Moving Beyond the Stethoscope: Diagnostic Point-of-Care Ultrasound in Pediatric Practice

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abstract

Diagnostic point-of-care ultrasound (POCUS) is a growing field across all disciplines of pediatric practice. Machine accessibility and portability will only continue to grow, thus increasing exposure to this technology for both providers and patients. Individuals seeking training in POCUS should first identify their scope of practice to determine appropriate applications within their clinical setting, a few of which are discussed within this article. Efforts to build standardized POCUS infrastructure within specialties and institutions are ongoing with the goal of improving patient care and outcomes.

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Editors' note: This month's State-of-the-Art Review article is the first of 2 on point-of-care ultrasound. The second article on interventional point-of-care ultrasound will follow next month.

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Point-of-care ultrasound (POCUS) is emerging as an essential addition to the 21st-century pediatrician's bag. Advances in ultrasound technology have resulted in improved image quality and portability (Table 1). This has increased ultrasound accessibility to pediatric providers beyond traditional imaging specialists, such as radiologists and cardiologists. In environments where imaging resources are limited, diagnostic POCUS has improved patient outcomes and even been used during spaceflight.[1–3] Incorporation of diagnostic POCUS in clinical decisions is fundamentally different from the traditional practice model, in which a pediatric provider orders a study, waits for an external service to acquire and interpret images, and then applies the information within the clinical context. Diagnostic POCUS is dynamic; that is, the same provider can perform and interpret the study, rapidly integrate this information within the immediate clinical setting, and then repeat the study to identify changes associated with intervention. Diagnostic POCUS complements history and physical examination to answer a specific clinical question, narrow differentials, guide clinical therapy, and direct consultations and disposition.[4–9] For this review, we assembled a group of international pediatric POCUS leaders to discuss the basics of ultrasound image generation, assess the scientific literature, and highlight current and emerging POCUS applications relevant to varied disciplines within pediatric practice.

REVIEW OF ULTRASOUND PRINCIPLES

Physics and Knobology

Ultrasound is a sound wave traveling through and interacting with human tissue. An ultrasound transducer spends a short time emitting ultrasound waves via piezoelectric crystals. The same transducer then spends time "listening" for the returning waves. Waves received by the transducer are processed and converted into a two-dimensional image on a screen. The amplitude of a returning wave is translated to the brightness of the image, and the return time for a wave is translated to the depth of the image. The frequency of

TABLE 1 POCUS Machine Types and Characteristics

Machine Type	Strengths	Weaknesses	Size	Approximate Cost, $ (USD)
Console	High-level image processing and quality	Large machine size, wt, portability	Full platform, often left stationary in an examination or operating room	~85 000–300 000 and higher
	Transesophageal echocardiography, other hardware-based special modalities	Expense, including maintenance		
	Postprocessing modalities	Ease of use for novices		
	Wide array of pediatric-specific customization	Few have batteries for portability and data protection		
Portable and/or compact	Size and mobility	Less pediatric customizability (eg, probes) than a full console	Cart-based, often detachable as a laptop configuration	~25 000–75 000 and higher
	Typically offers most core ultrasound modalities with measurement and image storage function; complete spectrum of POCUS applications	Decreased imaging quality compared with a console		
	Some advanced functionality seen in consoles may be available	Expense, including maintenance		
	Pediatric probes available			
Procedural	Size and mobility; some mountable in rooms or on procedure carts	Diagnostic capabilities limited	Stand-based or mountable small-footprint machines designed primarily for procedural guidance	~15 000 and higher
	Simplified interface for fast workflow	Advanced imaging functions unlikely		
	Simple tablet-shaped design in most for easy maintenance	Limited probe and/or pediatric options		
		Image storage and measurement may not be as precise if present		
Ultraportable	Rapid deployment for transport and critical situations	Readily misplaced	Handheld or tablet-based design for mobility	~2000–16 000
	Ease of use for novices	Limited probe and/or pediatric options		
	Some products have a multifunction probe	Dependent on battery longevity		
	Expense	Limited image quality and optimization options		
		Image storage and measurement not as precise (if present)		
		May require purchase of tablet or smartphone and monthly subscription		

USD, United States dollars.

[a] Retail costs are estimated and approximated for the US market. Final costs to providers and institutions are dependent on additional purchasing factors and may vary widely.

the emitted wave is dependent on the probe used, with modifications made by the provider. In general, the higher the frequency, the higher the image resolution, although this is at the expense of limited penetration. High-frequency probes are therefore ideal for evaluation of superficial structures. Linear probes have the highest frequencies, ranging from 8 to 22 MHz, and are often used for vascular-access procedures or pleural assessment in which the target for interrogation lies close to the probe. Conversely, low-frequency probes have good penetration but do not have the axial or longitudinal resolution found in higher-frequency probes. For example, a curvilinear probe (2–5 MHz) is ideal for abdominal assessment, which requires adequate tissue penetration for visualization of structures.

Image quality can be optimized by the following best practice: (1) Choose the right probe for study. Consideration of not only the ultrasound wave frequency but also the probe footprint (ie, size of the probe relative to the site of image acquisition) and appropriate probe preset (ie, commercially developed software specific to the POCUS study type) should be undertaken. (2) Adjust the depth of the image. Image resolution and interpretation is best optimized when a target organ is located in the middle of the image and surrounding structures can be visualized. (3) Adjust the gain of the image. In principle, image quality is optimized when the structure that should appear bright (fascia, bone, and air) appears bright and the structure that should appear black (blood, urine, and bile) appears black. Within the black-white spectrum are varied shades of gray that arise from the scanned medium. The dynamic range settings of the machine can increase or decrease the number of shades visualized to further optimize an image. The brightness of a structure is described as hyperechoic, hypoechoic, or isoechoic and is relative to the surrounding tissue. Anechoic brightness can be used to describe a structure that is completely black on the screen. The amplitude of a returning wave, and therefore its corresponding brightness, is dependent on the wave-tissue interaction (ie, absorption, scattering, reflection, and refraction).

There are 3 commonly used ultrasound modes: (1) B (brightness) mode is the most basic image, which displays the brightness and depth of the structure on the screen as a two-dimensional image. (2) M (motion) mode is a one-dimensional measurement set through the scanning plane and plotted over time. This allows for point-in-time measurement, such as fractional shortening of the diameter of the left ventricle (LV). (3) Doppler ultrasound visualizes movement. Typically, blood flow (color Doppler for the presence and direction of flow, pulsed-wave Doppler for flow velocities at a set depth, and continuous-wave Doppler for flow velocities at a set beam) or tissue movement (tissue Doppler) are measured with this technology.

Understanding Artifacts

Pediatric providers should be aware of common artifacts generated by ultrasound (Table 2, Fig 1 A–E). Understanding the reason why a particular artifact is generated is important because it will allow pediatric providers to use the artifact for image quality optimization, make a proper diagnosis, or avoid misinterpretation. A good example is lung ultrasound, which relies on the use of artifacts (or their absence) to identify pathologic processes.

