Intensive Care Medicine

WHAT'S NEW IN INTENSIVE CARE Un-edited accepted proof

WHAT'S NEW IN LUNG ULTRASOUND DURING THE COVID-19 PANDEMIC

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Introduction

The *SARS-CoV-2* pandemic is undermining the ability of many advanced healthcare systems worldwide to provide quality care [1, 2]. COVID-19 is the disease caused by infection with *SARS-CoV-2*, a virus with specific tropism for the lower respiratory tract in the early disease stage [3]. Computed tomography scans of patients with COVID-19 typically show a diffuse bilateral interstitial pneumonia, with asymmetric, patchy lesions distributed mainly in the periphery of the lung [4-6]. In the context of a pandemic, rapid case identification, classification of disease severity and correct treatment allocation are crucial for increasing surge capacity. Overtriage to admission and to intensive care by clinicians working in the department of emergency medicine (ED) will overwhelm system capacity. Undertriage can lead to loss of life and cross infections. Similarly, selection of those patients most likely to respond to specific treatments and determining the response to treatment in the intensive care unit (ICU) can conserve scarce resources. Lung ultrasound (LUS) is well known for its feasibility and high accuracy when used at the bedside for diagnosing pulmonary diseases [7, 8]. As the most striking manifestation of COVID-19 disease is in the pulmonary system, LUS performed by a trained and knowledgeable clinician may aid precisely in triage, classification of disease severity and treatment allocation in both the ED and the ICU. In this paper we describe the use of LUS in treating patients with COVID-19.

Case identification and classification of disease severity

Pending RT-PCR test results, other patients (or staff) may be unnecessarily exposed to those carrying the disease. Verifying that patients have COVID-19 therefore remains the rate-limiting step in patient triage. Alternatively, redundant implementation of precautions may lead to unnecessary resource consumption. The use of LUS in this context could revolutionize patient triage.

The LUS technique described in this paper is detailed in the supplementary material (Online Resources LUS_TECHNIQUE.docx and Figure_1-6 and Video_1-2). The pretest probability of gaining useful information from LUS is likely to be highest when the clinician seeks to correlate clinical findings with those seen in LUS and knows what information to seek in order to do so. COVID-19 presents with not only specific LUS signs but also with typical patterns of LUS findings.

LUS signs

The signs seen in the LUS of patients with COVID-19 are similar to those extensively described in patients with other types of pneumonia [7]. These include various forms of B-lines, an irregular or fragmented pleural line, consolidations, pleural effusions and absence of lung sliding (see Online Resources Video_3-10) [9]. The LUS of patients with COVID-19 usually shows an explosion of multiform vertical artifacts and separate and coalescent B-lines. The pleural line may be irregular or fragmented as is commonly observed in ARDS. As stated above none of these signs is pathognomonic to COVID-19 pneumonia and their presence is variable.

Conversely, a typical artifact that we named "**light beam**" is being observed invariably in most patients with pneumonia from COVID-19. This artefact corresponds to the early appearance of "ground glass" alterations typical of the acute disease that may be detected in computed tomography. This broad, lucent, band-shaped, vertical artefact moves rapidly with sliding, at times creating an "on-off" effect as it appears and disappears from the screen. The bright artefact typically arises from an entirely regular pleural line interspersed within areas of normal pattern or with separated B-lines (Online Resources Video_5). At times it seems to cover the A-lines, concealing them entirely. At other times A-lines may still be visualized in the background as it is observed. The light beam is observed also in other conditions with ground glass alterations. Nevertheless, the importance of this sign is given by the contingency of the terrible pandemic of COVID-19 that we are experiencing in our EDs. A multicenter study in progress is investigating the accuracy of this sign. To date, a pilot analysis of a monocenter series of 100 patients suspected for COVID-19 revealed the presence of multiple light beams in 48 of the 49 patients with confirmed disease and pneumonia. The same sign was never observed in 12 patients with alternative pulmonary diagnoses and negative swab test (unpublished data).

LUS Patterns

The LUS findings of patients with COVID-19 are unique in both combination and distribution. Therefore, patients presenting to the ED may be classified into four broad categories based on the presence of specific patterns of LUS findings (see Table 1). Patients presenting with the pattern described in category A have little or no pulmonary involvement and are therefore unlikely to have COVID-19 disease (i.e. asymptomatic *SARS-CoV-2* carriers or patients with no lung disease). In patients presenting with any of the LUS patterns described in category B (Online Resources Video_11-14) alternative diagnoses should be sought. These patients are most likely to have a condition other than COVID-19 causing their pulmonary disease. Patients presenting with the pattern of LUS findings described in category C (Online Resource Video_15) may have COVID-19 disease, whereas those presenting with the patterns of LUS findings described in category D (Online Resources Video_16-21 and Figure_7-8) probably have COVID-19 disease.

