EXPERT OPINION

Lung ultrasound in the ICU: from diagnostic instrument to respiratory monitoring tool

G. VIA [1], E. STORTI [2], G. GULATI [3], L. NERI [2], F. MOJOLI [1], A. BRASCHI [1]

[1]First Department of Anesthesia and Intensive Care, IRCCS Policlinico San Matteo Foundation, University of Pavia, Pavia, Italy; [2]General ICU, Azienda Ospedaliera Niguarda Ca' Granda, Milan, Italy; [3]Department of Anesthesia, Critical Care, and Pain Medicine, Beth Israel Deaconess Medical Center, Boston, MA - Harvard/MIT Division of Health, Sciences, and Technology, Harvard Medical School, Boston, MA, USA

ABSTRACT

Imaging has greatly contributed to the understanding of lung disease in the critically ill and currently serves as a tool to diagnose lung pathology, monitor its course, and guide clinical management. Lung ultrasound is a real-time imaging modality that is simple, non-invasive, potentially ubiquitous, and free of ionizing radiation. Its increasing popularity and supporting research data substantiate its role as an emerging technique for bedside chest imaging in critical care. Furthermore, the International Consensus Conference on Lung ultrasound (ICC-LUS) promoted by the World Interactive Network Focused on Critical UltraSound (WINFOCUS) recently standardized the nomenclature and technique for lung ultrasound, and provided recommendations supporting its use in clinical practice. While the utility of lung ultrasound in the emergency setting is unquestioned, its potential role in the more complex and resource-rich intensive care environment is still under investigation. The purpose of this paper was to describe current and potential uses of lung ultrasound in the specific setting of adult intensive care, with an emphasis on respiratory monitoring, and to provide a framework for the practical application of this tool at the bedside. *(Minerva Anestesiol 2012;78:1282-96)*

Key words: Thorax - Lung - Ultrasonography.

In the past 25 years, imaging has fostered an understanding of lung disease in the critically ill [1] and currently serves as a tool to diagnose lung pathology, monitor its course, and guide clinical management.[2] Every patient admitted to the ICU, whatever the illness, usually requires chest imaging. Available modalities today include the plain radiograph and the gold-standard CT-scan, along with more sophisticated techniques like positron emission tomography and electrical impedance tomography. The choice of modality is based not only on the specific indication, but also on local resources and patient condition. These factors may greatly affect the feasibility of lung disease investigation. Thanks to some unique features and growing scientific evidence, lung ultrasound (LUS) represents an emerging technique for bedside chest imaging in critical care. Additionally, with the recently published consensus statement by the International Consensus Conference on Lung Ultrasound (ICC-LUS [3] promoted by WINFOCUS, the World Interactive Network Focused on Critical UltraSound), the nomenclature, techniques, and indications for LUS have been standardized. While the usefulness of LUS in the emergency setting is

clear, its potential role in the more complex and resource-rich intensive care environment is still under investigation. This manuscript represents an ICC-LUS-conforming [3] description of current and potential applications of LUS specific to the adult intensive care setting, with a focus on respiratory monitoring. It also provides the intensive care physician with a framework for the practical implementation of this tool at the bedside.

Methods

A systematic literature search (January 1990-January 2012) on LUS was performed to gather the most recent evidence on the topic. Terms used in various combinations for the searches on the National Library of Medicine Medline, Cochrane library, Google Scholar, and Embase databases were: lung, chest, pulmonary, thoracic, pleural AND sonographic, sonography, ultrasonographic, ultrasonography, ultrasound, echographic, echography, AND bedside, point-of-care. Initial searches identified N.=305 articles. Only papers describing sequential LUS assessment and/or studying adult ICU populations (N.=57) were further selected as core source of data for the manuscript. Where applicable, recommendations from the recent ICC-LUS [3] regarding indications, terminology, and technique were considered. Evidence was supplemented with experts' opinion and personal clinical experience.

Fundamentals of lung ultrasound

LUS provides a representation of the lung that is based both on images and on artefacts. The key factor determining the appearance of the imaged area is the relative amount of air lying beyond the visceral pleura. Since sonography is a real-time, dynamic imaging technique, LUS offers instantaneous insight both into the state of aeration of the lung and into its ventilation.

The *state of aeration* of lung parenchyma is a measure of its "air/fluid ratio." This ratio determines the characteristics of the image produced by LUS. In areas of complete consolidation (that is, where there is complete absence of air), a real image of lung tissue is generated. Thus, the ability to generate real images of lung parenchyma always indicates pathology. On the other hand, in cases where air is present in the underlying parenchyma different types of image artefacts are produced. Different artefacts represent normally aerated lung tissue or rather tissue with diminished relative aeration, whatever the specific underlying pathological process. Relative aeration may, in fact, be diminished either by loss of air, (developing atelectasis), or by an accumulation of fluid or cells in the interstitial or alveolar spaces (pneumonia, contusion, oedema, fibrosis, or alveolitis).

The generation of ultrasound artefacts by aerated lung tissue is the result of sound wave reflection and reverberation. Both phenomena originate from the high-acoustic impedance interface between pre-pleural "watery" tissues and the aerated lung. The physical site of this interface is represented by the point of contact of the parietal and visceral pleural layers. It appears ultrasonographically as a hyperechoic transverse line (the "pleural line") located between, and deep to the ribs (Figure 1A). Since nearly all ultrasound waves are reflected at this level, visualization of anything real is impossible beyond the pleural layers. However, different types of artefacts are displayed on the far side of the pleural line, generated by the bouncing of the ultrasound beam between this specular reflector and the probe (reverberation artefacts). The specific features of these artefacts vary according to the physical properties of the reflector, which are in turn determined by the state of aeration of the lung immediately beneath the visceral pleura. Three situations may occur: 1) normally aerated lung - generates a homogeneous reflecting surface that yields transverse artefacts parallel to the pleural line ("A lines", (Figure 1A); 2) partial loss of aeration - due to fluid or cells in subpleural lung tissue, generates discrete microscopic 3-dimensional aerated structures (aerated alveoli/acina surrounded by fluid or cells); in these circumstances air/fluid interfaces act as specular reflectors, discrete foci of reverberation, yielding longitudinal laser-like artefacts ("B-lines", (Figure 1C) [4, 5]; 3) complete absence of air beneath the visceral pleura (in areas of consolidation, even if

