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Imaging of COVID-19 in critical care with a focus on chest ultrasound

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Imaging methods available at the bedside have become an indispensable part of the diagnostic process of COVID-19 in the intensive care setting. Chest ultrasound has been established as an exquisite bedside imaging tool to assess and diagnose a myriad of lung pathologies, assess the pleural space and diaphragm, and ultimately gauge therapeutic interventions. Furthermore, vital information can be attained on the haemodynamic status of a patient when chest ultrasound is combined with echocardiography and Doppler vascular assessment. Bedside chest x-ray has its technical limitations, is not sensitive in early stages of the disease, and exposes patients to radiation. Computed tomography has great spatial resolution and all the structures in the chest can be assessed, but on the other hand, it requires patient transport and exposes them to radiation and the potential side effects of contrast administration. Recently, chest ultrasound has proved to be extremely useful during the COVID-19 pandemic in assessing COVID-19 pneumonia and its complications with a resultant reduction in potential infectious cross-contamination of staff and patients due to transport to and from the radiology department. In this review, the authors compare the three most frequent modalities of chest imaging in the diagnosis of COVID-19 in critical care, with a focus on the benefits of chest ultrasound.

Key words: chest ultrasonography, chest X-ray, chest computed tomography, acute respiratory distress syndrome, pulmonary embolism, COVID-19 pneumonia, pneumothorax, pleural effusion, diaphragm dysfunction.

Zobrazovací metody u těžkých forem covid-19 se zaměřením na hrudní ultrasonografii

Zobrazovací metody dostupné u lůžka pacienta se staly nezastupitelnou částí diagnostického procesu u těžkých forem covid-19 v intenzivní péči. Hrudní ultrasonografie se etablovala jako unikátní zobrazovací modalita umožňující záchyt spektra plicních patologií, pleurálního prostoru a funkce bránice, což umožňuje bez prodlení volit adekvátní terapeutické intervence. Vitální informace je možné získat o funkci srdce a hemodynamice, pokud se hrudní ultrazvuk kombinuje s echokardiografií a ultrazvukovým vyšetřením cévního systému. Hrudní rtg u lůžka pacienta má svoje technická omezení, není senzitivní v časných fázích onemocnění a exponuje pacienty radiaci. Computerová tomografie má vynikající prostorové rozlišení s možností vizualizace všech struktur hrudníku a mediastina, nevýhodou je zátěž pacienta a personálu transportem, společně s radiací a vedlejšími efekty podávané kontrastní látky. Hrudní ultrasonografie se ukázala být výhodná během pandemie v diagnostice covid-19 pneumonie a jejích komplikací. Jedním z důvodů je redukce potenciální infekční kontaminace personálu a pacientů při transportu na radiologii a zpět. V tomto review autoři srovnávají tři nejčastější modality zobrazení hrudníku v diagnostice covid-19 v intenzivní péči a diskutují benefity a limitace hrudního ultrazvuku.

Klíčová slova: hrudní ultrasonografie, rtg hrudníku, computerová tomografie hrudníku, akutní respirační distress syndrom, plicní embolie, covid-19 pneumonie, pneumothorax, pleurální výpotek, dysfunkce bránice.

Introduction

Chest imaging is pivotal in the diagnosis and management of patients with respiratory pathologies including severe COVID-19 in the intensive care unit (ICU). In this review, the authors focus on the use of chest ultrasound (CUS) versus other routinely available imaging modalities such as chest x-ray (CXR) and the gold standard computed tomography (CT).

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For many years, CUS has been thought of as impossible and not feasible due to the very nature of the lungs being air-containing structures. CUS can be performed at the bedside when needed and waiting for a radiology report is eliminated as clinical information is acquired within a few minutes if not seconds. CUS is a portable, mobile imaging tool with a steep learning curve in contrast to other imaging modalities. Furthermore, the combination of CUS and echocardiography is extremely valuable in the assessment of not only lung pathology, but also in assessing the haemodynamic parameters of a patient.

CUS is also excellent in the diagnosis of pleural and diaphragmatic pathologies, guiding thoracentesis and aiding in the evaluation of pulmonary consolidations [1–4]. This reduces serial bedside CXRs, thus reducing unnecessary radiation exposure (for reference, one non-contrast chest CT (an effective dose of about 8 millisieverts (mSv)) equals about 400 chest anterior-posterior (AP) CXR examinations as one CXR has an effective dose of about 0.02 mSv). There is also a reduction in the potential side effects of contrast administration during CT, notably hypersensitivity reactions to contrast medium, contrast-induced nephropathy (CIN), and rarely, contrast-induced thyroid dysfunction [5–8].

