Application of Critical Care Ultrasound in Patients With COVID-19: Our Experience and Perspective

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***Abstract*— Up to April 4, 2020, the novel coronavirus disease-2019 COVID-19 has affected more than 1 099000 patients and has become a major global health concern. World Health Organization (WHO) has defined COVID-19 as a global pandemic. Critical care ultrasound (CCUS) can rapidly acquire the image of lung and other organs and demonstrate the pathophysiological changes to guide precise therapy in COVID-19 pneumonia without radiation or interfering with personal protective equipment. In addition, the application of CCUS can cover the whole courses from the fever clinic to the intensive care unit to improve the treatment. We would like to present the CCUS features about COVID-19 pneumonia and share the application experience of CCUS in Wuhan, China, and hope it works for physicians worldwide to solve the problem and improve the outcome.**

***Index Terms*— Coronavirus disease-2019 (COVID-19), critical care ultrasound (CCUS), experience, lung ultrasound (LUS).**

I. Introduction

SINCE the novel coronavirus disease-2019 (COVID-19) outbreak in December 2019 [1]–[4], there has been rapid spread across the world [5]. Due to the highly transmissible nature of COVID-19 [1], [6], [7], the full-body personal protective (PPE) is essential to protect the health providers, but this severely limits the traditional physical exam. For a primarily respiratory illness, such as COVID-19, the lung exam is critical but impeded by PPE [8]–[11]. Fortunately, critical care ultrasound (CCUS) can accurately evaluate the pathophysiological changes at the bedside on COVID-19 patients without interfering with PPE. One of the authors is among the first batch of medical staff from the West China Hospital to assist at a second senior hospital located near the outbreak epicenter in Wuhan, China. During a period of 50 days, about 80 COVID-19 patients were admitted to this 17-beds intensive care unit (ICU). As the COVID-19 cases reported by other investigators, many patients had rapidly evolving organ damage diseases, including acute respiratory distress syndrome (ARDS), shock, and renal failure [12]–[15]. In our ICU, basic lung and cardiac ultrasound exams were performed daily on each patient, with advanced assessments reserved for more severe cases. We would like to present the CCUS features about COVID-19 pneumonia we summarized during the past 50 days in this article, and hopefully, it can be helpful for physicians worldwide to evaluate the patients more efficiently and thoroughly while under the full protection of PPE.

Manuscript received July 2, 2020; accepted August 27, 2020. Date of publication September 1, 2020; date of current version October 26, 2020. This work was supported in part by the Scientific and Technological Project of New Coronavirus Pneumonia in West China Hospital of Sichuan University under Grant HX-2019-nCoV-045 and in part by the Key project of Sichuan Science and Technology Department under Grant 2019YFS0449. *(Corresponding author: Wanhong Yin.)*

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Digital Object Identifier 10.1109/TUFFC.2020.3020628

II. Methods

A. Ethics Declarations

The study was approved by the Ethics Committee of West China Hospital Review Board for Human Research, Chengdu, China, with the following reference number 2020167 and was registered on the Chinese Clinical Trials. Trial registration: ChiCTR2000030185.

B. Description of Participants and CCUS Exam Protocol

A total of 63 critically ill patients with COVID-19 pneumonia received 177 CCUS examinations between February 14, 2020, and March 25, 2020.

Patients were placed in a 30° semirecumbent left lateral position when performing a cardiac ultrasound, and supine position when performing lung, renal, and gastric antrum ultrasound. And patients will be placed in a 90° left or right lateral position when scanning the posterior chest wall lung ultrasound (LUS).

The ultrasound instrument (Wisonic Navi S, Shenzhen, China) had a low-frequency convex probe (3.5 Mhz) used for lung, kidney, and gastric images collection, and a phased array probe (2.5 Mhz) that was used for the echocardiography images collection. In order to obtain better LUS images, we have optimized the ultrasound image frequency as follows: 1) spatial compound imaging: turn OFF; 2) persistence: decrease the frame persistence to 1 or turn OFF.

Based on the critical care chest ultrasonic examination (CCUE) protocol [16], five standard views of the echocardiography and the measurement of each view were recorded. We used a 12-zone LUS examination protocol according to the

