Critical Care Ultrasonography

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INTRODUCTION

Resuscitation scenarios require rapid diagnostic and therapeutic decisions tailored to a patient’s underlying condition and evolving physiology. Diagnostic and monitoring tools that can reliably reveal organ failure or life-threatening conditions at the bedside are of the utmost value in these often overwhelming situations.

The use of point-of-care ultrasonography (POCUS) has become an integral part of critical care and resuscitative medicine in recent years. A major accelerant of the POCUS revolution, across all clinical domains, has been the miniaturization of ultrasonography machines, allowing them to be brought to patients easily, rather than requiring patients to be transported away from their clinical environment to be imaged.

Whether in a prehospital setting, the emergency department, or the intensive care unit, patients at risk of deterioration and/or death benefit most from the timely, multisystem bedside analysis provided by POCUS.

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From its origins in the trauma bay in the assessment for hemopericardium\textsuperscript{1,2} and hemoperitoneum,\textsuperscript{3,4} POCUS for the critically ill patient has a growing list of applications. Some applications are the foundation of resuscitation, such as the cause of shock in the undifferentiated patient, whereas other, newer concepts, like intracranial pressure determination from optic nerve sheath diameter, require more time to determine their clinical value. This article reviews the contemporary applications of POCUS that are most relevant to resuscitation.

Before discussing ultrasonography related to the care of the critically ill, a distinction should be made between what has classically been referred to as critical care ultrasonography as described by the American College of Chest Physicians (ACCP) in 2009 and resuscitative ultrasonography, as discussed here. Critical care ultrasonography has been described as a specific set of skills used in the ICU setting involving thoracic, abdominal, vascular, and cardiac ultrasonography and requiring a minimum standard of competence outlined by the ACCP.\textsuperscript{5} Resuscitative ultrasonography encompasses a wide range of practitioners of various skill levels using ultrasonography to assist with resuscitation across a variety of clinical settings. Although resuscitative ultrasonography in the ED is frequently labeled critical care ultrasonography, we therefore favor the more descriptive and nonpartisan term of resuscitative ultrasonography.

**APPLICATION 1: DIFFERENTIATING SHOCK STATES**

*Multisystem Protocols*

One of the most powerful applications of POCUS is in the rapid differentiation of shock states, which has been an area of intense clinical and academic interest over the past decade with the advent of several multisystem scanning protocols (Table 1) for shock published in the literature.\textsuperscript{6–11} The published protocols encourage the routine use of a systematic, multiorgan approach when assessing patients with undifferentiated hypotension. Because no single protocol has proved superior to another, it is the common systematic, multiorgan approach they all endorse, rather than the details of their exact execution that should be emphasized. In general, in the face of undifferentiated shock or hypotension, the following ultrasonography examination elements should be executed: focused point-of-care echocardiography, thoracic, abdominal, vascular, and cardiac ultrasonography and requiring a minimum standard of competence outlined by the ACCP.\textsuperscript{5} Resuscitative ultrasonography encompasses a wide range of practitioners of various skill levels using ultrasonography to assist with resuscitation across a variety of clinical settings. Although resuscitative ultrasonography in the ED is frequently labeled critical care ultrasonography, we therefore favor the more descriptive and nonpartisan term of resuscitative ultrasonography.

**Assessment for Cardiogenic Causes of Shock**

Evaluation of the heart with POCUS during shock can alter a patient’s treatment trajectory in a matter of seconds. In typical goal-directed echocardiography, a phased-array transducer is used to generate 4 standard echocardiographic views of the heart: the parasternal long axis (PLAX) and parasternal short axis (PSAX), the apical 4-chamber (A4C), and subxiphoid (SUBX) views. Each view provides new or complementary information about the relevant cardiac chambers’ size and function, gross valvular disorders, as well as the state of the pericardium. Imaging findings are rapidly synthesized to fit in to one of several clinical syndromes. A summary of the clinical syndromes and corresponding imaging details that are of interest in resuscitation are summarized in Table 2.