Bedside CXR is limited in diagnosing pulmonary consolidations, small to moderate pleural effusions, small to moderate-sized pneumothoraces or alveolar-interstitial syndrome [7–10] due to technical complications which arise when a bedside CXR is performed. The spatial resolution of bedside CXR is compromised by the fact that the patient cannot do a breath hold; thus, there is movement of the thorax. Furthermore, due to film cassette positioning (between the bed and the patient), the x-ray beam is shortened because of a shorter acquisition distance (3). This leads to suboptimal images which can be challenging to accurately interpret.

In critically ill patients who are extensively monitored by a number of invasive devices, CT scanning not only is cumbersome, but transportation to the CT suite and positioning of such patients in the gantry is a task in itself, with a potential for significant respiratory and haemodynamic derangements for the patients [11–13]. The limitations brought on by the aforementioned radiology methods make CUS the go-to method of assessing critically ill patients.

COVID-19 pneumonia and ARDS

During the worldwide pandemic due to COVID-19, there has been a greater need for accessible, reproducible, and safer means of imaging. In this regard, CUS can be extremely useful (just as it was during the H1N1 pandemic) to evaluate patients at the bedside for the evolution (either progression or regression) of the disease and the efficacy of any supportive treatment initiated for COVID-19 pneumonia, and can confer an easier, dynamic method of assessment since an ultrasound machine is widely available in specialised ICUs.

It needs to be stressed, however, that imaging findings related to COVID-19 are not specific to COVID-19 and a definitive diagnosis inevitably involves other methods such as microbiology sampling, serology and bronchoscopy, as similar imaging findings can be seen in cardiac and other pulmonary pathologies, e.g. in cardiac failure, other viral or bacterial pneumonias, and chronic pulmonary diseases [13, 14].

Chest radiographic imaging (CXR and CT)

CXR can help to guide therapy after the first 48 hours (hrs) of clinical COVID-19. Nonetheless, CXR performs inferiorly to CUS in terms of diagnosing COVID-19 associated pulmonary findings [1, 2, 4, 5, 15, 16] (Figs. 1 and 2). Changes seen on lung ultrasound and clinical presentation (Fig. 2) precede those seen on CXR and CT (Figs. 1 and 3). Beyond the first 48 hrs, CT has shown far more sensitivity than CXR where discrete lung changes are involved [17].

COVID-19 pneumonia has an evolution, starting off as microvascular damage which then progresses to acute fibrinous and organising pneumonitis (AFOP) or, less commonly, to diffuse alveolar damage (DAD). On CT, it typically has these features: predominantly peripheral ground-glass opacities (GGOs) with or without consolidations or crazy paving, with a bibasilar predominance [17–21] (Figs. 3 and 4).

Fig. 1. *Spectrum of COVID-19 lung changes in patients admitted with dyspnoea on oxygen. A normal CXR (A) can be seen, as well as the bilateral interstitial pattern (B) or visible infiltrates (C). Images reproduced with permission from the archives of the Department of Diagnostic Radiology, University Hospital Bulovka, Prague, Czech Republic*

