural line.

6.2.2 Lung Sliding

Lung sliding is the sliding of the visceral pleura against the parietal pleura during a breath [8, 19, 20, 21, 23, 24, 30, 31] (Figure 6.2). The thoracic wall does not move or moves in the opposite direction to the sliding motion [31]. This dynamic phenomenon manifests as movement of the Z-lines (Chapter 6.2.7) and B-lines (Chapter 6.2.5) and excludes pneumothorax. Lung sliding is much more pronounced at the lung bases and progressively decreases towards the apex [31].
The absence of lung sliding is pathologic [8].

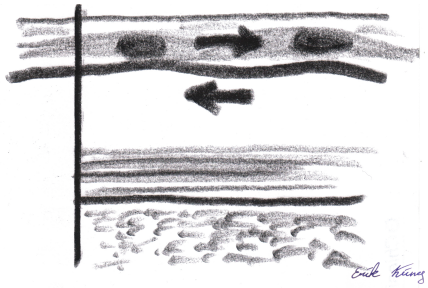

Figure 6.3: Picture of a seashore sign.

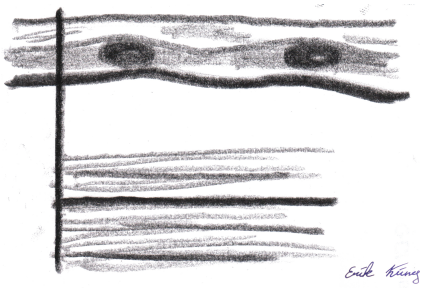

Figure 6.4: Picture of a stratosphere sign.

Seashore Sign

The seashore sign corresponds to the sandy beach sign. In M-mode, parallel lines appear in the area above the pleura (Sea) and a noise below the pleura (Shore) (figure 6.3). Reminiscent of a pictogram of a beach, hence seashore sign.
It is a sign of a healthy lung [8, 21, 30, 31].

Stratosphere Sign

The stratosphere sign corresponds to the barcode sign. In M-mode, parallel lines appear in the area above and below the pleura [8, 21, 30] (Figure 6.4). Reminiscent of a pictogram of a sky, hence Stratosphere Sign. It corresponds to the absence of lung sliding and is typical for pneumothorax, but may also be present during apnea, in congenital pulmonary airway malformation (CPAM), pneumatocele, marked hyperinflation, or interstitial or subcutaneous emphysema.

Lung Point

The point in B-mode and M-mode between lung sliding and no lung sliding; at which lung sliding and no lung sliding alternate with each breath [8, 20] (Figure 6.5) is called lung point. In M-mode, the point between stratosphere sign and seashore sign. This

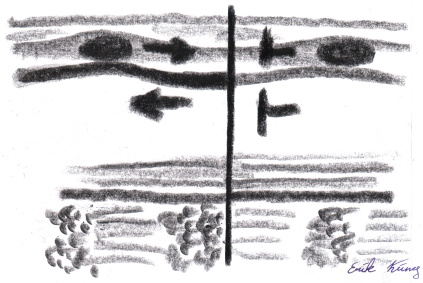

Figure 6.5: Picture of a lung point.

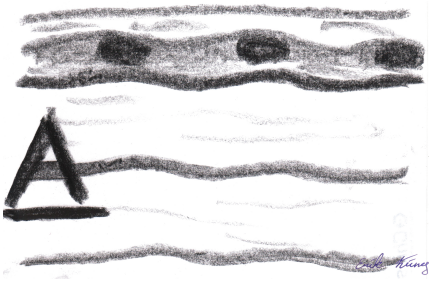

Figure 6.6: Picture of A-Lines.

point migrates with each breath as the lung advances into the pneumothorax area.
It is best to assess the lung point in the transverse plane (horizontal) to facilitate positional relationship to the anterior, middle, and posterior axillary lines.

6.2.3 Lung Pulse

The lung pulse is a pulsation of the pleura (similar to lung sliding but of much lower amplitude) or consolidation synchronous with the heart rate, which does not correspond to lung sliding [8, 36]. In M-mode, parallel lines appear in the area above the pleura; below the pleura, also parallel lines appear, but those are interrupted synchronously with the heart rate [36].
Lung pulse is a sign for complete atelectasis [20].
Because of its relative proximity to the heart, this sign is difficult to interpret in neonates.

6.2.4 A-Line

A-lines are horizontal, hyperechogenic, equidistant, smooth lines below the pleural line [8, 20, 21, 23, 24, 37] (figure 6.6). These are reverberation artifacts caused by repetitively reflected sound waves between the transducer, hyperechogenic line, e.g., subcutaneous, and pleura [8, 20, 21, 23, 30, 31, 34, 34]. Due to the multiplied time it

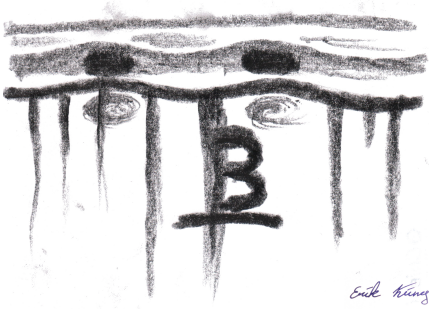

Figure 6.7: Picture of B-Lines.

takes for ultrasound waves to return due to reverberation, the device calculates A-lines as a mirrored pleural line equidistant (multiplied) below the pleural plane. A-lines in combination with lung sliding are indicative of a ventilated area [23].

6.2.5 B-Line

B-lines are discrete vertical hyperechogenic ring-down artifacts [34] that arise from the pleural line, move to the bottom of the screen without fading, and move in synchrony with lung sliding [8, 20, 23, 24, 30, 31, 37, 38] (Figure 6.7). They cover the A-lines [23]. B-lines occur physiologically and are a sign of interstitial fluid in the interstitial or alveolar compartment [19, 31] or may be due to scarring [24]. On the first day of life there are physiologically increased B-lines [24, 39], but these decrease within 24 h [24, 31, 39] and usually disappear by day three [31]. The physiological B-lines postnatally are found mainly in the posterior [40] and basal areas [39, 40].

Septal Rockets

3-4 B-lines per intercostal space (ICS) are called septal rockets. Septal rockets correlate with thickened subpleural interlobular septa [41].

Glass Rockets

5-12 B-lines per intercostal space are called glass rockets. Glass rockets correlate with ground-glass opacities in CT scans and are a sign of sever interstitial syndrome [34, 41].

Coalescent B-lines

B-lines are visible in the whole intercostal space [8] and are not countable. This is a sign for interstitial syndrome [8], alveolar syndrome, bronchiolitis, transient tachypnoea of the newborn and respiratory distress syndrome .

White Lung

A white lung are coalescent B-lines in all areas [8, 20] resulting in a literal white image in every view. This is a sign for interstitial syndrome, alveolar syndrome, transitory tachypnoea of the newborn [8] and respiratory distress syndrome.

Interpretation of B-lines

Musolino et al. postulated that cardiogenic B-lines can be differentiated from pneumogenic B-lines [19]. While cardiogenic B-lines are located in septal postion without consolidation or pleural abnormalities [42] and do change with positioning, pneumogenic B-lines are associated with pleural abnormalities and do not change with positioning [19]. The cardiogenic B-lines can be visible due to haemodynamic changes during sepsis [42]. In our experience, a differentiation of cardiogenic and pneumogenic B-lines is difficult. The number and the morphology of B-lines depend on the preset as well as the probe. Furthermore, the ESPNIC guidelines for POCUS stated that lung ultrasound can not differentiate between cardiogenic and non-cardiogenic B-lines.

6.2.6 E-line

E-Lines are discrete laser-like vertical hyperechogenic ring-down artifacts [34] that arise **above** the pleural line, and move to the bottom without fading [43]. They are a sign of soft tissue emphysema [43].

