Point-of-Care Ultrasound for Pediatric Shock

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Abstract: The evaluation of critically ill children in the emergency department is oftentimes challenging. Point-of-care ultrasound is an essential tool in the rapid identification of reversible pathology and provides unique insight into the appropriate treatment approach. In this article, we discuss a straightforward sonographic approach to pediatric patients who present in shock.

Key Words: ultrasound, shock, critical care

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TARGET AUDIENCE

This CME activity is intended for pediatric emergency medicine practitioners.

LEARNING OBJECTIVES

After completion of this article, the reader should be able to:

1. Diagnose and manage critically ill patients using point-of-care ultrasound (POCUS).
2. Recognize hypovolemic shock based on cardiac, inferior vena cava (IVC), and right upper quadrant (RUQ) evaluation.
3. Identify various causes of right ventricular (RV) outflow obstruction based on their sonographic features.

Critically ill children are a diagnostic and management challenge to all pediatric emergency medicine practitioners. Although hypovolemia from gastroenteritis is most commonly implicated in pediatric shock worldwide, hemorrhagic shock and septic shock are also frequently observed.[1] Cardiogenic and obstructive shock, albeit seen less frequently in children, still represent important but difficult diagnoses in the pediatric population. In those critically ill patients who arrive to the pediatric emergency department (PED), the common limitations of the history and examination may lead to delays in care or ineffective treatment. As the role of POCUS evolves in the PED, its potential to improve the care of this at-risk population is significant.[2,3] Ultrasound is particularly suited to the pediatric population because it may serve as an alternative to computed tomography and the increased risks of radiation-induced cancers.[4] Unfortunately, POCUS training has not been formally incorporated into pediatric residency training or pediatric critical care training.[5] However, there is increasing interest in ultrasound education, as demonstrated by a recent article by Conlon et al,[6] which describes successful implementation of a POCUS training program in a pediatric critical care program. Point-of-care ultrasound instruction is now a required component of pediatric emergency medicine fellowships, although there remains wide variation in the uses of POCUS and the quantity and quality of the training received.[7] It is clear from adult emergency medicine and critical care literature that POCUS training leads to effective skill acquisition, and comprehensive guidelines support its use in diagnosis and management.[8] Even medical students are increasingly exposed to POCUS, and longitudinal curriculums have demonstrated considerable success.[9–11]

Critically ill patients, especially patients with undifferentiated hypotension, may benefit greatly from a POCUS evaluation. The adult ultrasound literature has numerous studies and descriptive articles regarding a methodical approach to scanning this gravely ill patient population.[12–17] The Rapid Ultrasound in Shock examination is one of the more widely known approaches.[15] It highlights a bedside physiologic assessment of the pump (heart), the tank (intravascular volume status), and the pipes (large arteries and veins of the body). It is a comprehensive approach that includes views of the heart (parasternal long axis, parasternal short axis, subxiphoid, and apical 4-chamber), IVC, RUQ and left upper quadrant (LUQ), pelvis, lungs, aorta, and lower extremities (deep venous thrombosis). Although there is no validated sonographic protocol for the critically ill pediatric patient, this article describes a focused, algorithmic approach, derived from the Rapid Ultrasound in Shock examination, for the sonographic evaluation of critically ill pediatric patients, with the goal of rapidly and accurately identifying life-threatening pathology.

Case 1

An 11-year-old girl presents with cough and increased work of breathing. She has a history of autism and a chromosomal 1p36 deletion. Her mother states that she has had 1 week of upper respiratory symptoms and worsening fatigue. Her blood pressure is 74/40 mm Hg, heart rate is 147 beats per minute, respiratory rate is 45 breaths per minute, temperature is 38.1°C, and room air oxygen saturation is 88%. Her blood pressure does not improve after a 60-mL/kg bolus of normal saline. A bedside cardiac ultrasound is performed. The subxiphoid view is somewhat limited, and instead, a parasternal long axis view is obtained [Fig. A1, Supplemental Digital Content (SDC) 1, http://links.lww.com/PEC/A75]. The IVC is then identified in longitudinal axis during inspiration (Fig. A2, SDC 1, http://links.lww.com/PEC/A75). No intraperitoneal free fluid is noted on examination of the RUQ. On evaluation of the lungs, a diffuse B-line pattern is appreciated bilaterally (Fig. 1). On the basis of these findings, vasopressors are initiated, while rapid sequence intubation is performed because of respiratory failure.