The presence of large consolidations with air bronchograms mainly in the bases of the lungs should always raise suspicion of bacterial cross-infection. As noted above LUS findings are always most informative when they are interpreted in light of the clinical context; some asymptomatic or mildly symptomatic patients may have surprisingly impressive LUS findings. Conversely, in our experience, patients with COVID-19 disease who suffer from severe respiratory failure are not likely to have no or mild LUS alterations.

Treatment allocation

There are several ways LUS may be used to determine allocation of treatment resources to those patients most likely to respond. These include early quantification of the severity of lung involvement, periodic assessment for the appearance of findings suggestive of atelectasis or pneumonia and monitoring the effects of changes in mechanical ventilation and recruitment maneuvers on lung aeration.

The use of LUS to quantify and monitor changes in aeration has been described in critically ill patients with ARDS [10, 11]. It is our impression that, contrary to what has been described in ARDS, interstitial patterns and consolidations contribute almost equally to lack of aeration in patients with COVID-19 [12]. Rather, the severity of respiratory impairment seems to be related to the overall proportion of lung tissue showing ground-glass alterations [6]. Early quantification the severity of lung involvement in patients with COVID-19 may be obtained by estimating the overall amount of lung areas detected as being pathological with ultrasound. Documenting the ultrasound images obtained enables later assessment of lesion size and more precise calculation of the proportion of diseased lung. The diseased lung is identified by the presence of any pathological finding (e.g. separated and coalescent B-lines, light beams, consolidations) and the areas of diseased lung are measured. For each video clip the proportion of involved lung is calculated (0-30-50-70-100%) and the overall proportion is then calculated. This method of semi-quantification may be used to estimate the extent of lung involvement which could serve to identify at least some of the patients more likely to require invasive ventilation.

Periodic assessment for the appearance of findings suggestive of atelectasis or pneumonia can be highly informative. Identification of interstitial patterns or consolidations typical of pneumonia in patients with COVID-19 should lead to a change in care. Modifying ventilation parameters is simple but may not suffice for recruitment. We are adopting pronation guided mainly by LUS detection of extended lesions in the dorsal areas both in patients treated with continuous positive airway pressure (CPAP) and in invasively ventilated patients.

In patients that are invasively ventilated we suggest following evidence-based suggestions for monitoring aeration changes [10, 11]. The lung is studied in oblique scans in two anterior, two lateral and two posterior areas per side. Each area is assigned a score ranging from 0 to 3 (0=normal A-lines, 1=multiple separated B-lines, 2=coalescent B-lines or light beam, 3=consolidation). The sum of all the areas represents the aeration score. The dynamic changes in aeration can then be quantified by reassigning a new score to re-aerated areas (see Table 2). New methods for automated computer-aided measurement of aeration could be considered when available, with the advantage of a more standardized quantitative approach for monitoring [13].

In the setting of critically ill COVID-19 patients with severe pneumonia, the possibility of thromboembolic disease should be considered [14]. Even if there are no published studies thus far, COVID-19 patients are likely at increased risk for thromboembolism [15]. Critically ill patients should be treated accordingly and monitored by cardiac and venous ultrasound to diagnose deep venous thrombosis and cardiac signs of acute pulmonary embolism [16]. We show a case of COVID-19 with sudden deterioration and cardiac arrest due to acute pulmonary embolism with popliteal thrombosis (Online Resources Video_22-23).

Conclusion

Hospital flooding of patients with COVID-19 imposes a huge burden on the medical system. This burden can be somewhat mitigated with optimization of patient identification, triage and management. LUS is noninvasive and can be performed very rapidly. LUS may be used in the ED to identify likely COVID-19 patients and to identify those patients with more extensive pulmonary involvement who should probably be referred to the ICU. It may serve to differentiate between patients with acute signs of respiratory failure, patients with mild symptoms and normal respiratory function, patients with pre-existing chronic cardiac or pulmonary diseases (see flow charts in Online Resources Figure_9-11). In the ICU, LUS may be used to identify areas of poor lung aeration and to monitor the effect of changes in ventilation and recruitment maneuvers on lung aeration.