6.2.7 Z-Line

Z-Lines are ring-down artifacts [34] and correspond to Comet Tail Artifacts [31] that arise from the pleural line but with less echogenity compared to the pleural line, unclear differentiation and they fade after a short distance [37]. They cover the A-lines [31, 44]. Z-lines are not pathologic.

6.2.8 Still Lung Point

The still lung point is a point in parasternal transversal view in B- as well as in M-Mode between lung sliding and no lung sliding similar to the lung point; the still lung point does not move with every breath, it is fixed. It is a sign for pneumomediastinum [45].

6.2.9 Double Lung Point

The double lung point is a point where the lung is seemingly divided into one healthy (usually the upper anterior part) and one with coalescent B-lines (usually the inferior

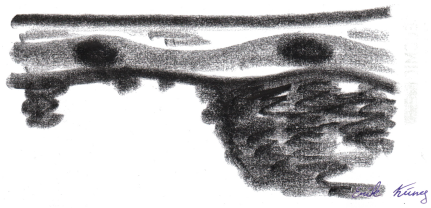

Figure 6.8: Picture of a consolidation.

and dorsal parts) uni or bilateral [20, 38, 46]. The double lung point is characteristic of transient tachypnoea of the newborn and is **not** seen in respiratory distress syndrome.

6.2.10 Consolidation

Consolidation is a region with tissue-like density [8,23,24,47] (Figure 6.8). Consolidation describes the image, not the cause. A consolidation can be seen in different pathologies (pneumonia, atelectasis, meconium aspiration syndrome, lung edema, lung hemorrhage, bronchopulmonary dysplasia, bronchiolitis, pulmonary embolism, contusion, tumor, drowning, lung infarction) [19, 41]. To differentiate lung from thymus, the liver or the spleen, or from another consolidation with a different origin (e.g.: tumor), the blood flow is visualized in color doppler. In lung tissue, the vessels have a tree-like pathway [31].

Shred Sign

Shred Sign is a hyperechogenic (similar to the pleura) irregular line or border between aerated lung and consolidation [8, 24].

Debris Sign

Debris sign are small connected consolidations, like sand. It is a sign for development of bronchopulmonary dysplasia. If debris sign is visible in a preterm infant, the OR for the development of a BPD is at 21.82 (95 % CI: 2.63-181.11) [48].

6.2.11 Aerobronchogram

Aerobronchogram are air-filled bronchi in a consolidation [24].

Static aerobronchogram

A static aerbronchogram are air-filled bronchi in a consolidation without movement of the bubbles. Static aerobronchogram is visible in atelectasis and pneumonias.

Dynamic aerobronchogram

A dynamic aerobronchogram are air-filled bronchi in a consolidation where the bubbles move with every breath. Dynamic aerobronchogram is visible in pneumonia [49]. Dynamic aerobronchogram excludes complete obstruction of the airways [31]. If dynamic aerobronchogram is visible, this is suggestive of an inflammatory process in the lung tissue. The airways are open and the loss of aeration is caused by inflammation.

6.2.12 Fluidobronchogram

Liquid in the bronchi of a consolidation is called static fluidobronchogram [19]. It is visible in obstructive atelectasis or pneumonia [19], because the liquid stops air movement to the lung. If the fluid in the bronchi moves, it is called dynamic fluidobronchogram. Up until now, there is no correlation with that sign.

6.2.13 Fluid-color Sign

Fluid-color sign describes the movement in color doppler in an effusion. This way, an organized effusion can be differentiated from a fluid one [50].

6.2.14 Jellyfish Sign

In a pleural effusion the basal part of the lung might be consolidated and swim in a movement in sync with every breath, like a jellyfish. This is called jellyfish sign and is visible in larger pleural effusions [51].

6.2.15 Sinusoid Sign

If M-mode is placed in a pleural effusion, this results in a hyperechogenic sinusoidal line below the pleural effusion visible as hypoechogenic area below the pleural line [51]. This sign is specific for a pleural effusion [24, 30, 51].

6.2.16 Mirrored Ribs

In pneumothorax, the high difference in acusitc impedance between the *Pleura parietalis* and air in the pleural space causes increased mirroring and reverberation. If the ribs are not ossified and visible as black round structures, they are visible as long line reverberation artifact below the pleural line multiple times [52].

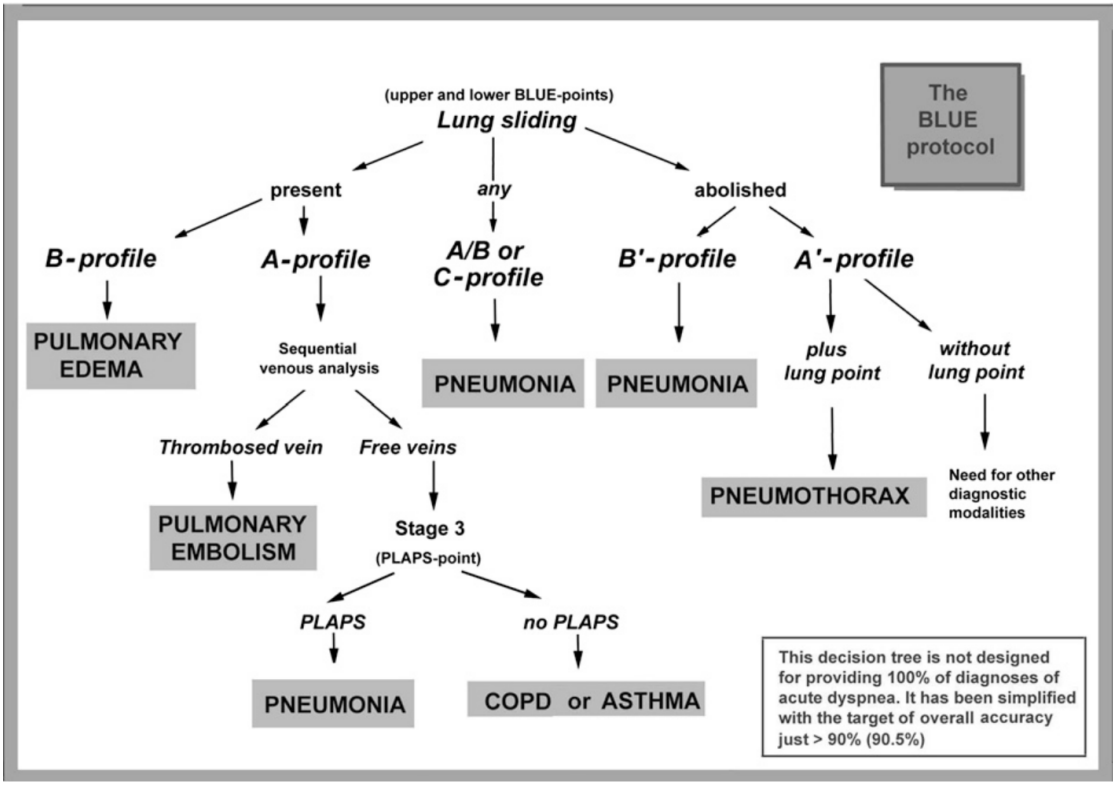

Figure 6.9: Flowchart BLUE protocol - Lichtenstein et al. [43]

6.2.17 Plankton Sign

The plankton sign describes slowly moving echogenic particles similar to plankton in pleural effusion. The movement is in sync with breathing or heart beat [51].

6.2.18 Sunray or S-Pattern (S-line)

The sunray or S-pattern describes vertical ring-down artifacts starting from a consolidation in a recruitment maneuver [53, 54].

6.2.19 BLUE Protocol - D. Lichtenstein [43]

The BLUE protocol (see figure 6.9) allows fast assessment in critically ill patients. It was developed by D. Lichtenstein. In contrast to conventional lung ultrasound it uses pattern recognition called profiles. The profiles are several pathologic consistent signs for underlying pathologies and therefore allow fast assessment and communication. [43]

Profiles in the Blue-protocol

A-profile A-profile describes anterior A-lines and a maximum of 2 B-lines per intercostal space [43]. This is also described as A-pattern [18], but A-profile is recommended.