Case 2

A 4-year-old boy without a significant medical history presents after suddenly collapsing at the playground. The child's father

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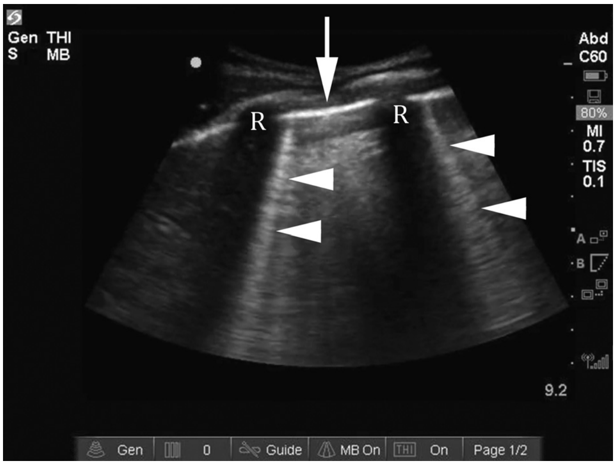

FIGURE 1. Lung evaluation with visualization of the pleural line (arrow), ribs (R), and B-lines (arrowheads).

rushes him to the PED, where he is noted to be unresponsive with diminished pulses. His blood pressure is not measureable, heart rate is 180 beats per minute, respiratory rate is 34 breaths per minute, temperature is 36.0°C, and room air saturation is unobtainable. While intravenous (IV) access is obtained, a quick cardiac assessment demonstrates normal LV function and no tamponade. The IVC is flat. The RUQ view reveals free fluid in the hepatorenal space (Fig. A3, SDC 1, http://links.lww.com/PEC/A75). No lung pathology is observed on ultrasound. While IV fluids and blood are being administered, the child loses pulses, chest compressions are initiated, and IV epinephrine is given. There is no return of spontaneous circulation, and the child is pronounced dead.

Case 3

A 10-year-old boy presents to the ED with a 2-week history of fever, rash, vomiting, diarrhea, shortness of breath, and chest pain. Recently, his pediatrician diagnosed him with dermatitis and costochondritis. Because of progression of symptoms, his parents brought him to the ED. His blood pressure is 80/48 mm Hg, heart rate is 115 beats per minute, respiratory rate is 32 breaths per minute, temperature is 38.0°C, and room air oxygen saturation is 99%. A POCUS is performed. The subxiphoid view demonstrates a large circumferential pericardial effusion, with collapse of the RV (Fig. 2). In addition, the patient has a noncollapsible IVC during inspiration (Fig. A4, SDC 1, http://links.lww.com/PEC/A75). Cardiology is emergently consulted, and the patient undergoes a bedside pericardiocentesis.

SHOCK ULTRASOUND TECHNIQUE

With regard to shock, the pathophysiology is traditionally separated into 1 of 4 categories:

1. Cardiogenic
   - Myocarditis, myocardial infarction, arrhythmia, and so forth

2. Volume loss
   - Bleeding, vomiting, diarrhea, poor oral intake, and so forth

3. Distributive
   - Sepsis or neurogenic causes

4. Obstructive
   - Cardiac tamponade, pneumothorax, pulmonary embolism, and so forth

In the initial assessment of patients in shock, the clinician may use POCUS to rapidly assess 4 areas to determine the cause of the patient's hypotension and help to guide treatment. These 4 areas include the following:

1. Heart
2. IVC
3. Intraperitoneal cavity
4. Lungs and pleura

Evaluating the Heart

When looking at the heart, the examiner should assess LV function and filling. Decreased filling indicates diminished venous return from either hypovolemia or obstruction of blood flow through the right heart or pulmonary vasculature. Poor function indicates heart failure. The examiner may also assess RV filling and function. Decreased filling of the right heart indicates diminished return from either loss of blood volume or increased capacitance from sepsis or neurogenic causes.

Background

The history of and indications for focused cardiac ultrasound is comprehensively described in the 2010 consensus statement between the American Society of Echocardiography and the American College of Emergency Physicians.[18] In this document, it was noted that focused cardiac ultrasound was a fundamental tool to expedite the diagnostic evaluation of the patient, to initiate emergent treatment, and to allow for rapid triage decisions. Point-of-care limited cardiac examinations have also been described in the pediatric literature for more than a decade. Pershad et al[19] were among the first to describe the role of point-of-care echocardiography in critically ill pediatric patients. They found that emergency physician sonographers compared favorably with experienced pediatric echocardiography providers in the performance of point-of-care studies, accurate assessment of LV function, and IVC volume assessment. Spurney et al[20] noted comparable results between

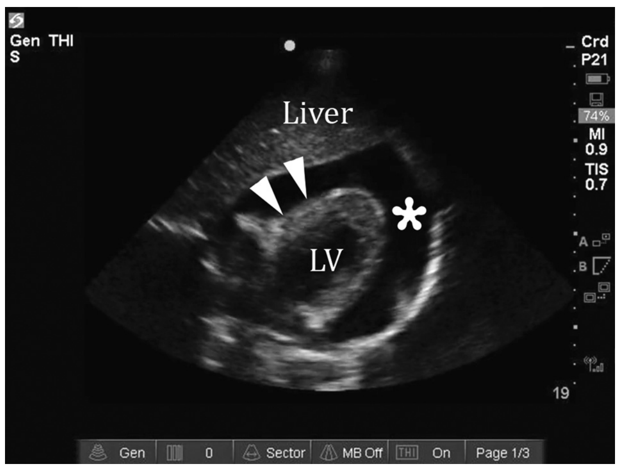

FIGURE 2. Subxiphoid cardiac view demonstrating a large pericardial effusion (asterisk), with a collapsed free wall of the RV (arrowheads), indicating tamponade. Also labeled are the liver in the near field and the LV.

noncardiologist sonographers and formal echocardiograms on pediatric patients with regard to the identification of pericardial effusion, LV size, and LV systolic function.