Assessment of the patient’s left ventricular function begins with obtaining the PLAX and PSAX views of the heart. The PLAX is often referred to as the scout view of the
heart, providing a broad overview of most relevant structures of interest. Most of the left ventricle (LV) is seen in this view, along with the right ventricular outflow tract, the left atrium, the aortic root, the pericardium, the descending aorta, and the mitral and aortic valves (Fig. 1A).

The PSAX view of the heart is orthogonal to the PLAX and although there are 5 levels of assessment in the short axis the level of the papillary muscles is the most representative of global left ventricular function and therefore is the preferred view when

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**Table 1**

Examples of protocols published for multiorgan ultrasonography assessment for undifferentiated hypotension

<table>
<thead>
<tr>
<th>Protocol Name</th>
<th>Organs Assessed</th>
<th>Patient Population</th>
<th>Comment/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undifferentiated hypotensive patient ultrasonography protocol</td>
<td>Abdomen, aorta</td>
<td>ED</td>
<td>The first standardized ultrasonography protocol for ED patients using 3 accepted POCUS applications. No quantitative data provided</td>
</tr>
<tr>
<td>Focused echocardiographic evaluation in life support</td>
<td>Cardiac</td>
<td>Prehospital</td>
<td>Limited echocardiography performed by an emergency physician in periresuscitation scenarios alters management in 78% of cases</td>
</tr>
<tr>
<td>Focused echocardiographic evaluation in resuscitation</td>
<td>Cardiac</td>
<td>ED, ICU</td>
<td>Proposed protocol for incorporating limited echocardiography assessment into ACLS with the goal of identifying reversible causes of cardiac arrest. Feasibility of limited echocardiography during CPR was shown</td>
</tr>
<tr>
<td>Abdominal and cardiac evaluation with sonography</td>
<td>Cardiac, IVC, abdomen, aorta</td>
<td>ED</td>
<td>Six-view structured approach to assess hypotensive patient with sonography. Examples of how results would change management are given, but no outcome data presented. Protocol remains to be validated</td>
</tr>
<tr>
<td>RUSH</td>
<td>Cardiac, IVC, abdomen, pleura</td>
<td>ED</td>
<td>Three-step bedside physiologic assessment of the pump, tank, and pipes of a hypotensive patient. Components of RUSH protocol studied previously, not the complete RUSH protocol</td>
</tr>
<tr>
<td>Echocardiography-guided life support</td>
<td>Cardiac, lung, IVC</td>
<td>ED, ICU</td>
<td>An algorithmic approach to optimizing early management of critically ill patients based on answering several clinical questions with ultrasonography. Incorporates aspects of several previously published protocols</td>
</tr>
</tbody>
</table>

**Abbreviations:** ACLS, advanced cardiac life support; CPR, cardiopulmonary resuscitation; IVC, inferior vena cava; RUSH, rapid ultrasonography in shock.

Data from Refs. 6-11
performing POCUS. The LV is seen as a thick circular ring of cardiac muscle with the smaller, thin-walled, and crescent-shaped right ventricle (RV) next to it. Also visible in the short axis is the echogenic pericardium (Fig. 2A).

Determining quantitative measures of left ventricular systolic function using POCUS is neither necessary nor practical. Estimating gross left ventricular function visually at the bedside has been studied and endorsed by both intensivists and emergency physicians. Although left ventricular function is a continuous variable, it is more clinically relevant to categorize the LV into broader gradations of function: normal, hyperdynamic, depressed, and severely depressed. Although this 4-category approach is arbitrary, many clinicians find that this approach strikes an appropriate balance between too few categories (resulting in overgeneralizations of function) and too many categories (resulting in clinically insignificant distinctions of function).

In the PLAX and PSAX views, a normal heart shows that the cardiac muscle thickens and contracts in unison during systole. The walls of the LV should contract toward the

