

Point-of-Care Ultrasound in the Intensive Care Unit



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KEYWORDS

• Ultrasound • Critical care • Point-of-care • Thoracic ultrasound • Cardiac ultrasound

KEY POINTS

- Point-of-care ultrasound has vast potential and is generally underused in the critical care setting.
- The rapid and portable nature of ultrasound makes it an ideal tool to help guide decision making in time-sensitive scenarios.
- As professional societies continue to formulate and adapt training protocols or standards in ultrasound, it is rapidly becoming an indispensable tool for the intensivist.



Video content accompanies this article at <http://www.chestmed.theclinics.com/>.

INTRODUCTION

Point-of-care (POC) ultrasound in medical intensive care units (ICUs) is increasingly used, to the extent that many intensivists now consider it the modern form of the stethoscope.¹ Further enhancing this claim is the increased portability of ultrasound because several current models are marketed as handheld units (Fig. 1). Although ultrasound has been recognized as an invaluable bedside tool for several decades, its rapid ascent arguably started within the emergency medicine community around 2008, when it was recognized as a fundamental component of resident training and education.² Not far behind came the critical care community with similar endorsements by several professional societies around the world.³ In 2009, the American College of Chest Physicians (ACCP) endorsed competency in critical care ultrasound as an important component to the intensivist's skillset.⁴ An expert panel through consensus opinion delineated 4 domains of a

bedside critical care ultrasound examination, including cardiac, thoracic, pleural, and vascular. In 2015, the Society of Critical Care Medicine (SCCM) put forth a comprehensive set of guidelines for use of ultrasound in the ICU.⁵ The SCCM guidelines cover a wide range of applications, spanning each of the 4 domains previously outlined by the ACCP. As a further example of the push toward moving ultrasound into the forefront of the ICU, the National Board of Echocardiography now offers a national-level certification in advanced critical care echocardiography that was previously only available to fellowship-trained cardiologists.⁶ The impact of POC ultrasound on clinical diagnosis and decision-making, especially in regard to cardiac function and fluid status, is substantial. One report showed that up to 25% of cases had the initial diagnosis altered based on ultrasound findings.⁷

A basic understanding of the underlying physical principles of ultrasound is important to help

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Fig. 1. Portable ultrasound unit (iViz, Fujifilm SonoSite Inc, Bothell, Washington, USA) featuring a 7-inch touchscreen, interchangeable probes, and weighing only 1.1 lb.

interpret the image output. Ultrasound machines use piezoelectric crystals to generate sound waves that are emitted from a transducer. The ultrasound waves are above the human threshold of hearing at 20 kHz, whereas most medical ultrasound emits waves at 2 to 15 MHz. As the ultrasound waves pass through various structures, they are reflected back to the transducer, which is able to convert mechanical vibrations to an electrical signal and vice versa.⁸ Another important concept is that as sound travels through a medium it will become attenuated or weakened. Tissue density also affects attenuation, with different types of tissues classified according to their attenuation coefficient. For example, water has a very low attenuation coefficient, thus making it an excellent acoustic window. Higher frequency sound waves will attenuate faster, whereas lower frequency sound waves can penetrate deeper before the image quality will suffer. These concepts formulate the basis of different probe options available for the user, primarily including the linear array, curvilinear array, and phased array (Fig. 2). The linear probe has a linear sequence

of piezoelectric crystals emitting a higher frequency of 7.5 to 10 MHz, thus allowing higher resolution for superficial applications such as vascular access. The curved array, also referred to as the abdominal probe, emits lower frequency sound waves of 2 to 5 MHz through linear arrays shaped into convex curves that grant a larger field of view. This allows visualization of deeper structures, which is useful in examining large pleural effusions or ascitic fluid collections. Finally, phased array transducers, or sector probes, also emit soundwaves at 2 to 5 MHz and provide a good view of deeper structures similar to the curvilinear probe. The phased array is smaller, thus in certain instances may be favored; for example, visualizing pleural effusions through tight rib interspaces in smaller patients. Additionally, for cardiac ultrasound, the phased array is the probe of choice. A more in-depth discussion of ultrasound physics is beyond the scope of this article but can be found elsewhere.⁹

As with other technical skills, there is a learning curve with bedside ultrasound before the operator can safely make diagnostic and therapeutic decisions based on the acquired images. Manipulation of the transducer to obtain ideal images is often the rate-limiting step for novices because small adjustments can alter the picture dramatically. The fundamental transducer movements have been codified into 6 elements: slide, rock, sweep, fan, compression, and rotation (Fig. 3).¹⁰ Experienced operators have the vocabulary with which to communicate to the novice user how to improve their image quality. Furthermore, operators should also be comfortable with the appropriate use of the gain and depth knob adjustments. The Accreditation Council for Graduate Medical Education (ACGME) mandates the incorporation of ultrasound into critical care fellowship training.¹¹ The ACGME explicitly mentions trainees' competence in ultrasound use for line placement and thoracentesis. A recent survey of academic centers found that there is a paucity of formal ultrasound

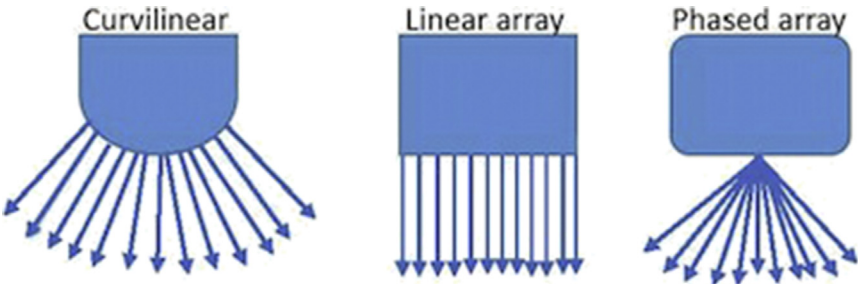


Fig. 2. Different types of ultrasound probes. Note that all sound waves are traveling in different directions on a paper-thin plane to create a 2-dimensional image of structures on that plane.