Technique

Because of its low frequency and small footprint, the phased array probe is the primary probe for performing cardiac ultrasound. A single cardiac view is generally recommended for the 4-step shock ultrasound protocol. Both the subxiphoid and parasternal long axis views are reasonable choices for the single cardiac view. Both views allow rapid identification of LV dysfunction and cardiac tamponade.

The subxiphoid view is one of the first views recognized by emergency physicians because of their familiarity with it from the Focused Assessment with Sonography for Trauma (FAST) examination. Although there is some variation in the orientation of the probe indicator for point-of-care cardiac ultrasound, this article will discuss maintaining the screen indicator in the upper left corner of the viewing screen ("abdominal" orientation) to maintain consistency with other point-of-care applications. The subxiphoid view is obtained by placing the probe on the patient's upper abdomen approximately 2 to 3 cm below the xiphoid process, with the probe indicator pointed toward the patient's right side. The probe is held on its anterior surface, relative to the patient. The probe is fanned so that its transmitting surface is pointing toward the patient's head and that the probe is held at an approximately 15-degree angle from the patient's abdomen. This approach maximizes the role of the liver as an acoustic window for visualizing the heart. The liver, appearing at the top of the screen (near field), has a gray echotexture with a "salt-and-pepper" appearance. Deep to this, the bright white (echogenic) pericardium is noted, followed by the RV and right atrium (RA), septum, and the LV and left atrium (LA) (Fig. A5, SDC 1, http://links.lww.com/PEC/A75). If feasible, the patient may be asked to "breathe deeply and hold" to improve the acoustic window.

The parasternal long axis view is obtained just lateral to the left border of the sternum. The parasternal views are useful for estimating ejection fraction and assessing ventricle size. The parasternal long axis view may be obtained in the second to fifth intercostal spaces, depending on the patient's anatomy. Different interspaces should be imaged to obtain the best sonographic window. In the parasternal long view, the probe indicator is generally pointed toward the patient's left hip. Imaging patients in a left lateral decubitus position may improve this view. In the long axis, the RV will be at the top of the screen. The LV, LA, mitral valve (MV), and LV outflow track are also visualized (Fig. A6, SDC 1, http://links.lww.com/PEC/A75). Minor adjustments of the probe, including clockwise and counterclockwise rotation, may be necessary to get a true long axis view demonstrating the entire LV. Although estimation of ejection fraction is performed by a visual estimation of an experienced sonographer, a relatively simple way to estimate ejection fraction is by the movement of the anterior MV leaflet. In diastole, the valve leaflet should almost touch the wall of the interventricular septum in patients with a normal ejection fraction. Decreased ejection fraction is associated with a larger distance between the MV leaflet and the septal wall (Fig. A1, SDC 1, http://links.lww.com/PEC/A75).

Evaluating the IVC

Ultrasonic evaluation of the IVC is used as a surrogate for central venous pressure and relative intravascular volume. However, it should be viewed within the context of other clinical indicators including vital signs, ejection fraction of the heart estimated by ultrasound, and the patient's symptoms. The examiner is looking for the amount of collapse of the IVC when the patient creates negative intrathoracic pressure by inspiration. This pulls blood from the IVC into the RA of the heart and causes the IVC to collapse. If the IVC is very large and collapses only a small amount, the patient likely has an elevated central venous pressure (CVP). Conversely, if the IVC is very thin and collapses with inspiration, the patient has a low CVP. An alternative is to perform a ratio of IVC to aorta, where volume depletion would be defined as an IVC-to-aorta ratio of less than 0.8.

In cases of suspected rapid volume loss (eg, hemorrhagic) or gradual volume loss due to vomiting, diarrhea, or poor oral intake, investigating the IVC by ultrasound may provide great value to the patient evaluation.

Background

The IVC has been extensively studied in an adult population and is considered a reasonable predictor of intravascular volume status.[21–23] Few studies exist in the pediatric literature, and there is some conflicting evidence as to its utility in estimating of volume status.[24–26] A recent study by Ng et al[24] found that IVC measurements did not correlate well with CVP measurements in a study of patients in the pediatric critical care unit, although two thirds of these patients were mechanically ventilated.