<table>
<thead>
<tr>
<th>Clinical Syndrome</th>
<th>Relevant Cardiac Ultrasonography Views</th>
<th>Findings</th>
<th>Pitfalls and Pearls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypovolemic shock</td>
<td>IVC, PSAX</td>
<td>IVC: narrow diameter, respiratory variation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PSAX: hyperdynamic function, kissing papillary muscles</td>
<td>Off-axis imaging falsely portraying narrow IVC or apical PSAX showing falsely hyperdynamic function</td>
</tr>
<tr>
<td>LV systolic failure</td>
<td>PLAX, PSAX, IVC</td>
<td>PLAX: hypocontractility, reduced EPSS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PSAX: hypocontractility</td>
<td>Off-axis imaging may show falsely normal function</td>
</tr>
<tr>
<td>RV failure</td>
<td>PSAX, A4C, IVC</td>
<td>PSAX: D-shaped septum</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4C: increased RV size</td>
<td>Off-axis imaging may show an elliptical RV and mimic a flattened septum</td>
</tr>
<tr>
<td>Catastrophic valvulopathy</td>
<td>PLAX, A4C</td>
<td>PLAX/A4C: vegetation on valves, chordae tendonae rupture, massive regurgitation with color Doppler</td>
<td>Color Doppler assessment best done when flow is toward or away from the transducer (ie, A4C)</td>
</tr>
<tr>
<td>Tamponade</td>
<td>PLAX, A4C, IVC</td>
<td>PLAX: large, circumferential effusion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4V: right atrial/ventricular collapse</td>
<td>Patients in shock with a nontrivial effusion and dilated IVC should be considered to have tamponade until proved otherwise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IVC: dilated</td>
<td></td>
</tr>
<tr>
<td>Circulatory arrest</td>
<td>SUBX</td>
<td>In cardiac standstill: no myocardial thickening. Valve fluttering may be seen</td>
<td>Best position to obtain view is SUBX. Standstill predictive of poor outcome</td>
</tr>
<tr>
<td>Vasodilatory (eg, septic) shock</td>
<td>PLAX, PSAX, A4C, IVC</td>
<td>Normal to hyperdynamic LV in all views; IVC of variable size. Otherwise normal examination</td>
<td>Early hyperdynamic state of the LV has been shown to be specific for ultimate diagnosis of sepsis</td>
</tr>
</tbody>
</table>

Abbreviations: EPSS, E point septal separation; LV, left ventricle; RV, right ventricle.
center of the LV cavity. In addition, the distance between the anterior leaflet of the mitral valve and the septum can also provide important information in the PLAX view regarding gross left ventricular function (a parameter known as E point septal separation [EPSS]). Under normal conditions, the anterior mitral valve leaflet should open vigorously and nearly meet the septum during diastole. When left ventricular function is reduced, wall thickening and contraction of the ventricular free walls and septum are reduced and the mitral valve does not open with the same vigor as in a normal heart (see Fig. 1B). If this EPSS distance is more than 1 cm, it is almost certain that the LV has depressed function.\(^\text{16}\) Severely decreased left ventricular function is characterized by an LV that shows further progression of the diminished muscle excursion and thickening seen in the depressed category. In addition, a hyperdynamic LV is one that is seen to be contracting overly vigorously, typically in the context of hypovolemia and/or low afterload conditions like septic shock. The walls of the ventricle are observed to collapse vigorously toward the center of the LV and often touch, or kiss, at the end of systole. Off-axis imaging, either in the PLAX or the PSAX view, can falsely mimic a hyperdynamic state, so attention to imaging through the middle of the LV cavity (PLAX) and avoiding being apically displaced (PSAX) help to avoid overestimating left ventricular function. Overall, grading LV function in a qualitative fashion is straightforward to do after acquiring appropriate experience.

Assessing the pericardium for pericardial effusion can be done in any of the 4 basic echocardiographic views of the heart, although many favor the PLAX view because it offers an ideal view for the posterior pericardium, in which even small pericardial

**Fig. 1. (A) Normal PLAX view. (B) Dilated LV in the PLAX with decreased E point septal separation.**

**Fig. 2. (A) Normal PSAX view. (B) D-shaped LV as a result of increased right-sided pressure.**
effusions may be observed in supine patients (Fig. 3). An effusion is seen as an anechoic collection between the bright echogenic layers of the pericardium. Most are free flowing around the pericardium, although loculated effusions are common after cardiac procedures, increasing the complexity of the assessment in this population. The hemodynamic influence of any given pericardial effusion depends on a variety of factors, including speed of accumulation, size, and the volume status of the patient.