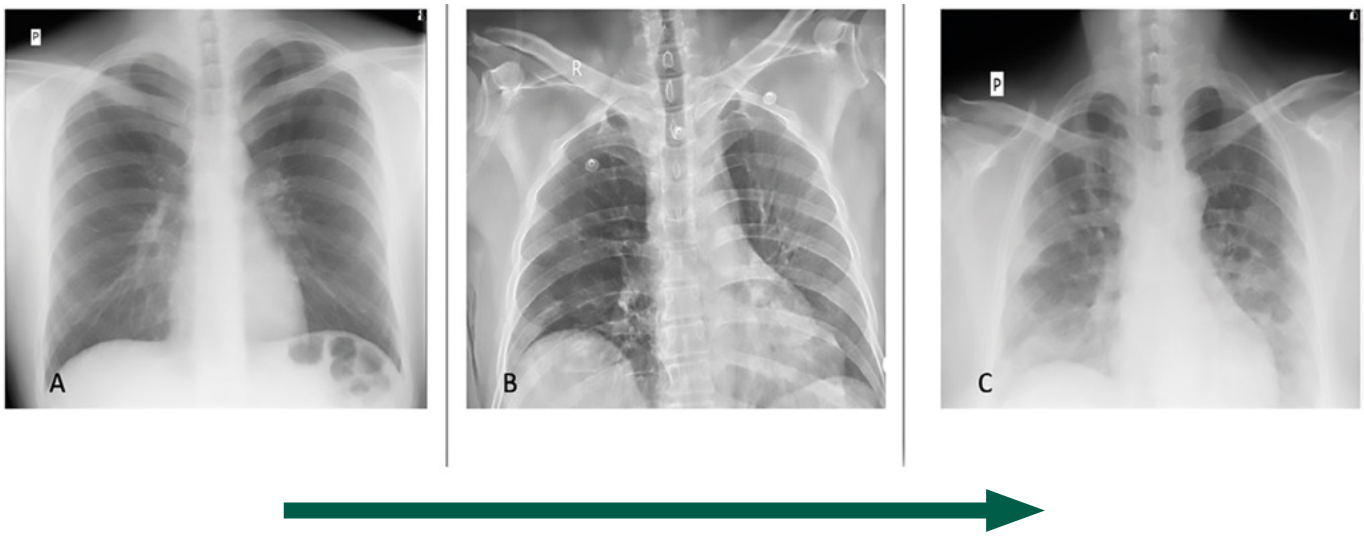


Fig. 2. *Early stage of severe COVID-19 on CUS and echocardiography, the patient is after intubation due to hypoxaemic respiratory insufficiency. CXR on admission and 24 hrs later depicts delayed progression on radiographic methods: A apical CUS with multiple B3-4 lines, B basal CUS with coalescent B lines, C apical four-chamber view with dilated right ventricle and severe tricuspid regurgitation, D trans-tricuspid CW Doppler gradient of 60 mm Hg in a patient with absent cardiac history, E CXR at the time of CUS and echocardiography showing CXR changes disproportionate to disease severity, F CXR after 24 hrs showing severe ARDS; note the bioimpedance belt across the chest. Pulmonary embolism was excluded by a CTAG prior to admission*

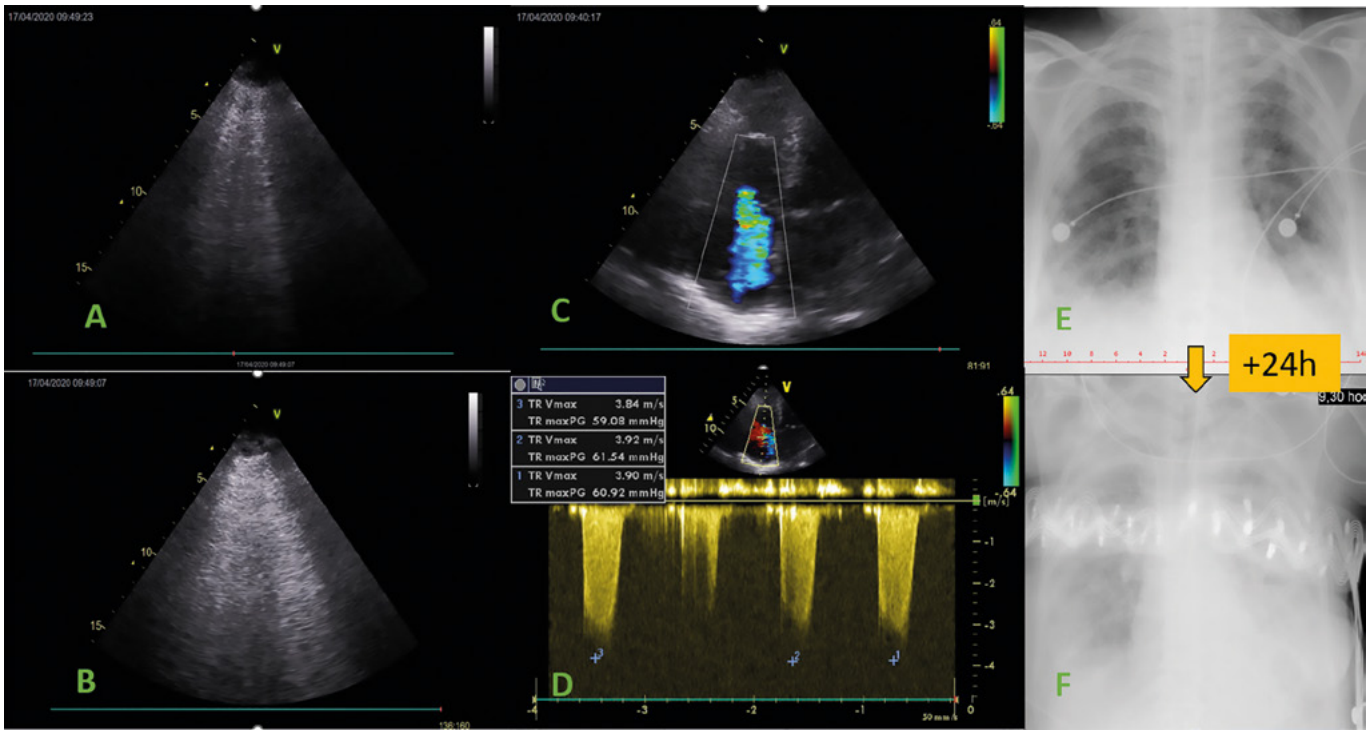
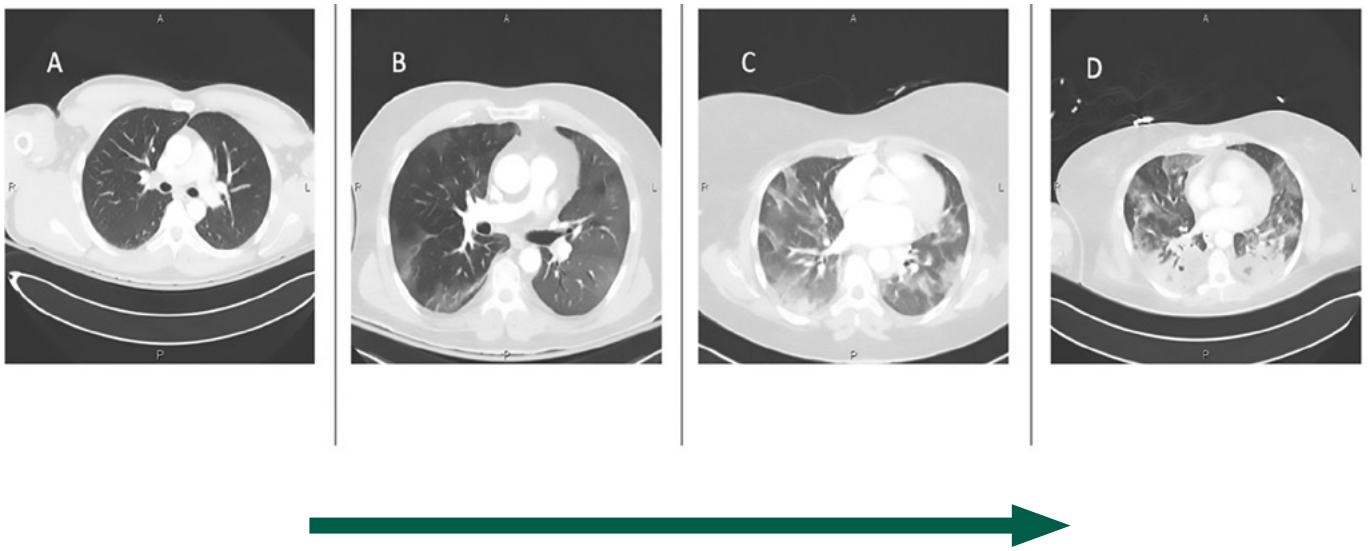