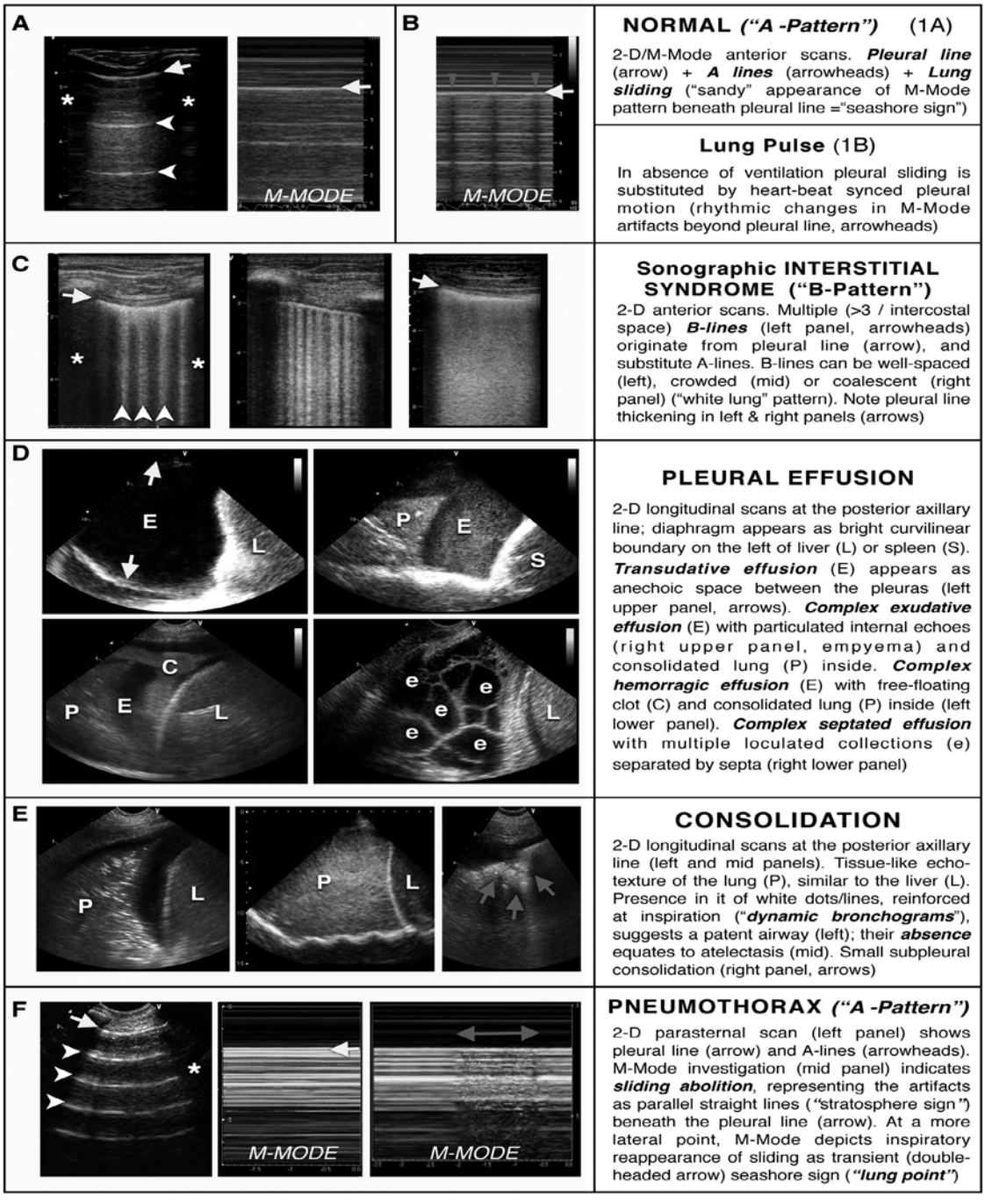

Figure 1.—*Synopsis of lung ultrasound semiotics.* Main segmental patterns are illustrated (left column) and described in their distinctive features (right column). Normal pattern (1A), sonographic interstitial syndrome (>3 B-lines/intercostal space) (1C) and pneumothorax (1F) are mutually exclusive artefact-based patterns. Pleural sliding (1A) and lung pulse (1B) are representations of visceral pleural motion (in a ventilated and a non ventilated lung area, respectively), and are here shown using M-Mode imaging as having a different appearance of artefacts beyond the pleural line. M-Mode provides representation over time of reflected echoes from a single scanning line: structures perpendicular to the ultrasound beam are represented by dots at a specific depth and appear as straight lines when motionless. Effusion (1C) and consolidation (1D) are image-based patterns, and their interpretation is more intuitive [3, 9] for a more extensive description. E: effusion; P: lung; L: liver; S: spleen; e: loculated effusion; asterisks indicate rib shadows).

small) - restores favorable conditions for ultrasound transmission with only partial reflection, generating a representation of lung tissue as a solid organ (Figure 1E).[6]

The *state of ventilation* of aerated scanned areas is evidenced by changes in the appearance of the pleural line over the respiratory cycle. Its respirophasic shimmering ("lung sliding"[3]), corresponds to the continued to and fro motion of the visceral pleura on the parietal pleura, indicating the presence of ventilation in the inspected area. On the other hand, a heart-beat synchronized motion of the pleural line ("lung pulse" [7]) implies the absence of ventilation, as in early atelectasis, before alveolar air resorption ensues. A motionless pleural line ("sliding abolition") potentially indicates a detachment of the two visceral layers with interposition of air.[8]

Additionally, LUS detects collections in the *pleural space* that can be further characterized by specific patterns. These patterns can be either artifactual or image-based depending upon the constituents of the pleural collection (air or fluid). In the case of a gaseous collection (pneumothorax), the sliding abolition in a dependent area is matched with the inspiratory coming-into-view (seen as the sudden re-appearance of lung-sliding) of a mobile, partially collapsed lung in a more lateral or dorsal site (the so called "lung point" [8]) (Figure 1F). The combination of these two signs based on artefacts (sliding abolition and lung point) allows the positive diagnosis of pneumothorax.[8] In the case of a fluid collection (pleural effusion), an image of variable echogenicity is generated between the two pleural layers (Figure 1D).