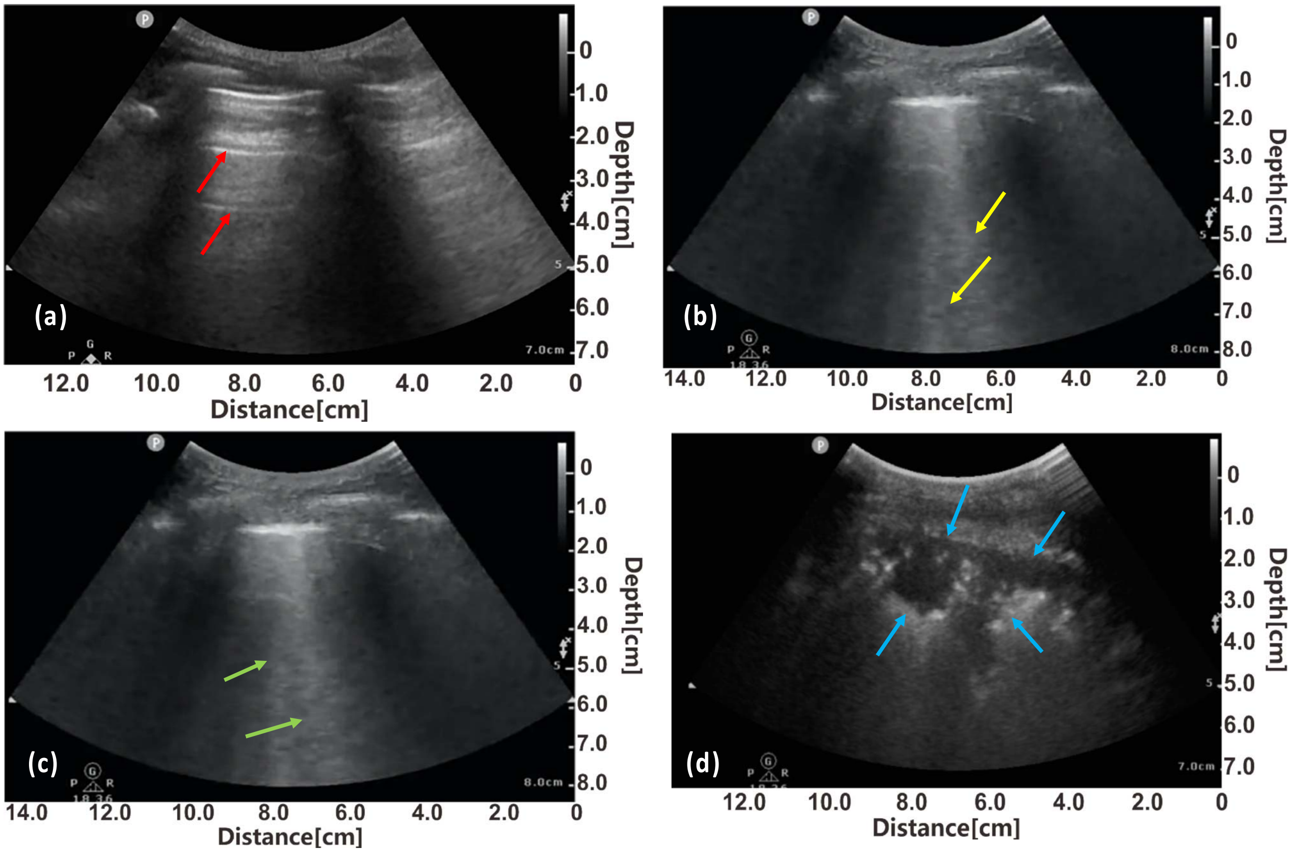

Fig. 1. Different LUS patterns [19]. (a) A-lines (hyperechoic horizontal line, marked by red arrows). (b) B1-lines (isolated hyperechoic vertical line, marked by yellow arrows). (c) B2-lines (coalescent hyperechoic vertical line, marked by green arrows). (d) Lung consolidation (tissue pattern, marked by blue arrows).

technical specification for the clinical application of critical ultrasonography [17], [18]. The LUS exam was required to identify four ultrasound aeration patterns: 1) normal aeration (N): the presence of lung sliding with A-lines or fewer than two isolated B-lines; 2) moderate loss of lung aeration: multiple, well-defined B-lines (B1-lines); 3) severe loss of lung aeration: multiple coalescent B-lines (B2-lines); and 4) lung consolidation (C), the presence of a tissue pattern characterized by dynamic air bronchograms (Fig. 1) [18], [19]. The A-lines reflect normal lung aeration of the examined zone [Fig. 1(a)]. The B-line is a discrete, laser-like, vertical, hyperechoic image that arises from the pleural line, extends to the bottom of the screen without fading, and moves synchronously with respiration [Fig. 1(b)]. Multiple B-lines (B2-line) are the sonographic sign of lung interstitial syndrome and their number increases along with decreasing air content [Fig. 1(c)]. When the air content is further decreased, such as in lung consolidations, the lung may be directly visualized as solid parenchymas, like the liver or the spleen [20], [21] [Fig. 1(d)].

Renal resistive index (RI) measured by Doppler ultrasonography, allowing to explore noninvasive renal hemodynamics, has been used to predict renal dysfunction. Increased RI has been shown to be associated with renal failure [22], [23]. Therefore, we used sonography and color Doppler mode to localize the kidneys and interlobar arteries. Pulse-wave Doppler was used to measuring blood velocities in the interlobar arteries. Peak systolic and end-diastolic velocities were measured on three consecutive pulses. RI was calculated as follows: RI = (peak systolic velocity − end-diastolic velocity)/peak systolic velocity [17], [22], [23].

Saving 4–6 s for each ultrasound video, ultrasound examination findings and clinical data were collected in a standardized recorded form.

III. Results

A. Lung Ultrasound in the Rapid Screening and Early Diagnosing of COVID-19 Pneumonia at Community Hospitals

We used LUS to rapidly recognize those patients who are more likely to have significant lung changes [for example, the peripheral distribution of ground-glass opacities (GGOs)], aiming to better triage of large group of patients under stressful and chaotic situations. Fig. 2(A) shows a typical CT scan image about one patient with COVID-19 pneumonia in the early stage, and the surrounding ultrasound images [Fig. 2(a)–(e)] are the corresponding LUS patterns, such as B-lines (multifocal, discrete, and confluent), small subpleural consolidation, and thickened pleura line, which are the main LUS features in COVID-9 pneumonia. AB1 sign is defined as the interface of the normal lung and the GGOs [Fig. 2(d)], which we found to be valuable in confirming the multifocal feature of B-lines in COVID-19 pneumonia.