Fig. 3. *Progression of COVID-19 infection on CT during 72 hrs in a patient with hypoxaemic respiratory failure. Images reproduced with permission from the archives of the Department of Diagnostic Radiology, University Hospital Bulovka, Prague, Czech Republic*



Furthermore, two CUS phenotypes in COVID-19 pneumonia have been proposed: 1) An L phenotype indicating preserved pulmonary compliance correlating with ground-glass opacities located in the periphery on CT and, 2) An H phenotype indicating significantly reduced pulmonary compliance seen in severe ARDS and with a correlating picture of CT consolidations [5, 22–24].

A severe COVID-19 infection is fraught with bacterial, viral, and fungal superinfections in up to 29% of patients on admission. Many patients suffered from COVID-19 associated multidrug-resistant bacterial infections, fungal (Aspergillus) infections, pneumocystis, and viral infections and reactivations (CMV, HSV) during their ICU stay [25–27]. These numbers have risen particularly in the first half of 2021 and were associated with increased ICU and hospital mortalities worldwide [28].

CT scanning has been utilised worldwide since the beginning of the pandemic. At this stage with limited access to high quality bedside antigen tests specific for viral load and with a sensitivity above 93% [29], imaging played an important role in the triage of patients. The potential of CT as a triage tool has already been demonstrated in the first datasets

from Wuhan in the early 2020 [30]. The Czech Society of Radiology has advocated for the use of CT on admission; however, the algorithm concedes to CT findings not being specific solely to the COVID-19 infection [17]. In contrast, due to the increased volume of CT examinations during the pandemic, a number of societal guidelines recommended against the use of CT as a screening tool [18–21]. A widespread use of CT in every patient with severe COVID-19 has been disregarded by several national and international radiology societies. The Radiologic Society of North America, the Canadian Society of Thoracic Radiology, and the Canadian Association of Radiologists have advocated against routine CT in every respiratory insufficiency due to unspecific findings and lack of sensitivity in the first 48 hrs. Instead, the diagnostic effort should be channelled towards appropriate sputum testing and CT should be limited to diagnosing complications such as lung abscesses or empyemas, or in cases where CT imaging can change the clinical management of the patient [18–20].

In summary, the pandemic era should not change the attitude of a critical care physician to chest CT in a patient with respiratory insufficiency. Alleged changes in therapy based on the calculated percentage of diseased lung parenchyma on radiology methods are not supported by any relevant clinical data. Moreover, in daily practice, we have seen multiple patients with a rather poor correlation between their radiology imaging findings and clinical status (Figs. 2 and 5). Detection of viral load, i.e. of a living virus, implies infectiousness, the need for virostatic therapy, and is not correlated to findings on chest imaging [31].