Based on these concepts, a well-defined semiotics has been validated,[3] and relies on easily distinguishable segmental patterns (Figure 1): normality, sonographic interstitial syndrome, pleural effusion, consolidation, and pneumothorax. A detailed description of LUS semiotics, beyond the purpose of this manuscript, is outlined elsewhere.[3 9] It may be understood from this short synopsis that LUS relates to the degree of aeration of the lung's outer, subpleural layer. Only consolidations that reach the visceral pleura (and effusions) permit deeper investigation. LUS is a surface imaging technique, and owes its accuracy to the fact that nearly all lung pathologies relevant to the critically ill have a peripheral manifestation.

Lung ultrasound technique: a shift in concept of lung imaging

In comparison to the overall lung picture displayed by routine techniques (monoplane, frontal, with chest X-ray, or multi-plane, either coronal/sagittal/transverse, with CT-scan), LUS provides *multisite regional representations of the lung*. The clinician must then reconstruct the overall three-dimensional picture by integrating all segments in his/her mind. This cognitive process more resembles the interpretation of auscultation findings rather than interpreting the images provided by CT or a plain radiograph. From a practical point of view, *a LUS examination in ICU patients should systematically investigate six areas of interest per side*, dividing each hemithorax into an anterior, lateral, and posterior region (according to anatomical landmarks represented by axillary lines), and each region into an upper and lower region (Figure 2). Scanning the patient's posterior regions just dorsal to the posterior axillary line with minimal patient tilting may many times suffice. Note that the posterior portions of upper lobes are often blind spots. The examination can either be *comprehensive* — every intercostal space is entirely scanned [10] — or *simplified* — one representative point per area is scanned [11] (similar to the simplified application of other imaging modalities on clinical grounds [12]). The time required can thus range from 5 to 15 minutes. In the simplified approach, if an abnormality is identified, inspection is further extended to define its boundaries. For the purpose of lung aeration quantification (see below), the most severe pathological finding can be considered representative of the entire region.

The peculiarities intrinsic to LUS imaging discussed above require specific tools to aid in communication and clinical use of examination findings. Archiving and reporting are mandatory. Simplified report forms, ideally electronic, are recommended (Figure 2) for their ease of use and their effectiveness in promoting learning and implementation of LUS in daily practice.[13]

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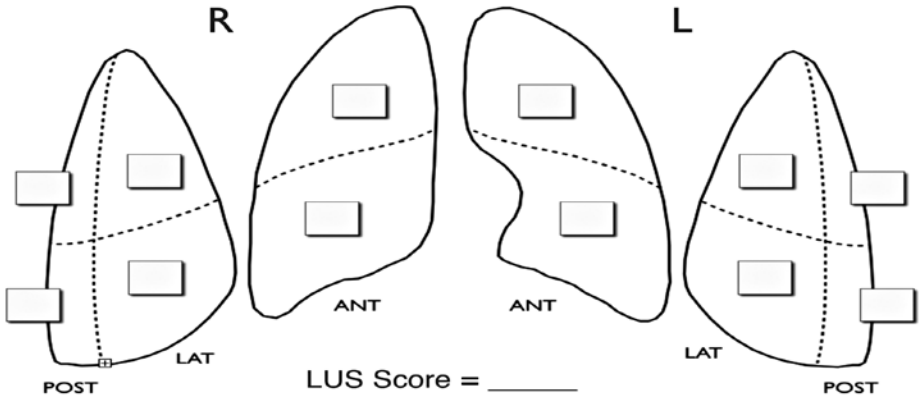
IRCCS POLICLINICO "*SAN MATTEO*"
Istituto di Ricovero e Cura a Carattere Scientifico di diritto pubblico
C.F. 00303490189 - P. IVA 00580590180
V.le Golgi, 19 - 27100 PAVIA
S.C. di Anestesia e Rianimazione I - DIRETTORE *Prof. Antonio Braschi*

LUNG ULTRASOUND
Report Form

PATIENT NAME: ..... GENDER: ☐ M ☐ F DATE OF BIRTH: .....
OPERATOR: ..... EXAM DATE: ..... HOUR ..... STORAGE CODE ....
HISTORY: .....
.....

SPONT VENTILATION: RR = ... Resp Distress: ☐ Yes ☐ No DECUBITUS: ☐ Sup ☐ Lat ☐ Pron ☐ Semirec
MECH VENTILATION: a) Modality: ☐ PCV ☐ DuoPAP ☐ ASV ☐ PSV ☐ SIMV ☐ NIV ☐ CPAP
b) Settings/Pattern: PEEP/Ps = ... /..... Ppeak ..... Pplat ..... RR ..... I:E ..... VT .....
EGA/EAB: pH ..... pCO2 ..... HCO3- ..... BE ..... PO2 ..... P/F ..... SpO2% ..... Hb .....

INDICATION: ☐ DIAGNOSTIC ☐ SCR.EENING ☐ MONITORING ☐ PROCEDURAL GUIDANCE
TYPE OF EXAM: ☐ simplified ☐ comprehensive ☐ focused (ANT / POST)



Legenda: 0 = A-Pattern (or nearly normal); **1** = B-Pattern (B-lines >3/field, well spaced); **2** = B-Pattern (crowded, coalescent +/- subpleural consolidations) **3** = Consolildation* **E**= Effusion*; **Pn** = Pneumothorax**; **NS**= Sliding Abolition; **LP**=Lung Pulse *(3 and E: characterize below in description) **(lindicate Lung Point(s))

DESCRIPTION .....
.....
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DIAGNOSIS .....

☐ Suspected ☐ Not made ☐ Second Opinion needed

Signature

Figure 2.—*Simplified report form for lung ultrasound in the ICU.* With simple check-boxing and minimal typing, it allows for rapid reporting of diagnostic, screening, monitoring and procedure-guidance examinations. Visual representation of different explored regions (2 anterior, 2 lateral, 2 posterior, according to anatomical landmarks set by axillary lines) and number-coded rating of findings provide instantaneous perception of the overall lung ultrasound representation. Calculation of a lung ultrasound (LUS) score allows semi-quantification of the state of aeration of the entire lung. Additional free-text description and presumptive diagnosis complete the report. The examamination can be conducted in a simplified manner (inspection at a single representative point per region), as comprehensive investigation (each intercostal space entirely inspected, with the worst finding per region considered for rating), or even as a focused, single-region examination (for example, just dorsal, to quantify a known effusion). For the purpose of correct interpretation, detailed history, clinical conditions, and ventilation are reported. Storage code for retrieval of images from an archive is indicated.