A'-profile A'-profile describes anterior A-lines without lung sliding [43].

B-profile B-Profile describes 3 or more B-lines per intercostal space (lung rockets) in anterior areas [43]. This is also described as B-pattern [18], but B-profile is recommended.

B'-profile B'-profile is a B-profile without lung sliding. [43]

A/B-profile A/B-Profile describes a unilateral B-profile. [43]

C-profile C-Profile describes anterior consolidations. [43]

6.3 Score

The assessment of lung ultrasound score (LUS-scores, see Table 6.1) [55, 56] is done per lung ultrasound image in the transthoracic or transabdominal view and is summed up for the whole lung.
The inter-observer reliability is high: kappa 0.79-0.83 [57] and the score can be performed during transport with high accuracy [58].
The sum of the scores correlate with molecular and cellular inflammation [59], with interleukin-6 [60], histologic changes and interpulmonary shunts in neonatal acute respiratory distress syndrome (nARDS) [61], the postnatal fluid readsorption [40], oxygenation-index in neonates [56,62,63,64,65] and children [12], the need for surfactant [56, 65, 66, 67] and the silverman-score [64] as well as aeration in RDS [63], the need for ventilation [66, 68], the need for respiratory support [66] the need for oxygen and longer duration of stay in acute bronchiolitis [69, 70]. In the animal model it was shown that lung ultrasound score detects large changes in total and regional lung volume in real time and correctly identified opening and closing pressure [71].
Furthermore, the score was used to predict successful extubation [72, 73, 74], see Chapter 9.2.
Normal values are mentioned in Table 6.2.
The inherent problem of a semiquantitative score is discussed regularly [75], but the published correlations remain unchanged.
The score in preterm infants is dependent on positioning and gravitation [76].
In 2020, Girona-Alarcón [77] proposed an adaption for children after cardiac surgery, see Table 6.1.

In 2021, Szymański et al. [78] proposed an adaption expanding the score by one view, see Table 6.1.
In 2022, Rodriguez-Gonzalez et al. proposed an extended score weighting consolidations and their sizes higher [79]. In the same year Jiang et al. [80] proposed an alternative score with 14 regions by adding the basal areas using abdominal views to the 12-region method. This score correlated with the need for surfactant and need for ventilation in 88 neonates [80]. A very similar approach was used by Sun et al., the basal areas were added to the 6-region method. This score is associated with BPD, increased oxygen requirements and length of stay [81].
Although different adaptions and expansions were published and proposed, the current standard is the lung ultrasound score published by Brat et al. in 2015 [56].

6.3.1 Score and Different Diseases

The lung ultrasound score can be used to predict the need for surfactant or ventilation in respiratory distress syndrome and the development of a bronchopulmonary dysplasia. In most studies, two anterior and one lateral view were performed on the right and on the left side. Loi et al. proposed that the lung ultrasound score should be divided by the gestational age to achieve higher accuracy [64]. This could not be reproduced in a systematic review with meta analysis [82].
The lung ultrasound score develops differently depending on the gestational age at birth [83]: In preterm infants born at a gestational age of 23-27 weeks the score increased up until the 5^{th} week of life, but there still remains a significant difference between patients developing a bronchopulmonary dysplasia and others on the 3^{rd} day of life, after 1 week and after 3 weeks of life. In preterm infants born at a gestational age of 28-32 weeks, the lung ultrasound decreases rapidly within the first days of life and there is a significant difference between patients developing BPD and others between the 3^{rd} day of life and the 7^{th} week of life. [83]
Chapter 7.2.3 represents a detailed list of possibilities to predict bronchopulmonary dysplasia and Chapter 7.2.16 a detailed list for the prediction of need for surfactant or ventilation in RDS.

Score and Patent Ductus Arteriosus Botalli

The lung ultrasound score correlates with the duration of stay [84] and the diameter of the PDA [84, 85] as well as the LA/AO ratio [85]. The amount of pulmonary flooding in a haemodynamically significant PDA can be quantified using the lung ultrasound score [84]. A score >9 predicts a PDA with a sensitivity of 93.75 % and a specificity of 50.95 % [85]. A score >9 detects 93.75 % of patients with PDA correctly, but 50.95 % of patients without PDA correctly. This means, is the score ≤ 9, a PDA is unlikely. Is the score >9, a PDA but also another pathology can be present. Therefore the lung

Table 6.1: LUS-Score by Brat et al. [56], Taveira et al. [55] and Perri et al. [67]. Modified by Rodriguez-Gonzalez et al. [79], Jiang et al. [80], Girona-Alarcón et al. [77] and Szymański et al. [78].

Score	Description
Brat et al. (current standard) [56]	
0	Normal pleural line with horizontal A-lines
1	3 or more B-lines per intercostal space and a regular thin pleural line
2	Coalescent B-lines and a thick pleural line with or without small consolidations
3	Thick irregular pleural line with consolidations
Szymański et al. [78]	
0	Normal pleural line with horizontal reverberations of the a-lines (A-profile)
1	3 or more B-Lines per intercostal space and a regular thin pleural line (B-profile)
2	Coalescent B-lines and a thick pleural line; white lung
3	White lung with fluid alveologram and no consolidations (debris sign)
4	A thick irregular pleural line with consolidations
Rodriguez-Gonzalez et al. [79]	
0	2 or less B-lines per intercostal space
1	3 or more B-Lines per intercostal space or one intercostal space with coalescent B-lines
2	2 or more intercostal spaces with coalescent B-lines
3	Consolidations
+0	No consolidations
+1	1 consolidation <1 cm
+2	1 >1 cm or more small consolidations
Jiang et al. [80]	
0	2 or less B-lines per intercostal space
1	3 or more B-lines per intercostal space
2	Partly coalescent B-lines
3	Coalescent B-Lines
4	Irregular pleural line with consolidations <1 cm
5	Irregular pleural line with consolidations >1 cm
LUCAS - Girona-Alarcón et al. [77]	
0	A-lines without B-lines
1	2 or less B-lines per intercostal space
2	3-7 B-lines per intercostal space
3	Coalescent B-lines or >7 B-lines per intercostal space
4	Pleural effusion
LUCAS - scoring in 6 regions [77]	
0-5	Normal
6-9	Mild lung edema
10-14	Moderate lung edema
>14	Severe lung edema

Table 6.2: LUS-Score normal values for term neonates [40] for the score published by Brat et al. [56] OS, observational study.

Healthy term neonates					
Age	Regions	Median (Quartile)	n (mean gestational age)	Type	Reference
<3 h	12	8 (7-11)	66 (38.75)	OS	[40]
6 h	12	2 (0-4)	66 (38.75)	OS	[40]
24 h	12	1 (0-2)	66 (38.75)	OS	[40]

ultrasound score can only be seen as screening parameter rather than diagnostic test. After ligation of PDA, it takes 12 h until the score decreases [86].

6.3.2 Score and Extracorporal Membrane Oxygenation

A missing improvement of lung ultrasound score during weaning of ECMO is associated with increased mortality [12].

6.4 Diaphragm

6.4.1 Diaphragm Excursion

The diaphragm excursion allows interpretation of work of breathing and tidal volume. Especially a unilateral or paradox movement can be suggestive of diaphragmatic nerve palsy. Using a linear probe, the excursion is measured in subcostal transversal view orthogonal to the pleura in M-mode by measuring the difference between in- and expiration.

6.4.2 Diaphragmatic Shortening Fraction by Alonso et al [87]

The transducer is placed between anterior and posterior axillary line between 8^{th} and 9^{th} rib orthogonal to the pleura (coronar/vertical). There are two echogenic lines, the one closer to the transducer is the pleura parietalis and the deeper one is the peritoneum. The diaphragm is the hypoechogenic structure between those two. In M-Mode, the minimal (TET) and the maximal thickness (TIT) during a breathing cycle are measured three tines with the following formula:
$DSF(\%) = \frac{TIT-TET}{TET} \times 100$
The TIT and the TET are higher in term neonates compared to preterm neonates, but the DSF is equal. Physiologic values in the first 24 h are visible in Table 6.3.