Physicians should avoid extremes supported by an inappropriate use of CT. An example is denying treatment to someone with excessive lung involvement on CT and with more than seven days of clinical findings, which has been part of some guidelines [32]. Coronavirus mutations (Beta, Delta) replicate often beyond 10 days, especially in an immunocompromised population where half of the patients may still be antigen positive [33, 34]. Therefore, parenchymal changes may also resolve slowly and, in many patients, may persist regardless of clinical resolution of the disease.

Chest ultrasound

CUS has demonstrated its usefulness during the pandemic when evaluating patients at the bedside for the evolution of the disease and the efficacy of treatment initiated for COVID-19 pneumonia. The ultrasound machine has become widely available in intensive care units and is easier to clean and disinfect than other radiographic imaging methods. This reduces the potential of complicated transport to the CT suite for imaging indicated for establishing the diagnosis of COVID-19. Unless other confounding factors are at play which can only be assessed by CT, CUS also reduces unnecessary infectious and radiation exposure of both personnel and patients [9, 23, 35, 36].

CUS should be performed systematically in an algorithmic way. The comprehensive 12-zone method (6 zones per hemithorax) of examining

Fig. 4. *COVID-19 on CT scans: four different patients with various disease severity: A oxygen by face mask (O2 mask); B non-invasive ventilation; note the asymmetry with predominant right lung ground-glass opacities; C IPPV and VV-ECMO, acute fibrinous organising pneumonitis; D IPPV and VV-ECMO, diffuse alveolar damage*

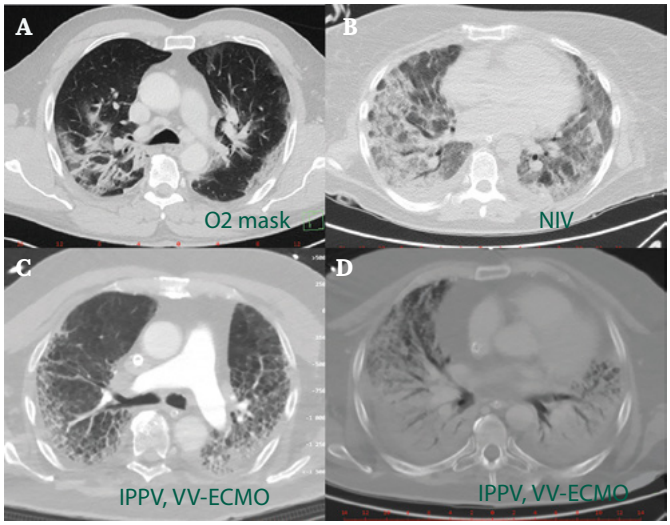
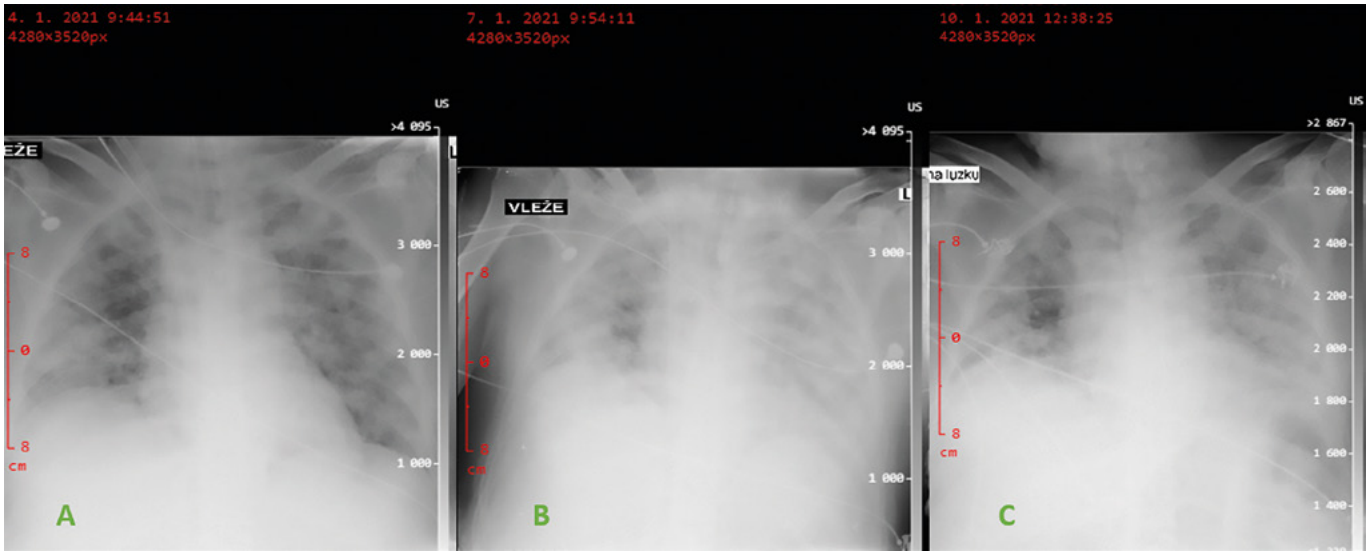