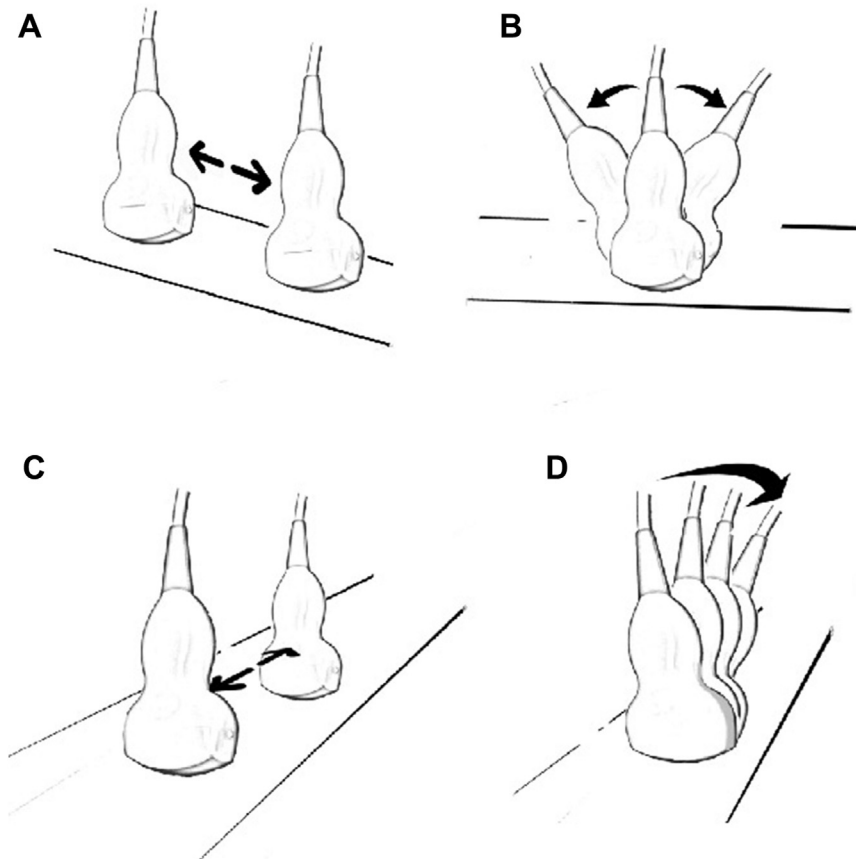


Fig. 3. Overview of the probe movements (arrows) to change the plane of the ultrasound waves commonly used to examine and localize a point of interest. (A) Slide: linear movement along long axis of the probe. (B) Rock: tilting movement of the probe on the short axis of a fixed point. (C) Sweep: linear movement along the short axis of the probe. (D) Fan: Tilting movement of the probe along the short axis on a fixed point.

curriculums in place, although most institutions did have plans to adopt one in the ensuing years.¹² Although no national, standardized curriculum is in place for critical care ultrasound, there are models of institutions ensuring adequate ultrasound experience and didactics for their trainees.^{13,14} The ACCP currently offers a simulation-based 3-day course that provides a good foundation for the intensivists beginning their ultrasound journey. However, they acknowledge that further education and training is needed beyond the confines of the course.¹⁵ As previously mentioned, there is an option for obtaining certification in critical care echocardiography through the National Board of Echocardiography; however, as of now, there is no national accreditation for critical care ultrasound.

Ultimately, ultrasound is accepted as a safe modality without ionizing radiation or nephrotoxic contrast dye. Theoretical concerns about potential harms stem from the known physiologic changes induced by ultrasound, including tissue heating,

ultrasonic cavitation, gas body activation, and mechanical stress.¹⁶ Also, there are applications in which high-intensity focused ultrasound is used to induce cell death in solid tumors (eg, pancreatic cancer) via a thermal mechanism.¹⁷ However, the energy to generate such a focused ultrasound beam is far beyond the traditional medical or diagnostic range. Thus far, there are no data in humans suggesting a major physiologic consequences of ultrasound exposure during routine imaging.¹⁸

INTENSIVE CARE UNIT PROCEDURES AIDED BY ULTRASOUND

Central Venous Catheter Access

Central venous access is quintessential in the resuscitation of critically ill patients because it allows for rapid volume resuscitation, administration of medications and blood products, and real-time hemodynamic monitoring. Although central venous access using ultrasound guidance was first described in 1984, the first case series

describing its routine use would not be published for more than a decade.¹⁹ Before the widespread availability of ultrasound units, an anatomic approach for internal jugular cannulation was used that was first described in 1966.²⁰ Complications with this approach were not uncommon (eg, pneumothorax, arterial puncture, or hematoma) and related primarily to anatomic variability and operator experience. Over several decades, multiple studies have proven that ultrasound guidance of central venous catheters (CVCs) is superior to anatomic guidance in terms of insertion attempts, time to cannulation, and rate of complications.^{21–33} Additionally, examining the vessel of interest with ultrasound before needle puncture allows determination of vessel patency, including any potential thromboses or strictures, as well as the best angle of approach. Thus, ultrasound-guided central venous catheterization is widely accepted as the standard of care in central venous access.^{5,34}

Two ultrasound views are available to help with central venous access. The short-axis, or out-of-plane, view is the most commonly used modality and allows visualization of the target vessel in relation to nearby structures (eg, internal jugular vein adjacent to internal carotid artery) (**Fig. 4, Video 1**). The long-axis, or in-plane, view allows the user to track the entire length of the needle continuously during line placement; however, the neighboring structures and their proximity to the vessel of interest is not as defined as in the short-axis view (**Fig. 5**). Novice users tend to be more comfortable with the short-axis view and there is a heavy bias toward this approach in clinical practice. However, the major pitfall of the short-axis approach is discerning the needle shaft from the tip, thus potentially leading the operator to inadvertently puncture the carotid or other structures posterior to the target vessel, such as the

lung.^{35,36} The long axis is preferred in some centers given the ability to more accurately visualize the needle tip, which leads to faster procedures, fewer redirections of the needle, and fewer posterior wall punctures.^{37,38} Due to more technical difficulty and higher rates of complications, the right internal jugular site is preferred to the left.³⁹ Proponents of the subclavian approach cite its lower incidence of thrombosis and infection compared with the internal jugular and femoral sites. However, the risk of iatrogenic pneumothorax requiring chest tube drainage is higher, even among experienced operators.⁴⁰ Ultrasound-guided subclavian CVC placement from either a supraclavicular or infraclavicular approach has recently been described.⁴¹ The technique allows identification of the pleural line around the vessel, thus mitigating the risk of pneumothorax compared with the landmark approach.⁴² Femoral CVC access is another viable option with infection and thrombosis rates similar to the internal jugular site (and likewise inferior to subclavian); however, there is no risk of iatrogenic pneumothorax with this approach.⁴³ The authors suspect that, as operators become more comfortable with ultrasound-guided subclavian CVC lines, this will become the standard. Verification of line placement and ruling out iatrogenic pneumothorax can also be done via ultrasound. The use of chest radiography for this purpose is likely superfluous, although confirmatory chest radiography continues to be used at many centers because it can validate the position of the central line catheter tip.^{44–47}

Lumbar Punctures

Lumbar punctures are routinely performed in cases of suspected meningitis or encephalitis, or when there is the concern for a subarachnoid hemorrhage not visualized on imaging. Often, the