Ergonomics

Optimizing provider, patient, and machine position is essential to consistently obtaining high-quality studies. For procedural guidance, it is essential that the provider, procedural site, and ultrasound screen are in the same line of vision. Typically, an ultrasound probe should gently touch a patient's body surface without strong pressure. This is particularly important when a targeted organ is easily collapsible (ie, central or peripheral vein), although some studies require pressure as a diagnostic component of the assessment (eg, deep venous thrombosis or appendicitis evaluation). The hand holding a probe should be anchored to the patient's body surface, typically using the fifth digit as a contact, to avoid unintended probe sliding. Especially in small infants, small movements may cause significant changes in the image.

HEMODYNAMIC POCUS

Hemodynamic POCUS, also referred to as functional, focused, or targeted echocardiography, provides physiologic information regarding preload, contractility, and afterload

TABLE 2 Common Ultrasound Artifact Findings, Image Interpretation, and Diagnostic Assessment

Ultrasound Artifact	Image Interpretation	Diagnostic Assessment
Acoustic shadowing (Fig 1A)	A structure that reflects most of ultrasound wave, resulting in a bright image and underlying dark area	Diagnostic clue for strong reflector (eg, gall stone or calcified structure)
Posterior acoustic enhancement (Fig 1B)	Relative brightness behind a structure that is hypoechoic or anechoic	Diagnostic clue for presence of an abscess in soft tissue ultrasound
		Adjust gain to avoid missing free fluid in abdominal ultrasound when evaluating structure behind urinary bladder
Reverberation artifact (Fig 1C)	Presence of highly reflective structures makes ultrasound waves bounce multiple times before they return to a probe	The presence of vertical lines in lung POCUS (known as B or Z lines) is due to the apposition and reverberation of the visceral and parietal pleura and can exclude the diagnosis of pneumothorax
Mirror image (Fig 1D)	Presence of strongly reflective surface refracts ultrasound wave in an altered direction; the returned wave is misinterpreted as though it comes from a deeper structure	The common appearance of normal lung (no parenchymal disease, pleural effusion, or pneumothorax) in a right-upper—quadrant ultrasound is often visualized as the liver "mirrored" over the diaphragm
Edge artifact (Fig 1E)	A dark line generated by a lateral border of an anechoic circular structure (eg, gall bladder)	Be aware of the presence of the artifact in image interpretation, for example, avoid misinterpreting the artifact as acoustic shadowing from a gall stone

Adapted from Boniface KS. Ultrasound basics: physics, modalities, and image acquisition. In: Brown SM, Blaivas MM, Hirshberg EL, et al, eds. *Comprehensive Critical Care Ultrasound.* Mount Prospect, IL: Society of Critical Care Medicine; 2015.

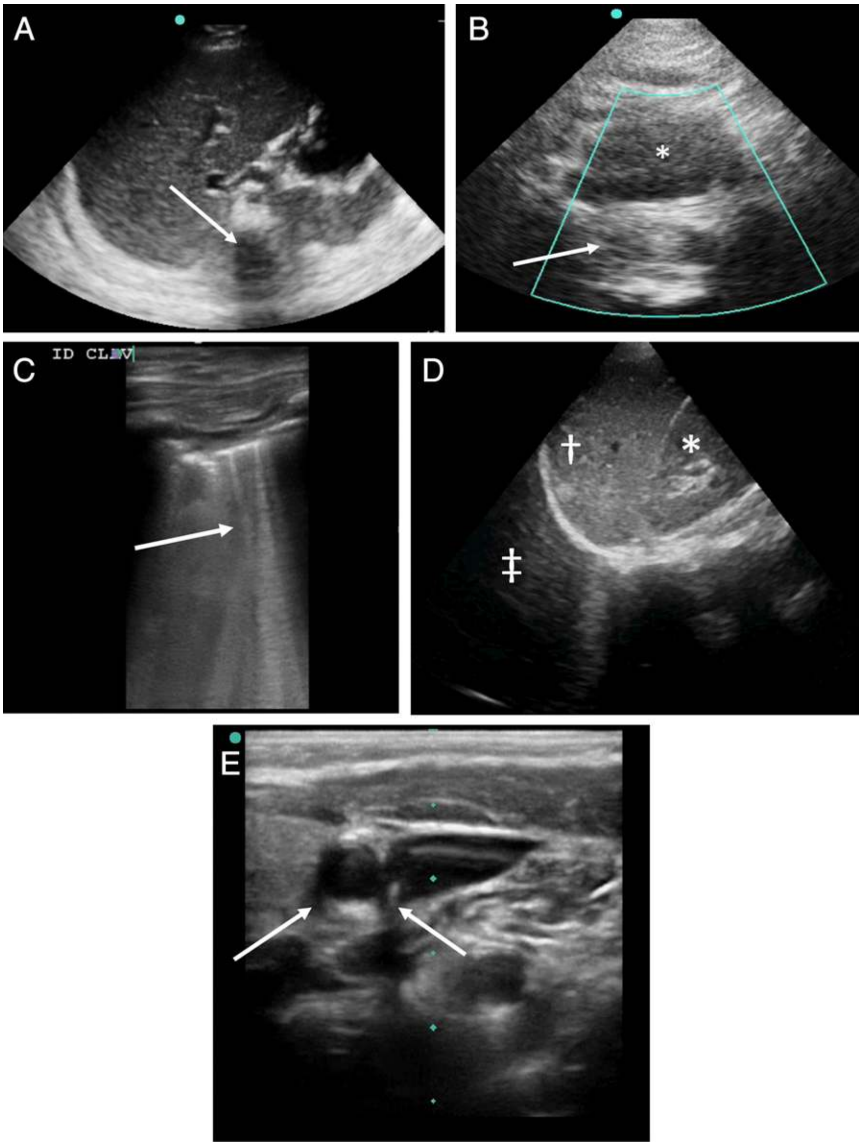

FIGURE 1

A, Arrow pointing to acoustic shadowing demonstrated in this transverse abdominal view. Ultrasound waves are unable to penetrate bone (in this case, the vertebral body), thus resulting in a dark field deep to the structure. The vertebral body is commonly used as a landmark when evaluating IVC and aorta diameter for volume assessment. B, Posterior acoustic enhancement (arrow) on a transverse view of a bladder (shown by the asterisk). This is a normal finding in bladder assessment because ultrasound waves travel freely without loss of energy through a urine-filled bladder. Thus, ultrasound waves returning to the probe after having traversed the bladder will be interpreted as being brighter than adjacent waves after having traversed through soft tissue. C, B lines, or "comet tail artifacts," are a type of reverberation artifact. B lines arise from the pleural surface and can be seen in conditions in which pulmonary interstitial inflammation and edema arise. D, Right-upper–quadrant view of the kidney (shown by the asterisk) and liver (shown with the dagger symbol), with the bright, white line being the diaphragm. Well-aerated lungs will not allow ultrasound waves to be transmitted; thus, the image on the screen cranial to the diaphragm has the appearance of the liver, which is caudal to the diaphragm, resulting in a mirror artifact (shown by the double-dagger symbol). E, Edge artifact whereby an ultrasound wave is deflected obliquely from a rounded surface, resulting in shadowing around the edges of that structure. In this case, there is soft shadowing along the edge of the carotid artery, which is identified by the arrows.

conditions to identify pathophysiology and target therapies. Hemodynamic POCUS does not aim to identify congenital heart defects or complex anomalies, which requires pediatric cardiologist expertise, although it may provide information to suggest structural cardiac abnormalities. Hemodynamic POCUS is currently used in many NICUs and PICUs around the world, and 2 American and European consensus guidelines for neonatologists have been published.[11,12] However, despite these guidelines, there remains significant variation in practice.[13] Hemodynamic POCUS can provide invaluable information for indications commonly encountered in varied areas of pediatric practice,[14] a few of which we describe below.