Fig. 5. *The course of a severe global respiratory failure on bedside X-ray documents a poor correlation between CXR lung findings and disease severity: A CXR on Day 2 after cannulation of VV-ECMO for severe hypoxia in an intubated patient with severe COVID-19 ARDS; B CXR on Day 5 pre-extubation on VV-ECMO; note the radiographic worsening of the bilateral parenchymal opacities contrasting with grossly improved lung mechanics allowing for extubation; C CXR on Day 8, the patient is extubated on an oxygen face mask and with the ECMO cannulae removed, i.e. not seen on X-ray. Overall gross improvement is not followed by the bilateral lung findings on X-ray, similar to A (one day after admission)*



Tab. 1. *CUS derived lung score, adapted from Bouhemad and Mongodi (37, 38). Pleural involvement is described as subpleural consolidations and thickened pleura. Tissue-like pattern = consolidation*

Lung score	Description	Classic interpretation on LUS	Modified interpretation on LUS
Score 0	Normal aeration	A lines, 2 B-lines maximum	A-lines, 2 B-lines maximum
Score 1	Moderate loss of aeration	≥ well-spaced B lines	Involvement of the pleura < 50 %
Score 2	Severe loss of aeration	Coalescent B lines	Involvement of the pleura > 50 %
Score 3	Complete loss of aeration	Tissue-like pattern	Tissue-like pattern

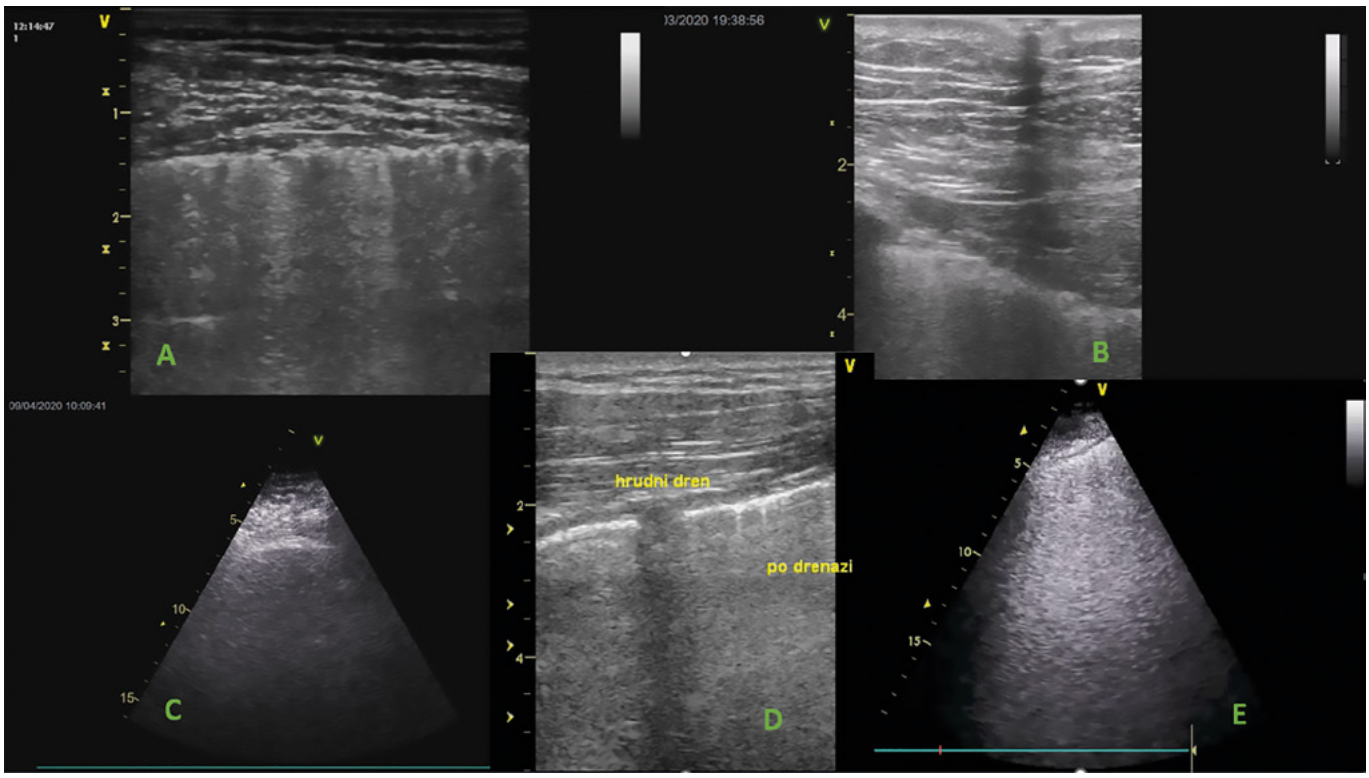
the lungs is reproducible and can quantify pulmonary involvement [37–40]. A complete examination of all the lung zones (anterior and posterior divided by mid-axillary line) needs to be performed. Each zone is scored in four degrees from 0-3 depending on the pattern of B-lines and A-lines that is visualised by the investigator. By assessing each zone, one should be able to describe and quantify the perceived lung changes which will eventually culminate to a score, the maximum of which is 36 (Tab. 1). An overall degree of alveolo-interstitial syndrome can be quantified as mild disease (score 1-5), moderate disease (score 5-15), severe disease (score > 15) [15, 16, 37].