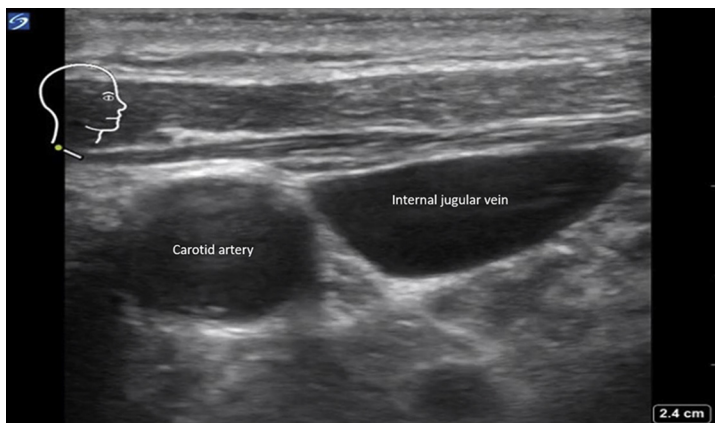


Fig. 4. Short-axis view of the internal jugular vein with visualization of the adjacent carotid artery. (Courtesy of Dr David P. Bahner.)

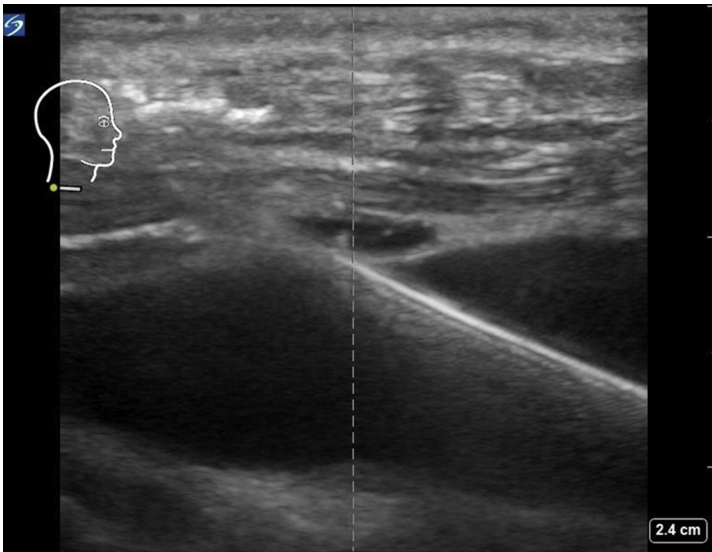


Fig. 5. Long-axis view of the internal jugular vein with the needle visualized entering the vessel. (Courtesy of Dr David P. Bahner.)

operator is unable to successfully perform the procedure because of technical aspects, especially in morbidly obese patients. Utilization of adjunct specialists to assist (eg, interventional radiology with fluoroscopic guidance) often takes hours to days to arrange, which is problematic given the time-sensitive nature of the cases that typically merit sampling of the cerebrospinal fluid urgently. For example, starting empiric antibiotics for suspected meningitis before obtaining cerebrospinal fluid cultures is known to compromise the yield. Ultrasound is useful in patients who lack palpable spinal landmarks for lumbar puncture. Using ultrasound, operators can identify the spinous processes and the lumbar interspace, even in morbidly obese patients (**Fig. 6**).^{48,49} By localizing

the lumbar interspace, the optimal location for needle insertion can be marked. In some cases, the ligament flavum, the fibrous structure that lies immediately superficial to the epidural space, can be seen and used to gauge the approximate depth from the skin to the subarachnoid space.⁵⁰

Pleural Cavity Assessment and Access

Thoracentesis is a common procedure performed by the intensivist to alleviate symptoms caused by a pleural effusion (eg, shortness of breath or chest pain), as well as to provide valuable diagnostic information. Although considered relatively safe, the feared complication is an iatrogenic pneumothorax requiring chest tube management.⁵¹ This



Fig. 6. The spinous process under ultrasound. (Courtesy of Dr David P. Bahner.)

risk has greatly been reduced following the widespread adaptation of ultrasound guidance.⁵² Localization of pleural fluid is one of the oldest applications of ultrasound, albeit not widely used until the recent few decades.⁵³ Typically, real-time ultrasound needle guidance is not performed; instead, ultrasound is used to mark an appropriate insertion point for the needle where a safe fluid pocket is visualized. Ultrasound is superior to chest radiography regarding detecting pleural effusions, albeit not as good as computed tomography (CT) scanning.^{54,55} Regardless, ultrasound still has a 95% sensitivity for detecting pleural effusions and does not involve ionizing radiation.⁵⁵ For accurately predicting the volume of pleural fluid, an ultrasound assessment while the patient is supine is more reliable than a lateral decubitus chest radiograph.⁵⁶ Also, ultrasound is routinely used to mark the port of entry during pleuroscopy procedures to avoid injury to the lungs.

Because bone will reflect the ultrasound waves, the acoustic window for the pleural space is limited to the intercostal spaces. The recommended probe for examination of the pleural space is the convex array transmitting at 3.5 to 5 MHz, although in smaller patients the phased array probe may be better suited.⁵⁷ The optimal area to assess for the presence of a pleural effusion with ultrasound is the posterolateral portion of the lungs. If enough fluid is in the pleural space, the parietal and visceral pleura can be distinguished as 2 hyperechoic lines separated by an anechoic fluid-filled pleural space (Fig. 7).⁵⁸ The quad sign is highly specific for characterizing a pleural fluid collection.⁵⁹ The 4 constituent boundaries are marked by the parietal pleural line (upper border), rib shadows (lateral borders), and the lung or visceral pleural line (lower border). Diagnostic accuracy can be further improved by observing the sinusoid sign, which is observed in M mode,

whereby the dynamic movement of the lung toward the pleural line is displayed as a sinusoidal pattern.⁶⁰ An additional dynamic finding is that with Doppler imaging the pleural fluid will show a change in color with respiratory and cardiac motion.^{61,62} The appearance of fluid on ultrasound can provide insight into its composition; that is, whether the fluid will be transudative or exudative.⁶³ Although transudates are usually anechoic, exudates can also be, thus limiting the discrimination under such appearances.⁶⁴ Septated or homogeneously hyperechoic fluid will usually be exudative (Fig. 8).^{65,66} Septations on ultrasound, which are commonly seen with empyema, predict the need for intrapleural fibrinolysis via a chest tube or surgical debridement.⁶⁷ Given recent data, the current preference for septated fluid collections, including complicated parapneumonic effusions and empyema, is a trial of chest thoracostomy with intrapleural fibrinolytic. Failing medical management, surgical debridement (eg, video-assisted thoracoscopic surgery) should be considered.^{68,69}