In the noted studies, volume status was assessed by comparing the ratio between the diameters of the IVC to the aorta. Because the absolute IVC diameter changes with developmental age, the ratio of the IVC to the aorta normalizes the IVC size. The maximal diameter of the aorta in systole and the IVC in expiration are compared. A lower ratio of IVC-to-aortic size correlates with dehydration. It is reported that an IVC-to-aorta ratio of greater than 0.8 suggests normal volume status.[26] Inferior vena cava collapsibility may also provide information regarding volume statues. An IVC that collapses more than 50% is concerning for hypovolemia, whereas if the IVC has little respiratory variation and appears plethoric, there is concern for right-sided heart overload, strain, or hypervolemia. Ventilated patients present a diagnostic challenge with regard to evaluation by ultrasound. These patients receive positive intrathoracic pressure that generally results in a large, noncollapsible IVC. However, a small collapsible IVC in a ventilated patient may signal hypovolemia.

Technique

A short axis (transverse) view of the IVC is obtained by placing the phased array or curvilinear probe (although the linear array probe is reasonable for infants) in the midepigastric region of a supine patient, with the probe indicator toward the patient's right side (Fig. A7, SDC 1, http://links.lww.com/PEC/A75). The first step is to identify the echogenic vertebral body (Fig. 3). Differentiating the IVC from the aorta in transverse is relatively easy. The aorta always runs directly anterior to the vertebral body, with the IVC oriented to the patient's right. The aorta is a thicker walled structure and is more pulsatile than the IVC. A measurement of the anterior-posterior diameter of both the IVC and the aorta is recommended in this view (Fig. 3).

An alternative way to measure the IVC is in its long axis (sagittal). The probe is again placed high in the midepigastrium but is now oriented toward the patient's head (Fig. A8, SDC 1, http://links.lww.com/PEC/A75). If the probe is placed precisely in the midline of the abdomen, the aorta is typically visualized first. It may be necessary to drag or fan the probe across the midline to the patient's right side to adequately visualize the IVC. The IVC can be seen posterior to the right lobe of the liver, coursing cephalad into the RA. The hepatic vein may be seen just anterior to the IVC. The area of interest when evaluating IVC collapsibility

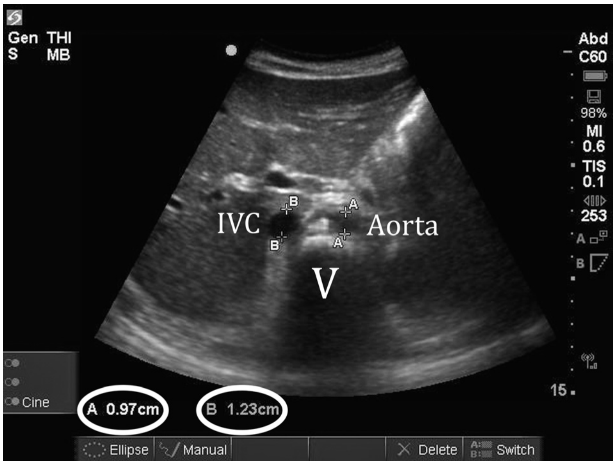

FIGURE 3. Transverse view of the IVC. Note the vertebral body (V). anterior-posterior diameters of the IVC and aorta are measured.

is 2 to 3 cm distal to the RA-IVC junction. M-mode may be used to assess for IVC collapsibility with tidal respirations (Fig. A9, SDC 1, http://links.lww.com/PEC/A75). An IVC collapsibility index may be calculated or visually estimated to assess for hydration status.

Evaluating the Abdomen for Intraperitoneal Free Fluid

When assessing for intraperitoneal free fluid in the pediatric patient, the 2 areas providing the greatest yield are the RUQ and the pelvic or suprapubic space. Of the described views of the FAST examination, these are the most sensitive for the detection of free fluid.

Background

In an adult patient with blunt abdominal trauma and hypotension, the FAST examination is a reliable diagnostic tool for free intraperitoneal fluid and may predict the need for exploratory laparotomy.[27] However, pediatric blunt abdominal injuries are more complicated because many solid organ injuries remain intracapsular and do not manifest free fluid.[28] A 2007 meta-analysis that included around 4000 pediatric patients confirmed that the FAST examination was useful in detecting free fluid but was inadequate as a screening tool for abdominal injury.[29] In general, though, a positive FAST examination in a hypotensive trauma patient confirms an intraperitoneal source of blood loss and may guide disposition and surgical management.

In the supine patient, free intraperitoneal fluid can accumulate in 3 dependent areas: the hepatorenal recess (Morison pouch), the splenorenal recess, and the rectouterine space in women (pouch of Douglas) or rectovesical pouch in men. It is important to keep in mind that the most commonly injured structures in the pediatric patient are the liver and the spleen.[30] The most common area where free fluid collects is the RUQ via the right paracolic gutter, although fluid also commonly collects in the suprapubic (pelvic) space. The LUQ, even in cases of a splenic injury, may first shunt blood to the RUQ and pelvis before demonstrating free fluid in the subphrenic and splenorenal recesses.