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Table 1: Categories of probability of the disease based on patterns of LUS findings

Category	***LUS findings***
A. Low probability of COVID-19 disease (normal lungs)	Regular sliding A-lines observed over the whole chest Absence of significant B-lines (i.e. isolated or limited to the bases of the lungs)
B. Pathological findings on LUS but diagnosis other than COVID-19 most likely	Large lobar consolidation with dynamic air bronchograms Large tissue-like consolidation without bronchograms (obstructive atelectasis) Large pleural effusion and consolidation with signs of peripheral respiratory re-aeration (compressive atelectasis) Complex effusion (septated, echoic) and consolidation without signs of reaeration Diffuse homogeneous interstitial syndrome with separated B-lines with or without an irregular pleural line. *Patterns suggestive of specific diagnoses:* Cardiogenic pulmonary edema → Diffuse B-lines with symmetric distribution and a tight correlation between the severity of B-lines and the severity of respiratory failure (anterior areas involved in the most severe conditions); in this case distribution of B-lines must be uniform; extending the sonographic examination to the heart will support the alternative diagnosis. Pulmonary fibrosis and interstitial pneumonia from alternative viruses → the pattern has greater spread and there are no or limited "spared areas" (alternating normal A-lines pattern). Chronic fibrosis → diffuse irregularity of the pleural line.
C. Intermediate probability of COVID-19 disease	Small, very irregular consolidations at the two bases without effusion or with very limited anechoic effusion Focal unilateral interstitial syndrome (multiple separated B-lines) with or without irregular pleural line Bilateral focal areas of interstitial syndrome with well-separated B-lines with or without small consolidations.
D. High probability of COVID-19 disease	Bilateral, patchy distribution of multiple cluster areas with the light beam sign, alternating with areas with multiple separated and coalescent B-lines and well-demarcated separation from large "spared" areas. The pleural line can be regular, irregular or fragmented.

	Sliding is usually preserved in all but severe cases. Multiple small consolidations limited to the periphery of the lungs A light beam may be visualized below small peripheral consolidations and zones with irregular pleural line.

Table 2. Quantification of reaeration and loss of aeration by the observation of changes of the LUS pattern in each of the 12 chest areas. The final score is the sum of the 12 areas.

<table>
<tr><th colspan="3">Re-aeration score</th><th colspan="3">Loss of aeration score</th></tr>
<tr><th>+1 point</th><th>+3 points</th><th>+5 points</th><th>-5 points</th><th>-3 points</th><th>-1 point</th></tr>
<tr><td rowspan="2">B1 to Normal</td><td rowspan="3">B2 to Normal</td><td rowspan="6">C to Normal</td><td rowspan="6">Normal to C</td><td rowspan="3">Normal to B2</td><td rowspan="2">N to B1</td></tr>
<tr></tr>
<tr><td rowspan="2">B2 to B1</td><td rowspan="2">B1 to B2</td></tr>
<tr><td rowspan="3">C to B1</td><td rowspan="3">B1 to C</td></tr>
<tr><td rowspan="2">C to B2</td><td rowspan="2">B2 to C</td></tr>
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B1: multiple separated B-lines; B2: coalescent B-lines or light beam; C: consolidation.

ONLINE RESOURCES (captions)

LUS Technique (Image set up)

Video_Add_Linear1 and Video_Add_Convex1: Two videos from a patient with confirmed pneumonia from COVID-19. It is shown the worse performance of the linear probe compared to a convex probe in imaging the intense B-line pattern with a small peripheral consolidation.

Figure_1. A longitudinal scan of the chest wall showing the pleural surface in between and below the two ribs

Figure_2. An oblique scan showing the maximal extension of the pleural surface without interposition of the ribs

Figure_3. Anterior chest between the parasternal line (PSL) and the anterior axillary line (AAL). The scan 1 is performed longitudinally to examine the 4-5 anterior intercostal spaces

Figure_4. Lateral chest between the anterior axillary line (AAL) and the posterior axillary line (PAL). The scan 2 is performed longitudinally to examine the 4-5 lateral intercostal spaces. The scan 3 is performed in oblique to examine the costophrenic angle to diagnose effusion

Figure_5. Posterior chest between the scapula and the spine line (SL). The scan 4 is performed longitudinally to examine 6-7 posterior intercostal spaces. The scan 5 is performed in oblique to examine in steps the 3-4 intercostal spaces below the inferior margin of the scapula

Figure_6. The "tilting" adjustment to optimize the visualization of the pleural surface and the lung artifacts. This regulation is particularly crucial in the dorsal scans