Abdominal Cavity Assessment and Access

Ascites is a common problem encountered in the ICU, which can lead to situations requiring urgent management such as perturbed ventilator mechanics and abdominal compartment syndrome. Although paracentesis is considered a relatively safe procedure, there are instances of fatal hemorrhages and bowel perforations in the literature.^{70–72} Because hemorrhagic complications are rare, several professional societies advise that thrombocytopenia or prolonged prothrombin time are not contraindications, nor should reversal of these parameters take place before paracentesis.^{73–75} Such complications can be avoided via the use of abdominal ultrasonography to visualize

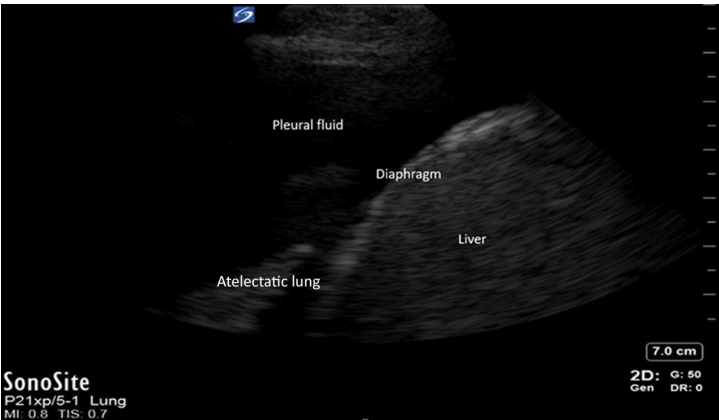


Fig. 7. Ultrasound of the chest showing a large pleural effusion with the diaphragm and liver. Atelectatic lung visible at the lower left corner.

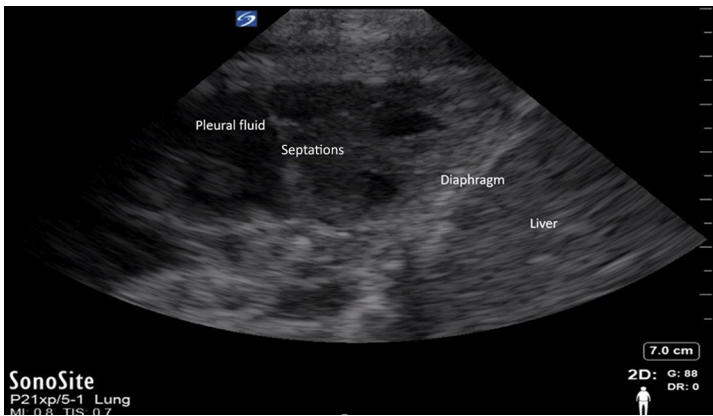


Fig. 8. Ultrasound of the chest showing a large pleural effusion with septations and hyperechoic fluid.

an adequate pocket for drainage along with the vascular ultrasound to localize the inferior epigastric vein, which is usually located 4 to 6 cm lateral to the midline.⁷⁶ Doppler can also identify superficial mesenteric varices and abdominal wall collateral vessels that ideally can be avoided. The best area for paracentesis is approximately 2 cm below the umbilicus in the white line or 5 cm superomedial to the anterior superior iliac spine (**Fig. 9**).⁷⁷ A thorough examination of the abdominal cavity with ultrasound is a good practice to locate the largest area of ascites amenable to drainage.

Percutaneous Dilational Tracheostomy

Percutaneous dilational tracheostomy (PDT) is a commonly performed procedure in the ICU for patients who are unable to be weaned off mechanical ventilation.⁷⁸ With data suggesting PDT results in fewer wound complications, less bleeding and scarring, and perhaps a mortality benefit, PDT is preferred to surgical tracheostomy.⁷⁹ The

exception is in patients who have difficult anatomy, such as a nonpalpable cricoid cartilage, and who may be better served with a surgical approach.⁸⁰ Bronchoscopy is currently used by most operators to confirm midline puncture of the trachea, as well as to help avoid injuries to the posterior wall of the trachea.^{81,82} However, bronchoscopy may interfere with the patient's ventilation and can be difficult to coordinate, thus techniques omitting adjunctive bronchoscopy have been described.⁸³ The use of ultrasound with PDT is not widely adopted despite numerous examples of its utility. A feared complication of PDT is fatal hemorrhage, which occurs in approximately 5% of cases.^{84–87} By examining the anterior neck with ultrasound before tracheostomy, vessels that could be punctured during the procedure or eroded following prolonged tracheostomy placement can be avoided.^{88,89} Additional uses of ultrasound with PDT include identifying anatomic landmarks, choosing the appropriate tracheostomy size (eg, regular vs extra-long), and



Fig. 9. Abdominal ultrasound showing large-volume ascites. The anechoic black area represents the ascitic fluid collection and the loops of bowel appear as hyperechoic rounded areas.

providing real-time guidance for needle penetration.^{90–92} Ultrasound-guided PDT is faster than a surgical tracheostomy and, compared with the landmark method, the first-attempt success rate in the correct tracheal puncture site is close to 100%.^{93,94} No studies as yet have compared bronchoscope-guided PDT alone with ultrasound-guided PDT, thus it is unclear which option provides the safest, most efficient, and cost-effective approach. A hybrid approach using real-time ultrasound-guided PDT followed by a bronchoscopic examination to determine if the posterior wall of the trachea sustained injury may be the ideal scenario.^{92,95} Regardless, the utility of ultrasound is undeniable, especially given the ability to avoid catastrophic bleeding complications.

ULTRASOUND IN THE CLINICAL ASSESSMENT OF THE CRITICALLY ILL PATIENT

Physicians in ICU routinely evaluate patients suffering from undifferentiated shock and respiratory distress. Such circumstances call for accurate and timely diagnoses to attain the best possible patient outcomes. In addition to the history and physical examination, along with standard laboratory workup and imaging, a bedside multiorgan POC ultrasound can provide crucial information to guide further management decisions.⁹⁶ Importantly, the ultrasound examination does not require an unstable patient to be transported, such as with a CT or MRI scan. Although the focused assessment with sonography for trauma (FAST) protocol has been widely adapted for trauma patients over several decades, there is less of an accepted standard for the critically ill medical patients.⁹⁷ Emergency medicine physicians are familiar with the rapid ultrasound in shock (RUSH) examination that is designed to quickly investigate patients in unexplained shock. However, this protocol is not commonly used in the medical ICU.⁹⁸ Because of the lack of an accepted ultrasound standard for the ICU patient, and taking lessons from other specialties, the bedside examination should at least include the lungs, heart, inferior vena cava (IVC), and abdomen.