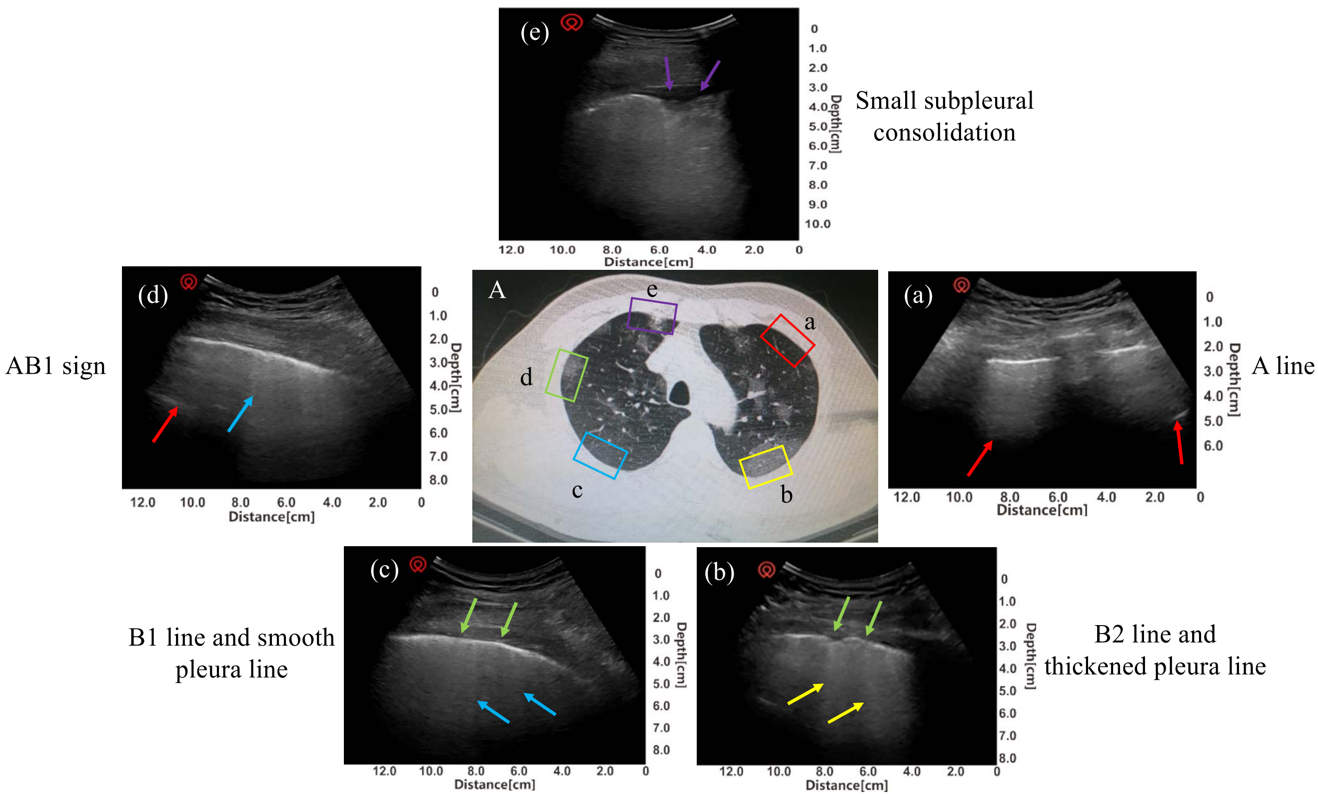

Fig. 2. LUS patterns and corresponding CT images about patients with COVID-19 pneumonia in an early stage. (A) Pulmonary CT image in patients with novel coronavirus infected in an early stage. CT scan presented variably, such as manifestations of the normal lung (marked by red square), pulmonary infiltrating shadow (marked by yellow square), ground-glass opacity (marked by blue square), small exudation (marked by green square), and small subpleural nodule(marked by purple square). The LUS images surrounding the CT scan are the corresponding LUS patterns of different CT presentation. Normal lung on CT scan corresponded with A-line [marked by red arrows in (a) and (d)] at LUS; a pulmonary infiltrating shadow on CT scan corresponded with confluent B-lines (B2-line) [marked by yellow arrows in (b)] and thickened pleural line [marked by green arrows in (b)]; ground-glass opacity corresponded with discrete B-line (B1-line) [marked by blue arrows in (c) and (d)] and smooth pleura line [marked by green arrows in (c)]; small exudation correspond with AB1 sign [marked by red and blue arrow in (d)], which presented as normal A-line at the left-hand side and B1-line at the right-hand side on an LUS view and small subpleural nodule corresponding small subpleural consolidation [marked by purple arrows in (e)]. Those LUS signs found on the same patient combined with clinical manifestation may suggest the diagnosis of COVID-19 pneumonia.

B. Lung Ultrasound Assisting Early Selecting Patients With COVID-19 Pneumonia at Module Hospitals Who Need Transferring to Designated Hospitals

During the COVID-19 outbreak at Wuhan, COVID-19 confirmed patients with mild symptoms were centralized to so-called "module hospitals," and each physician at those hospitals needs to take care of 30–40 patients. Due to the large number of patients gathering at module hospitals, the shortage of CT equipment was a key limitation. Therefore, rapid bedside LUS was widely utilized at those "module hospitals" to view the imaging changes of the lung if we see a tendency of deterioration of clinical symptoms. The LUS examination results showed the air content of the lung is decreased, which manifested as the area of consolidation extends further than the day before [Fig. 3(e) and (f)], the AB1 sign [Fig. 3(a)] turns into the B2-line [Fig. 3(b)], and the B2-line area [Fig. 3(c)] becomes consolidated [Fig. 3(d)] when patients with COVID-19 pneumonia were getting worse. Those changes guided targeted CT reexamination and timely transfer to the designated hospital for advanced care. On the other hand, we found that in the patients whose pneumonia is improving, the lung ultrasonography manifested as lung consolidation area decreases, the LUS pattern changed from consolidation to B-lines, and the B-lines turn into A-lines, which indicated the air content is increased.

C. Critical Care Ultrasound Applying to Evaluate Therapeutic Effects and Alert for Early ICU Admission

In the hospital, COVID-19 patients were given standardized treatment as guidelines provided by an expert group of government [24]. A pulmonary image is an important modality to evaluate the therapeutic effects on top of clinical symptoms and laboratory tests. Under the circumstance of shortness of CT and the risk of transportation to the radiology department, we daily perform LUS at the bedside to evaluate the progress of pneumonia and early identifying lung complications in our unit in Wuhan. And we found that when a patient's clinical condition is deteriorating, the LUS patterns are also getting worse, which requires the caregivers to adjust the treatment plan (for example, transfer to ICU and intubation). Furthermore, patients who need to be admitted to ICU are more likely to have ARDS, renal dysfunction, heart injury, and shock when we daily monitor organ function by CCUS.

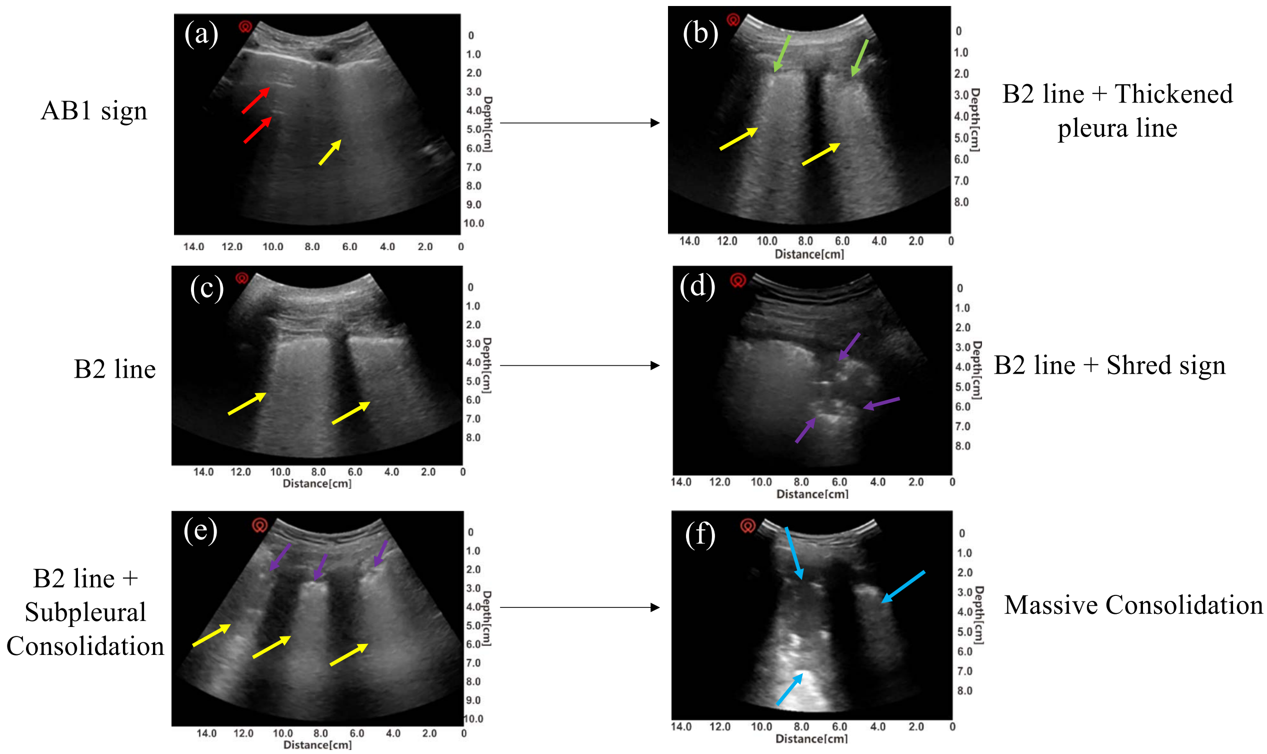

Fig. 3. LUS patterns changing in patients with COVID-19 pneumonia. It showed the LUS patterns switching in the same exam zone that the AB1 sign [marked by red and yellow arrows in (a)] turns into the B2-lines [marked by yellow arrows in (b)] combined with thickened pleura line [marked by green arrows in (b)], or B2-line [marked by yellow arrows in (c)] turns into small lung consolidation [marked by purple arrows in (d), and B2-line [yellow arrows in (e)] and subpleural consolidation [marked by purple arrows in (e)] turns into massive consolidation [marked by blue arrows in (f)] represents the deterioration of the lung disease.