Assessment of Volume Status and Fluid Responsiveness

Fluid responsiveness is an increase in stroke volume on fluid loading.[15,16] Static measures, or single clinical measurements at 1 point in time (eg, central venous pressure, heart rate, and arterial pressure), are unreliable for assessing pediatric volume responsiveness.[17] Dynamic measures for fluid responsiveness are those altered by changes in intrathoracic pressure associated with breathing. Pediatric literature demonstrates that quantification of changes in inferior vena cava (IVC) diameter as well as aortic outflow velocity are strong predictors of fluid responsiveness (Fig 2 A and B),[17,18] although this has yet to be validated in neonates.

Cardiac Function and Establishing Etiology of Shock

Hemodynamic POCUS can qualitatively assess cardiac contractility ("eyeballing") as well as semiquantitatively assess LV function by measuring fraction shortening. Pediatric providers consistently demonstrate rapid skill acquisition and accurate interpretations in varied hemodynamic POCUS applications.[19–22] Furthermore,

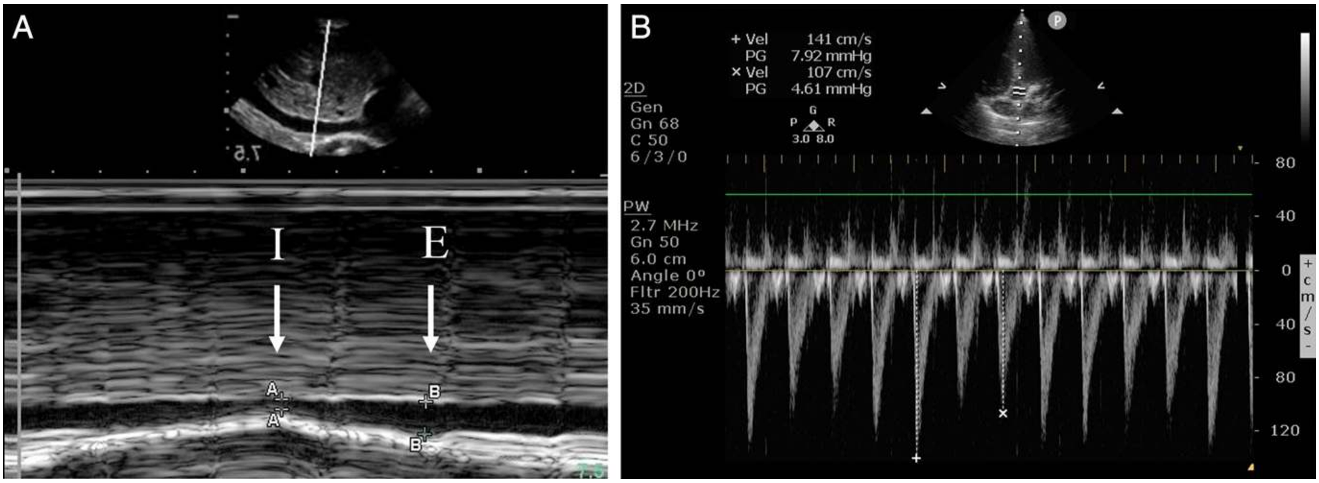

FIGURE 2
A, Respiratory variation of the IVC measured by using M mode. In a spontaneously breathing patient, inspiration (I) with negative inspiratory force results in inward movement of the IVC, whereas expiration (E) results in outward movement of the walls. Measurements can be made with threshold values suggestive of fluid responsiveness. B, Respiratory variation of aortic flow velocity measured by pulsed-wave Doppler is another method to identify a fluid-responsive patient.

hemodynamic POCUS, when compared with clinical examination and laboratory-based data, alters our perceptions of underlying hemodynamic status and may change our management.[23,24] We know that cardiac output can be variable in states of shock, such as sepsis, and that titration of therapies can improve outcomes.[25–27] Cardiac output can either be inferred or directly measured within hemodynamic POCUS. In neonatology, superior vena cava flow has been used as a surrogate of cardiac output to determine systemic blood flow during transitional circulation, with a value $>$ 40 mL/kg per minute being associated with improved neurologic outcomes and survival.[28–30]

Clarifying an individual hemodynamic profile through direct real-time imaging may have important outcome benefits for patients and force us to challenge common paradigms and algorithms.[31] In fact, international guidelines for resuscitation in shock are increasingly embracing "echocardiography [as] the preferred modality to initially evaluate the type of shock as opposed to more invasive technologies,"[32] "enabl[ing] a more detailed assessment of the causes of the hemodynamic issues."[33]

Pulmonary Hypertension

Persistent pulmonary hypertension of the newborn (PPHN) is a common cause of neonatal hypoxic respiratory insufficiency that results from a failure of normal circulatory transition after birth. Most commonly, PPHN is secondary to impaired or delayed relaxation of the pulmonary vasculature due to diverse neonatal pulmonary pathologies, and its presence is associated with high mortality.[34] Hemodynamic POCUS can be used to diagnose PPHN, estimate pulmonary artery pressure, direct therapies, and evaluate response to therapy by serial reassessment. Signs of pulmonary hypertension, such as hypertrophy with or without dilatation of right ventricle (RV), enlarged right-sided cardiac structures, and flattening of the interventricular septum, can be recognized by using hemodynamic POCUS (Fig 3 A and B).[18,35] More advanced echocardiographic methods for the

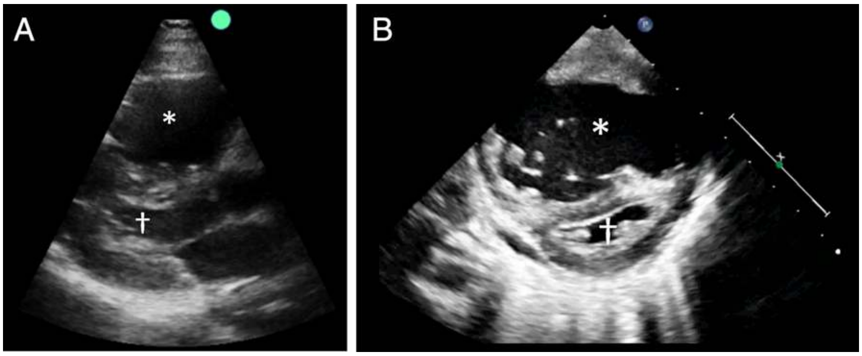

FIGURE 3
A, Dilated RV (shown by the asterisk) relative to the LV (shown by the dagger symbol) suggesting elevated right-sided pressure in an adolescent patient presenting to the emergency department with pulmonary embolism. B, Parasternal short-axis view of the interventricular septum bowing into the LV (shown by the dagger symbol) in a neonate, also suggestive of elevated RV (shown by the asterisk) pressure.