If pericardial pressure exceeds right-sided filling pressures, cardiac tamponade ensues. In a patient with shock in whom a nontrivial pericardial effusion is identified, providers should generally assume that tamponade physiology is present until proved otherwise. For advanced sonographers, appreciation of the echocardiography findings of tamponade physiology, including right atrial or right ventricular collapse (Fig. 4) or variation in mitral inflow Doppler patterns, may be possible and further boosts diagnostic confidence and influences management accordingly. Although these features of tamponade physiology are commonly described, the diagnostic performance of these findings outside of controlled echocardiography laboratories is unknown. It is therefore proposed that a more useful adjuvant tool in the context of a pericardial effusion is assessment of IVC size and respiratory variation. When tamponade is present, the IVC must be dilated. Because the IVC is easily imaged by POCUS, a nondilated IVC can be an effective bedside tool for ruling out tamponade physiology with high sensitivity. POCUS also provides the opportunity to guide and visualize pericardiocentesis in real time, aiming for the area of the largest collection of pericardial fluid while avoiding overlying lung.

The presence or absence of right ventricular failure can radically alter the therapeutic decisions and prognosis of critically ill patients. Acute cor pulmonale is usually the result of a pulmonary embolism or an exacerbation of a chronic lung condition causing increased right-sided pressures. Assessment for right ventricular failure with POCUS should start with determining the size of the RV compared its larger neighbor, the LV. This determination is best done using the PSAX and A4C views. In the short axis, increased right-sided heart pressure results in an enlargement of the RV and a flattening of the usually rounded interventricular septum, creating a D-shaped LV (see Fig. 2B). In the A4C view, the RV should be seen to be no more than two-thirds the size of the LV during diastole. Further, under normal conditions, the LV should dominate the apex (Fig. 5A). In acute cor pulmonale, the weaker RV

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Fig. 3. Small posterior pericardial effusion (PE) in the PLAX.
quickly becomes overwhelmed and increases in size to become moderately dilated (more than two-thirds the size of the LV) or severely dilated (larger than the LV) and may displace the LV and occupy most of the apex (see Fig. 5B). Right ventricular dysfunction is an area of intense study in the resuscitation literature. In turn, precise and well-accepted management strategies for a failing or strained RV are not discussed in this article.

Fig. 4. Cardiac tamponade; right ventricular outflow collapse in the PLAX. RVOT, right ventricular outflow tract.

Fig. 5. (A) Normal apical 4-chamber view. (B) Right ventricular enlargement in the apical 4-chamber view. (C) Tricuspid valve vegetation; subxiphoid view.
Acute valvular regurgitation may be the cause of, or may complicate, a patient’s shock state and should form part of a thorough point-of-care echocardiogram. Although valvular heart disease and the Doppler applications required for accurate valvular analysis are complex, color Doppler may be used to crudely screen across the tricuspid valve (TV) or mitral valves (MV) in the A4C or the aortic valve (AV) in the neighboring apical 5-chamber view for severe regurgitation. Important causes of severe regurgitation include endocarditis (MV, AV, and TV; see Fig. 5C), ischemia (MV), aortic dissection (AV), or acute cor pulmonale (TV).

Identification of any of the constellation of cardiac findings discussed earlier is of little value until they are appropriately clinically integrated. A one-size-fits-all algorithm for incorporation of these findings into clinical care is not realistic; however, there are some important points worth mentioning.

Identifying a hyperdynamic LV has been shown to be associated with early sepsis or hypovolemia, both of which are amenable to rapid fluid administration. Depressed or severely depressed left ventricular function may be associated with late sepsis, toxins, or cardiogenic shock, in which case moving toward administration of inotropic medications earlier may be of benefit as well as transferring the patient for cardiac catheterization if the clinical situation is more likely cardiac in origin. Identification of pericardial effusions and cardiac tamponade at the bedside allows more rapid initiation of a potentially life-saving pericardiocentesis. Recognizing patients with right heart strain or acute cor pulmonale is valuable because it often represents an acute pulmonary embolus that requires anticoagulation, thrombolysis, or potentially surgery. Patients with right heart strain on POCUS should undergo further evaluation with computed tomography (CT) pulmonary angiogram, if stable enough, or transesophageal echocardiography (TEE) or potentially thrombolysis if the patient continues to deteriorate or has cardiac arrest.