Lung Ultrasound

The bedside lung ultrasound in emergency (BLUE) protocol is a rapid and efficient way to categorize and use findings from the lung in cases of respiratory distress or failure.⁹⁹ The transducer is placed on 6 standardized points on the chest: 2 anterior and 1 posterior view of each hemithorax.¹⁰⁰ The intersection of the lower anterior point and the

posterior axillary line form the so-called PLAPS-point, which is the ideal point to assess for effusion or consolidation. At each point, the operator assesses the pleural line, looks for lung sliding, and identifies the accompanying lung artifacts. By the acquired images, 5 sonographic patterns are described: normal lung pattern, pneumothorax, interstitial syndrome, alveolar consolidation, and pleural effusion. The presence or absence of each of these signs can effectively narrow down the differential diagnosis within minutes and significantly alter the course of management.¹⁰¹

A normal lung pattern has A-lines with lung sliding on the anterolateral chest examination bilaterally, and no alveolar consolidation or pleural effusion on the posterior examination. A-lines are artifacts generated by horizontal reflections of the pleural line and are a normal finding. Lung sliding is the movement of visceral and parietal pleura over one another with respiration, which can also be visualized in the motion (M)-mode as the sandy shore sign (*Video 2*). Note that, although a normal lung pattern may be reassuring, several pathologic states can have this pattern, including exacerbations of chronic obstructive pulmonary disease (COPD) and asthma, as well as the pulmonary embolus (PE). In a patient in respiratory distress, a normal lung pattern combined with the finding of a deep venous thrombosis (DVT) is highly sensitive and specific for PE.¹⁰²

For patients with suspected pneumothorax, several aspects of the lung ultrasound are emphasized. The absence of lung sliding in and of itself is not a good marker for pneumothorax regarding its specificity. There are other conditions that cause an absence of lung sliding, including acute respiratory distress syndrome (ARDS), atelectasis, and mainstem intubation.^{103,104} The presence of lung sliding in combination with B-lines and a lung pulse effectively rules out a pneumothorax because it signifies the parietal and visceral pleura are sliding on each other.¹⁰⁵ Lung pulse is an early sign of atelectasis in which the heartbeats at the pleural line can be seen through a noninflating lung; its absence on the right side is a good way to rule out mainstem intubation.¹⁰⁶ The classic pathognomonic sign of a pneumothorax is the presence of a lung point, which is where the visceral pleura begins to separate from the parietal pleural by air at the margin of a pneumothorax.¹⁰⁷ The M-mode is the preferred method of confirming the presence of the lung point. In this mode, the operator will see a transition from the sandy shore sign (indicating that lung sliding is present) to the stratosphere or barcode sign (indicating absent lung sliding) at the lung point.¹⁰⁸ Although the lung point is extremely specific for pneumothorax,

with some investigators citing close to 100%, there is a case report of large bullae causing a similar appearance to a pneumothorax, suggesting that other, rare etiologic factors are possible.¹⁰⁹ Finally, large pneumothoraces that encircle the lung parenchyma will not have a lung point. Thus if clinical suspicion is high enough (eg, patient in shock with mediastinal shift to the contralateral side and a plethoric IVC on subxiphoid view), chest tube insertion should not be delayed.⁹⁶

B-lines, also referred to as comet-tail artifacts, are hyperechoic vertical rays emanating from the pleural line and extending the length of the screen (Fig. 10). Their presence is highly sensitive and specific for an alveolar-interstitial syndrome, which may include pulmonary edema, ARDS, or interstitial lung disease.¹¹⁰ Three or more B-lines between 2 ribs are referred to as lung rockets and usually (>93% accuracy) indicate pulmonary edema.¹⁰¹

Early recognition of large pleural fluid collections is important in that the potential hemodynamic insults may include compression of the heart or IVC, leading to profound obstructive shock.¹¹¹ Mechanically ventilated patients with large pleural effusion have been shown to come off respiratory support sooner with chest tube management (see previous discussion of ultrasound-aided thoracentesis).¹¹²

If lung consolidation is present, the optimal site for detection is the previously mentioned PLAPS-point.¹¹³ Nontranslobar, or partial lobar, consolidation is due to fluid-filled or pus-filled alveoli, and demonstrates the fractal or shred sign (Fig. 11). This sign is due to the border between consolidated and aerated lung being irregular. Translobar consolidation will generate increased echogenicity referred to as hepatization of the lung, also referred to as the tissue-like sign

(Fig. 12). A dynamic air bronchogram that exhibits inspiratory centrifugal movement is a highly specific sign of pneumonia and can differentiate it from other causes of consolidation (eg, atelectasis, pulmonary infarction, or lung cancer).¹¹⁴ One application of this concept is that ventilated patients in the ICU are at risk of acquiring ventilator-associated pneumonia (VAP). Correct and expeditious diagnosis of VAP is crucial given the increased morbidity, mortality, economic burden, and risk of fostering drug resistance.^{115,116} For such a prevalent problem, there is not a widely accepted diagnostic standard. There are various VAP criteria and definitions, all of which lack adequate sensitivity or specificity. The latest Infectious Disease Society of America guidelines do not advocate the use of any of the scoring systems currently available.¹¹⁷ However, the diagnosis of VAP could be made with bedside ultrasound by looking for the previously mentioned findings. Another benefit of evaluating for the presence of lung consolidation on ultrasound is following patients for resolution of their pneumonia, which is similar to current practice with chest radiographs and CTs but without the radiation exposure.¹¹⁸

Diaphragm dysfunction, in particular ventilator-induced dysfunction, is underdiagnosed in the critical care setting and is an important contributor to failed weaning from mechanical ventilation.^{119,120} The classic test of diaphragm function is the fluoroscopic sniff test, which is adequate for detecting unilateral diaphragm paralysis but in cases of bilateral paralysis or dysfunction the test will not be revealing.¹²¹ In addition, the sniff test is not ideal for the critically ill patient because the fluoroscopy requires spontaneous breathing off positive pressure ventilation for accurate assessment of diaphragmatic motion.¹²² More invasive means have also been described, such as phrenic nerve

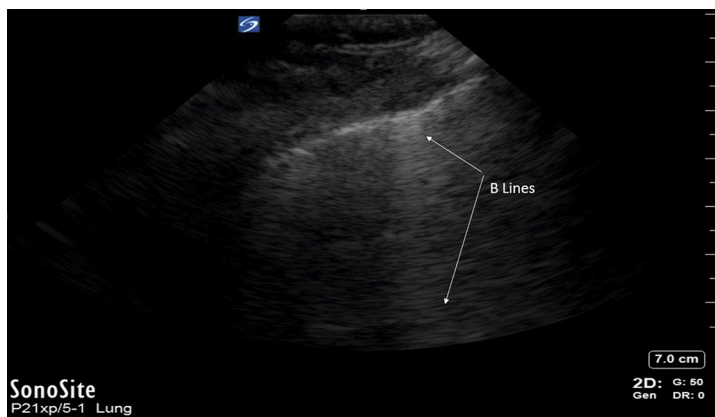


Fig. 10. Ultrasound of the chest showing B lines.