The amount of fluid that needs to accumulate in the abdomen before it can be reliably detected on ultrasound depends on the size of the patient, the quality of the examination, and the experience of the sonographer. Smaller patients may require smaller amounts of fluid to have a positive examination. The typical volume of fluid needed to elicit a positive FAST examination is between 200 and 600 mL.[31]

The RUQ: Technique

In the RUQ, Morison pouch is a potential space between the liver and the kidney. The probe is typically placed in a coronal view, with the probe indicator toward the patient's head and positioned in the anterior axillary line (Fig. A10, SDC 1, http://links.lww.com/PEC/A75). It is essential to visualize the following potential spaces as part of a complete evaluation of the RUQ: the pleural space, the subphrenic space, Morison pouch, and the inferior pole of the kidney, which communicates with the paracolic gutter. Free fluid will appear as an anechoic (black) strip layering in between these spaces (Fig. 4).

The Pelvis: Technique

The pelvis is considered to be the most dependent area on the pediatric abdomen. Blood from either the liver or the spleen can travel down the right paracolic gutter into the pelvis and create a positive examination due to the absence of a phrenicocolic ligament on the right side of the peritoneal cavity.

The goal of the suprapubic view is the obtain views of the rectouterine pouch (pouch of Douglas) in women and the rectovesical pouch in men. As opposed to the RUQ and LUQ that are typically evaluated in a single plane (coronal), the pelvis should be scanned in 2 planes. An axial (short axis) view of the pelvis is obtained by placing the transducer just cephalad to the pubic symphysis, with the probe indicator toward the patient's right side (Fig. A11, SDC 1, http://links.lww.com/PEC/A75). It should be angled so that the ultrasound signal is directly caudally into the pelvis. A sagittal or longitudinal view of the pelvis is obtained by rotating the transducer 90 degrees so that the probe indicator is pointing to the patient's head (Fig. A12, SDC 1, http://links.lww.com/PEC/A75). In the transverse orientation, anechoic free fluid may be visualized in the retrovesical space that outlines the posterior wall of the bladder (Fig. A13, SDC 1, http://links.lww.com/PEC/A75). In the female pelvis, fluid will collect posterior to the uterus or between the body of the uterus and bladder. In the longitudinal orientation (sagittal), fluid will collect posterior to the bladder

FIGURE 4. RUQ view. Free fluid (arrowheads) in Morison pouch. Kidney (K) and rib shadowing (arrows) also noted.

and the bowel in men and between the uterus and the bowel in women (Fig. A14, SDC 1, http://links.lww.com/PEC/A75).

Evaluating the Lungs for Pneumothorax, Pulmonary Edema, and Pleural Effusions

An extended FAST examination has been widely adopted by emergency practitioners and incorporates lung ultrasound to identify important thoracic injuries. Examining the thorax by ultrasound can be difficult because structures are surrounded by air in the lungs and bony ribs. However, there are 3 important pathologic processes that can be detected easily by thoracic ultrasound: pneumothorax, pulmonary edema, and pleural effusions (blood, pus, etc).

Background

Using ultrasound to detect pneumothorax has been shown to be superior to chest radiography.[32,33] The examiner focuses on the interface of the visceral and parietal pleura looking for an ultrasound finding referred to as "pleural sliding." Normally, the movement of the 2 pleura against each can be seen with ultrasound. With 2-dimensional ultrasound, pleural sliding is characterized by a "shimmering" appearance along the pleural interface that is created by the movement of the pleura against each other. However, with pneumothorax, air is between the visceral and parietal pleura, and this blocks the ultrasound signal from reaching the visceral pleura. Therefore, the examiner cannot see sliding.

With M-mode ultrasound, the examiner analyzes the pattern of the image superficial and deep to the pleural line. Normally, there is a difference between these 2 areas. The area superficial to the pleura has horizontal lines, and the area deep to the pleura has a speckled appearance. This finding is referred to as "seashore sign," with the horizontal lines representing waves approaching a sandy beach represented by the speckled area of the image. With pneumothorax, horizontal lines are seen above and below the pleural line (Fig. A15, SDC 1, http://links.lww.com/PEC/A75).

Ultrasound is also an excellent study for the detection of pulmonary edema. Normally, air-filled lungs do not allow ultrasound signals to pass into deeper tissue. When fluid leaks into the alveoli with pulmonary edema, an air-water emulsion is created. Now, ultrasound signals begin to "bounce" back and forth between the air bubbles suspended in fluid, and eventually, they are reflected back to the ultrasound transducer. The net effect is that identical echoes repetitively return to the ultrasound transducer, and a vertical, echogenic line is created on the viewing screen. This process is an ultrasound artifact referred to as "reverberation," and when seen during pulmonary ultrasound, these lines are called "B lines"[34] (Fig. A16, SDC 1, http://links.lww.com/PEC/A75).