Pulmonary changes due to COVID-19 can be seen on CUS as an interstitial profile with singular or confluent B-lines originating from the surface of the pleura and a thickened and irregular pleural line (resulting in diminished lung sliding). With further progression, small patchy subpleural consolidations are seen; then, the evolution and progression of these subpleural consolidations can be found in a picture mirroring the pattern of ARDS that would necessitate ventilatory support [7, 8, 13, 23] (Figs. 2 and 7).

CUS can also help to triage a patient to admission to hospital or even to an intensive care unit. If a patient is exhibiting symptoms of COVID-19 and presents with the A-pattern/profile, significant COVID-19 pneumonia can be largely excluded. With a progression from the prevailing A-profile in the anterior and apical regions towards the B-lines, the question raises as to how many B-lines and what B-line density there are as they correlate with ground-glass opacities, consolidations, and crazy paving seen on a CT scan. The condition is easier to diagnose with progression to the confluent B-lines, lung consolidation with or without dynamic bronchogram, and the 3rd to 4th degree of the alveolo-interstitial syndrome often with pleural enhancement (Fig. 4). At this stage, CUS findings are highly specific for some of the advanced stages of ARDS including COVID-19 related (Fig. 6) and, therefore, the patient will likely require ICU admission [6, 23, 38, 41].

Volpicelli has suggested triaging patients based on CUS finding into four groups as follows: 1) high probability CUS pattern; 2) intermediate probability CUS pattern; 3) alternate CUS pattern; and 4) low probability CUS pattern [1, 41]. This triaging system also allows for finding probable alternate diagnoses that may be masquerading as the COVID-19 disease. The intermediate pattern with less dense B-lines (e.g., B4-7) may not correlate with the aforementioned CT picture of COVID-19 interstitial pneumonitis or ARDS, and those patients may benefit from a CT examination to confer a differential diagnosis [6, 42] (Figs. 3 and 4). The high probability CUS group has been described as potentially indicating peripheral ground-glass opacities on CT and, thus, as a compelling predictor of an impending positive RT-PCR test. The light beam sign (described as a linear artefact seen emerging and disappearing with respiration) in early disease seen in the high probability LUS group has been described as a CUS sign potentially

Fig. 6. *CUS findings of severe COVID-19: A enhancing pleura with multiple B3-4 lines, B thickened pleura with coalescent B-lines on the left side of the image, correlating with ground-glass opacities; C thickened pleura due to inflammation; D pleural space after drainage of pneumothorax due to barotrauma; note the chest drain in between the pleural layers confirming full lung expansion (35); E coalescent B-lines, 3rd degree alveolo-interstitial syndrome and ARDS*



indicating acute disease and peripheral ground-glass opacities on CT and, thus, as a compelling predictor of an impending positive RT-PCR test [11, 41, 43].

Echocardiography greatly increases the specificity of isolated CUS findings. SARS-CoV-2 related endothelial inflammation raises pulmonary artery pressure causing RV overload, especially when on mechanical ventilation (Fig. 2). Those patients may, however, present with a negative CT angiography, also due to the limited sensitivity to pick up subsegmental thrombosis which is a nature of later developing acute fibrinous organising pneumonitis (AFOP) with obstructive lung mechanics [44]. It is, however, understood that in patients who have no documented pulmonary or heart disease, it can take about 30-50% of pulmonary bed obstruction to induce pulmonary hypertension. Those with an existing pulmonary or heart disease, minor derangements of the pulmonary circulation due to inflammatory changes and microthrombi are enough to produce pulmonary hypertension [45].