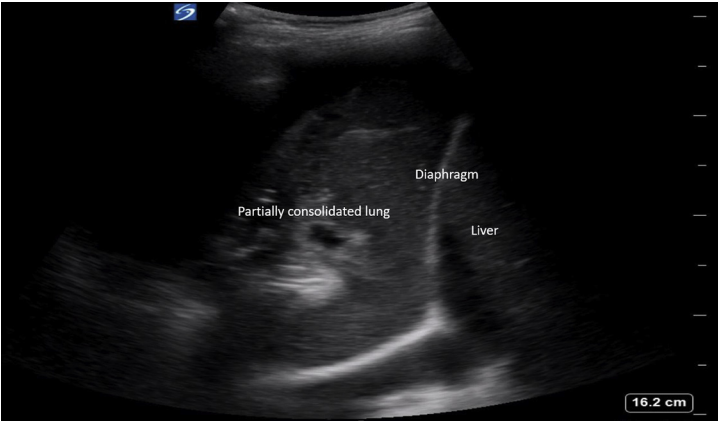


Fig. 11. Ultrasound of the chest showing the shred sign indicating partial lung consolidation.

stimulation but, again, a critical care atmosphere is not conducive to such studies.¹²³ Ultrasound of the diaphragm, although not common practice, is an easy way to accurately assess diaphragm function in the critically ill, mechanically ventilated patient.¹²⁴ Two methods are described in the literature. The first places a high-frequency probe at the midaxillary line around the 8th to 10th intercostal space where the thickness of the diaphragm is measured at rest and with an inspiratory hold, then compared with a normal range.¹²⁵ Alternatively, the operator places an abdominal probe in the subcostal area between the anterior-axillary and midclavicular lines and then measures the inspiratory excursion of the diaphragm while in M-mode.¹²⁶ A negative inspiratory excursion signifies paradoxical diaphragmatic movement due to diaphragmatic paralysis and use of accessory muscles.¹²⁷

Cardiac Ultrasound

The focused cardiac ultrasound (FoCUS) evolved in the emergency medicine setting in the 1990s

and is a distinct entity differing in scope from the comprehensive examination performed by trained echocardiographers.¹²⁸ As in traditional transthoracic echocardiography, 4 principal views are obtained: left parasternal long-axis and short-axis, apical 4-chamber, and subxiphoid 4-chamber. In FoCUS, subcostal visualization of the IVC is used to assess volume status (see later discussion). The FoCUS is now routinely performed at the bedside by trained intensivists or emergency medicine physicians.¹²⁹ The FoCUS is intended to quickly answer key questions in the management of an acutely ill patient, especially the patient in shock. The core skillset of cardiac ultrasound for the intensivist includes recognizing the presence of pericardial effusion with or without cardiac tamponade, severe right ventricular (RV) and left ventricular (LV) failure, regional wall motion abnormalities that may indicate the presence of coronary artery disease, gross anatomic valvular abnormalities, and the size and collapsibility of the IVC.¹³⁰ Beginning competence in the FoCUS can be achieved by noncardiologists after a 12-hour training program blending didactics,

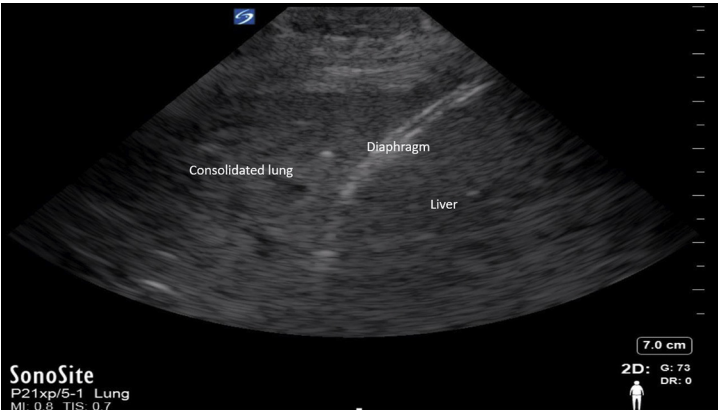


Fig. 12. Ultrasound of the chest showing hepatization of the lung, indicating total lung consolidation. The diaphragm separating the consolidated lung on the left from the liver on the right show similar appearance.

interactive clinical cases, and tutored hands-on sessions.^{131,132}

A systematic approach is recommended for the FoCUS, an example is outlined in the SIMPLE approach, which is a mnemonic encompassing the crucial elements of the cardiac ultrasound exam including: chamber size and shape (S), IVC size and collapsibility (I), presence of a mass in the heart chambers and myocardial thickness/motion (M), pericardial or pleural effusion (P), left ventricular systolic function (L), and abdominal aorta in the epigastrium (E).¹³³ The parasternal long-axis view is a good starting point to evaluate the pericardial and pleural space, LV chamber size and function, and the structure of the mitral and aortic valves (Fig. 13A). The lateral decubitus position may enhance the image quality. Next, the parasternal short-axis view offers an assessment of LV function, as well as a view of the interventricular septum (Fig. 13B). The apical 4-chamber view is best suited to compare LV to RV size and function (Fig. 13C). This is a challenging view to obtain and may be easier in the left lateral decubitus position; note that off-axis views may give an inaccurate estimate of the RV size. Often, the only view readily obtained in the ICU is the subxiphoid, especially in obese and mechanically ventilated patients (Fig. 13D). The subxiphoid view may be a reliable indicator of gross LV to RV function, and identification of pleural and pericardial fluid collections; however, ideally the findings would be verified on another view. Finally, the subcostal region is examined to assess the size of IVC and the

abdominal aorta, which may be involved in aortic dissection or aneurysmal rupture (Fig. 14).