More than 3 B-lines present within a single lung interspace are pathologic and consistent with pulmonary edema, and adult studies show that B-lines facilitate the diagnosis of pulmonary edema from heart failure.[35–37] By comparison, chest x-ray findings may lag behind clinical symptoms in pulmonary edema. B-lines can also be seen in other interstitial lung processes such as pneumonia, pulmonary contusion, acute respiratory distress syndrome, and infant respiratory distress syndrome.[34] B-lines found in the lower lung fields can be created by ventilation-perfusion mismatching and are usually normal.

When compared with supine chest x-ray, ultrasound also has a higher sensitivity for diagnosing pleural effusions and may detect an effusion as small as 20 mL.[38,39] Fluid in the pleural space will collect posteriorly and caudally in each hemithorax in the more dependent locations. Ultrasonography for the detection of traumatic hemothorax is also useful (sensitivity, 96.2%).[34] Finally, ultrasound can pinpoint the ideal site for thoracentesis.

Technique

It is important to understand that, with many of the pulmonary pathologies detected by ultrasound, the transducer must be placed directly over the pathology to visualize it. As an example, a small pneumothorax might be missed if the operator is looking in the lateral chest of a supine patient in which the pneumothorax is only present in the anterior area of hemithorax.[32,33]

Imaging for pneumothorax begins in the sagittal orientation along the midclavicular line (Fig. A17, SDC 1, http://links.lww.com/PEC/A75). The probe of choice is a high-frequency linear probe. Alternatively, a lower frequency curvilinear or phased array probe may be used, although a shallow depth should be chosen. The indicator for the probe will point toward the patient's head in the third intercostal space, and the area between 2 ribs is examined for pleural sliding. In B-mode, oval-shaped rib shadows are observed on each side of the echogenic pleural line (Fig. A18, SDC 1, http://links.lww.com/PEC/A75). The probe is moved caudally to examine 2 to 3 different interspaces in each lung. Next, the probe is positioned over the anterior axillary line in the third-to-fifth intercostal spaces and examined in a similar fashion. The examination is then repeated for the contralateral lung.

Hemorrhage in the thoracic cavity due to blunt trauma is often located in the dependent areas of each hemithorax and may be detected on ultrasound. The evaluation of the each inferior pleural space can be achieved as an extension of the FAST examination. The examiner may use either the phased array or curvilinear transducer to evaluate the hemithoraces for free fluid. On the right side, the liver is used as the acoustic window, and the technique is nearly identical to the approach used to evaluate Morison pouch, except that the probe is tilted slightly cephalad, into the pleural space (Fig. A19, SDC 1, http://links.lww.com/PEC/A75). This same approach is used to evaluate the left hemithorax using the spleen as the acoustic window. Hemothorax may appear in a variety of ways depending on the age of injury. Acute hemorrhage will appear hypoechoic, whereas partially clotted blood

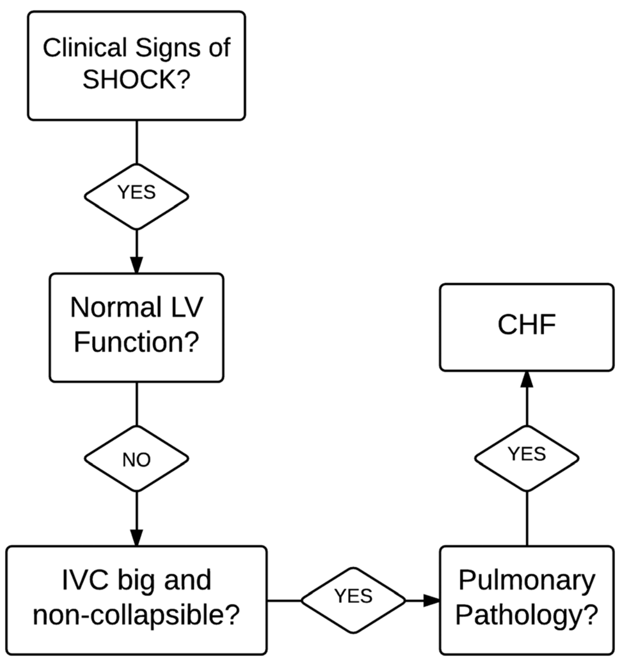

FIGURE 5. Shock algorithm 1.

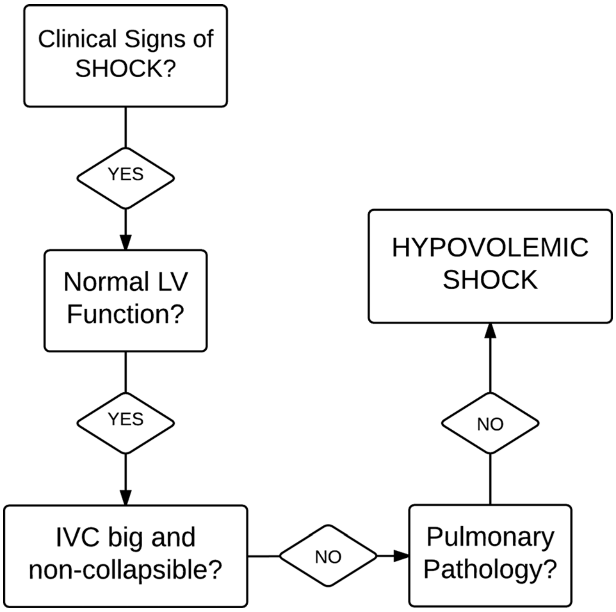

FIGURE 6. Shock algorithm 2.

will take on a more hyperechoic appearance (Fig. A20, SDC 1, http://links.lww.com/PEC/A75).