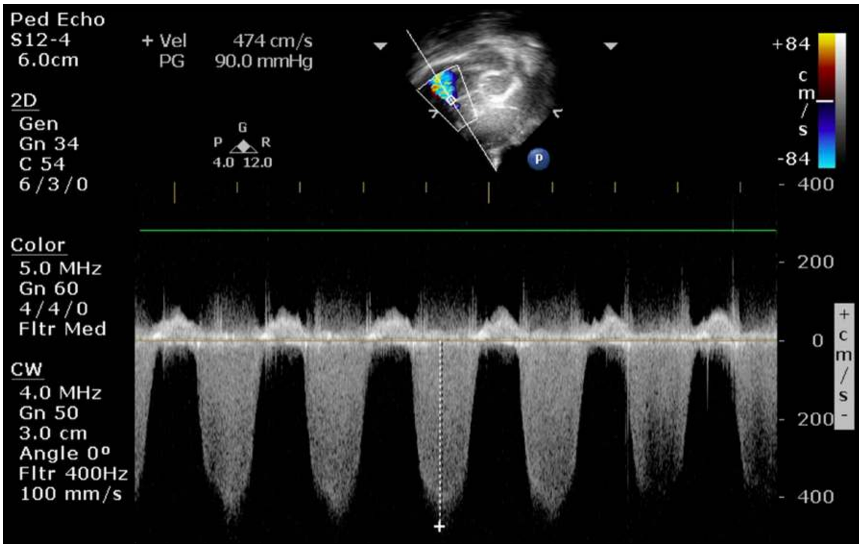

FIGURE 4

Continuous-wave Doppler across the tricuspid valve in this parasternal short-axis view at the level of the base measuring the peak regurgitant velocity. The velocity can be incorporated into the modified Bernoulli equation to quantify RV pressure.

estimation of pulmonary artery systolic pressure can be performed by measuring pressure gradients across the tricuspid valve (Fig 4), ventricular septal defect, and patent ductus arteriosus. In patients with pulmonary embolism and thrombus, ultrasound can demonstrate the above findings as well as a direct visualization of a clot.[36,37]

Use of POCUS During Cardiopulmonary Resuscitation

Rapid assessment with bedside ultrasound can provide crucial information regarding the etiology of cardiac arrest and provide critical information for management. Especially in patients with pulseless electrical activity, bedside ultrasound can differentiate etiologies such as pericardial tamponade and pneumothorax, which lead to life-saving intervention.[38,39] Hemodynamic POCUS during cardiac arrest has not been well evaluated in pediatric populations[40]; therefore, this practice must be thoughtfully integrated with high-quality cardiopulmonary resuscitation, especially because adult studies have demonstrated prolonged pulse-check duration when it is incorporated into practice.[41,42]

LUNG POCUS

Well-aerated lungs cannot be directly visualized because of the high acoustic impedance between soft tissue and air, resulting in ultrasound wave reflection at the pleural line. As lungs become diseased and less aerated, different artifacts arise, and on extreme ends of disease, lung parenchyma may be directly visualized. Pathologic processes and their corresponding ultrasound findings are now well described in the pediatric thoracic POCUS literature.[43] Because lung POCUS does not use ionizing radiation and is readily available at the bedside, trained providers envision the technology as a potential replacement for chest radiography for a number of pediatric thoracic conditions. A formal program introducing lung ultrasound as the first-line imaging technique in NICUs has reduced radiation exposure by ~70%.[44] Integration of clinical data with lung ultrasound complements diagnosis capabilities.[45]

Pneumonia

Pneumonia has consistent ultrasound findings across ages, including areas of consolidation with irregular borders and air bronchograms (Fig 5 A and B, Supplemental Videos A and B).[39] Thoracic POCUS for assessment of pneumonia seems equally useful for neonates and older children. Two recent studies demonstrated that ultrasound findings have optimal diagnostic accuracy and performed better than conventional radiology to diagnose neonatal pneumonia.[46,47] This is confirmed by a recent pediatric study showing that ~60% of pneumonia signs identified by lung ultrasound were undetected by conventional radiology.[48] Moreover, a randomized controlled trial of thoracic POCUS versus conventional radiology for pediatric pneumonia in emergency departments showed no missing cases of pneumonia and a 30% to 60% reduction in the use of chest radiographs.[49] These results are confirmed on a larger scale by 3 meta-analyses of thoracic ultrasound diagnostic accuracy in children, all reporting high specificity and sensitivity.[50–52]

Studies also indicate that thoracic POCUS is useful and reliable in diagnosing pediatric pneumonia in different settings, including general pediatric wards,[53] PICUs,[54] emergency departments,[55] and hospitals in developing countries[56] with high interrater agreement. Automated image analysis is under investigation because it may provide the diagnosis of pneumonia without expert ultrasonographers and be particularly useful in low-resource countries.[57]

Pneumothorax and Pleural Effusion

Classic lung ultrasound signs of pneumothorax are the absence of lung sliding and any parenchymal sign and the presence of the so-called stratosphere sign (also known as the barcode sign) when using M mode (Fig 6, Supplemental Video).

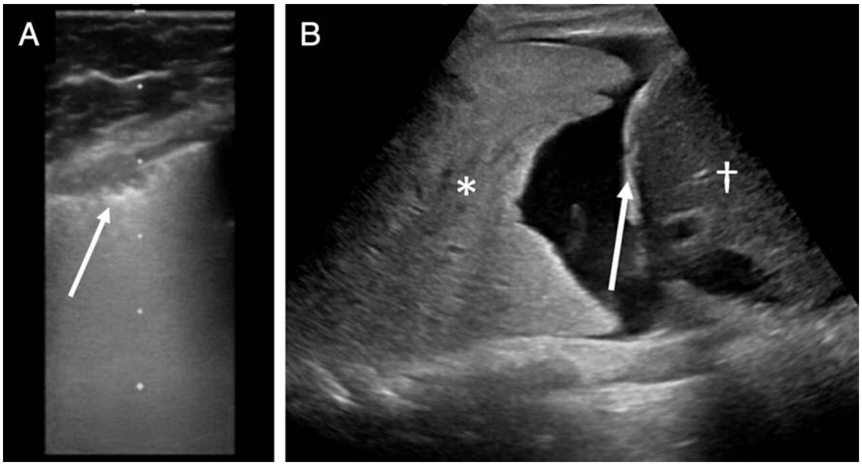

FIGURE 5
A, Subpleural consolidation (arrow) and either B-line patterns or, in this instance, diffuse hyperechoic appearance of the underlying lung suggesting pulmonary edema or inflammation can be seen early in bacterial pneumonias as well as in bronchiolitis, RDS, pediatric acute respiratory distress syndrome and meconium aspiration syndrome. B, The lung (shown by the asterisk) in severe pneumonia may appear "hepatized" (ie, resembling the solid organ architecture of the liver; shown by the dagger symbol; diaphragm marked by the arrow) and is often surrounded by pleural effusion (black).