POCUS allows for frequent reassessment of a patient’s hemodynamic status as their clinical situation progresses. Those septic patients with an initially hyperdynamic LV may progress to an LV with depressed function as their conditions evolve. It is also useful to monitor the effects of interventions, whether these are intravenous fluids, pharmacologic (eg, vasopressors), or a physical intervention such as insertion of an intra-aortic balloon pump. Frequent monitoring with POCUS is advantageous because there is no radiation exposure, it is portable and noninvasive, and it offers real-time evaluation of important physiology in the critically ill patient.

**Estimating Fluid Responsiveness Using the IVC**

A long-axis view of the IVC, obtained from the subcostal window, can provide information about volume status and, occasionally, volume responsiveness. Through interpretation of its absolute size as well as how it varies with respiratory efforts, approximations of central venous pressure (CVP) can be made (in spontaneously breathing patients) and predictions of volume responsiveness can accurately be made in patients who are passively mechanically ventilated. When assessing the size and variation of the IVC, attention should be directed to the confluence of the vertically oriented hepatic vein and the IVC, or about 2 cm distal to the right atrium–IVC junction (Fig. 6).

IVC examination can help corroborate additional cardiac findings. For instance, in the context of a hyperdynamic LV for which the cause could be multifactorial (vasodilatory shock, right ventricular obstruction, hypovolemic shock, or high-output states), a small IVC (<1.0 cm in a spontaneous breathing patient) suggest a hypovolemic state.

Although imaging the IVC is easy, its interpretation requires thoughtful reflection by the provider regarding the respiratory physiology of the patient and the way it
influences the IVC. The strongest evidence for use of IVC ultrasonography comes from mechanical ventilated patients who are passively (ie, not triggering) being ventilated.\textsuperscript{24,25} In these patients, distention of between 12\% and 18\% of the IVC during inspiration predicts volume responsiveness.

Because of the variable respiratory effort with all other states of spontaneously breathing physiology, it has not been possible for research to provide a similar level of evidence or a single algorithm to predict volume responsiveness using the IVC. However, the IVC has been shown to predict CVP and, in keeping with this, many clinicians advocate that an IVC showing greater than 50\% collapse (corresponding with a CVP of 0–5 mm Hg) under spontaneously breathing physiology can support fluid administration. Despite the reliance on CVP in prominent resuscitative guidelines,\textsuperscript{26} it has never been proved to predict volume responsiveness and therefore relying on CVP for fluid management, no matter how it is derived, is coming under increasing scrutiny.\textsuperscript{27}

Despite the ease of imaging the IVC, it cannot be applied in the same fashion or with the same value across all critically ill patients. Alternative, more laborious and advanced ultrasonography approaches have been explored. Common to many of these advanced techniques is reliance on spectral Doppler profiles from various sites in the body, including the left ventricular outflow tract and the brachial or carotid arteries.\textsuperscript{28,29} The variation of the amplitude of the stroke volume envelope that is displayed (known as the velocity time integral) can be measured, in response to respiratory efforts, volume administration, or passive leg raising (Fig. 7). Various thresholds of variation exist to predict volume responsiveness.

The use of a more complex Doppler tissue method of determining increased left atrial pressure by determining the ratio (E/E') of transmitral pulsed-wave Doppler flow (E) to the relaxation velocity of the LV (E') has promise but uptake is limited by expertise and time demands.\textsuperscript{30,31}

**Assessment of the Abdomen and Aorta as Potential Causes of Shock**

Assessing the abdominal compartment for free fluid and the aorta for an abdominal aortic aneurysm (AAA) are fundamental POCUS skills for any emergency physician. There is strong evidence supporting the accuracy and speed with which this examination can be performed in the ED in the setting of trauma (focused assessment with sonography for trauma [FAST]) or suspected aneurysm.\textsuperscript{32–34}
Aortic dissection remains a diagnostic challenge for emergency physicians. Diagnosis of a type B or extensive type A dissection is occasionally made through abdominal aorta assessment when an intimal flap is revealed (Fig. 8). In an unstable patient, too sick to go to a CT scanner, an examination of the AV, aortic root, and proximal ascending aorta (with the PLAX view) and the pericardium should immediately be undertaken to assess for features supportive of a type A aortic dissection such as severe aortic regurgitation, a dissection flap in the proximal aorta, and hemopericardium.