Some technical notes concerning probes and machine settings deserve mention, as they may greatly affect LUS findings and interpretation. As described in the literature, LUS can be performed with any probe (high frequency, such as linear or micro-convex, or low frequency, such as convex or phased array). But different range of frequencies suit better different targets of the ultrasound inspection: high frequencies (9-12 MHz) visualize at best the pleuras, their anatomy and lung sliding; lower frequencies (2.5-5 MHz) allow better appreciation of the in depth extension of B-lines and of consolidations/effusions. The microconvex probe, with its small footprint (fitting into intercostal spaces) and its wide range of frequencies (5-11 MHz) is regarded by many as the ideal probe.[9] For a correct execution of LUS examination, specific adjustments of machine settings are required: removal of harmonic-imaging and lowering of "reject" post processing (which otherwise diminish artefacts); elimination of multi-focus modality and focus setting at the level of the pleural line; depth setting at 6-7 cm from the pleural line (for full appreciation of the extension of B-lines); storage clip length set to include an entire respiratory cycle. Other technical issues specific to the ICU (ultrasound machine features, disinfection) are described exhaustively elsewhere.[10]

Basis for ultrasound suitability for monitor lung aeration changes

Ease of use, bedside availability, and repeatability make LUS particularly suited to detect spatial and temporal heterogeneity of lung aeration in patients with respiratory failure, providing key information for their clinical management.[1] A continuum from normally aerated tissue to complete loss of aeration exists in LUS semiotics, and each different LUS pattern corresponds to a given degree of aeration[3]. In human study subjects submitted to separate lung ventilation (a model of iatrogenic gradual resorptive atelectasis),[14] LUS characterized the sonographic appearance of the progressive loss of air from normality to the appearance of B-lines and pleural irregularities, followed by an increase in B-line number and density. This was in turn followed by the appearance of sub-pleural consolidations, which finally enlarged and deepened , eventually encompassing the entire lung [14] (Figure 3).

The accuracy of LUS in assessing aeration of the lung has been further demonstrated in critically ill patients, both in the context of ventilator-associated pneumonia (VAP) and acute lung injury (ALI)/acute respiratory distress syndrome (ARDS). LUS score-quantified aeration changes observed in VAP patients upon initiation of antimicrobial therapy show a tight *correlation with CT-measurements* of lung aeration (Day 0 *vs*. Day 7);[15] scoring was based on a comprehensive 12 area per lung investigation, according to progression or regression of patterns of: normality, spaced B-lines and/or small subpleural consolidation, coalescent B-lines, and consolidation. When compared with *the pressure-volume curve method* for assessing PEEP-induced lung recruitment in ALI/ARDS,[16] the same score was accurate in detecting significant increases in lung aeration (>600 mL, detected by a score ≥18). Accuracy diminishes for milder degrees of re-aeration (a 75-450 mL increase is associated to a score≥14).[16] Thus, turning images into numbers (semi-quantitation) is the key to effective LUS assessment of changes in the overall state of lung aeration.

At single lung areas, *qualitative estimation of aeration loss with LUS* (whatever its etiology) correlates well to CT findings,[3] and can be graded as:

1) moderate: multiple, well spaced, B-lines. This corresponds to an interstitial process (thickened interlobular septa, as in edema [4] or fibrosis,[17] which generates regularly spaced B-lines), or to an alveolar process (disseminated foci of pneumonia [15] or ongoing, but not complete yet, atelectasis,[14] which generates irregularly spaced B-lines);

2) severe: closely spaced/coalescent B-lines (fluid-filled alveoli). This corresponds to ground glass opacities on CT;[18]

3) complete: ultrasound consolidations. This corresponds to complete loss of aeration seen on CT.[18]

In comparison to other bedside techniques like the wash in-wash out [19] and the pressure-volume curve methods,[20] LUS offers thus the appealing ability to semi-quantitatively describe

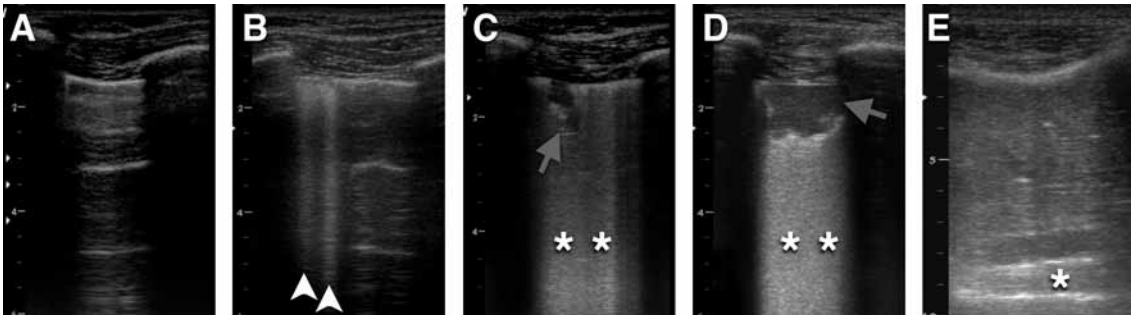

Figure 3.—*Sequential lung ultrasound inspection at the same intercostal space (4th, left antero-superior) during iatrogenic atelectasis*. In double lung ventilation, upon exclusion of the left lung, repeated lung ultrasound assessment shows signs of progressive loss of air (A to E), up to complete de-aeration. B-lines (B, arrowheads) appear, increase in number and crowding to become coalescent, eventually creating a "white lung" pattern (C, asterisks); pleural thickening appears; a small peripheral consolidation (C, arrows) becomes visible; consolidation then becomes the prevailing pattern (D, note also coalescent B-lines, asterisks, originating from its boundaries); finally, complete lung consolidation ensues (E, scanning at increased depth and parallel to the intercostal space, to better show whole lung extension: note the descending aorta is visible in its long axis, asterisk).

regional aeration as well, rather than only the global amount of lung air content.[14-16] However, in comparison to electrical impedance tomography,[21] it suffers the limitation of providing neither quantitative nor continuous data.