Semiquantification of pneumothorax volume is feasible and has been previously described.[58] Two diagnostic studies demonstrated that lung ultrasound may be sensitive and specific to detect pneumothorax in neonates,[59,60] and case reports suggest similar usefulness in critically ill children.[61,62] Thoracic POCUS is safe and useful to quickly guide chest drainage or needle aspiration in neonates with pneumothorax.[63] These data are consistent with adult critical care data showing that lung ultrasound has a comparable specificity, but higher sensitivity, than conventional radiology for the diagnosis of pneumothorax.[64]

Pleural effusion is easily visualized as an extrapulmonary hypoechoic image between the parietal and visceral pleural membranes. Effusions are commonly categorized as simple or complex, which has assisted in guiding treatment course (Fig 7 A and B).[65,66] Thoracentesis and chest tube placement for pleural effusion are commonly performed under ultrasound guidance in adult critical care.[67] This is shown to reduce complications and is therefore recommended by current international guidelines.[68] No specific pediatric data are available; however, this is a well-recognized use of ultrasound.

Neonatal Respiratory Distress Syndrome and Need for Surfactant Replacement

Lung POCUS assists in the diagnosis of neonatal respiratory failure.[39] Moreover, it is useful to guide surfactant administration in neonates with respiratory distress syndrome (RDS). Surfactant should be considered in preterm infants with RDS when continuous positive airway pressure fails and within the first hours of life to maximize its effect.[69] Surfactant is usually administered when the inspired oxygen fraction is beyond a given threshold.[70,71] However, inspired oxygen cannot adequately describe oxygenation and may increase after the optimal time frame for surfactant administration. Semiquantitative POCUS lung scores describing lung aeration strongly correlate with oxygenation and are accurate in predicting need for surfactant in preterm and extremely preterm infants.[72,73] A similar correlation has been demonstrated between lung ultrasound scores and oxygenation in adult patients.[74] Thus, a new protocol, called echography-guided surfactant therapy (also known as ESTHER), has been recently proposed to guide surfactant replacement in preterm neonates treated with continuous positive airway pressure. Use of the protocol improved the timeliness of surfactant therapy and reduced the duration of invasive ventilation.[75]

ABDOMINAL POCUS

The use of abdominal POCUS is common for several clinical presentations across the pediatric age spectrum, such as abdominal pain or emesis. Therefore, abdominal POCUS is an important diagnostic adjunct for a variety of clinical situations.

Abdominal Pain

Abdominal POCUS can help diagnose many specific conditions and enhance medical decision-making in undifferentiated abdominal pain by narrowing and expediting the workup.[76] Familiarity with abdominal sonography may even allow an astute sonologist to pick up rare diagnoses of abdominal pain, such as ascaris lumbricoides infection.[77]

Appendicitis

Acute appendicitis is the most common childhood surgical emergency associated with abdominal pain and benefits from early recognition. To minimize radiation, ultrasound should be the initial imaging modality in assessment (Fig 8, Supplemental Video).[78] Skilled operators can achieve accuracy that approximates that of computer tomography imaging.[79,80] Combining POCUS with other imaging modalities in a stepwise approach is another way to improve overall diagnostic accuracy, decrease costs, and reduce computer tomography scan

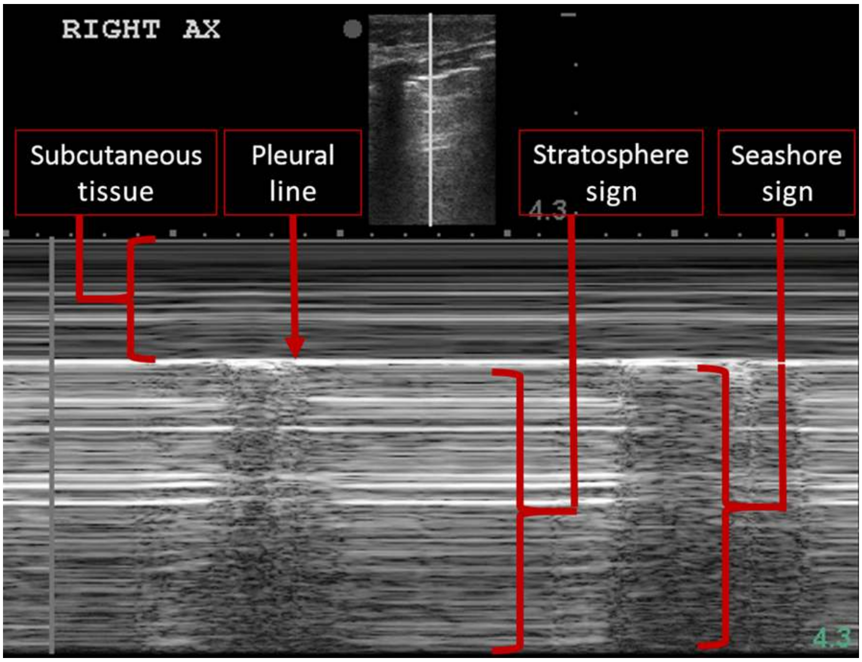

FIGURE 6
M mode capturing a “lung point,” which indicates the presence of a pneumothorax. The apposition of the parietal and visceral pleura in well-aerated lungs results in a bright, white line in M mode (arrow, pleural line). Movement of the parietal and visceral pleura against one another in well-aerated lungs during inspiration and expiration creates lung slide and on M mode is characterized by granularity below the pleural line (termed “seashore sign”). A pneumothorax creates an air-filled separation between the visceral and parietal pleura. Lung slide is no longer present and on M mode is characterized as the absence of lung-sliding straight lines (also termed barcode sign or stratosphere sign). In this image, a patient is taking breaths with the presence of pneumothorax and normal lung crossing the one-dimensional M-mode path on inspiration and expiration. On inspiration, the aerated lung displaces the free air of the pneumothorax, resulting in lung slide and, thus, seashore sign. On expiration the lung moves away from the M-mode path, resulting in barcode sign due to the free air between the visceral and parietal pleura, thereby preventing lung slide.

usage.[81–83] Even with limited training, providers can achieve a reasonable level of accuracy to help guide further management.[84]

Emesis

Vomiting in the newborn period can represent a host of etiologies, both benign and emergent. POCUS can help rapidly differentiate more serious causes and expedite definitive management. Malrotation with midgut volvulus, inflammatory bowel disease, and pancreatitis have specific sonographic findings, yet these are not frequent POCUS applications. Some of the more common diagnostic applications of POCUS include evaluation for pyloric stenosis and intussusception.