D. LUS Is Used to Identify ARDS and to Detect the Pathophysiology Appropriate for Prone Position

One typical sign of severe COVID-19 infection is respiratory failure, which in most of the cases requiring intubation and mechanical ventilation. Although severe COVID-19 pneumonia and ARDS are both manifested as severe hypoxia, the treatment strategy is different as the pathophysiology behind each condition is different. We found that the LUS findings of severe COVID-19 pneumonia manifesting as an alveolar interstitial pattern, severe bilateral interstitial pattern, and mild lung consolidation, which is different from the gravity-dependent inhomogeneity of ARDS. We use LUS to detect the gravity-dependent pattern to identify ARDS patients early and to initiate prone position early. The non-ARDS patients who were characterized by bilateral diffused alveolar interstitial patterns on LUS did not require a prone position. Fig. 4(A) shows an ARDS patient with nonhomogeneously distributed alveolar-interstitial syndrome, pleural thickening, subpleural consolidations, and consolidations in gravity-dependent regions, which indicate the positive responsiveness to the prone position. After 1-h prone position, the PaO_2/FiO_2 ratio (PaO_2/FiO_2 is a parameter measured by blood gas analysis device and widely used to represent the result of lung damage. The higher the PaO_2/FiO_2, the less lung damage) raised from 80 to 160. Fig. 4(B) presents a prediagnosed "ARDS" COVID-19 patient with the severe bilateral interstitial syndrome, who did not benefit from the prone position as the PaO_2/FiO_2 did not increase accordingly.

E. Critical Care Ultrasound Utilization in Optimizing Circulation Management

The pathophysiological characteristics of late COVID-19 pneumonia and ARDS are pulmonary vascular endothelial barrier damage and increased lung leakage, which can lead to poor tolerance to even a small amount of volume overload. Fig. 5 shows the diameter of inferior vena cava (IVC) and LUS pattern changes of a patient after 1500-ml positive fluid balance. The LUS pattern was AB1 sign [marked by red and blue arrows in Fig. 5(a)] and the diameter of IVC was 0.83 cm [marked by yellow arrow in Fig. 5(b)] on the first day. After 1500 ml of positive fluid balance in 24 h, the LUS pattern turned into B2-lines [marked by green arrows in Fig. 5(c)] combined with subpleural consolidation [marked by purple arrows in Fig. 5(c)], and the diameter of IVC increased to 2.14 cm [marked by yellow arrow in Fig. 5(d)]. The above-mentioned changes in LUS patterns and IVC diameter indicated the poor fluid tolerance in patients with severe COVID-19 pneumonia.

F. Utilization of Critical Care Ultrasound to Monitor the Kidney and Gastrointestinal Function

Most critically ill patients had multiorgan dysfunction, including acute renal injury, cardiac injury, and gastrointestinal dysfunction, especially in elderly patients. Therefore, we use renal ultrasound to evaluate the size of the kidney, renal blood flow, and RI and use those images to make earlier diagnoses of acute kidney injury (AKI) and to evaluate the reversibility of