Table 6.3: Physiologic values for daphragmatic shortening fraction (DSF), minimal (TIT) and maximal (TET) thickness of diaphragm in the first 24 h in term- (T) and preterm infants (PT) [87].

Parameter	T	PT
Right		
TIT (mm)	2.6 (2.2-3.2)	1.6 (1.5-1.9)
TET (mm)	1.9 (1.6-2.4)	1.2 (1.1-1.4)
DSF (%)	24 (15-37)	33 (24-46)
Left		
TIT (mm)	2.6 (1.9-3.2)	1.6 (1.3-2.1)
TET (mm)	1.9 (1.6-2.4)	1.2 (1.1-1.6)
DSF (%)	32 (15-40)	32 (26-39)

Chapter 7

Diagnostic Findings in Lung Ultrasound (alphabetic)

7.1 Physiologic Findings in Lung Ultrasound

- Smooth straight pleural line [8]
- Smooth straight A-lines [8]
- 0-2 B-lines per intercostal space [8]. Especially in the first days of life, more B-lines are physiologic [39] but decrease in the first 24 h [31, 39] and vanish before the third day of life [31].
- Lung sliding [8]
- Seashore sign [8]
- In neonates: lung pulse

7.2 Pathologic Findings in Lung Ultrasound

Lung ultrasound is based on the interpretation of artifacts. Artifacts can be physiologic or pathologic. The direct visualization of tissue-like structures or tissue itself is always pathologic. A well aerated lung produces exclusively artifacts.
Only pathologies with a connection to the pleura are visible in lung ultrasound. Therefore, central consolidations, central pneumonias, cPAMs or lung sequester are not detected.

7.2.1 Alveolar Pneumonia

The ESPNIC POCUS Guidelines state that lung ultrasound is useful in the detection of pneumonia [88]. Lung ultrasound is effective in the diagnosis of pneumonia with a sensitivity of 96 % (95 % CI: 94-97 %) and a specificity of 93 % (95 % CI: 90-96 %) in a systematic review with meta analysis [89].
Together with procalcitonin, lung ultrasound can be used to detect pneumonia with a sensitivity of 90 % and a specificity of 78 % [90].
The following signs are suggestive of pneumonia in patients with the corresponding clinical picture.

- Consolidation (hepatization) with dynamic aerobronchogram (tree-like or linear) and irregular borders, the shred sign [8, 29, 91, 92, 93]. The presence of a dynamic aerobronchogram suggests an inflammatory process.
- Thick, rough pleural line with coarse areas, disruptions and absence of the pleural line [8, 91]
- Lung edema / interstitial syndrome, the presence of three or more B-lines per intercostal space up to a white lung [8, 29, 91].
- Lung pulse in affected area [92]
- Pleural effusion locally or basally [8, 93]

Ventilator Associated Pneumonia

Lung ultrasound can be used to detect ventilator associated pneumonia (VAP). A multiparameter score developed by Tusor et al. [93] includes lung ultrasound and achieves a high accuracy (sensitivity: 94-94 %, specificity: 67-83 %, AUC 0.91-0.97). Lung ultrasound (AUC 0.98) is superior in the diagnosis of VAP compared to chest-X-ray if the clinical diagnosis is used as gold standard [94]. The following signs were used:

- Consolidation (>0.5 cm [93]) with aerobronchogram [93, 94]: Sen: 96.5 %; Spe: 100 % [94]
- Interstitial syndrome: Sen: 98.3 %; Spe: 28.6 % [80]
- Pleural effusion [93, 94]: Sen: 10.4 %; Spe: 28.6 % [80]
- Abnormal pleural line [94]: Sen: 99.1 %; Spe: 14.3 % [94]
- Lung pulse [94]: Sen: 13 %; Spe: 100 % [94]

7.2.2 Atelecatasis (Neonatal Pulmonary Atelectasis)

Lung ultrasound has a very high accuracy for neonatal pulmonary atelectasis with a sensitivity of 100 % and a specificity of 100 % [47].

- Consolidation with smooth borders to other lung-structures (specificity 100 %) [8, 47]
- Absence of lung sliding in affected area [8, 30, 47]
- **Possible:** Presence of aerobronchogram [47]; a dynamic aerobronchogram is suggestive of inflammatory processes; DD: pneumonia.
- **Possible, in neonates not valid:** lung pulse [47] in complete atelectasis [8,20,91]
- **Possible:** In color doppler, blood flow is visible [8]

In one case report, Liu et al. reported a successful treatment of atelectasis using broncheoalveolar lavage until the signs in lung ultrasound were not visible anymore [95].

Radiologic Classification

Atelectasis can be divided into radiologic classifications. If there is a corresponding finding in chest-X-ray, it is a focal type atelectasis. If there is no corresponding finding in chest X-ray, it is a occult lung atelectasis.

Focal Type Atelectasis Neonatal pulmonary atelectasis with corresponding finding in chest X-ray.

- Consolidation with clear border [47]
- **Possible:** Aerobronchogram [47]

Occult Lung Atelectasis Neonatal pulmonary atelectasis without corresponding finding in chest X-ray.

- Small consolidation with punctual aerobronchogram [47].
- Abnormal pleural line and absence of A-lines in affected area [47].
- Normal pleural line, A-lines and lung sliding in unaffected areas [47].

Pathognomonic Classification

Atelectasis can be divided into atelectasis by compression or atelectasis by obstruction depending on the cause.

Atelectasis by compression

- Central static aerobronchogram
- Pleural effusion

Atelectasis by obstruction

- Initial static aerobronchogram [49].

7.2.3 Bronchopulmonary Dysplasia

One third of patients with signs in lung ultrasound for bronchopulmonary dysplasia (BPD) have a different diagnosis: pneumonia, atelectasis or interstitial syndrome [96].

- Bilateral changes of the pleura and lung [21, 97]
- Inhomogenic image of irregular pleura with small consolidations [21, 97] neighboring areas with A-lines.
- 2 or more B-lines per intercostal space up to a white lung [21, 97]
- Increased echogenity in the bases using transabdominal views [97, 98]
- Debris sign [48]

Overdistension

In severe hyperinflation the lung sliding might vanish [99]. But there is no valid sign for overdistension.

Prediction of Bronchopulmonary Dysplasia

A systematic review reported that lung ultrasound is able to predict the development of BPD in preterm infants born <32 weeks gestational age and that an extended score (score divided by gestational age) does not improve accuracy [82]. The accuracy of the lung ultrasound score is superior to NT-proBNP [57].
The different possibilities to predict the development of BPD in lung ultrasound are visible in Table 7.1. In preterm infants born in 23-27 weeks gestational age, the scores are higher up until the 5^{th} week of life, but there is still a significant difference between patient developing BPD and others on the day 3, after the first week of life and after the third week of life. In preterm infants born in 28-32 weeks gestational age, the lung ultrasound score decreases rapidly in the first days of life and shows a significant difference between patients developing BPD and others in the third day of life and 7^{th}

week of life [83]. The best diagnostic accuracy was achieved in preterm infants born under <31 weeks gestation on day 7 and 14. [64], with a difference between preterm infants <32 weeks gestation between day 9 and 15 [100].
Most studies used three views per side: two anterior and one lateral view. Loi et al. showed in 2021 that using posterior views as well does not lead to a higher accuracy in predicting BPD in preterm infants <31 weeks gestational age [64]. In contrast Liu et. al. found a significantly better prognosis using posterior views as well [100]. But to get a proper posterior view when the patient is in supine position, the patient must be brought into lateral position twice.
Woods et al. stated in an observational study that lung ultrasound was able to predict the development of BPD in preterm infants born <28 weeks gestation, but the main factor of prediction was gestational age and not lung ultrasound score [101].
One special aspect of lung ultrasound is the possibility to monitor the development of this chronic disease and start therapy accordingly (e.g. vitamin A injections or in future stem cell therapy) [102].