Pyloric Stenosis

Pyloric stenosis typically presents between 1 and 3 months of age and is the most common surgical cause of nonbilious emesis in the newborn (Fig 9, Supplemental Video). The primary method of diagnosis is ultrasound. Pediatric emergency medicine physicians should feasibly perform this evaluation at the point of care, which helps facilitate decisive management.[85]

Intussusception and Necrotizing Enterocolitis

Any child presenting with vomiting, abdominal pain, altered mental status, or blood in the stool should be promptly evaluated for intussusception. Several studies demonstrate that this application can be easily learned by trainees (Fig 10 A and B, Supplemental Video).[86,87] In addition to helping in making the diagnosis, ultrasound may help reveal signs of ischemia or other high-risk features that may prompt surgical management as opposed to typical reduction.[88] Echogenic foci within the bowel wall, representing intraluminal air, can also be seen in other diseases associated with bowel-wall necrosis, such as necrotizing enterocolitis in newborns.[89]

Pediatric Abdominal Trauma

In children with blunt abdominal trauma, a focused assessment with sonography for trauma (FAST) protocol can help identify hemorrhage in the intraperitoneal cavity. Although no large studies have demonstrated a clear benefit of a single FAST evaluation, there is also minimal harm from this study.[90] Dynamic or serial FAST evaluations may help safely monitor pediatric trauma patients and avoid unnecessary ionizing imaging tests.[91]

Forays into the use of abdominal POCUS to estimate stool burden in constipation or in presedation evaluation of stomach contents open new avenues for future exploration of this modality.[92,93] The introduction of contrast-enhanced methods into the POCUS arsenal will also introduce new diagnostic possibilities for evaluation of solid organ injury and disease.

CEREBRAL POCUS

Neurologic ultrasound has increasingly become an application of interest, although brain imaging modalities are frequently user dependent, extremely nuanced, and understudied. Direct neurosonology of the brain and its vessels is complicated by view obstruction from bone, although this is commonly performed through open fontanelles and represents the first-line neuroimaging technique commonly performed in NICUs.[94] It is

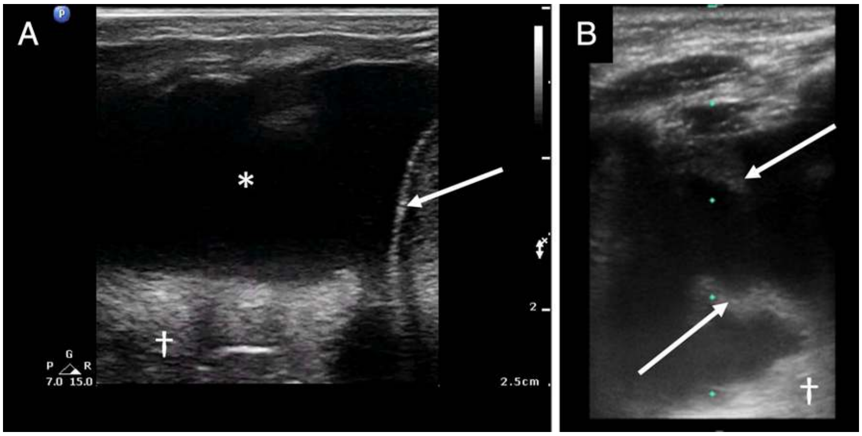

FIGURE 7
A, Simple pleural effusion (shown by the asterisk) at the costophrenic recess outlined by the thoracic wall, lung (shown by the dagger symbol), and diaphragm (arrow). B, Complex pleural effusion with fibrinous stranding (arrows) outside the lung (shown by the dagger symbol).

remarkably useful even in the hands of novice leaners in low-resource settings.[95] Alterations in cerebral arterial flow allow inferences to be made regarding brain pathology, although the current literature is insufficient to support its use in POCUS applications because of difficulty distinguishing changes in blood flow velocity from compression versus those due to intrinsic stenosis or changes in relative perfusion.

Ophthalmic ultrasound has also been an extension of neurologic ultrasound applications. The iris can be examined by holding the probe in the coronal plane above the upper eyelid. This is particularly useful in clinical scenarios in which a pupillary response is difficult to assess on physical examination because of congenital corneal opacification or in situations in which the eyelids cannot be opened because of edema or injury (Fig 11 A and B, Supplemental Video). The orbit and its extraocular movements can also be inspected in these situations, and asking patients to move their eyes while being assessed with ultrasound in trauma and orbital cellulitis has been described.[96] In situations in which the retina is injured and separated from the internal wall of the eye, the separation of the tissue planes has been detected by using ultrasound.[97] This is potentially useful in the assessment of patients with retinal injury from abusive head trauma, and additional studies regarding its applicability as a survey instrument are warranted. Ophthalmic ultrasound should be avoided in situations in which there is a known traumatic globe injury. Furthermore, although ultrasound is typically considered a low-risk diagnostic tool, the cornea can be damaged by the heat (thermal index), vibration (mechanical index), and radiation force (acoustic power) from ultrasound waves produced by the machine. Machines often have an “ophthalmic safety mode” within probe presets to minimize the risk of injury during ophthalmic examinations.

FIGURE 8
Appendicitis characterized by an inflamed appendix (arrow) with hyperechoic fat stranding (shown by the asterisk).

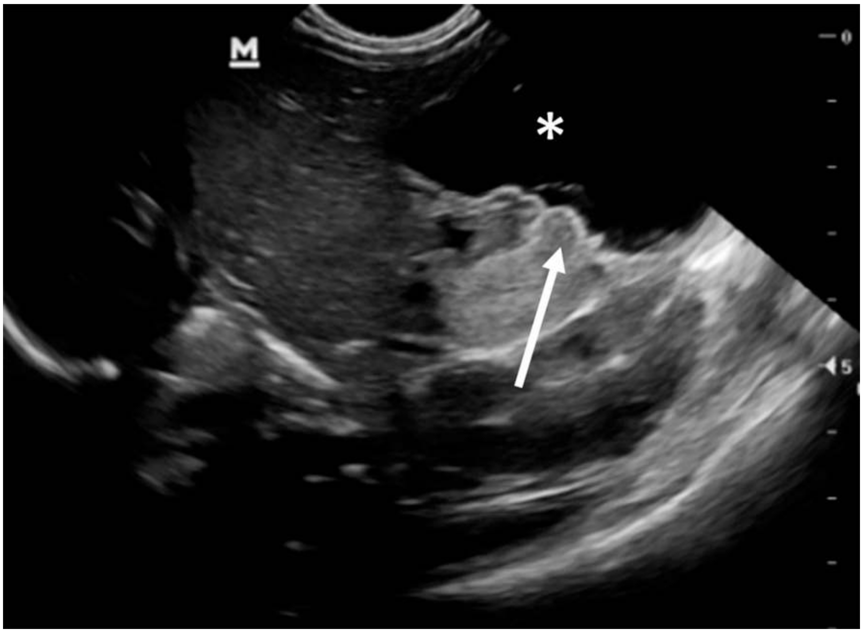

FIGURE 9
Fluid-distended stomach (shown by the asterisk) and thickened pylorus (arrow) in a patient with pyloric stenosis.