Given the prothrombotic nature of the COVID-19 infection, pulmonary embolism (PE) has a cumulative incidence of as much as 30% according to the literature, and is mostly seen in ICU patients [45–48]. These patients are routinely reffered to CT pulmonary angiography (CTPA) for the diagnosis. Pulmonary angiography diagnostic yield indicated upon positivity of d-dimers reaches 27%-30%, with the remainder of patients showing no pathology [48–50]. Combining CUS with echocardiography and Duplex ultrasound of the legs (multiorgan ultrasound) can further aid in the early detection of pulmonary embolism (PE) and avoid CTPA, thus reducing the radiation burden in all patients with suspected pulmonary embolism and in those who cannot undergo CTPA because of other factors [49, 50]. On CUS, a pulmonary infarct due to PE may be seen as a triangular subpleural consolidation in addition to suggestive echocardiography/Doppler findings [51].

The use of CUS in COVID-19 offers the detection of complications such as pneumothorax, pleural effusion, empyema, atelectasis, or cardiogenic pulmonary oedema [35, 36, 52, 53].

Pleural effusions are not commonplace in COVID-19 patients with incidences reaching 4%, and may suggest an alternate aetiology such as arrhythmia-induced heart failure, stress cardiomyopathy, or polyserositis [15]. The incidence of barotrauma in the most severe forms of COVID-19 hovers around 12-15% and reaches 26% in high-volume ECMO centres admitting patients and also due to their mechanical ventilation associated complications [28]. A prompt diagnosis of pneumothorax with bedside ultrasound is essential in ventilated patients [35] (Fig. 7).

CUS assessment can also help to guide positioning and proning seeing that the posterior zones of supine patients are the most affected coupled with physiologic hypostatic-hypoventilation changes occurring in the dorsal parts of the lungs whilst the anterior and lateral zones may be better aerated at CUS. The lung score can be utilised to monitor the dynamics of lung aeration of the patient [54].

With dysfunction of the diaphragm, there is a reduced diaphragmatic amplitude and thickening of the diaphragm with a concomitant adaptation of the extra-diaphragmatic apparatus whence the extra-diaphragmatic muscles are recruited and this manifests, for example, as a thickening of the parasternal intercostal muscles [22, 23].

By incorporating the lung ultrasound score and echocardiography, mechanical ventilation weaning failure can be anticipated by visualisation of aeration changes of the lung on LUS before and during the weaning. When patients are placed on mechanical ventilation with positive pressures, there is a reduction in venous return, preload, and afterload of the left ventricle (LV). Therefore, when a patient is liberated from mechanical ventilation, the ensuing decrease in the intrathoracic pressure raises the central blood volume, systemic venous return, preload and afterload of the LV. This is seen clinically as a subsequent rise in LV filling pressure and, ultimately, pulmonary oedema on CUS as an increase in the number of B-Lines [12, 38].

Limitations of CUS

There are several limitations related to performing and accurately interpreting CUS. CUS is not able to visualise deep lung parenchyma and mediastinal structures. The inability to detect central lesions not abutting the pleura can be particularly limiting in morbidly obese patients with a thick chest wall. Typical limitations in the intensive care setting are also subcutaneous emphysema and extensive wound dressings. A chronic interstitial disease can make interpretation of the CUS findings difficult as can chest wall deformities and technical limitations [1, 5, 7].

Conclusion

CUS is an excellent tool in the assessment of various pulmonary pathologies due to the fact that there is virtually no radiation involved and it is easy to perform at the bedside. Especially in ICU patients, there is a reduction in cumbersome transport to the CT suite and in suboptimal bedside CXR limiting adequate diagnosis. An array of pulmonary and extrapulmonary pathologies can be assessed and accurately diagnosed. However, there may be limitations impeding the CUS examination, especially subcutaneous emphysema. In the recent COVID-19 atmosphere, there is a huge potential for CUS in being used as a tool in triage, in indicating invasive measures, in the assessment of response to therapy, and as a guide in mechanical ventilation setting, weaning and patient positioning.

Take-home message: Imaging methods in severe COVID-19

- Chest ultrasound (CUS) is the method of first choice in suspected severe COVID-19.
- CUS becomes far more specific if combined with at least basic echocardiography protocol.
- Radiographic methods (CT, X-ray) lack sensitivity in the first 48 h of the disease, i.e. 5-6 days after acquisition including the incubation period.
- Computed tomography (CT) is not indicated as a default diagnostic method in every patient with respiratory insufficiency.
- Calculation of percentage of diseased lung parenchyma on CT has a limited prognostic value and does not possess any therapeutic implications.
- Absence of significant alveolo-interstitial syndrome on CUS may exclude lung involvement and severe respiratory COVID-19 with sufficient specificity.
- A significant alveolo-interstitial syndrome on CUS is specific for COVID-19 pneumonitis and ARDS.
- CT may help in triage of intermediate severity patients where a lack of CUS specificity, if combined with echocardiography, cannot exclude COVID-19.

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