The intensivist's initial visual interpretation of LV systolic function is garnered from the concentric contraction of the walls and should essentially come down to a finding of hyperdynamic (ejection fraction [EF] >70%), normal, or severe dysfunction (EF <30%). In suspected pulmonary embolism, the sonographic images of the heart provide valuable diagnostic and prognostic information. In normal cardiac function, the apical 4-chamber view will show an end-diastole area ratio of RV to LV of less than 0.6, with the LV forming the apex. A ratio higher than 0.6 signifies RV enlargement and, if the RV wall thickness is normal (<5 mm in parasternal long view), this suggests acute cor pulmonale due to massive PE (Fig. 15A).¹³³ A thickened RV wall suggests chronic cor pulmonale from such underlying conditions as COPD and chronic PE. Furthermore, flattening of the interventricular septum or a D-shaped appearance of the LV on the parasternal short-axis view during early diastole indicates high RV pressure (Fig. 15B).¹³⁴ Hemodynamically unstable patients who lack sonographic evidence of RV overload or dysfunction can effectively be ruled out for PE as the prime etiologic factor of shock.¹³⁵ A more detailed evaluation of RV function (eg, tricuspid annular plane systolic excursion) is described elsewhere.¹³⁶

Pericardial effusions appear sonographically as an anechoic stripe surrounding the heart. An

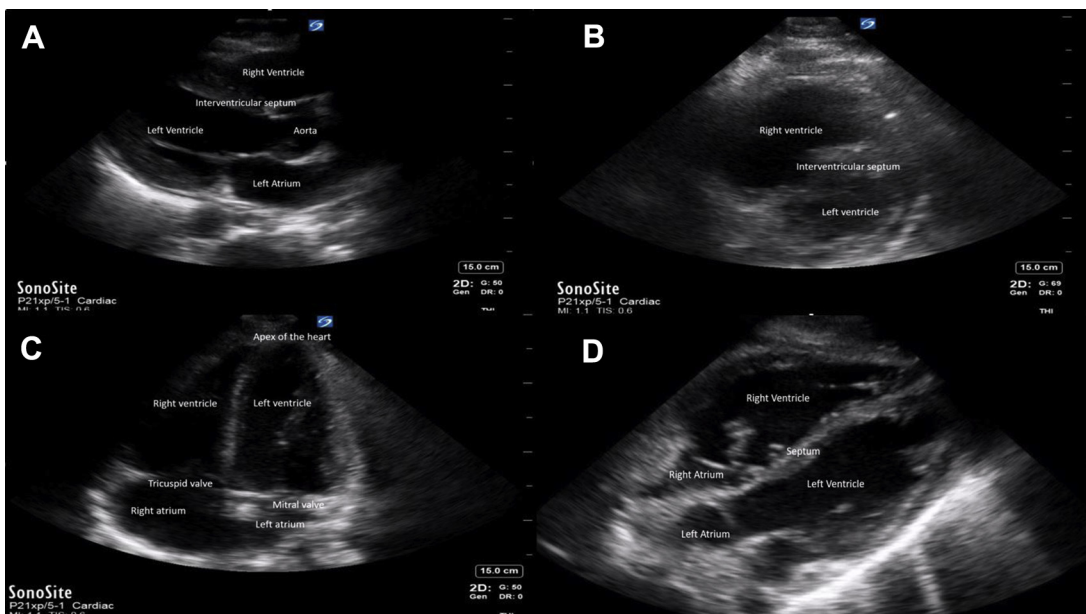


Fig. 13. (A) Parasternal long-axis view of a normal heart. (B) Parasternal short-axis view of a normal heart. (C) Apical 4-chamber view of a normal heart. (D) Subcostal 4-chamber view of a normal heart.

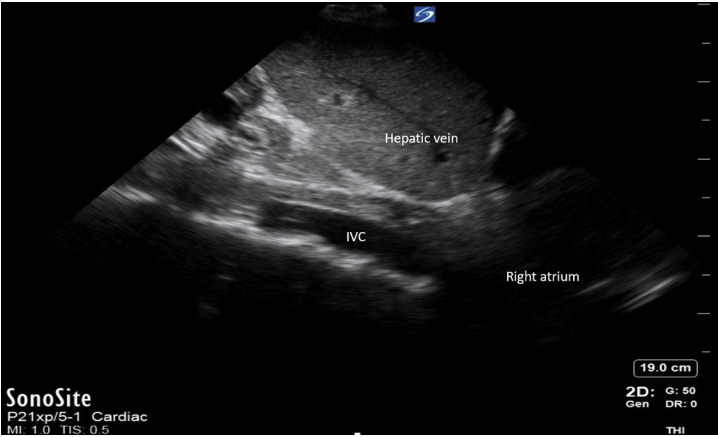


Fig. 14. The IVC as it drains into the right atrium with probe placed in the substernal area with a long-axis orientation.

important distinction to make is whether the fluid collection is pericardial or pleural in nature. In the parasternal long-axis view, the descending aorta is used as a landmark to help locate the posterior pericardial reflection, which is immediately anterior to this structure. The fluid anterior to the posterior pericardial wall is pericardial, whereas fluid located posteriorly is pleural.¹³⁷ Smaller pericardial effusion will often not extend fully around the heart and layer out posteriorly with gravity, whereas larger effusion will fully encircle the heart. The size of the effusion does not necessarily correlate with the potential physiologic consequence of tamponade.¹³⁷ Cardiac tamponade is the collapse of either the right atrium or the right ventricle during the diastolic phase of the cardiac cycle. Ultrasound findings range from an inward serpentine diastolic deflection of the right atrial or RV free wall to complete diastolic collapse of the chamber wall. Furthermore, the finding of IVC plethora with loss of respiratory collapse confirms tamponade.

Regarding analyzing the valves, the primary aim of the FoCUS is to exclude significant valvulopathies that can lead to cardiogenic pulmonary edema, as well as endocarditis. Methods in quantitative spectral Doppler measurements of the valves are beyond the scope of the FoCUS. However, the intensivist should be comfortable identifying an obvious mechanical failure of the mitral or aortic valve leading to severe regurgitation (eg, flail leaflet or ruptured chordae or papillary muscle). Valvular stenosis is difficult to appreciate without Doppler techniques, therefore a comprehensive echocardiography is still recommended for a detailed valvular analysis.

Lower Extremity Vascular Ultrasound

In critically ill patients, especially those being mechanically ventilated with indwelling central lines, venous thromboembolism is frequently a concern despite adequate prophylaxis.^{138,139} Bedside lower extremity compression ultrasound is a rapid and

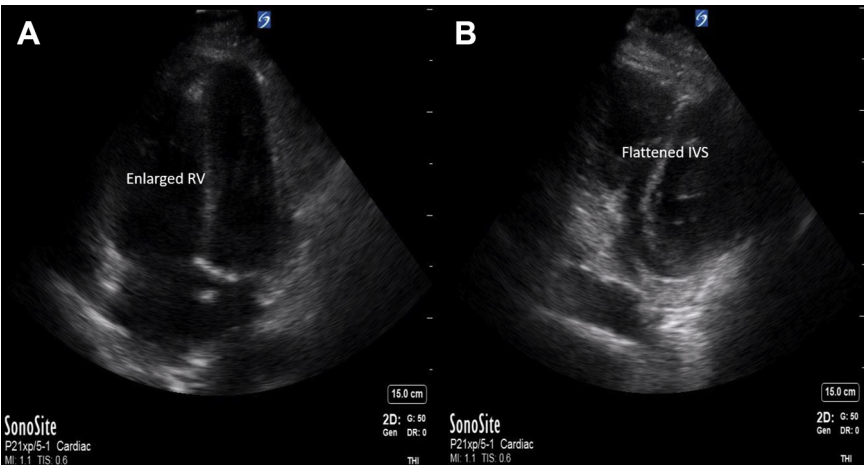


Fig. 15. (A) Apical 4-chamber view with an enlarged right ventricle, suggesting acute right heart strain. (B) A parasternal short-axis view with flattening of the interventricular septum, suggesting acute right heart strain.