Examination of the gallbladder in a hypotensive septic patient that is otherwise undifferentiated may occasionally reveal cholangitis as the cause. The sonographic

Fig. 7. Pulsed-wave Doppler of the left ventricular outflow tract showing respiratory variation in stroke volume from end expiration (solid arrows) and end inspiration (dashed arrows) in a spontaneously breathing patient, suggesting volume responsiveness.

Fig. 8. Aortic dissection flap seen in cross section.
changes associated with an infected gallbladder include any combination of the presence of gallstones, a sonographic Murphy sign, a thick gallbladder wall (>3 mm), pericholecystic fluid, or a dilated common bile duct (Fig. 9).\textsuperscript{35,36} Given the need for early, invasive source control, the benefits of identifying or excluding an abdominal source of septic shock, such as cholangitis, cannot be overstated.

**Hemothorax and Pneumothorax as Causes for Hypotension**

Particularly in the setting of trauma, the pleural space may conceal a hemodynamically important amount of blood that can be readily be identified with ultrasonography.\textsuperscript{37} Hemothorax typically appears as an anechoic free space cranial to the diaphragm and may look similar to a simple medical effusion. However, a hemothorax may show some distinguishing features such as fibrin or clot formation (Fig. 10) or the so-called hematocrit sign as red cells separate from plasma. Nontraumatic causes of hemothorax, such as thoracic aneurysm rupture, are plausible but uncommon to reach hospital.

Pneumothorax, particularly tension pneumothorax, is a commonly implicated cause for shock in the setting of trauma, after a procedure, or during mechanical ventilation. With the diagnostic performance of supine chest radiograph leaving much to be desired (sensitivity of 28%–79%), lung ultrasonography offers a significant diagnostic advantage (sensitivity of 82%–98%) and is much faster to acquire than an urgent portable chest film.\textsuperscript{38–40} Assessing for pneumothorax involves identifying reliable artifacts produced by the contact of the visceral and parietal pleural membranes, which are referred to as lung sliding (or shimmering), comet-tails (or B lines), and lung-point (Fig. 11).\textsuperscript{41–43} In particular, it should be emphasized that the sensitivity of lung ultrasonography makes it an excellent tool to rule out pneumothorax. Tension pneumothorax is rare compared with other causes of hypotension or shock that are commonly lumped with the so-called Hs and Ts of the advanced cardiac life support dogma and the ability of lung ultrasonography to eliminate this distracting diagnosis from a list of more plausible causes makes it an exceptional tool in the rapidly evolving shock or cardiac arrest state.

**CAUSES OF RESPIRATORY FAILURE**

There is increasing literature advocating the use of lung ultrasonography to assist the clinician in determining a diagnosis at the bedside of an acutely dyspneic patient. The

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Fig. 9. Gallbladder (GB) with multiple gallstones (GS) and a thick wall (1.16 cm).
air-filled lungs provide reliable artifact patterns in health and in various disease states that allow, with some training and reflective integration, the categorization of most patients in to a lung profile. The study and protocol best showing the feasibility and diagnostic accuracy of this approach was Lichtenstein and Meziere’s\textsuperscript{44} BLUE protocol study.

The BLUE protocol requires the clinician to perform an ultrasonography scan of the anterior and anterolateral thorax bilaterally, as well as 2 dedicated views of the pleural space, looking for specific lung artifact patterns: sliding lung, A lines (horizontal reverberation artifact) or B lines (vertical, hyperechoic lines that descend from pleural line to bottom of the ultrasonography screen), pleural effusion, or consolidation pattern (hepatized lung, suggesting atelectasis or pneumonia). Three or more B lines in a single rib space (B\textsubscript{3} lines) indicates the interstitial syndrome, consistent most commonly in the ED with pulmonary edema but also seen with acute respiratory distress syndrome and lung fibrosis. An A/B pattern of lung artifacts consists of one hemithorax with an A-line pattern and the contralateral hemithorax with a B-line pattern, and indicates pneumonia. The C profile is characterized by anterior consolidation and indicates pneumonia as well. The use of this protocol allowed the investigators to correctly diagnose the cause of a patient’s respiratory failure in 90.5\% of 260 cases (Table 3).\textsuperscript{44}

**Fig. 10.** Large left-sided hemothorax caused by an aortic injury. The effusion is showing a more isoechoic density caused by the early clotting.