Table 7.1: Different criteria (echogenity of diaphragm (Di), Score (Number of views and localization anterior and lateral (a+l)) in lung ultrasound and the development of bronchopulmonary dysplasia (BPD) at a time point (day (d) or week of life (w)) with corresponding sensitivity (Sen), specificity (Spe), negative predictive value (NPV) and positive predictive value (PPV) and the characteristics of the analysed patients (number and mean/median gestational age) and studies (observational study (OS), retrospective study (RS)) and the references.

Criteria (regions)	d/w	BPD definition	Sen (%)	Spe (%)	NPV (%)	PPV (%)	n (mean/median gestational age)	Type	Reference
LUS Score >6 (6)	1 d	28d O_2 /36 w & CPAP/O_2	80	71.4	90.9	50	64 (27.4; 29.5 w)	OS	[103]
LUS Score >20 (12)	1 d	36 w & CPAP/O_2	18.6	95.8	66	72.7	130 (29.2 w)	OS	[100]
LUS Score >16 (12)	2 d	36 w & CPAP/O_2	36	86.3	62.1	62.1	130 (29.2 W)	OS	[100]
LUS Score >18 (12)	3 d	36 w & CPAP/O_2	38	88.8	67.9	69.6	130 (29.2 w)	OS	[100]
LUS Score >10 (6)	3 d	36 w & CPAP/O_2	89	80	92	92	152 (25.8 w)	OS	[104]
LUS Score >13 (12)	6 d	36 w & CPAP/O_2	46	87.5	69.7	72.2	130 (29.2 w)	OS	[100]
LUS Score ≥8 (8)	7 d	28d O_2/36 w & CPAP/O_2	90	81			42 (29.5; 27 w)	OS	[105]
LUS Score >8 (6, a+l)	7 d	28d O_2/36 w & CPAP/O_2	70	79			298 (26; 29 w)	OS	[106]
LUS Score ≥5 (8)	7 d	28d O_2/36 w & CPAP/O_2	90	81			42 (29.5; 27 w)	OS	[105]
LUS Score ≥8 (8)	7 d	36 w & CPAP/O_2	93	91			42 (29.5; 27 w)	OS	[105]
$\frac{LUSScore}{GA}$ >0.23 (6, a+l)	7 d	36 w & CPAP/O_2	71	74	54	73	147 (27.1 w)	OS	[64]
LUS Score >10 (6)	7 d	36 w & CPAP/O_2	89	90	87	92	152 (25.8 w)	OS	[104]
Echogenität Zw	9 d	28 d & abnormales C/P	100	50	100	43	59 (29.27 w)	OS	[98]
LUS Score >11 (12)	9 d	36 w & CPAP/O_2	64	85	72.7	79.1	130 (29.2 w)	OS	[100]
LUS Score >8 (12)	12 d	36 w & CPAP/O_2	74	84.6	75.5	83.5	130 (29.2 w)	OS	[100]
$\frac{LUSScore}{GA}$ >0.31 (6, a+l)	14 d	36 w & CPAP/O_2	66	81	77	71	147 (27.1 w)	OS	[64]
LUS Score >5 (6)	2. w	28d O_2 / 36. w & CPAP/O_2	73.7	100	78.3	100	64 (27.4; 29.5 w)	OS	[103]
LUS Score >10 (6)	7 d	36 W & CPAP/O_2	77	92	88	84	152 (25.8 w)	OS	[104]
LUS Score >8 (12)	12 d	36 w & CPAP/O_2	72	82.3	72	82.3	130 (29.2 w)	OS	[100]
Echogenität Zw	18 d	28 d & O_2	100	95.2			105 (29.1; 32.7 w)	OS	[107]
LUS Score >6 (8)	2-8. w	36. w & CPAP/O_2	76	97	88	97	27 (26; 28 w)	RS	[108]
LUS Score ≥4 (8)	28 d	28d O_2/36 w & CPAP/O_2	95	86			42 (29.5; 27 w)	OS	[105]
LUS Score ≥6 (8)	28 d	36 w & CPAP/O_2	85	82			42 (29.5; 27 w)	OS	[105]

7.2.4 Bronchiolitis

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful to describe viral bronchiolitis but not to diagnose its cause [88]. In a case series, Walsh et al. were able to show that lung ultrasound was able to detect children with bronchiolitis faster compared to auscultation [109]. The lung ultrasound findings in bronchiolitis are associated with oxygen requirements and the severity of the disease [60, 110].

- Thick, rough pleural line [29, 88]
- 2 or more B-lines per intercostal space [29, 41, 88, 110].
  The number of B-lines correlates to the severity of the disease and the oxygen requirements [110].
- **Possible:** Consolidations of different sizes [29, 88, 110] especially paravertebral and posterior [110] but smaller compared to pneumonias ($<$1 cm). The area of consolidation correlates with the severity of the disease and the oxygen requirement [110].

Score and Bronchiolitis

The lung ultrasound score by Brat et al. [56] correlates with oxygen requirement, severeness of the disease and length of stay [69, 70]. A score $>$6 predicts the necessity of PICU administration with a sensitivity of 90.9 % and a specificity of 88.89 % [111]. An adapted score giving more weight to consolidations could predict with a cut-off at 10 the necessity of ventilation with a sensitivity of 44 %, and a specificity of 88 %, a positive predictive value of 64 % and a negative predictive value of 77 % [79].

COVID-19

The signs visible in SARS-CoV-2 infections (COVID-19) are the same as visible in any viral bronchiolitis [112, 113, 114]. Lung ultrasound is able to detect the signs of COVID-19 in neonates [60, 113, 114], especially in patients without clinical symptoms [115]. Furthermore, lung ultrasound is very useful in assessment in the outpatient setting.
A systematic review identified the following signs:

- Absence of A-lines [116]
- Increased B-lines [116]
- Thick pleural line, disrupted pleural line [116]
- Consolidations especially bilateral in inferior areas [116]

7.2.5 Contusion

A contusion can be seen in ultrasound [19].

- Consolidation [19]

7.2.6 Lung Edema

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful in the detection of lung edema [88]. Lung ultrasound can not differentiate between cardiogenic and non-cardiogenic lung edema [88]. Lung edema is a gradual process. 2 or less B-lines per intercostal space are physiologic fluid in interstitium and in the interlobal space. If the interstitial fluid increases, the number of B-lines increases as well leading to an interstitial syndrome. If the interstitial compartment is full (severe interstitial syndrome) the fluid passes into the alveolar space and causes consolidations (alveolar syndrome) [117]. If the fluid increases further, the consolidation increases with aerobronchogram [117] and pleural effusion.

Interstitial Syndrome

- 3 or more B-Lines per intercostal space in every area (e.g. PDA, VSD) [19, 20, 84, 91, 118]
- **Or:** two or more intercostal spaces with coalescent B-lines [8].

Severe Interstitial Syndrome

- Glass rockets: 5-12 B-lines per intercostal space [41]
- **Or:** White lung [8]

Alveolar Syndrome

- Two or more adjacent intercostal spaces with coalescent B-lines [8, 41]
- Rough, thickened pleural line

7.2.7 Sequester of the Lung

- Consolidation in affected area [119, 120]
- Absence of pleural line in affected area [119, 120]
- Abnormal feeding vessel [119, 120]

7.2.8 Pulmonary Hemorrhage of the Newborn

- Abnormal pleural line [8]
- Shred sign [8]
- Consolidation with aerobronchogram [8]
- Pleural effusion uni- or bilateral [8]

7.2.9 Infarction of the Lung

Infarction of the lung is visible as consolidation without normal perfusion [24].

7.2.10 Meconium Aspiration Syndrome

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful in the detection of meconium aspiration syndrome [88].