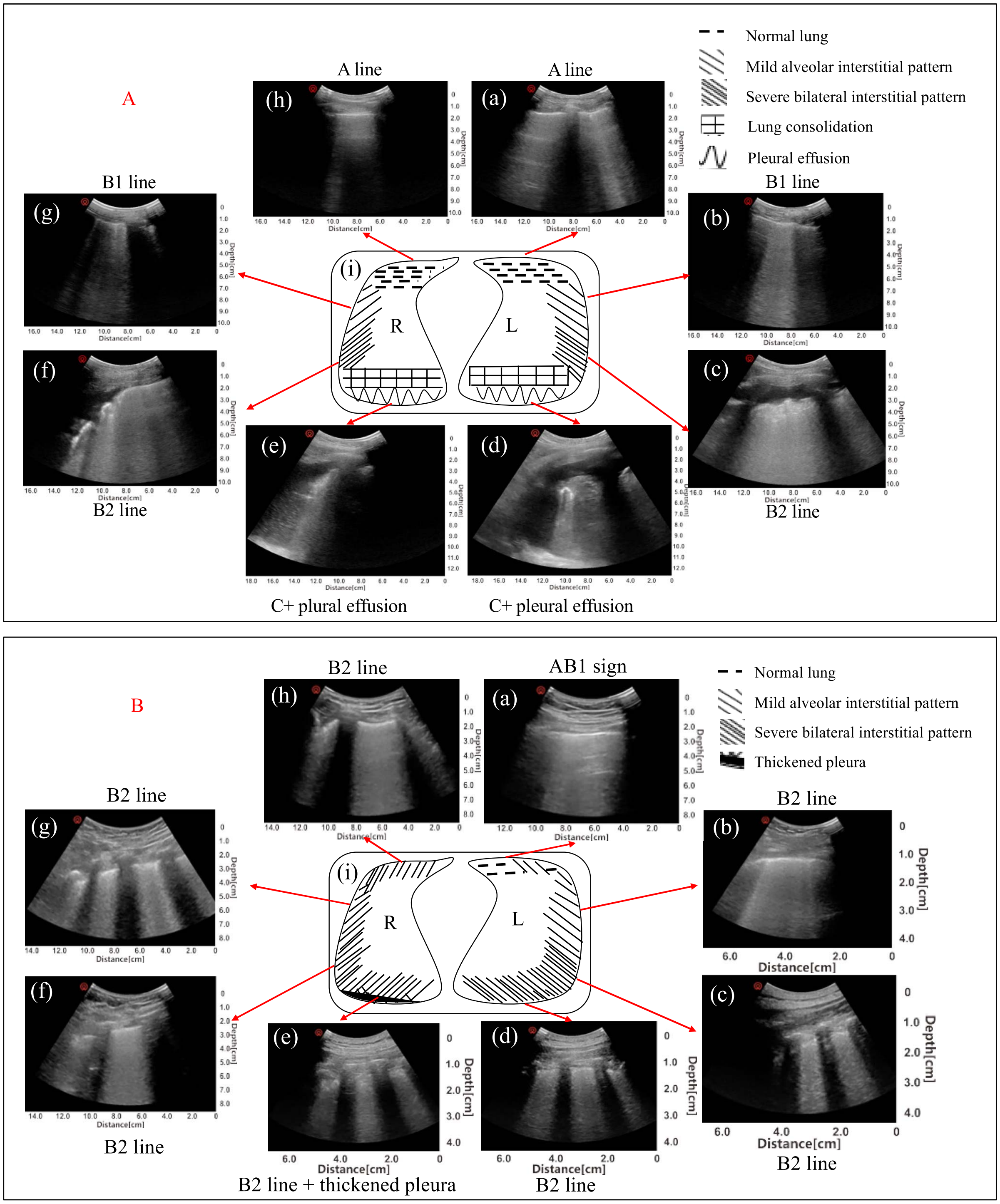

Fig. 4. Pathophysiological characteristics and lung ultrasonography images of patients with COVID-19 pneumonia and ARDS. (A) Sixty years old male diagnosed with COVID-19 pneumonia was admitted to ICU because of acute respiratory failure. His PaO_2/FiO_2 ratio was 80, and the LUS showed nonhomogeneously distributed alveolar-interstitial syndrome, subpleural consolidations, pleural effusion, and consolidations in gravity-dependent regions (i). After a 1-h prone position, the PaO_2/FiO_2 ratio was improved to 160, and the prone treatment was continued. (i) Schematic of typical ARDS, which presented as nonhomogeneously distributed alveolar-interstitial syndrome. The LUS images surrounded (i) is the corresponding LUS patterns. (B) Sixty-two years old female diagnosed with COVID-19 pneumonia was admitted to ICU because of acute respiratory failure. Her PaO_2/FiO_2 ratio was also 80, and the LUS showed diffused alveolar-interstitial syndrome and thickened pleura line at the posterior region (i), which is different from typical ARDS. After 1-h prone position, the PaO_2/FiO_2 ratio was not improved (86 compared with 80); therefore, we stopped the prone position. (i) Schematic of COVID-19 pneumonia, which presented as a homogeneously distributed alveolar-interstitial syndrome. The LUS images surrounded (i) is the corresponding LUS patterns.

renal function in ICU. Fig. 6 shows the renal blood flow and RI changes over time of a patient with AKI. And we performed a gastric ultrasound to measure antrum area and motility index to guide enteral nutrition and to identify gastric residual

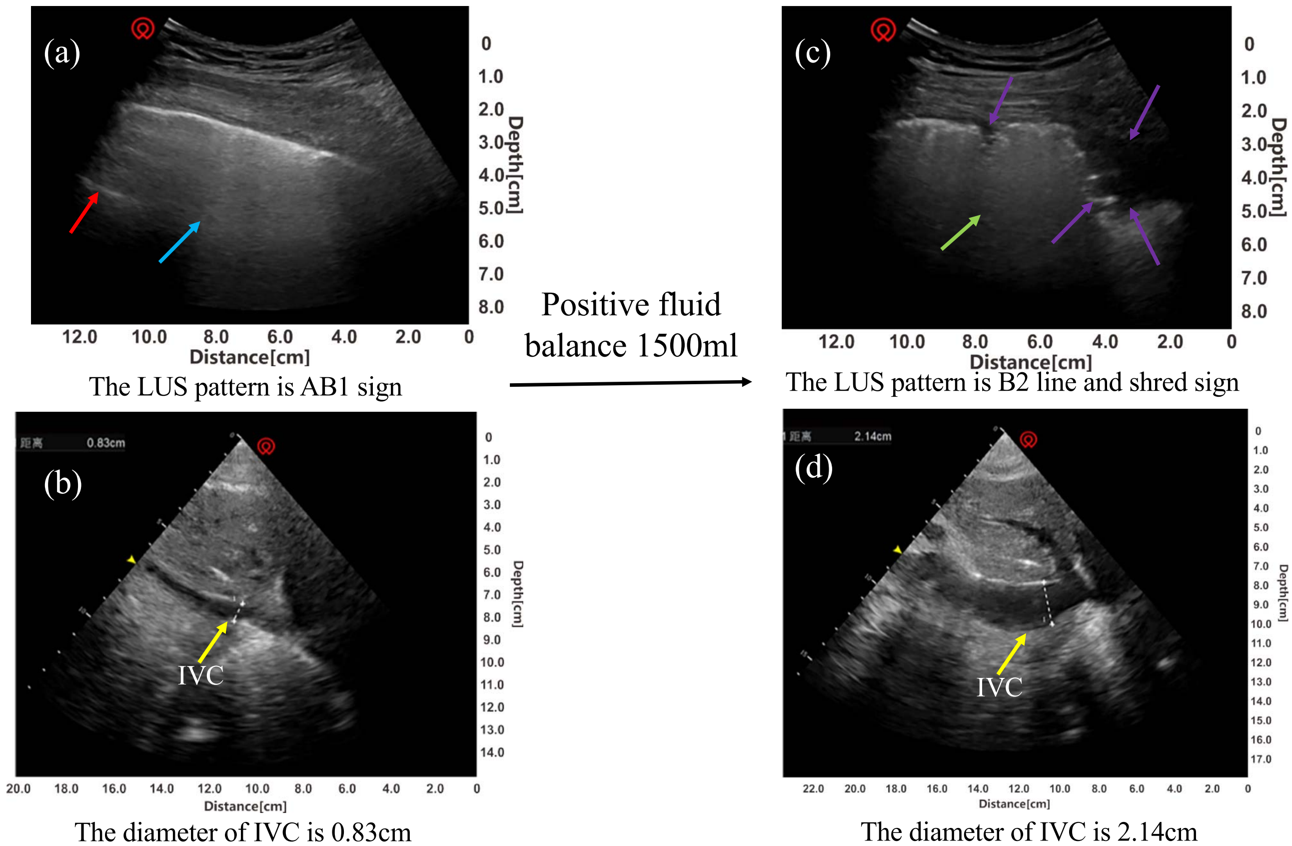

Fig. 5. CCUS can assist in circulation management. (a) LUS pattern was AB1 sign and (b) diameter of IVC was 0.83 cm on the first day. After 1500 ml of positive fluid balance in 24 h, (c) LUS pattern turned into B2-lines combined with subpleural consolidation, and (d) diameter of IVC increased to 2.14 cm.

before prone position for patients with ARDS. Furthermore, the CCUS also assisted our nurses in obtaining intravenous access to screen deep vein thrombosis before rehabilitation exercise and to evaluate the bladder urine residue on a daily basis.

IV. Discussion

CCUS has been widely used in diagnosing and monitoring treatment effects for pulmonary diseases, cardiac dysfunction, and organ dysfunction [16], [20], [25]–[27] with the added advantage of the ease of use at the point of care, repeat-ability, absence of radiation exposure, and low cost [18], [28]. The advantages supported the value of CCUS, which worked as a useful tool to solve the problem throughout the rescue of patients with COVID-19 pneumonia. Both our ICU and other units in the frontline at Wuhan agree that the performing of LUS was easy, timesaving, and low cost without the need to change PPE frequently, and the results were reproducible [8], [10], [20], [18].

Since the novel COVID-19 outbreak, a large amount of patients presented at the hospital with COVID-19 symptoms, to perform chest computed tomography (CT) scan on all of those patients is impracticable [4], [29], [30]. The situation supported the decision that some patients should receive a priority to have a CT scan than those. We used LUS to rapidly recognize and triage those patients who are more likely to have significant lung changes according to the typical LUS patterns in the early stage. The LUS findings presented in Fig. 2 were commonly found in the early stage COVID-19 pneumonia in Wuhan [11], [31], [32]. Therefore, we recommend a rapid LUS examination be performed on suspected COVID-19 patients at the ER or temporary ER. Patients with positive changes on the LUS should be prioritized for chest CT examination and then can be rapidly admitted to ICU or other isolated units for prompt treatment.