**Fig. 11.** B-line artifact arising from the pleural line.
<table>
<thead>
<tr>
<th>Clinical Syndrome</th>
<th>Lung Ultrasonography Pattern</th>
<th>Additional Sonographic Findings</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary edema</td>
<td>Diffuse B-line pattern</td>
<td>+ Lung sliding</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>COPD</td>
<td>A-line pattern</td>
<td>± Lung sliding</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Asthma</td>
<td>A-line pattern</td>
<td>+ Lung sliding</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>PE</td>
<td>A-line pattern</td>
<td>+ Lung sliding</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ DVT</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Pneumothorax</td>
<td>A-line pattern</td>
<td>– Lung sliding</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Pneumonia</td>
<td>A/B pattern</td>
<td>+ PLAPS</td>
<td><img src="image7.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>± Lung sliding</td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>Pneumonia</td>
<td>C pattern</td>
<td>—</td>
<td><img src="image9.png" alt="Image" /></td>
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</tbody>
</table>

**Abbreviations:** COPD, chronic obstructive pulmonary disease; DVT, deep vein thrombosis; PE, pericardial effusion; PLAPS, posterolateral alveolar and/or pleural syndrome.
**RESUSCITATIVE END POINTS**

Under-resuscitation and over-resuscitation for circulatory failure can both contribute to excess mortality.\(^{45,46}\) Serologic values (such as lactate and central venous oxygen saturation) and invasive measures (CVP) remain endorsed by the Surviving Sepsis Campaign Guidelines\(^ {26}\) and are measures of preload and oxygen delivery that are frequently used in the ED. There has been a natural enthusiasm for the ability of ultrasonography to either complement or replace some of these measures in guiding the intensity of resuscitation. As earlier, relying on the IVC for assessing a patient’s fluid status and potential fluid responsiveness has many pitfalls. It is thus important to consider other methods by which clinicians can tailor resuscitation and identify, in particular, when volume resuscitation remains indicated and when further volume may cause harm.

Lichtenstein and Karakitsos\(^ {47}\) advocated looking at the main vital organ (the lung) rather than following indirect parameters such as changes in the LV or IVC size. Lichtenstein and Karakitsos’s\(^ {47}\) fluid administration limited by lung sonography (FALLS) protocol can be used to guide fluid administration strategies during resuscitation scenarios using lung ultrasonography. Pulmonary edema is a classic resuscitation end point that is easily assessed for using POCUS. The FALLS protocol advocates for frequent imaging of the thorax throughout a resuscitation, looking for an evolving B-line pattern indicating pulmonary edema. A diffuse B-line pattern, with persistent shock, signals the resuscitationist to alter the management strategy (ie, vasopressors) because continued fluid administration may be harmful. This strategy works best when the initial lung ultrasonography reveals an A-line pattern (Fig. 12). If patients present with an initial diffuse B-profile on lung ultrasonography, then alternate strategies must be used to assess potential fluid responsiveness, as discussed earlier.

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**Fig. 12.** Simplified FALLS fluid administration protocol.
It is readily apparent that there are several important aspects to assessing a patient in shock with POCUS when evaluating for potential causes, as well as potential therapeutic interventions. Integrating information gleaned from cardiac, lung, and IVC ultrasonography at the patient’s bedside aids the astute clinician in managing these complex patients. Again, one of the strongest advantages of POCUS when treating critical patients is the ability to repeat the examination at various stages of treatment in determining not only the potential cause of the shock state but in initiating appropriate and potentially life-saving interventions.