- Heterogeneous changes in both lungs [8, 20, 121]
- Consolidations (hepatization) with aerobronchogram and irregular borders [8, 20, 121]
- B-lines and consolidations with spared areas inbetween [8, 20, 121]

In one case report, Liu et al. describe the successful therapy of meconium aspiration syndrome by performing bronchoalveolar lavage until the signs vanished in lung ultrasound [95].

7.2.11 Neonatal Acute Respiratory Distress Syndrome

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful in the semi-quantitative assessment of aeration in the management of neonatal acute respiratory distress syndrome (nARDS) [88]. This recommendation is consistent with published animal-studies [61].

- Bilateral diffuse areas with consolidations and an increased number of B-lines [88]
- Abnormal (thickened, rough) pleural line [88]
- Pleural effusion [88]

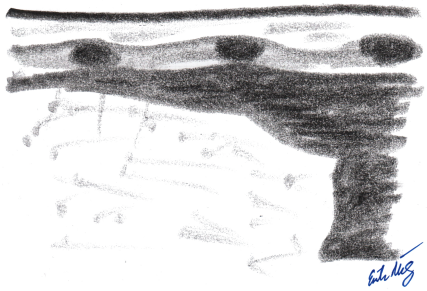

Figure 7.1: Picture of a pleural effusion.

7.2.12 Paediatric Acute Respiratory Distress Syndrome

Desanti et al. showed that a blinded lung ultrasound was able to detect the pathology behind a paediatric acute respiratory distress syndrome (pARDS) in 56 % of cases [122].

7.2.13 Pleural Effusion

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful in detecting pleural effusion [88]. The use of ultrasound for puncture reduces the likelihood of complications [88].
An anechoic or echogenic area between the parietal and visceral pleura (Figure 7.1) [13]. Only a chest-tube presents a sure diagnosis—the ultrasound can only give an indication [51].

- Jellyfish sign [51]
- Sinusoid sign [19, 51]
- Quad sign: liquid between pulmonal and parietal pleura [24].

Transsudat

- always anechoic [51]

Exsudat

Visible in hemorrhage, fibrin or pus.

- anechoic or echogenic or with particles (plankton sign, Chapter 6.2.17) or septae [19, 51].

Purulent effusion

- Echogenic [51]
- **Possible:** fine echogenic septae [51].
- **Possible:** multiple echogenic alveoli similar to honeycomb [19, 51].
- **Possible:** plankton sign (Chapter 6.2.17): slowly swimming echogenic particle similar to plankton. The movement is synchron to breathing or heart beat [51].
- **Possible:** In pneumococci, the pleural effusion has an echogenic border [51].

Hematothorax

- Echogenic with plankton sign [51].

7.2.14 Pneumothorax

The first report describing the diagnosis of pneumothorax using ultrasound in humans was done by Wernecke et al. 1987 [123], including the often repeated absence of lung sliding and absence of B-lines.
The ESPNIC POCUS Guidelines state that lung ultrasound is helpful and effective in detecting pneumothorax [88]. Lung ultrasound is efficient in the diagnosis of pneumothorax [19, 124, 125] and at least equal compared to chest-X-ray [124, 125] with a sensitivity of 82.9-99 % (95 % CI: 78.3-98 % to 86.9-100 %) and a specificity of 98-98.2 % (95 % CI: 94-97 % to 99 %) if chest-X-ray was used as reference, in two systematic reviews with meta analysis [124, 125].
There is one retrospective study evaluating the efficacy of lung ultrasound and chest-X-ray using computerized tomography or aspiration of air as reference. In this study, lung ultrasound was superior compared to chest-X-ray [126].
Lung ultrasound can be used to diagnose pneumothorax in neonates during reanimation [127]. In this case, it is recommended to use the ventilation phase for ultrasound examination; otherwise, lung sliding can be missed. Lung pulse is hard to interpret in this situations [127].
Especially if pneumothorax occurs in atypical localizations, lung ultrasound is of great advantage [128].

- Absence of lung sliding [8, 21, 30, 124, 129, 130]
  Sensitivity: 82.1 % (95 % CI: 71.7-89.8 %), specificity: 100 (95 % CI: 97.6-100 %) [124]
  Sensitivity: 100 %, specificity 100 % [126]

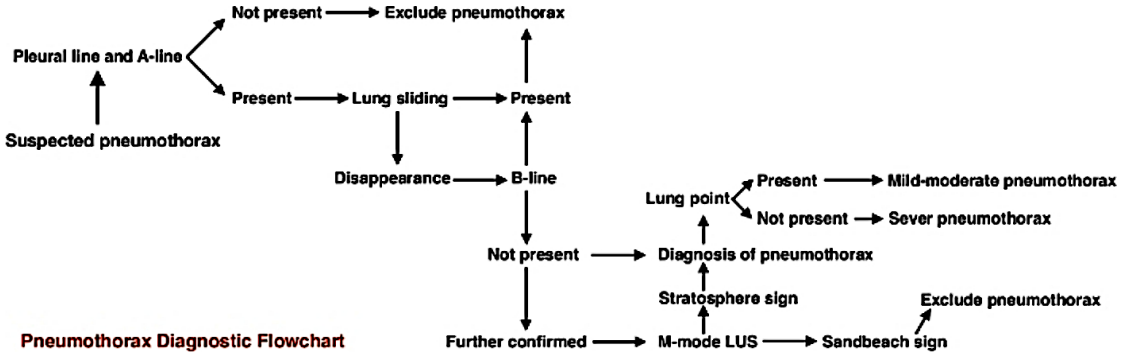

Figure 7.2: Diagnose flowchart pneumothorax, Liu et al. [130]

- Stratosphere sign in M-mode [8, 21, 130]
- Absence of lung pulse [21, 126]
  Sensitivity: 100 %, specificity: 100 % [126]
  Because of its relative proximity to the heart, this sign is difficult to interpret in neonates. A lung pulse can also be seen in tension pneumothorax [127].
- Lung point [8, 20, 21, 124, 129, 130]
  Sensitivity: 87.2 % (95 % CI: 77.7-93.7 %), specificity: 99.4 (95 % CI: 96.5-100 %) [124]
  Sensitivity: 94.28 %, specificity: 100 % [126]
- Absence of B-lines in affected area [8, 21, 30, 129, 130]
  Sensitivity: 100 %, specificity 100 % [126]
- Mirrored Ribs: at least one clear mirroring of at least one rib and intercostal structures in B-mode [52].
- A-lines behind the sternum in transversal view [131].

Diagnosis following Liu et al. protocol [130]

1. Identify pleural line, A-lines and B-lines in B-mode
2. Identify lung sliding and lung point
3. Identify stratosphere sign in M-mode

Table 7.2: Classification of pneumothorax (PTX) size using lung ultrasound (LUS) and the position of lung point (LP) relative position to the median axillary line (MAL) compared to classification using computerized tomography (CT) by Volpicelli et al. [134] and Liu et al. [130].

Volpicelli et al. [134]		
Lung collapse in CT (%)	Lung point position in LUS	Predictive value (95 % CI)
Class 1 (≤ 10)	anterior to MAL	78,1 (59,7–90,9)
Class 2 ($11 - 29$)	on MAL	88.5 (69,8–97,6) - 97,5 (86.6–99.9)
Class 3 (≥ 30)	posterior to MAL	50 (26,0-74,0)
Liu et. al. [130]		
Category	Definition	
Mild PTX	PTX sign anterior. No lung sliding in $<$50 % of lobe of the lung.	
Moderate PTX	PTX signs anterior and lateral. No lung sliding in $>$50 % of lobe of the lung.	
Severe PTX	PTX sign anterior. No lung point visible.	