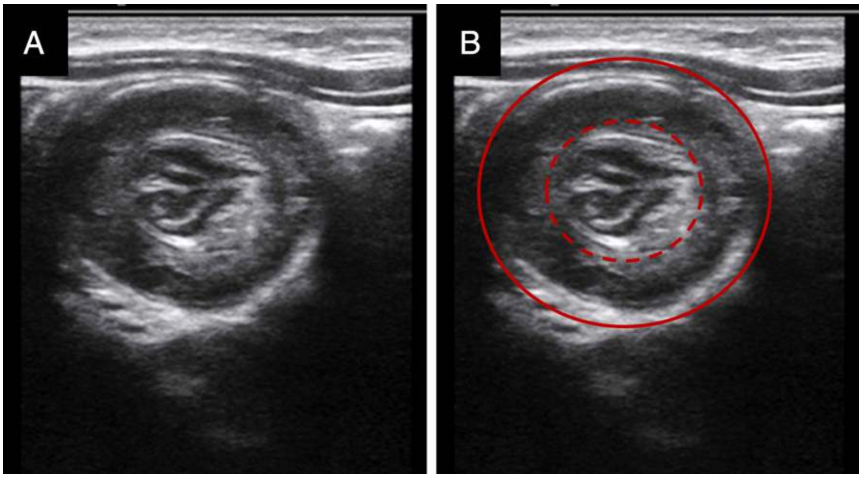

FIGURE 10
A, Target sign identified in ileocolic intussusception. B, Outer layers (solid line) represent the intussuspient bowel wall and lumen, whereas inner layers (dash line) represent intussusceptum consisting of the bowel wall, lumen, and mesenteric fat.

Measurement of the optical nerve sheath diameter is suggestive of papilledema and increased intracranial pressure (Fig 12); however, sources conflict on threshold measurements, and papilledema may persist despite normalization of intracranial pressure.[94] Despite having some elasticity, the sheath may become stretched over time, as seen in both shunted and nonshunted patients with a history of obstructive hydrocephalus.[98] Conceivably, other patients with chronic papilledema, such as those with pseudotumor cerebri and craniosynostosis, would also have wider baseline optic nerve sheath diameters.[99]

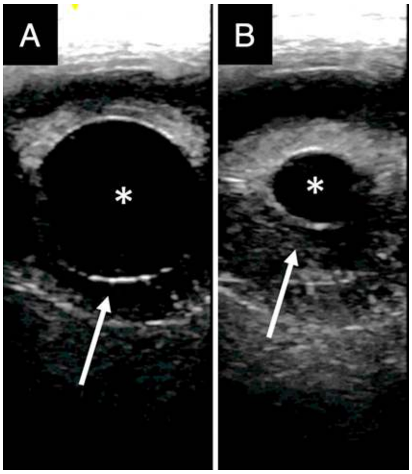

FIGURE 11
A, Pupil (shown by the asterisk) and surrounding iris (arrow) in transverse view with the eyelid closed. B, Consensual pupillary light reflex of the eye with the eyelid remaining closed.

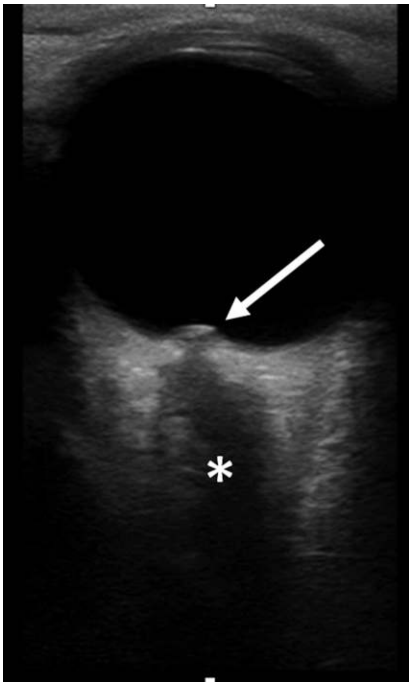

FIGURE 12
Optic nerve (shown by the asterisk) visualized in the anterior-posterior view of the eye and nerve head elevation noted within the vitreous chamber (arrow).

VASCULAR POCUS

Although clinician ultrasound in vessel imaging has been described much more in the procedural arena, the technology has also been applied to assessing thrombosis.[100] Thrombi extension through the vascular system obstructs flow and can appear cylindrical, pedunculated, and linear and is often related to intravascular devices, most commonly central venous catheters.[100] Techniques to image the obstruction involve using color-flow or spectral Doppler (pulsed or continuous) to identify aberrant flow at the level of the thrombosis.

Noncompressibility of a vascular structure is a concerning finding, suggesting the presence of a thrombus. Lower-extremity ultrasound scanning for thrombus identification by bedside practitioners requires serial compression of thigh vessels from the inguinal ligament to the popliteal fossa. This has been termed the 3-point compression technique because in addition to the inguinal and popliteal areas, the 3-point compression technique includes the superficial femoral vein.[101] The 3-point technique has been demonstrated to be superior to the 2-point technique.[101–103] It is crucial that the operator recognize the potential for dislodging thrombi with serial compression, especially when a thrombus can be directly visualized. It is clear that pediatric patients develop deep vein thrombosis for reasons that are different from those of adults; therefore, a pediatric study in deep vein thrombosis screening is needed.

SOFT TISSUE AND MUSCULOSKELETAL POCUS

Soft Tissue

Similar to in adult studies, POCUS has been shown to improve the ability of pediatric clinicians to distinguish soft tissue abscesses from simple cellulitis[104] as well as to affect clinical management.[105] Foreign bodies in particular are notoriously difficult to diagnose and manage and are considered 1 of the leading causes of malpractice suits in emergency medicine.[106] Ultrasound allows clinicians to diagnose the presence of foreign bodies as well as guide their removal by allowing for visualization of the orientation, size, and depth of the object while avoiding adjacent structures (vessels, nerves, etc; Fig 13 A and B).[107] This is especially important for nonradio-opaque foreign bodies, for which fluoroscopy would be rendered useless.