The "module hospital" is a temporary hospital that is quickly established, and its main task is to isolate mild confirmed COVID-19 patients in a centralized manner. Therefore, the number of patients is large, and the radiological examination equipment is relatively underequipped. Triaging patients who have rapidly worsening lung damage without significantly worsening symptoms to higher level hospitals in a timely manner was a huge challenge the physicians were facing.

The lung imaging changes of patients with COVID-19 pneumonia are a very important sign to evaluate the changes in the condition and the effect of treatment. However, the commonly used chest X-ray and CT examinations involve the transfer of patients to the radiology department, which increases the workload of medical staff and the patient's transport risk. And the handhold ultrasound can be worked as a mobile chest CT to screen and diagnose patients with COVID-19 pneumonia, due

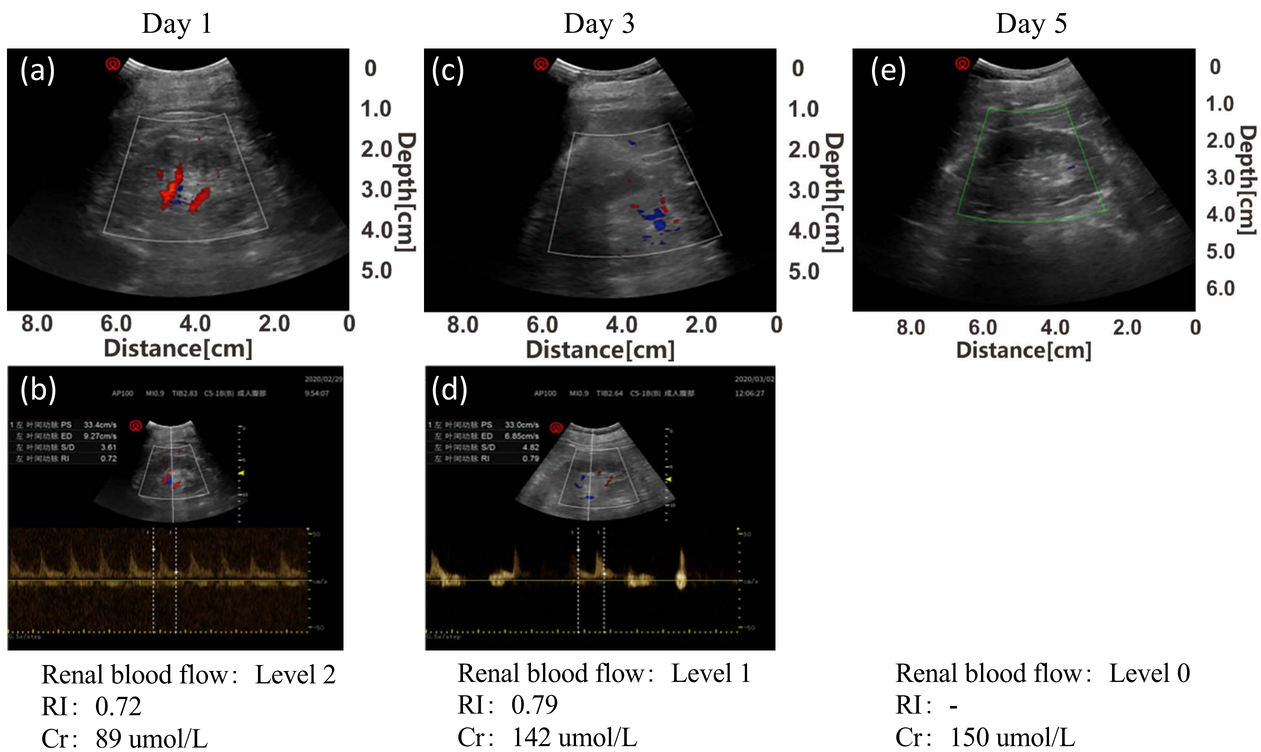

Fig. 6. Renal function changes over time. The renal ultrasound assessment for pre-AKI and during AKI of a COVID-19 patient. (a) and (b) showed the renal blood flow and RI on day 1, (c) and (d) showed the renal blood flow and RI on day 2, and (e) showed the renal blood flow on day 3, because color Doppler cannot detect blood flow, and the RI cannot be calculated.

to it gave the pictures of the lung by the different LUS patterns. When the air content of the lung is decreased, the LUS will switch to worse patterns, such as A-lines turns into B-lines, B-lines become lung consolidation, and so on. Patients with the worsening LUS signs we mentioned earlier deserve more advanced care and recheck CT immediately if possible, and those patients also were ranked higher on the list that need be transferred to a higher level hospital. Our observation recommends using LUS to triage COVID-19 patients, which can promote the efficiency of detecting critically ill patients and possibly improve clinical outcomes.

Severe patients with multiorgan dysfunction and respiratory failure who need to be intubated and mechanical ventilation are transferred to ICU. Therefore, we had to be very cautious whether the ARDS and multiorgan dysfunction happened since the literatures have shown that about 30.6% of critically ill COVID-19 patients developed shock [12], [15], about 12.2% cases were complicated by acute cardiac injury [2], and about 20.1% severe patients complicated with ARDS [2], [3]. We daily perform LUS at the bedside to evaluate the progress of pneumonia and early identifying lung complications in our unit in Wuhan. The LUS patterns getting worse, accompanied by the deterioration of the clinical conditions, require the caregivers to adjust the treatment plan. Other organs were monitored daily by CCUS and laboratory tests to detect renal dysfunction, heart injury, and early signs of shock, which were also the indication that the patients need intensive care. According to our experience, CCUS was valuable to daily evaluate therapeutic effects, monitor the organ function in high-risk patients, and rapidly triage severe patients to ICU. Noteworthy, as our experience in treating COVID-19, patients with newly onset of cardiac dysfunction or reduced peripheral tension observed on CCUS deserve intense care since they tend to deteriorate to severe shock rapidly.

It is very important for intensivists to discover the gravity-dependent air–fluid distribution in the lungs in time, which is, water is more distributed on the patient's back, and gas is distributed on the patient's front chest wall in the supine position [33]. The ARDS patients are characterized by the gravity-dependent inhomogeneity by chest CT, and they require prone position treatment to increase lung recruitment [33], whereas the severe COVID-19 pneumonia patients are featured by the diffuse interstitial infiltrate, accompanied by less consolidation and little pleural effusion, and there is no significant benefit from the prone position [11], [31]. LUS can timely and reproducibly evaluate the prone treatment effect [28]. In the desperate situation of manpower limitation and the lack of invasive ventilator, extracorporeal membrane oxygenation, even oxygen source at the early stage of the pandemic, utilization of bedside LUS to timely identifying the causes of hypoxia, and distinguishing typical ARDS with other causes of respiratory failure was extremely important in our practice [27]. Daily perform LUS for patients in the ICU to monitor the lung pathophysiology changes, which has helped early diagnosing ARDS and guided proper treatment. We also utilized the daily evaluation of the LUS pattern of the posterior of the lung to assess the effectiveness of the prone position and to determine the time duration and the frequency for prone.