easy way to initially evaluate for proximal DVT with a diagnostic accuracy of trained intensivists of around 95%.¹⁴⁰ Using the adjacent artery as a reference point, if direct pressure from the transducer causes the walls of the vein to collapse together and obliterate the lumen, this indicates no thrombus. Lack of compressibility or echogenic intraluminal material signifies a thrombus (Video 3). The vessels analyzed include the common femoral vein at the level where the great saphenous vein enters and the popliteal vein in the popliteal fossa. Note that for visualizing the popliteal vein, the patient's leg should be flexed at a 45° angle at the knee with the vein positioned anterior to the artery. Additional ultrasound analytical strategies, such as pulse wave and color Doppler, do not increase the accuracy of the examination and thus are superfluous for the intensivist.^{141–145} If the ultrasound is negative yet clinical suspicion remains high, further diagnostics such as a CT of the chest with intravenous contrast bolus or ventilation-perfusion scan are indicated. As previously mentioned, a DVT on ultrasound combined with an abnormal-appearing lung ultrasound is highly specific for PE for the patient in respiratory distress.

VOLUME STATUS ASSESSMENT

Perhaps the arena within critical care ultrasound that garners the most interest is an accurate volume assessment of the critically ill patient to help guide management. There are numerous examples demonstrating the superiority of ultrasound compared with other diagnostic measures in this regard. Although some practitioners may continue to argue in favor of the physical examination, ultrasound is more accurate in detecting decompensated heart failure, even when a chest radiograph is available.¹⁰⁵ A recent, large multicenter study demonstrated that ultrasound could distinguish cardiogenic from noncardiogenic dyspnea better than clinical assessment, chest radiography, or brain natriuretic peptide levels.¹⁴⁶

The importance of assessing a critically ill patient's fluid status partly lies in that aggressive fluid resuscitation may be harmful to a certain subset of patients in shock.¹⁴⁷ For example, a conservative fluid management strategy was shown to have better outcomes when compared with a liberal fluid strategy in ARDS.¹⁴⁸ Identifying the nonresponders via invasive or noninvasive means is a controversial topic that has yet to settle on a gold standard. As central venous pressure measurements have proven to be unreliable, attention has shifted to other potential candidates.^{149,150} There is a controversial utility of subcostal visualization of the IVC to assess volume status and fluid responsiveness in

hypotensive patients. The IVC is best visualized and measured at the subcostal area slightly off midline to the right of the abdominal aorta approximately 2 cm caudal to where the hepatic vein joins the IVC before emptying into the right atrium.¹⁵¹ In patients breathing spontaneously, the IVC will collapse on inspiration and distend on expiration due to changes in intrathoracic pressure, whereas under mechanical ventilation the opposite holds true. For spontaneously breathing patients, an IVC diameter less than 2.1 cm that collapses more than 50% with inspiration corresponds to a volume-depleted state (estimated RA pressure 0–5 mm Hg), whereas the converse holds true as well (Fig. 16).¹³⁶ For mechanically ventilated patients, a 15% change in IVC diameter between inspiration and expiration has been shown to accurately predict fluid responders and nonresponders.^{152–154} Thus the SCCM endorses IVC measurement as a grade IB recommendation.¹³⁰ Important caveats to keep in mind are that these parameters assume that RV function is normal, and the cutoff value of 15% only applies to mechanically ventilated patients on a volume-control mode with tidal volumes approximately 8 mL/kg ideal body weight.

Another modality of volume assessment is the size of the left ventricle at the end of diastole.¹⁵⁵ In the parasternal short-axis view at the level of the papillary muscles, a normal LV area at the end of diastole (LVEDA) is approximately 10 to 20 cm². Areas less than 10 cm² or complete obliteration of the LV cavity indicate hypovolemia, whereas values greater than 20 cm² suggest volume overload.^{156,157} There are important clinical considerations to take into account that can cause a decreased LVEDA not related to hypovolemia, such as RV failure, concentric LV hypertrophy, and constrictive pericarditis.¹³³

The fluid administration limited by lung sonography (FALLS) protocol is a useful algorithm to help

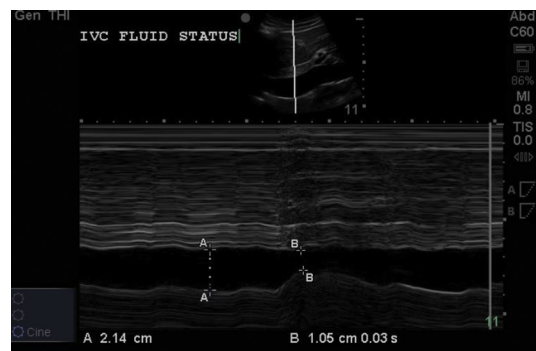


Fig. 16. Measurement of IVC variation in M-mode during spontaneous breathing.

address the question of which patients in shock should receive aggressive fluid resuscitation.¹⁵⁸ The FALLS protocol first rules out obstructive shock (ie, no pericardial tamponade, no RV dilatation to suggest PE, and no tension pneumothorax). Then, cardiogenic shock from left heart failure is ruled out by noting the absence of B-lines. Under these circumstances, the clinician then begins to administer fluid and monitors for an appropriate hemodynamic response. Importantly, under the FALLS protocol, the endpoint of fluid administration is the appearance of anterior B-lines, indicating iatrogenic interstitial syndrome. Interstitial edema is often clinically silent yet precedes alveolar edema, which leads to worsening respiratory failure and, at this point, further fluid is unlikely to augment cardiac output.¹⁵⁹

SUMMARY

The use of POC ultrasound by nonradiologist clinicians has changed the current paradigm of management of critically ill patients with pleural effusion, pneumothorax, shock, or poor cardiac function. As the role of ultrasound in the ICU continues to expand, the authors suspect it will soon become as integral a part of the care of the critically ill patient as chest auscultation once was. Intensivists should continually use the bedside ultrasound examination to gain comfort and familiarity with the techniques and findings discussed. As various societal organizations formalize an ultrasound curriculum, the authors expect that it will be considered a standard-of-care diagnostic and therapeutic tool in the very near future.

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SUPPLEMENTARY DATA

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