DISCUSSION

It is imperative to understand the cause of shock to correctly facilitate management. Intravenous fluid is used for a relative loss of volume caused by the expansion of the vascular system due to sepsis or neurogenic injuries. Blood products may be needed for shock caused by hemorrhage. On the other hand, "drugs" are used for heart failure and for processes that obstruct blood being pumped from the heart; the most common example of which is pulmonary embolus. Examples of medications that might be used include vasopressors, inotropes, prostaglandins, anticoagulants, thrombolytics, and antiarrhythmics.

There are 3 distinct algorithms that incorporate the evaluation of the 4 areas previously discussed for the management of the shock. For each algorithm, the clinician will initially evaluate LV function. The second step is to estimate CVP based on IVC size and collapsibility. Next, an RUQ view is used to rule out free intraperitoneal fluid. Finally, the clinician determines whether the patient has pulmonary pathology in the form of pneumothorax, pulmonary edema, or pleural effusion.

Shock Algorithm 1

In shock algorithm 1, the patient has the following (Fig. 5):

- Poor LV function
- An elevated CVP
- Pulmonary edema

Diagnosis: Cardiogenic shock.

These are the findings noted in the first case. Poor LV function in the setting of an enlarged, noncollapsible IVC is highly suggestive of cardiogenic shock. There is severely decreased LV wall motion on all views. In addition, the septal leaflet of the MV has limited excursion and barely approaches the interventricular septum. The finding of bilateral B-lines indicating pulmonary edema is present. The appropriate therapy in this case is to use medication for preload reduction and inotropic support, rather than further aggressive IV hydration.

During the patient's ED course, it is noted that the 1p36 deletion predisposes her to cardiomyopathy. Her respiratory viral panel is positive for rhinovirus/enterovirus. It was assumed that this viral infection produced the decompensated congestive heart failure in the setting of a baseline cardiomyopathy. Formal echocardiogram performed by pediatric cardiology noted biventricular systolic dysfunction.

Shock Algorithm 2

In shock algorithm 2, the patient has the following (Fig. 6):

- Normal LV function
- A decreased CVP based on IVC size and inspiratory collapse, with intraperitoneal free fluid on RUQ examination
- No suggestion of pneumothorax or edema

Diagnosis: Hypovolemic shock.

This case is hemorrhagic shock. Eventually, the child's father admitted to striking the child several times on his back and abdomen in an effort to discipline him. The FAST examination revealed large amounts of intraperitoneal hemorrhage secondary to solid organ injury. The IVC completely collapses with inspiration indicating a low CVP in the setting of ongoing blood loss. Unfortunately, despite resuscitation efforts, the child died.

Hypovolemic shock may be due to an array of disease processes including gastroenteritis, diabetic ketoacidosis, sepsis, and acute blood loss. The treatment is fluids, either in the form of crystalloids or, if indicated, blood products. This case illustrates the importance of including nonaccidental trauma in the differential diagnosis in a patient presenting with undifferentiated hypotension. It also highlights the utility of performing a FAST examination to fully investigate potential etiologies of shock.

Shock Algorithm 3

In shock algorithm 3, the patient has the following (Fig. 7):

- Hyperdynamic LV function

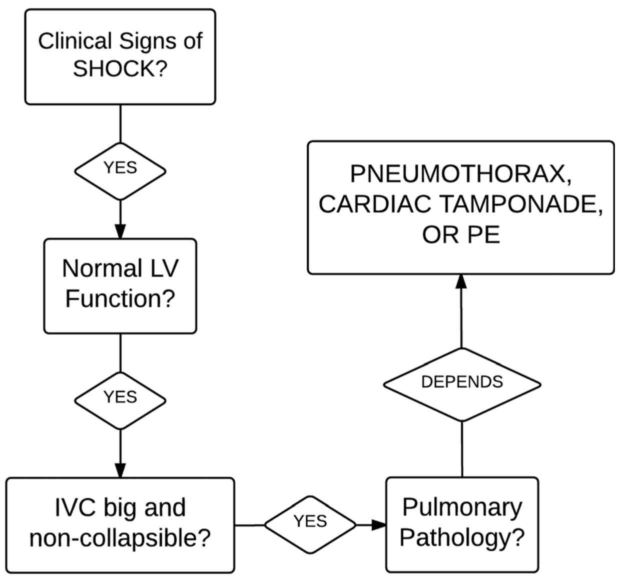

FIGURE 7. Shock algorithm 3.