Studies showed that about 30.6% of critically ill COVID-19 patients developed shock [12], [15], and about 12.2% of cases were complicated by acute cardiac injury [2]. The underlying etiologies of critical illness in these patients could be multifactorial. Rapid identification, correct diagnosis, and prompt treatment are of great importance to the survival of those patients [34]. Central venous pressure (CVP), pulse-indicated continuous cardiac output, which aims to monitor the pressure of the right atrium, pulmonary edema, and cardiac output, and other invasive monitoring methods were limited in the isolation units. Echocardiography based on five standard views could rapidly assess the cardiac structure, volume status, cardiac function, and peripheral resistance, which can help to identify the type of shock and to guide clinical treatment precisely [16], [35]. Prior to the COVID-19 outbreak, our research group has published a critical care chest ultrasonic examination protocol (CCUE protocol) as a simple assessment workflow to rapidly and accurately assess the etiologies of pulmonary and cardiovascular failures at the bedside [16].

The pathophysiological characteristics of late COVID-19 pneumonia and ARDS are pulmonary vascular endothelial barrier damage and increased lung leakage, which can lead to poor tolerance to even a small amount of volume overload [36], [37]. Thus, the volume status monitor in COVID-19 patients is important in either shock or no shock patients. During the Wuhan COVID-19 epidemic, we daily performed a CCUE protocol to monitor the hemodynamic changes, volume status, cardiac function, lung recruitment, prone positioning, and focal sources of potential infection in the ICU. To sum up, those advantages of CCUS enable us to assist in optimizing circulation management and evaluate the value of the treatment effect and have also been confirmed to be competent by our practice experience.

Multiorgan injury is an important characteristic of COVID-19, especially in critically ill patients. To restrict fluid intake or actively diuresis patients because of the fear of volume overload may accelerate kidney injury. In addition, a large portion of patients with severe COVID-19 pneumonia was elderly with chronic kidney disease [4], [29], [38], [39]. Therefore, the monitor of kidney function is important in those patients.

Patients with severe hypoxemia requiring sedation, prone position, and neuromuscular blockade usually presented with gastrointestinal dysfunction, stasis, regurgitation, and aspiration [40], [41]. With the ability of multiorgan monitoring, the ultrasonography helped us to early detect the damage out of the lung and protect the involved organs before the dysfunction happens.

Although the utility of LUS in the rescue of patients with COVID-19 was widely reported, less experience has presented the best practicable experience that integrated the application of ultrasonography into the whole process of diagnosis and treatment practice. According to our best practice experience in the fighting COVID-19 pneumonia on the frontline in Wuhan, the utility of CCUS can help to promote rapid screen and early diagnose of COVID-19 pneumonia at community hospitals, assisting early select patients with COVID-19 pneumonia at module hospitals who need transfer to designated hospitals, to evaluate therapeutic effects and alert for early ICU admission, to identify ARDS, and to guide the precise treatment.

There are also some pitfalls when using ultrasonography. For example, it is difficult for the LUS to detect the lesion area when the lesions are in the deep, and the IVC examination is affected by the inspiratory effort, the ventilation, and the intra-abdominal pressure. Keeping in mind that the clinical conditions and epidemiological history of the patients need to be considered and integrated in practice, by which the disadvantages could be limited.

V. Conclusion

In summary, CCUS played an important role in caring for COVID-19 patients owing to its excellent imaging capability and the advantages of assessing the pathophysiological changes. It worked as one of our core technologies covering the rapidly screening, evaluating therapeutic effects, alerting for early ICU admission, and more importantly, supporting the diagnosis and decision making in ICU, which represented with identifying ARDS, detecting the pathophysiology appropriate for prone position, assisting optimizing circulation management, and monitoring organ function.

Again, here, we presented that CCUS is an effective, convenient, and affordable tool for the physicians in this worldwide pandemic. We deeply hope our presentation can be beneficial to other physicians who are fighting against COVID-19.

Acknowledgment

The authors would like to thank Maxwell Diddams from the Department of Pulmonology and Critical Care Medicine, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA, and Dong Wang from the Department of Critical Care Medicine, West China Hospital of Sichuan University, Chengdu, China.

The authors have no conflict of interest to declare on the reported studies.

References

[1] Q. Li *et al.*, "Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia," *New England J. Med.*, vol. 382, pp. 1199–1207, Mar. 2020.

[2] C. Huang *et al.*, "Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China," *Lancet*, vol. 395, no. 10223, pp. 497–506, 2020.

[3] N. Chen *et al.*, "Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: A descriptive study," *Lancet*, vol. 395, no. 10223, pp. 507–513, Feb. 2020.

[4] W. J. Guan *et al.*, "Clinical characteristics of coronavirus disease 2019 in China," *New England J. Med.*, vol. 382, no. 18, pp. 1708–1720, 2020.

[5] WHO. (2020). *Corona-Virus Disease (COVID-2019) Situation Reports*. [Online]. Available: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports/

[6] J. Riou and C. L. Althaus, "Pattern of early human-to-human transmission of Wuhan 2019 novel coronavirus (2019-nCoV), December 2019 to January 2020," *Euro Surveill*, vol. 25, no. 4, Jan. 2020, Art. no. 2000058.

[7] J. F.-W. Chan *et al.*, "A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: A study of a family cluster," *Lancet*, vol. 395, no. 10223, pp. 514–523, Feb. 2020.

[8] G. Volpicelli *et al.*, "International evidence-based recommendations for point-of-care lung ultrasound," *Intensive Care Med.*, vol. 38, no. 4, pp. 577–591, Apr. 2012.

[9] F. Mojoli, B. Bouhemad, S. Mongodi, and D. Lichtenstein, "Lung ultrasound for critically ill patients," *Amer. J. Respir Crit. Care Med.*, vol. 199, no. 6, pp. 701–714, Mar. 2019.

[10] F. Corradi, C. Brusasco, and P. Pelosi, "Chest ultrasound in acute respiratory distress syndrome," *Current Opinion Crit. Care*, vol. 20, no. 1, pp. 98–103, 2014.

[11] Y. Huang *et al.*, "A preliminary study on the ultrasonic manifestations of peripulmonary lesions of non-critical novel coronavirus pneumonia (COVID-19)," Tech. Rep., Feb. 2020. [Online]. Available: http://ssrn.com/abstract=3544750 and http://dx.doi.org/10.2139/ssrn.3544750

[12] C.-C. Lai, T.-P. Shih, W.-C. Ko, H.-J. Tang, and P.-R. Hsueh, "Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): The epidemic and the challenges," *Int. J. Antimicrobial Agents*, vol. 55, no. 3, Mar. 2020, Art. no. 105924.

[13] X. Yang *et al.*, "Clinical course and outcomes of critically ill patients with SARS-CoV-2 pneumonia in Wuhan, China: A single-centered, retrospective, observational study," *Lancet Respiratory Med.*, vol. 8, no. 5, pp. 475–481, May 2020.