Lung ultrasound applications in the ICU

Differential diagnosis of respiratory failure

The chest radiograph is often unable to satisfactorily answer the most common diagnostic questions about patients with respiratory failure:[22, 23] "Is there extravascular accumulation of fluid in the lung?", "Is the edema cardiogenic or not?", "Is an impending pulmonary infection the potential source of this new septic state?", "Has the lung de-recruited?", "Is this an atelectatic or an alveolar consolidative process?". Some questions are even raised after radiographs have been interpreted: "Does that opacity represent consolidation or effusion?", "Is that a pneumothorax or a false image?", "Are there bronchopneumonia foci behind the heart?". These may become critical issues when time, clinical conditions, and logistic burden hinder access to CT scan. LUS characterizes pleural and lung pathology with higher sensitivity and specificity than the current ICU bedside references of auscultation and chest X-ray,[18 24] and a *systematic LUS approach* [3] as outlined below, usually provides quick explanation of the causes of lung failure:

— step 1: identification of landmarks - Identification of the diaphragm (to appropriately attribute findings to the chest) and the intercostal space (to correctly recognize the pleural line) must be performed before identification of regional ultrasound patterns (Figure 4);

— step 2: segmental assessment - Each area of interest (whether a representative spot in a region or each entire intercorstal space) is sonographically characterized (Figure 1). A binary sequential interpretation is easy and effective (Figure 4);

— step 3: overall lung integration ("sonographic diagnosis"). Cumulative impression from single scans is translated into typical lung patterns (Table I). Recognizing spatial (focal/diffuse, monolateral/bilateral, homogeneous/inhomogeneous) and temporal (acute/pre-existing, stable/evolving) distribution of ultrasound findings is the key to correct interpretation. Potentially associated pleural abnormalities can provide important clues[3], especially in differentiating between cardiogenic and non-cardiogenic aetiologies[25]. Findings from all regions must be considered, as partial interpretation may be deceptive[26]. In the ICU, in contrast to the emergency room setting, limited dorsal sonographic interstitial syndrome may not be related to any specific aetiology other than the effect of long-lasting supine position/passive ventilation. Also in the ICU, overlapping diseases easily coexist;

— step 4: in-context interpretation (clinical-instrumental diagnosis). It must be stressed how

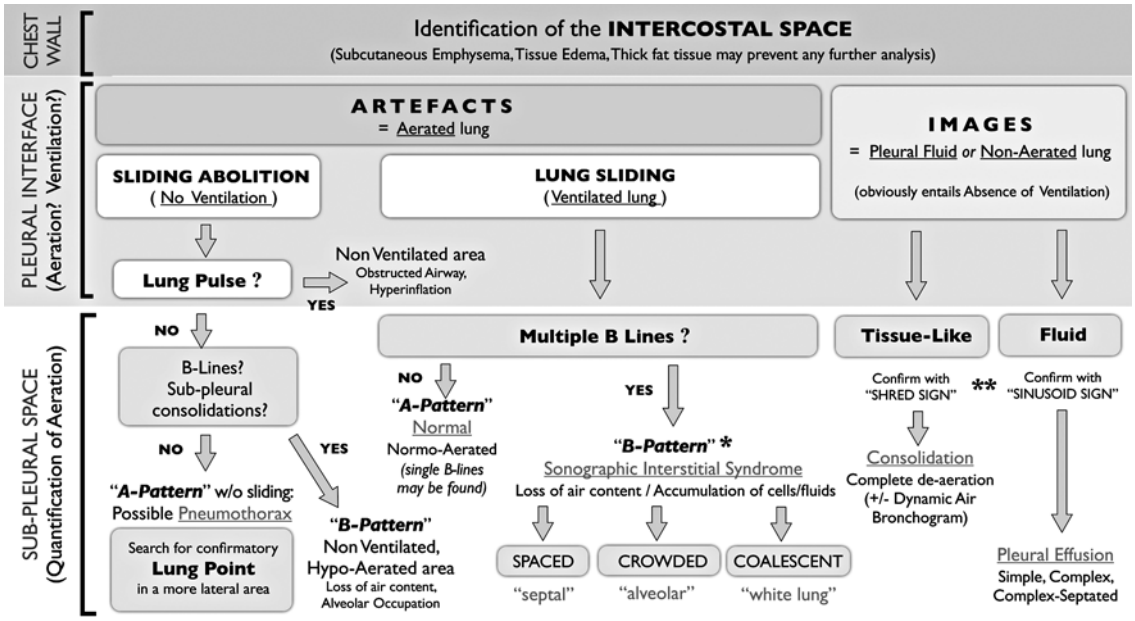

Figure 4.—*Sequential interpretation of lung ultrasound findings at a single scan area.* Each area explored with ultrasound is characterized to fit into one of the segmental patterns described in Figure 1: normality, sonographic interstitial syndrome, effusion, consolidation, or pneumothorax. Upon preliminary assessment of the adequacy of the acoustic window on the lung and detection of the landmarks (recognizable intercostal space and pleura), interpretation of the pleural interface comes first: its definition as fluid-air interface (yielding artefacts) or as fluid-fluid interface (yielding images) is a key step to characterize the state of aeration of the explored area. Assessment of visceral pleural motion (sliding/no sliding/lung pulse) speaks to lung ventilation. Artefacts or images beyond the pleura are then interpreted to yield a final segmental sonographic diagnosis. *In B-pattern (sonographic interstitial syndrome, more than 3 B-lines/intercostal space), the presence of pleural thickening/abnormalities and subpleural small consolidations favors inflammation/de-aeration while a smooth non-thickened pleura favours increased extravascular lung water. **Differential diagnosis between poorly echogenic consolidations and effusion may not always be easy: a fluctuating appearance of the far boundary of the lesion (represented by M-Mode as the "sinusoid sign" [9]) stands for free fluid (effusion); an irregular, ragged far border of the lesion (the "shred sign" [9]) represents the deep boundary of consolidation, the junction between consolidated and aerated parenchyma. Lobar consolidations have instead a regular boundary, but rarely a hypoechoic appearance.

only a balanced and pertinent interpretation of sonographic findings in light of the patient's history, clinics, biochemistry, other instrumental data, and ongoing treatment will provide the correct diagnosis. Additionally, integration with venous [27] and cardiac ultrasound (in a "whole body approach [9]") has the potential to reach a very high diagnostic accuracy.