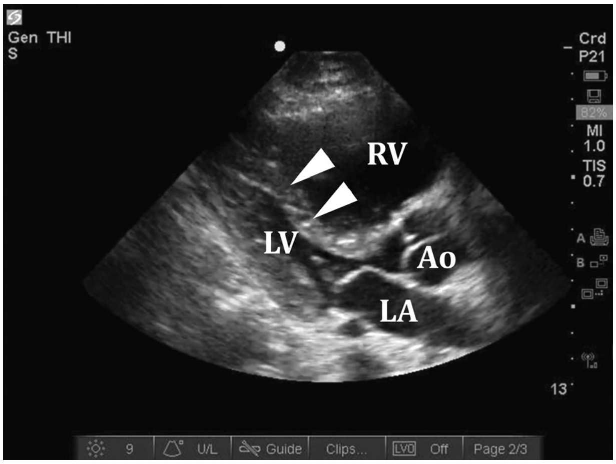

FIGURE 8. Parasternal long axis view of the heart with an enlarged RV causing septal bowing (arrowheads) into the LV. Left atrium (LA) and aortic outflow tract (Ao) also noted.

- A hyperdynamic heart by ultrasound is an increased ejection fraction with near-complete LV emptying due to decreased diastolic filling.
- Although a patient has an accelerated heart rate, the overall cardiac output is decreased due to a large reduction in stroke volume.
- An enlarged and noncompliant CVP
- No suggestion of pneumothorax or edema

Diagnosis: Right heart outflow obstruction (pneumothorax, cardiac tamponade, or pulmonary embolism).

This case demonstrates a large pericardial effusion causing RV outflow obstruction. The treatment for RV outflow obstruction depends on the primary disease process. Shock is caused by decreased LV filling resulting in decreased cardiac output. The LV is hyperdynamic, the IVC is large and noncompliant, and the lung examination is normal. In addition to cardiac tamponade, pulmonary emboli and tension pneumothorax cause obstruction of RV outflow.

Although cardiac tamponade is an uncommon cause of shock in children, it can be seen in ICU patients who have had procedures such as central lines and cardiac surgery, as well as infectious, rheumatologic, and neoplastic causes.[39] Initially, small pericardial effusions may not affect cardiac output. However, as the effusions enlarge, they compress the right atria and ventricles preventing them from filling with blood. This leads to the progressive reduction of blood getting to the LA and ventricle and thus a decrease in stroke volume and cardiac output.

Right atrial systolic collapse as well as RV diastolic collapse will be seen on ultrasound. The examiner may also see a "swinging heart" in late tamponade that causes the classic (although uncommon) electrocardiographic finding of electrical alternans.[40] The IVC will appear dilated and show little or no collapse with inspiration.

Pericardiocentesis in this case yielded over 600 mL of inflammatory pericardial fluid. His hemodynamic status improved markedly after the procedure. He was admitted to intensive care and ultimately diagnosed with systemic lupus erythematosis.

Tension pneumothorax increases thoracic pressure and prevents adequate filling of the RA and ventricle. This may be seen after trauma, chest wall procedures, or vascular access procedures or as a result of barotrauma from positive pressure ventilation. Pulmonary ultrasound allows the examiner to differentiate pneumothorax from the other causes of RV outflow obstruction. The treatment of patients with tension pneumothorax is needle decompression followed by definitive tube thoracostomy.

Although pulmonary embolism also causes shock by RV outflow obstruction, it has distinct sonographic features. With pericardial effusion and pneumothorax, there is decreased filling of the RA and ventricles. However, large pulmonary emboli will impede blood flow through the pulmonary arteries and cause a sudden increase in right heart pressures. The obstruction of the pulmonary vasculature will reduce LV diastolic filling, stroke volume, and cardiac output. On ultrasound, large pulmonary emboli will cause the RV to appear dilated and hypocontractile with the septum bowing into the LV (Fig. 8). Unfortunately, transthoracic echocardiography has a poor sensitivity (around 50%) for detecting all pulmonary emboli, and it should not be used to rule out pulmonary embolism.[41] However, it can facilitate management in an acutely decompensated patient requiring immediate thrombolysis and/or anticoagulation to treat the underlying cause of shock.

CONCLUSIONS

Determining the etiology of shock in critically ill children is oftentimes challenging, yet expeditious diagnosis and focused treatment may be lifesaving. Point-of-care ultrasound may be used to rapidly identify reversible causes of pediatric shock. A methodical approach to critically ill pediatric patients is advocated, with a stepwise approach that includes evaluation of the heart, the IVC, the RUQ or pelvis, and the lungs. Using this 4-view approach in a simple shock algorithm allows the sonographer to rapidly determine the type of shock and the management options for the patient. This sonographic approach to critically ill pediatric patients has not been validated. In the future, well-designed studies to assess outcome measures with regard to POCUS in this patient population are necessary.

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