[14] N. Zhu *et al.*, "A novel coronavirus from patients with pneumonia in China, 2019," *New England J. Med.*, vol. 382, no. 8, pp. 727–733, Feb. 2020.

[15] D. Wang *et al.*, "Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China," *JAMA*, vol. 323, no. 11, pp. 1061–1069, 2020, doi: 10.1001/jama.2020.1585.

[16] X. Wang *et al.*, "Using critical care chest ultrasonic examination in emergency consultation: A pilot study," *Ultrasound Med. Biol.*, vol. 41, no. 2, pp. 401–406, Feb. 2015.

[17] W. H. Yin *et al.*, "Technical specification for clinical application of critical ultrasonography," *Zhonghua Nei Ke Za Zhi*, vol. 57, no. 6, pp. 397–417, 2018.

[18] A. Soummer *et al.*, "Ultrasound assessment of lung aeration loss during a successful weaning trial predicts postextubation distress*," *Crit. Care Med.*, vol. 40, no. 7, pp. 2064–2072, Jul. 2012.

[19] W. Yin *et al.*, "Poor lung ultrasound score in shock patients admitted to the ICU is associated with worse outcome," *BMC Pulmonary Med.*, vol. 19, no. 1, p. 1, Jan. 2019.

[20] L. Gargani, "Lung ultrasound: A new tool for the cardiologist," *Cardiovascular Ultrasound*, vol. 9, no. 1, p. 6, Feb. 2011.

[21] R. Moshavegh, K. L. Hansen, H. Moller-Sorensen, M. B. Nielsen, and J. A. Jensen, "Automatic detection of B-lines in *in vivo* lung ultrasound," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 66, no. 2, pp. 309–317, Feb. 2019.

[22] N. Lerolle, E. Guerot, C. Faisy, C. Bornstain, J. L. Diehl, and J. Y. Fagon, "Renal failure in septic shock: Predictive value of Doppler-based renal arterial resistive index," *Intensive Care Med*, vol. 32, no. 10, pp. 1553–1559, Oct. 2006.

[23] F. Beloncle *et al.*, "Determinants of Doppler-based renal resistive index in patients with septic shock: Impact of hemodynamic parameters, acute kidney injury and predisposing factors," *Ann. Intensive Care*, vol. 9, no. 1, p. 51, Apr. 2019.

[24] *COVID-19 Pneumonia Diagnosis and Treatment Plan? Seventh Edition Trial Implementation?* Nat. Health Commission People's Republic China, Beijing, China, 2020.

[25] D. Lichtenstein, "Lung ultrasound in the critically ill," *Current Opinion Crit. Care*, vol. 20, no. 3, pp. 315–322, Jun. 2014.

[26] G. Koster and I. C. C. van der Horst, "Critical care ultrasonography in circulatory shock," *Current Opinion Crit. Care*, vol. 23, no. 4, pp. 326–333, Aug. 2017.

[27] R. Copetti, G. Soldati, and P. Copetti, "Chest sonography: A useful tool to differentiate acute cardiogenic pulmonary edema from acute respiratory distress syndrome," *Cardiovascular Ultrasound*, vol. 6, no. 1, p. 16, Apr. 2008.

[28] X.-T. Wang *et al.*, "Lung ultrasound can be used to predict the potential of prone positioning and assess prognosis in patients with acute respiratory distress syndrome," *Crit. Care*, vol. 20, no. 1, p. 385, Dec. 2016.

[29] M. Chung *et al.*, "CT imaging features of 2019 novel coronavirus (2019-nCoV)," *Radiology*, vol. 295, no. 1, pp. 202–207, 2020.

[30] J. P. Kanne, "Chest CT findings in 2019 novel coronavirus (2019-nCoV) infections from Wuhan, China: Key points for the radiologist," *Radiolology*, vol. 295, Feb. 2020, Art. no. 200241.

[31] Q.-Y. Peng, X.-T. Wang, and L.-N. Zhang, "Findings of lung ultrasonography of novel corona virus pneumonia during the 2019–2020 epidemic," *Intensive Care Med.*, vol. 46, no. 5, pp. 849–850, May 2020.

[32] L. Zieleskiewicz, G. Duclos, O. Dransart-Rayé, N. Nowobilski, and B. Bouhemad, "Ultrasound findings in patients with COVID-19 pneumonia in early and late stages: Two case-reports," *Anaesthesia Crit. Care Pain Med.*, vol. 39, no. 3, pp. 391–392, Jun. 2020.

[33] A. D. T. Force *et al.*, "Acute respiratory distress syndrome: The Berlin definition," *JAMA*, vol. 307, no. 23, pp. 2526–2533, 2012.

[34] J.-L. Vincent *et al.*, "Clinical review: Update on hemodynamic monitoring–a consensus of 16," *Crit. Care*, vol. 15, no. 4, p. 229, 2011.

[35] W. Yin *et al.*, "The PIEPEAR workflow: A critical care ultrasound based 7-step approach as a standard procedure to manage patients with acute cardiorespiratory compromise, with two example cases presented," *Biomed. Res. Int.*, vol. 2018, Jun. 2018, Art. no. 4687346.

[36] J. Pugin, G. Verghese, M.-C. Widmer, and M. A. Matthay, "The alveolar space is the site of intense inflammatory and profibrotic reactions in the early phase of acute respiratory distress syndrome," *Crit. Care Med.*, vol. 27, no. 2, pp. 304–312, Feb. 1999.

[37] R. MacLaren and K. A. Stringer, "Emerging role of anticoagulants and fibrinolytics in the treatment of acute respiratory distress syndrome," *Pharmacotherapy*, vol. 27, no. 6, pp. 860–873, Jun. 2007.

[38] D. Wang *et al.*, "Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus–infected pneumonia in Wuhan, China," *JAMA*, vol. 323, no. 11, pp. 1061–1069, 2020.

[39] Y. He, W. Li, Z. Wang, H. Chen, L. Tian, and D. Liu, "Nosocomial infection among patients with COVID-19: A retrospective data analysis of 918 cases from a single center in Wuhan, China," *Infection Control Hospital Epidemiol.*, vol. 41, no. 8, pp. 982–983, 2020, doi: 10.1017/ice.2020.126.

[40] S. A. McClave *et al.*, "Guidelines for the provision and assessment of nutrition support therapy in the adult critically ill patient: Society of critical care medicine (SCCM) and American society for parenteral and enteral nutrition (A.S.P.E.N.)," *J. Parenteral Enteral Nutrition*, vol. 40, no. 2, pp. 159–211, Feb. 2016.

[41] A. R. Blaser, J. Starkopf, Ü. Kirsimägi, and A. M. Deane, "Definition, prevalence, and outcome of feeding intolerance in intensive care: A systematic review and meta-analysis: How to define feeding intolerance?" *Acta Anaesthesiologica Scandinavica*, vol. 58, no. 8, pp. 914–922, Sep. 2014.

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