Quantifying and Size

In adults, the position of lung point is associated with the size of pneumothorax measured in computerized tomography, this is superior to chest-X-ray and classic graduations. Volpicelli et al. showed that the median axillary line (correlates to $\geq$30 % collapsed lung) is the best anatomical cut-off between severe and minor pneumothorax, see Table 7.2.
Is a pneumothorax with a collapsed lung of $\leq$ 15 % conservatively treated, no air leak occurs and the recurrence rate is very low, significantly less compared to interventionally treated cases [132, 133]. This size correlates to the position of lung point anterior to the median axillary line. In suspected severe pneumothorax in lung ultrasound but completely stable clinical condition, sequestration of the lung or cystic malformation of the lung (CPAM) has to be considered as differential diagnosis and evaluated. Furthermore, hyperinflation or interstitial emphysema can cause severely diminished lung sliding [99]. Ultrasound image alone is no indication for drainage.
Liu et al. established a classification system based on lung ultrasound signs, see Table 7.2.

Dynamic Evaluation

For dynamic evaluation, the lung point is documented with a pen per intercostal space on the skin. After some time (e.g. 1 h) reevaluation can be performed: if the pneumothorax extends, is stable or decreases.
This method is not validated in humans, but is efficient and tested in animal study [135].

Ultrasound Guided Pleura Puncture by Liu et al. [130]

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful in performing chest tube placement or in pleura puncture in spontaneous pneumothorax. Ultrasound should be used before a chest tube is placed or a puncture performed to evaluate the lung borders and abdominal organs minimizing complications [88]. The child is placed in supine, lateral or prone position depending on the position of the pneumothorax. An elevated chest position helps to aspirate more air. If a severe pneumothorax is present, pleural puncture must be performed immediately. A mild pneumothorax can be treated conservatively, but can profit from therapy. In moderate pneumothorax, the pleural puncture should be performed in the area without lung sliding. The pleural puncture is performed after sterile draping of the ultrasound machine and under direct visualization [130]. This method showed satisfactory results [128, 136] and allows for targeted puncture [128].

7.2.15 Pneumomediastinum

Pneumomediastinum can be diagnosed using lung ultrasound.

- Still lung point [45]
- Thickened curved line below the thymus [31, 137]
- Gap sign: no parasternal view possible for echocardiography [138]
- Stratosphere sign [138]
- Hyperechogenic line between chest wall and thymus [139].
- Stairway sign: stairway-like arrangement of horizontal hyperechogenic reflections due to trapped air below the thymus [140].

7.2.16 Respiratory Distress Syndrome

The ESPNIC POCUS Guidelines state that lung ultrasound is helpful to differentiate between respiratory distress syndrome (RDS) and transient tachypnoea of the newborn (TTN) [88]. Lung ultrasound has the same accuracy compared to chest-X-ray in the diagnosis of RDS [38, 141, 142] with the sensitivity of 92-99 % (95 % CI: 89-92 % to 94-100 %) and a specificity of 95 % (95 % CI: 87-93 % to 97-98 %) if chest-X-ray was used as reference in two systematic reviews with meta analysis [141, 142].
Lung ultrasound can be effective to differentiate between RDS and TTN [143, 144]. In RDS, abnormalities are visible in the whole lung and the pleural line is rough with consolidations [144], in TTN the changes are mainly in the basal and dorsal areas, the pleural line remains smooth and there are no consolidations.

- Thickened and rough pleural line [8, 29, 31, 38, 88, 145, 146, 147, 148, 149]
- Consolidations [31, 88, 145, 146, 147, 148, 149], especially posterior [8], occasionally with aerobronchogram [8]
  With snowflake sign: consolidations with many bronchograms [148].
- White lung (=coalescent B-Lines) [29, 31, 38, 88, 145]
- Abnormalities in all areas [8, 29, 31, 38, 145, 149]
- No A-lines [88, 147, 149]
- No mirroring of the liver or spleen in subcostal transversal view [31].

Surfactant Application

The need for surfactant supplementation can be evaluated using lung ultrasound [150]. This assessment can be performed 20-30 min after birth and has higher accuracy compared to chest-X-ray [151]. After surfactant application, changes are visible in lung ultrasound after a delay [29, 147]. The score decreases significantly over 24 h [150]. After 4 h the number of consolidations decreases, the number of B-lines decreases and the areas with A-lines increase [147] especially in anterior areas [152]. After 6 h the image is normalized, the B-lines are significantly reduced and A-lines are visible. [31, 147]

Ventilation

The need for ventilation can be assessed using six different image constellations [153]. Basically, this is an adaption of the widely used lung ultrasound score.

Score and Respiratory Distress Syndrome

The different possibilities to detect the development of RDS in lung ultrasound and the need for ventilation is shown in Table 7.2.16. Nearly all studies used six views (left and right: anterior cranial, anterior caudal, lateral). Starting from nCPAP (6 cmH_2O) in RDS a change in ventilation mode to (6-12 cmH_2O) leads to significant improvement of lung ultrasound scores and oxygenation after 2 h [63].
Raimondi et al. used an adapted version of the lung ultrasound score with six views: posterior and anterior axillary line as well as medioclavicular line [150].

7.2.17 Transitory Tachypnoea of the Newborn

Corresponds to wet lung [8]. The ESPNIC POCUS Guidelines state that lung ultrasound is helpful to differentiate between RDS and TTN [88]. Lung ultrasound has the same

Table 7.3: Different cut-offs in lung ultrasound score to predict need for ventilation or surfactant in RDS with corresponding sensitivity (Sen), specificity (Spe), negative predictive value (NPV) and positive predictive value (PPV) and patient characteristics (number and mean/median gestational age) of studies (observational study (OS), systematic review (SR)) and references. Nearly all studies used six views (left and right: anterior cranial, anterior caudal, lateral).

1.Surfactant							
Score (views)	Sen (%)	Spe (%)	NPV (%)	PPV (%)	n (GA)	Type	Reference
>2 (6)	91	25	93	20	65 (30 w)	OS	[56]
>12 (6)	92.9	92.5	97.4	81.3	62 (29-31 w)	OS	[154]
>4 (6)	100	61	97	54	65 (30 w)	OS	[56]
>6 (6)	90	80	88	82	133 (28 w)	OS	[62]
>8 (6)	82	92	83	88	133 (28 w)	OS	[62]
>4 (6)	96	100			45 (30 w)	OS	[155]
> 9 (6)	79	84	82	79	240 (29.5 w)	OS	[150].
2.Surfactant							
>10 (6), 2h after 1.Surf	94	60	95	56	46 (32 w)	OS	[156]
Ventilation							
>25.5 (12)	81.3	88.8			146 (29 w)	OS	[68]
>12 (6)	100	77.6	100	31.2	62 (29-31 w)	OS	[154]
Ventilation/Surfactant							
>5-6 (6)	88	82			485	SR	[157]

accuracy compared to chest-X-ray in the diagnosis of TTN [38, 158] with a sensitivity of 55-98 % (95 % CI: 51-92 % to 58-100 %) and a specificity of 98-99 % (95 % CI: 98-91 % to 99-100 %) if chest-X-ray was used as reference in a systematic review with meta-analysis [158].
Lung ultrasound score can be used to document the development of TTN. After 3 d there is no significant difference to healthy neonates [159].
Lung ultrasound can be effective to differentiate between RDS and TTN [143, 144]. In RDS, abnormalities are visible in the whole lung and the pleural line is rough with consolidations [144], in TTN the changes are mainly in the basal and dorsal areas, the pleural line remains smooth and there are no consolidations.

- Can start with a white lung [8]
- Thickened or blurred (regular) pleural line [8, 20, 46, 88, 146]
- No consolidations [8, 20, 46, 146]
- Double lung point possible: coalescent B-lines in inferior areas and less coalescent B-lines in anterior/superior areas; uni- or bilateral [8, 20, 31, 38, 46, 88, 118, 160]
  Sensitivity: 67 % (95 % CI: 63-71 %), specificity: 97 % (95 % CI: 95-98 %) [161]
  Sensitivity: 85.9 %, specificity: 94.4 % [160]
  or
  increased non coalescent B-line uni-or bilateral [20, 46]

7.2.18 Subglottic Hematoma

Ultrasound can detect a subglottic hematoma as cause of a stridor [162]. In case of subglottic hematoma there is a consolidation in the trachea [162].