Monitoring of specific lung diseases

Repeated systematic LUS assessment can effectively track the course of pleural and lung disease in the ICU.[3] As already demonstrated for consolidative non-severe community-acquired pneumonia,[28] LUS provides accurate follow-up of pneumonia in ICU patients as well. By means of a re-aeration score calculated from LUS pattern changes in 12 regions of interest,[15] LUS accurately described aeration changes related to successful antimicrobial treatment of *ventilator-associated pneumonia.*[15] A particularly significant correlation was found between CT and LUS re-aeration (Rho=0.85, $P<0.0001$): a LUS score >5 was associated with a CT-measured re-aeration >400 mL and a successful therapy, while a score ≤-10 was associated with a loss of CT aeration >400 mL and a failure of treatment.[15]

In *cardiogenic pulmonary edema* ("wet lung" LUS appearance), the overall number and density of B-lines are accurate markers of lung congestion severity. They correlate with chest X-ray findings,[29] arterial blood oxygenation,[30] natriuretic peptide levels,[31] transpulmonary thermodilution measured extravascular lung water,[32] and pulmonary capillary wedge pres-

TABLE I.—*Differential diagnosis of potential causes of lung failure in the ICU.*

Suspected cause of lung failure	Hallmark	Extension	Distribution	Pleural features
Normal lung (as reference)	"A Pattern" *(Dorsal B-Pattern frequent in ICU)	Diffuse	Bilateral, symmetrical	Thin pleura, sliding
Pneumonia, Broncho-pneumonia	Consolidation tissue-like or hypoechoic (early essudative phase) texture, w/ irregular, blurred margins + dynamic air bronchograms or fluid bronchograms	Focal, multifocal Dorsal (>frequent) Anterior/Lateral (possible)	Monolateral (at onset); bilateral, asymmetrical (If evolving)	N/A
	Sono-interstitial syndrome (B-Pattern) (interstitial pneumonia) Irregularly spaced B-lines	Focal, multifocal Anterior/Lateral/ Dorsal	Monolateral (at onset); bilateral, asymmetrical (If evolving)	Pleural abnormalities (thickened/ fragmented pleura, subpleural consolidations) if B-Pattern Reduced sliding/ No sliding/lung pulse
Atelectasis	Consolidation with regular margins No dynamic bronchograms	Focal Anterior/Lateral/ Dorsal	Monolateral	N/A
	A or B pattern (ongoing atelectasis)	Focal anterior/ lateral/dorsal	Monolateral	Lung pulse
Hydrostatic/ Cardiogenic Pulmonary Edema	Sono-interstitial syndrome (B-pattern) Regularly spaced B-Lines (septal edema) Crowded/coalescent (alveolar edema)	Diffuse Antero-lateral (untreated, acute phase) Lateral (treated, subacute) *Do not consider Dorsal (misleading in ICU) Gravity gradient	Bilateral, symmetrical Homogeneous	Smooth/non-thickened pleural line Preserved sliding
ALI/ARDS	Sono-interstitial syndrome (B-pattern) Irregularly spaced B-lines Consolidations Dorsal	Diffuse Unrelated to gravity	Bilateral, symmetrical Inhomogeneous (patchy distribution, "spared areas")	Pleural abnormalities (thickened/ fragmented, anterior subpleural consolidations) Reduced sliding Lung pulse
Lung Contusion	Sono-interstitial syndrome (B-pattern) (at onset) irregularly spaced B-lines Consolidation (evolving)	Focal multifocal	Monolateral bilateral, asymmetrical	Pleural abnormalities (thickened/ fragmented, subpleural consolidations) Preserved/reduced Sliding/lung pulse
Alveolitis	Sono-interstitial syndrome (B-Pattern)	Diffuse	Bilateral, symmetrical	Pleural abnormalities (thickened/ fragmented) Preserved/reduced sliding

Table I.—*Differential diagnosis of potential causes of lung failure in the ICU.*

Suspected cause of lung failure	Hallmark	Extension	Distribution	Pleural features
Pulmonary fibrosis	Sono-interstitial syndrome (B-Pattern)	Diffuse (>dorsal lower lobes)	Bilateral, symmetrical	Pleural abnormalities (thickened/ fragmented, subpleural cysts) Preserved/reduced sliding
Pneumothorax	Pneumothorax (A-Pattern + Lung Point)	Focal	Usually monolateral	No sliding
Pleural effusion	Intra-pleura anechoic collection (transudate) Echogenic, particulated in complex effusion (exudate, blood) May be septated (exudate)	N/A	Monolateral, bilateral	N/A
Pulmonary infarction	Consolidations, 2/more, Small (1-3 cm) Echo-poor, wedge-shaped	Focal > Dorsal (> right lower lobe)	Monolateral (at onset); bilateral, asymmetrical (if repeated)	N/A
COPD exhacerbation, asthma	A-pattern	Diffuse	Bilateral, symmetrical	Preserved sliding Reduced sliding (hyperinflation)

COPD: chronic obstructive pulmonary disease.

sure.[32, 33] The clinical observation that LUS is a more sensitive means for detecting extravascular lung water variations when compared to chest X-ray or auscultation matches with findings in an animal model of inflammatory edema, where B-lines appeared even earlier than a decrease in arterial oxygen tension.[34] Moreover, favorable response to treatment is associated with progressive, real-time, reduction in the number of B-lines, up to their complete clearance, as demonstrated with continuous positive airway pressure/ non-invasive ventilation [35, 36] and fluid removal by means of diuretics [14, 35] and dialysis.[37, 38] Evidence supports the use of LUS as a point-of-care, real-time, simple tool to directly image and monitor extravascular lung water.[3] Additionally, detection of an overall LUS pattern of "dry lung" (antero-lateral normal pattern) suggests that initial fluid loading may be given without concern for hydrostatic pulmonary edema.[33]

The number and crowding of B-lines correlates with severity in *ALI/ARDS* as well.[16 34] Interestingly, in an experimental model of ALI, a tight correlation was found between the number of B-lines and the gravimetry-measured wet/dry ratio of the lung tissue.[39] LUS evaluates the time course and response to treatment of ALI/ARDS [40, 41] by reliably tracking aeration and extravascular lung water changes upon PEEP titration,[16] recruitment maneuvers, pronation,[42] lung re-expansion after pleural drainage, and negative water balance.