Video_1: Demonstration of the effect of "tilting", that is the fine movement of the probe to change its angulation on the chest wall, on the correct visualization of the pleural line and other lung artifacts in a dorsal longitudinal scan

Video_2: The deleterious effect of changing the position of the focus on the visualization of vertical lung artifacts in the lung image

LUS Signs

Video_3: Normal LUS pattern showing regular respiratory sliding and A-lines

Video_4: Separated multiple B-lines with regular respiratory sliding

Video_5: The "light beam" sign. This sign typically indicates acute ground glass alterations. The pleural line is regular, and the sign is an echoic band moving rapidly with respiration. It is the most specific sign of pneumonia in COVID-19

Video_6: Irregular pleural line with interstitial pattern (multiple separated B-lines and "light beam" area). This patient was confirmed COVID-19

Video_7: Fragmented pleural line due to multiple small peripheral consolidations. This patient was confirmed COVID-19

Video_8: Small peripheral consolidation. This patient was confirmed COVID-19

Video_9: Large lobar consolidation with dynamic air bronchograms. This patient was confirmed COVID-19 and bacterial cross infection.

Video_10: Large pleural effusion with compressive atelectasis of the base of the lung, showing regular re-aeration during inspiration. This patient was diagnosed with lung cancer and negative COVID-19

Patterns

Video_11 and Video_12: Alternative LUS pattern in a patient with acute dyspnea suspected for COVID-19. Typical pulmonary edema pattern (Video 11) detected in the whole lung without the typical patchy distribution and combined with visualization of impairment of the left ventricle function (video 12)

Video_13: Alternative LUS pattern in a patient with acute dyspnea, fever and cough suspected for COVID-19. The video shows an isolated consolidation in the base of the lung with dynamic air bronchograms due to bacterial pneumonia.

Video_14: Alternative LUS pattern in a patient with acute dyspnea suspected for COVID-19. The video shows a massive pleural effusion and pericardial effusion that revealed to be hemorrhagic and neoplastic.

Video_15: Intermediate LUS pattern in a patient feverish without any respiratory symptom suspected for COVID-19. The video shows a focal isolated interstitial syndrome with multiple coalescent B-lines and a peripheral consolidation. Patient was then confirmed COVID-19 with radio-occult viral pneumonia

Video_16-21: Positive LUS patterns in six patients complaining of fever and respiratory acute failure suspected for COVID-19. The videos show typical "light beam" signs (also detected in patchy distribution in other areas in both lungs), well demarcated by contiguous "spared areas". Patients were all confirmed COVID-19.

Figure_7. CT image of the same confirmed COVID-19 case of the Video 20, showing the ground glass opacity corresponding to the light beam sign detected by LUS in the left lateral area of the chest

Figure_8. CT image of the same confirmed COVID-19 case of the Video 21, showing the ground glass opacity corresponding to the light beam sign detected by LUS in the left superior lateral area of the chest

Treatment allocation

Video_22 and Video_23: A critically ill patient with COVID-19 who unfortunately experienced sudden deterioration and cardiac arrest due to thrombosis of the popliteal vein (video 20) and acute dilation of the right ventricle due to pulmonary embolism (video 21)

Patient's triage

Figure_9-11. Flow charts for patient's flow: patients with **acute respiratory failure** (Figure_9) are those complaining of fatigue and peripheral oxygen saturation <92-93% on room air without history of chronic cardiac and/or lung diseases. Patients with **mild symptoms** (Figure_10) are those with no signs of respiratory failure. Patients with exacerbation of symptoms of **chronic**

cardiac or respiratory diseases (Figure_11) are those with chronic heart failure, cor pulmonale, or any chronic respiratory disease. PCT: serum procalcitonin. LC: Leukocyte counts. See text for explanation about the LUS patterns and differentiation between regular ward, ward dedicated to patients with pending RT-PCR, units dedicated to COVID-19. Our proposal of the patient triage is based on a dedicated structural organization of the hospital, with availability of: 1) CT scan facility 24 hours a day; 2) isolation areas in the ED; 3) ICU, sub-intensive emergency ward and general ward dedicated to COVID-19; 4) intermediate wards were patients can be isolated in specific areas separated from other patients, waiting for the confirmation by RT-PCR; 5) general wards dedicated to negative patients with other diseases. LUS allows the diagnosis of COVID-19 pneumonia while swab RT-PCR allows confirmation of the SARS-CoV2 infection. Absence of signs of pneumonia at LUS cannot exclude that the patient carries the SARS-CoV2 anyway. General wards should be organized to maintain distance and test any admitted patient and also personnel to reduce the possibility of cross infections.