7.2.19 Congenital Diaphragmatic Hernia

Lung ultrasound can be used to diagnose and exclude a congenital diaphragmatic hernia (CDH) [6]. In one case with CDH diagnosed by chest-X-ray, lung ultrasound was able to identify multiple lung cysts caused by *S. aureus* infection [6].

- Absence of diaphragm [163]. Discontinuation of hyperechogenic line in transabdominal view [164]
- Absence of pleural line in affected area [163, 164]
- Absence of A-lines in affected area [164]
- Consolidations in adjacent areas [164]

- Paradox movement of the abdominal organs (abdominal view)
- Intrathoracic parenchymatic organs (liver, spleen) [163, 164]
  or
  Presence of multilayered area with hyperechogenic content (intrathoracic intestines) [163, 164]
- **Possible:** Peristalsis in affected area [164]

7.2.20 congenital pulmonary airway malformation

Lung ultrasound can be used to detect a cystic malformation of the lung [10, 119, 120, 165, 166]

- One or more hypoechogenic cystic lesions [10, 13, 120, 166]
- Consolidation in affected area [10, 13, 120, 166]
- Absence of pleural line in affected area [10, 13, 120]
- No abnormal feeding vessel [119, 120]

Chapter 8

Lung Ultrasound in Critical Situations

Lung ultrasound can be used efficiently in critical situations by experienced users. Structured studies are scarce for this indication. Bilateral ventilation can be verified within 15 s but clear recommendations are missing [167]. In the evaluation of a desaturation in a ventilated child, the first four letters of the acronym DOPES (Dislocation, Obstruction, Pneumothorax, Equipment and Stomach) can be assessed by lung ultrasound. Bilateral lung sliding and visualizing the endotracheal tube in the trachea in transversal view at the glottis plane excludes dislocation, obstruction, pneumothorax and equipment failure [167].

Chapter 9

Lung Ultrasound and Procedures

9.1 Position of Endotracheal Tube

Whether lung ultrasound can be used to confirm the correct position of an endotracheal tube is unclear. It is possible to visualize the tube directly. Bilateral lung sliding was inefficient in a observational study in a PICU [168].

9.2 Extubation

In preterm infants born below <32 weeks of gestation, lung ultrasound score of <11.5 predicted extubation success with highest sensitivity and a score <7.5 with highest specificity on the 3 rd and 7 th day of life [74].
In 80 intubated neonates (mean gestational age 34 weeks) a score of $\leq$ 4 predicted extubation success with a sensitivity of 83 % and a specificity of 88 % before and a score of $\leq$ 6 with a sensitivity of 89 % and specificity of 90 % after 6 h [72]. Six regions were used: two anterior (cranial and caudal) and one lateral view [72].
In 220 intubated neonates (mean gestational age 33 weeks) a score of >18 in 12 regions predicted extubation failure with a sensitivity of 86 % and a specificity of 86 % [73].

9.3 Weaning from Extracorporal Membrane Oxygenation

Lung ultrasound can evaluate the aeration of the lung during weaning from ECMO [27].

9.4 Weaning from nCPAP

Lung ultrasound can be used to detect readiness for weaning from nCPAP [169]. A score of under 8 had a sensitivity of 88 % and a specificity of 90 % for successful discontinuation of nCPAP [169].

9.5 Targeted Surfactant Therapy by Rodriguez-Fanjul et al. [1]

In a prospective randomized controlled study, 56 preterm infants with a gestational age of <32 weeks were assessed using lung ultrasound score and clinical parameters based on FiO_2.

1. LUS within 1 h in 6 regions, anterior, lateral and posterior
2. Score >8: Surfactant therapy

The lung ultrasound group received surfactant earlier at lower FiO_2 values, without influence on ventilation days, BPD or hospital stay [1].

9.6 Targeted Recruitment

Lung ultrasound score was able to detect large changes in total and regional lung volume in real time and correctly identified opening and closing pressures but lacked the precision to detect small changes in lung volume [71].

9.6.1 Recruitment During Ventilation

Lung ultrasound can be used for recruitment on conventional ventilation. Shady et al defined the MAP at which consolidated areas in posterior lung fields are opened as P_{Open} and the MAP under gradual reduction at which they revert to increased B-lines or consolidations as P_{Close}. The MAP was then set 2 mbar above the P_{Close} [170].
A very similar protocol was followed by Pierro et al. [54]. They defined an S pattern as ring-down artifacts starting from consolidations after raising the PEEP/CDP, called S(unray) pattern (see Chapter 6.2.18), [53] to detect recruitability.
In the protocol, as in Shady et al. [170], the PEEP/CDP is increased by 1cm H_2O every 1-2 min until consolidations disappear, this corresponds to the P_{Open}, and then reduced again until consolidations appear, this corresponds to the P_{close}. The optimal PEEP/CDP was chosen closely above the P_{close}. [54].

9.7 Targeted Broncheoalveolar Lavage by Liu et al. [2]

Liu et al used lung ultrasound for the need of bronchoalveolar lavage in 35 neonates [2]. Recruitment and lavage were performed until no consolidations were visible on lung ultrasound [2].

9.8 Targeted Physiotherapy

Lung ultrasound allows the targeted application of physiotherapy [28] and its success monitoring in atelectasis. This is particularly relevant when the patient should be mobilized as little as possible, e.g. on ECMO [28].

9.9 Targeted Puncture

9.9.1 Pneumatocele

Muniraman et al. successfully punctured a pneumatocele using lung ultrasound [171].

9.10 Lung Ultrasound after Central Venous Line Placement

In the context of a catheterization, a quick look at the lungs in terms of a Fast-LUS can detect complications (PTX, etc.).

9.11 Lung Ultrasound and Thoracic Ultrasound in Cases of Battered Child

Lung ultrasound and especially thoracic ultrasound with a focus on the ribs and corresponding fractures represents a rapid and sensitive diagnostic tool in cases of suspected child abuse [172]. Appropriate training and experience are essential in this regard.

Chapter 10

Implementation and Digitalization of Lung Ultrasound

10.1 Implementation

At the University of Manitoba, Canada, lung ultrasound was introduced as first line diagnostic in 2016. Chest X-ray was only performed when results of lung ultrasound were inconclusive or rare diseases were suspected. At first only physicians were trained in lung ultrasound, but since 2019 also respiratory therapists and nurse practitioners are trained [6].

10.2 Digitalization

Bassiouny et al. have created a promising machine learning model for lung ultrasound that also allows clinician assessment [173]. Wu et al. have been able to diagnose respiratory distress syndrome with an AUC of 0.96 using Artificial Intelligence Algorithm [174].

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Abbreviations

BPD	Bronchopulmonary dysplasia
CDH	Congenital diaphragmatic hernia
CDP	Continuous distending pressure
CPAM	Congenital pulmonary airway malformation
CPAP	Continuous positive airway pressure
CT	Computerized tomography
CV	Conventional ventilation
ECMO	Extracorporal membrane oxygenation
ETT	Endotracheal tube
GA	Gestational age
HFNC	High flow nasal cannula
HFOV	High frequency oscillation ventilation
HMD	Hyaline membrane disease
ICR	Intercostal space
INSURE	Intubation surfactant application extubation
LUS	lung ultrasound
LISA	Less invasive surfactant application
MAL	Median axillary line
MAP	Mean airway pressure
MI	Mechanical index
NIV	Non-invasive ventilation
NPA	Neonatal pulmonary atelectasis
NPV	Negative predictive value
PDA	Persistent ductus arteriosus botalli
PPV	Positive predictive value
RDS	Respiratory distress syndrome
Spe	Specificity
Sen	Sensitivity
TTN	Transitory tachypnoea of the newborn
VAP	Ventilator associated pneumonia
VSD	Ventricular septum defect