The amount of a *pleural effusion* can be accurately determined with LUS, either semi-quantitatively [43, 44] or quantitatively.[45] One can also monitor the clinical course of a pleural effusion and track its response to medical treatment.[46] This ability to monitor pleural collections is especially important in the setting of stable patients with chest trauma, as in these settings it may be more appropriate to closely follow the evolution of hemothoraces or pneumothoraces rather than to drain them immediately. In particular, the superficial extension of a

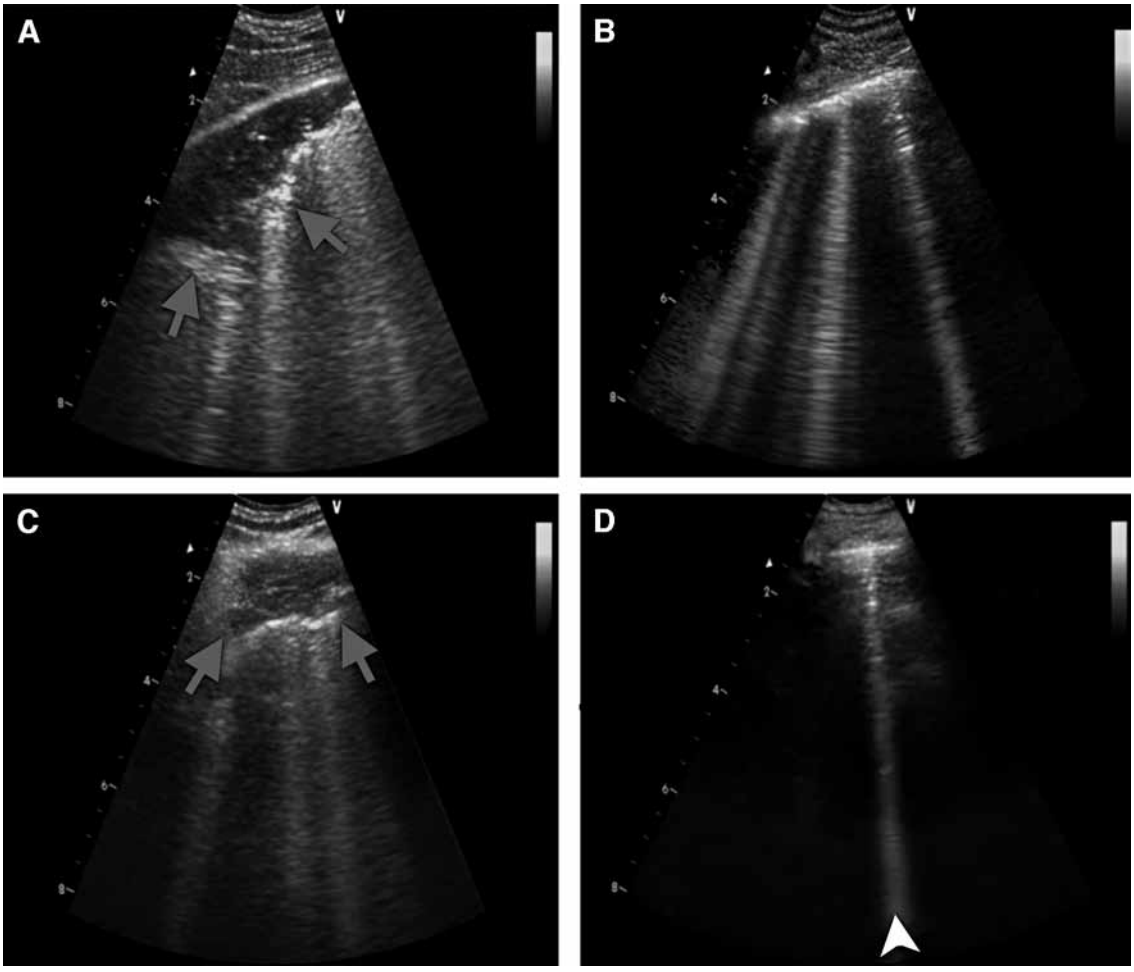

Figure 5.—*LUS changes in dependent areas upon pronation in an ARDS patient.* Left (upper panels) and right (lower panels) show sequential dorsal scans in an ARDS patient subjected to pronation on day 3 of disease course. In both areas of investigation, LUS findings shifted from a pattern of consolidation (6A and 6C, arrows) to a B-pattern on the left (6B) and a nearly normal pattern (6D: just one B-line, arrowhead) on the right side. Time elapsed between the 2 sequential acquisitions was 30 minutes.

pneumothorax can be mapped and monitored according to the lateral location of the lung point(s).[8]

Lung-related procedures and their monitoring

A wide range of bedside procedures performed on critical respiratory disease patients benefit from information provided by lung imaging. As such, many of them represent either established or potential applications of LUS. Since ultrasonographic investigation of the heart is acknowledged as a key tool in the ventilatory management of ALI/ARDS patients,[47] it is not surprising to observe that exploring the lung directly with the same technology yields even more information.[41] LUS has the potential to predict lung recruitability based on observations of lung morphology, which is a key predictor of the response to *recruitment maneuvers.*[48] Early-stage focused distribution of aeration loss (a state associated with poor recruitability and major risks of overdistention of aerated regions) is represented by a nearly normal LUS pattern or a paucity of B-lines in antero-lateral areas and consolidation or crowding of B-lines in dorsal ones. On the other hand, early-stage diffuse de-

aeration is associated with a more homogeneous interstitial pattern characterized by coalescent B-lines. However, hyperinflation cannot be accurately diagnosed with LUS, even if one observes markedly reduced sliding in the context of a normal LUS pattern. LUS findings cannot be used in isolation to determine appropriate PEEP settings. Along with the overall clinical picture, LUS can support the choice of pronation (if dorsal consolidations prevail) and monitor its effects in real time [42] (Figure 5). Very empirically, but effectively, detection of derecruited areas even in less severe contexts than ALI/ARDS allows optimization of ventilatory strategy,[49] for example, by means of postural *therapy*, or in the choice of using non-invasive ventilation rather than CPAP in spontaneously breathing patients.