**NEUROLOGIC APPLICATIONS**

Altered mental status and lateralizing features of brain dysfunction are easily recognized on cursory physical examination in the ED. Unlike other organs, little else can be done in the ED via laboratory or plain radiograph to further characterize or exclude anatomic causes of CNS failure, which frequently results in the need to transport critically ill patients out of the resuscitation room for CT scans of the head. Because of the time and risk of transport, the role of ultrasonography to image the brain at the point of care is attractive. Despite the sonographically impenetrable nature of bone, there are 2 distinct areas of the head (in an adult) where acoustic windows exist and create the opportunity for assessment: (1) the ocular window, imaging through the globe of the eye; and (2) the transcranial windows at the perimeter of the skull.

Identifying increased intracranial pressure (ICP) through imaging the optic nerve sheath diameter (ONSD) has received considerable attention. The optic nerve has a sheath that is fenestrated and, under conditions of increased ICP, the diameter of the nerve increases. Measurements more than 5 mm in width in the ED have been shown to correlate with increased ICP and in a prospective trial showed 100% sensitivity for the identification of increased ICP, with a specificity of 63%. The high-sensitivity 5-mm cut value for ONSD provides a helpful binary tool for the resuscitation physician to assist in ruling out increased ICP as the cause of an altered mental status in a critically ill patient (Fig. 13). ONSD is much less useful when increased because there are many false-positives (low specificity) and these patients all require CT scanning. Further, in true-positives with increased ONSD and increased ICP, what is needed is the ICP value to help guide blood pressure and corresponding cerebral perfusion pressure (CPP) titration.

Transcranial Doppler (TCD) ultrasonography makes use of transcranial windows (typically transtemporal) to measure velocity and resistance profiles of blood flow, typically via the middle cerebral artery. This Doppler information may be applied to determine the presence or absence of increased ICP given the reliable effect that increased ICP has on systolic (increased) and diastolic (reduced) velocities (Fig. 14). This modality has shown feasibility for use in an ED setting to identify both increased ICP and midline shift successfully. However, TCD outperforms ONSD in its ability to provide real-time feedback in response to therapy for increased ICP. In an ED study on traumatic brain injury, a goal-directed protocol using TCD to guide blood pressure (and thus CPP), TCD was able to show normalization of systolic and diastolic velocities in response to a corrected CPP. Despite the advantages that TCD may offer, TCD requires additional expertise in image acquisition and a good understanding of Doppler and its pitfalls, and is not routinely part of ultrasonography training in North America.

**FUTURE DIRECTIONS**

TEE for critically ill patients is a powerful tool in answering hemodynamic and anatomic questions regarding circulatory failure. TEE has several advantages compared with
Fig. 13. Ultrasonography of the optic nerve sheath in a patient with traumatic brain injury. Caliper measurements show an optic nerve diameter of 6.5 mm, suggesting increased ICP.

Fig. 14. Transcranial Doppler profile of the left middle cerebral artery as obtained in the ED from a patient with increased ICP that corresponds here subjectively with a heightened difference between the peak systolic velocity (solid arrow) and the diastolic velocity (dashed arrow) or, more objectively, a resistive index (systolic velocity – diastolic velocity/systolic velocity) of 0.80 (normal: <0.60).
the transthoracic approach, including more reliable, high-quality images and its indwelling location that enables continuous monitoring of the heart during resuscitation, including cardiopulmonary resuscitation (CPR) (Fig. 15). Despite these advantages, uptake in the ED has been limited to this point, largely because of the cost and limited training opportunities. It is anticipated that, with the advent of high-fidelity TEE simulators and the increased uptake of emergency physicians with critical care training, TEE use in the ED for critically ill patients will continue to increase.

SUMMARY

Resuscitative ultrasonography provides rapid, repeatable, and multisystem assessment to guide diagnosis and management of critically ill patients in the ED. Cardiac ultrasonography offers new anatomic and hemodynamic information, previously unavailable in an ED setting, whereas other applications match or exceed the speed and utility of existing tests such as chest radiograph (thoracic ultrasonography) or CVP determination (IVC ultrasonography). Evolving areas of resuscitative ultrasonography, including neurologic assessment and TEE, are increasing, further maximizing the ability for ultrasonography to enhance the provision of critical care in the ED.

REFERENCES