By helping the intensivist recognize the atelectatic nature of a consolidated area (absence of a "dynamic air bronchogram" or presence of "fluid bronchogram",[28] positive predictive value 94% [6]), LUS can suggest the need to restore bronchus patency by means of *fiberoptic bronchoscopy*. When a *distal airway specimen* is indicated by the suspicion of pneumonia, LUS can identify the best lobe to target,[50] with higher accuracy than chest X-ray. *Management of pleural effusions*, whatever the setting or the purpose, is greatly aided by LUS. The decision to perform pleural drainage is based on estimating the potential compressive effect of the effusion, which depends on the volume of the effusion. LUS can estimate pleural effusion volume semi-quantitatively (an expiratory inter-pleural distance at the thoracic base >45-50 mm or >50 mm accurately predicts >800 mL [43] or 500 mL [44] effusions, respectively) or quantitatively (multiplane approach, based on the effusion length times mid-height area formula).[45] These estimates tightly correlate with CT-scan estimates and collected fluid volumes. The procedure itself is optimized by identifying the most dependent and safest site of puncture [51] and by monitoring the results of the thoracentesis in real-time. Furthermore, LUS has shown superiority to standard chest X-ray and CT-scan in characterizing the internal complexity of an effusion:[52] detection of complex septated or complex non-septated effusions (internal echoes, mobile particles), as in hemothorax/empyema, can suggest the use of *chest tube drainage.*[53] Ultrasound-aided management of pleural effusions in febrile ICU patients also hastens diagnosis and aggressive treatment of empyema.[54] *Pneumothorax drainage* with LUS guidance has utility only in the life-threatening scenario of hypertensive pneumothorax, since ultrasound can only diagnose the presence of intra-pleural air collections and surface extension, but cannot gauge their depth.[8] However, LUS can be used effectively for *pneumothorax follow-up*. The accuracy of LUS for detecting residual pneumothorax after drainage and for defining the timing for chest tube removal is greater than that of chest X-ray.[55]

Assessment of weaning from mechanical ventilation.—LUS has been shown to be useful in *monitoring and managing the weaning process from mechanical ventilation*. Firstly, it allows for detection and treatment of obstructive atelectasis, de-recruited areas, and relevant effusions so as to optimize the starting conditions for extubation and spontaneous breathing.[56] Furthermore, LUS provides information that can be used to potentially predict the success or failure of a spontaneous breathing trial (SBT). By multisite quantification with a LUS four-tiered score (0=normal pattern; 1=multiple spaced B-lines; 2=multiple coalescent B-lines; 3=consolidation) the state of lung aeration before the SBT and the amount of de-recruitment after the trial can be described. Higher scores are detected in patients more likely to subsequently develop post-extubation respiratory distress.[57] The LUS score at the end of an SBT predicts post-extubation distress with an area under the ROC curve of 0.86, 95% CI (0.79-0.93), with 0.82 sensitivity and 0.79 specificity for a LUS score >14, a better performance than plasma BNP values and echocardiographic-derived parameters. A LUS score at end SBT of ≤12 or >17 accurately identifies patients with a low or high likelihood of postextubation distress, respectively.[57] As an accurate tool for the differential diagnosis of cardiogenic and obstructive causes of respiratory failure,[58] LUS may also allow prompt recognition of a cardiogenic component of acute post-extubation respiratory distress.

Finally, *diaphragm ultrasonography*, easily obtained during LUS scanning of lower quadrants, provides additional insights on tolerance to weaning. Preliminary studies in cohorts of pa-

tients scheduled for extubation showed that one could identify patients at high risk of difficulty weaning during an SBT (M-Mode measured diaphragmatic descent <10mm correlates with higher rates of primary, 83% *vs*. 59% P=0.01, and secondary weaning failure, 50% *vs*. 22% P=0.01).[59] Furthermore, a cut-off value for spleen and liver downward displacement of >11 mm can predict successful extubation (84.4% and 82.6% sensitivity and specificity respectively, better than traditional weaning parameters).[60] In another study, the work of breathing was indirectly estimated in extubated patients at high risk for failure subjected to planned non-invasive ventilation. Investigators found an inverse correlation between fractional diaphragmatic thickening in the chest wall apposition zone and the pressure support level (spontaneous breathing *vs*. 5 cmH_2O incremental steps, P<0.05).[61] LUS even has the potential to monitor recovery from diaphragmatic weakness or paralysis.[62]

Advantages and limitations of lung ultrasound Knowledge gaps and future directions

LUS has many appealing features that make its application in the ICU potentially advantageous. It uses basic technology (only 2D and M-Mode capabilities are required) and is free of ionizing radiation. It is also non-invasive, repeatable, cost-effective,[63] and in trained hands, more accurate than the bedside lung imaging alternative, chest X-ray.[18, 24] Moreover, unlike CT-scan, LUS does not require the patient transport outside the unit. More subtly, thanks to the ready availability of LUS in the clinician's hands, patients may benefit from a lower threshold for performing the ultrasound examination than for ordering an alternative test. Therefore, earlier and more frequent lung investigations may be the consequence of LUS use. Furthermore, since image-based patterns are intuitively recognized and artifactual ones are mutually exclusive (interpretation proceeds in a binary fashion, Figure 4), LUS technique is largely operator-independent, in contrast to other ultrasound applications.[31 64-66] Still, appropriate training is crucial, especially for those LUS diagnoses that are more difficult to master (for example pneumothorax confirmation).[67]

Lung ultrasound nevertheless suffers many limitations. The main limitations are based on an overall lower diagnostic accuracy than CT-scan (especially concerning precise quantification of the extension of lung lesions and deeper lesions without consolidation/effusion), inability to image paravertebral regions (beneath the scapulae), and hypo-echogenicity of some patients (with obesity, wounds/dressings, tissue edema). Even though LUS can provide an accurate semi-quantitative assessment of lung aeration, it cannot evaluate hyperinflation, a relevant issue in ALI/ARDS patients management.[68]

The issue of infection transmission via the ultrasound probe also deserves attention and further investigation.[69] Finally, as with every novel tool, implementing LUS requires an organized ward/department effort with a standardized approach, common language, and uniform staff training. At this time, the systematic use of LUS in ICUs is still scarce in comparison to the field of emergency medicine.

LUS has the potential to become a reference tool for bedside dynamic respiratory monitoring in the ICU and can fill the image-resolution gap between chest radiographs and CT-scans. Continued research is needed to place LUS in evidenced-based diagnostic imaging strategies and implement it into goal-directed diagnosis and monitoring.

Key messages

— Lung ultrasound quickly provides at the bedside relevant information on the state of aeration and ventilation of the lung. It has the capability to describe spatial and temporal heterogeneity of lung aeration and extravascular lung water content.

— Lung ultrasound can track effectively the course of lung and pleural disease in the ICU and guide several aspects of the management of respiratory failure.

— In the hands of adequately trained physicians, lung ultrasound has the potential to fill the image-resolution gap between chest radiographs and CT-scans, and to greatly contribute to bedside respiratory monitoring in the ICU.

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Corresponding author: G. Via, First Department of Anesthesia and Intensive Care, IRCCS Policlinico San Matteo Foundation, University of Pavia, piazzale Golgi 2, 27100 Pavia, Italy. E-mail: gabriele.via@winfocus.org