Fractures

There are numerous studies that have established a role for POCUS as a screening test or diagnostic method for suspected fractures, especially of the long bones.[108–110] Ultrasound can also help identify radiographically occult fractures of the ankle and wrist[111] (Fig 14) as well as radiographically occult avulsion fractures,[112] and it has been shown to have higher discriminatory ability to detect certain fractures, such as sternal fractures.[113] Furthermore, POCUS can be used to guide reduction attempts and potentially obviate the need for fluoroscopy,[114] thereby decreasing exposure to potentially harmful ionizing radiation.

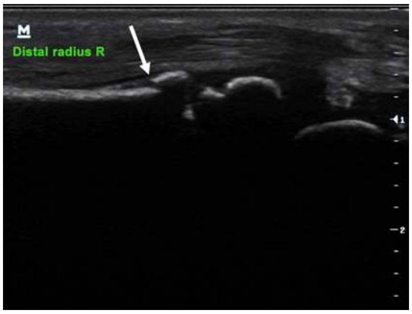

FIGURE 14
Salter Harris type 2 fracture of the distal radius (arrow) not identified on initial radiography.

Hip Effusion and Dysplasia

Numerous studies have shown that POCUS can be used to diagnose pediatric hip effusions with high sensitivity and specificity compared with radiography.[115–117] Broadened use of POCUS for hip effusions will likely translate to increased comfort and skill with performing ultrasound-guided diagnostic needle aspiration. Small case series have shown that there is potential for front-line providers to perform these types of procedures safely and competently.[117] Ultrasound is also well known for the diagnosis of congenital dysplasia of the hip and may be performed by pediatricians, neonatologists, or radiologists.[118]

Novel applications such as POCUS for the diagnosis of osteomyelitis as well as ultrasound-guided aspiration of periosteal pus[119] (Fig 15, Supplemental Video) may, in the near future, significantly improve outcomes for children by facilitating as well as expediting the diagnosis of the organisms causing these infections.

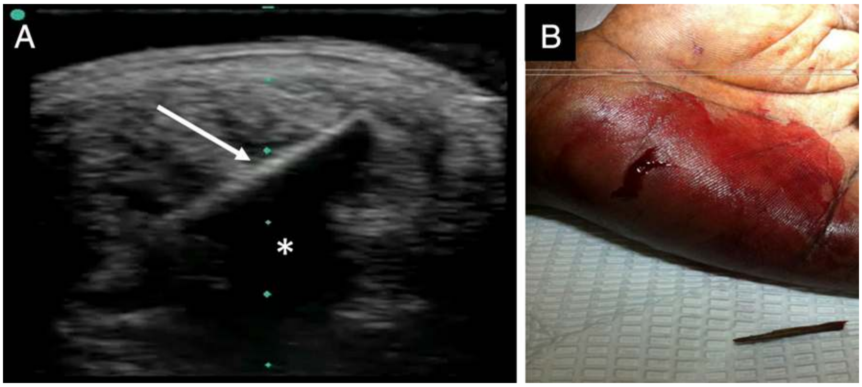

FIGURE 13
A, Foreign body (arrow) with posterior shadowing (shown by the asterisk) identified on ultrasound of the palmar aspect of the hand, which was unable to be visualized on radiography. B, Ultrasound guided the extraction of this foreign body.

CONSIDERATIONS FOR TRANSLATION TO CARE

Defining a scope of practice is fundamental for bedside ultrasound practice and is dependent on many factors, including practice specialty, local patient population, and hospital structure. Three fundamental elements should be considered when determining if a POCUS application should be included in practice: (1) Is the clinical question amenable to ultrasound interrogation? (2) Is the question answerable with discrete qualitative or semiquantitative measures (ie present or absent; mild, moderate, or severe; etc)? (3) And is this a clinical question I encounter frequently in my practice? Amenability, measurability and frequency allow for translation of applications to learning objectives. Defining scope of practice results in the identification of specific skills that

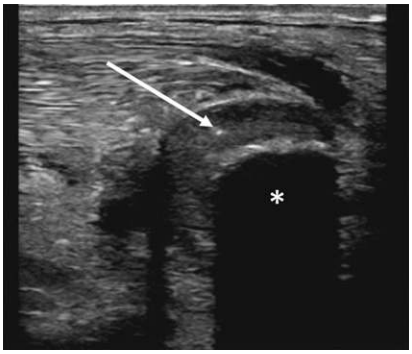

FIGURE 15
Purulent supraclavicular periosteal fluid identified and drained under ultrasound guidance. The provider is using the out-of-plane (short-axis) technique and can directly visualize the needle tip (arrow) within the fluid collection immediately above the clavicle in the transverse plane, which is identified by its posterior shadowing (shown by the asterisk).

will necessarily require structured training. Development of structured training creates a path to competency in practice.

Literature supports rapid acquisition of skill when goals are defined and training is structured. Longjohn et al[20] described a 2-hour, didactic, 15-patient training program for pediatric emergency medicine providers to assess 3 hemodynamic ultrasound parameters: (1) LV function, (2) the presence of pericardial effusion from the parasternal long-axis view, and (3) IVC respiratory variation from the subcostal view. In patient care, studies performed by trained providers had good to very good agreement with cardiologists across all evaluative domains ($\kappa = 0.87$, 0.77, and 0.73, respectively). A recent meta-analysis of POCUS for accuracy in identifying appendicitis found a 91% sensitivity and 97% sensitivity. The training and experience of providers were heterogenous within the 21 evaluated studies, with at least 3 studies describing training courses ≤1 hour.[120] Although short amounts of intensive training can train novice providers to be reliable in image acquisition and interpretation, recent literature suggests that knowledge[121] and skills[122] are difficult to maintain over time, and greater research should be focused on the best methods of sustaining excellence in practice.

Although many consider the integration of new technologies to be a risk in clinical practice, data suggest that not using ultrasound, when the technology is available, may actually place providers at increased medical-legal risk.[123,124] Multidiscipline courses in pediatric POCUS can be found around the world, although the translation of this training to practice requires infrastructural support that is often not present within departments and institutions.[125] Well-developed guidelines from adult and pediatric emergency medicine leaders may help standardize and grow local POCUS programs when adopted.[126,127]

Finally, defining the scope of practice may avoid conflicts with other specialists. We do not perform diagnostic POCUS simply because we can. We have a fundamental belief that diagnostic POCUS makes us better physicians within our own respective domains of expertise. In undifferentiated shock, images characterizing pathophysiologic processes to guide fluids and inotropes seems more elegant than making decisions by pressing on a nail bed. Waiting for a chest radiograph often neither expedites nor improves accuracy in clinical decisions. Blind insertion of needle into a pericardial sac as the final intervention before a declaration of death does not align with doing no harm when an ultrasound machine is readily available. We do POCUS because we should. Regardless of specialty, we have an individual and collective responsibility to improve our performance and the outcomes of the children we serve. Ultrasound harbors the potential to realize those ideals.

CONCLUSIONS

Ultrasound technology is more readily available for providers beyond traditional imaging disciplines. Pediatric diagnostic POCUS is being practiced in a variety of disciplines and has a meaningful impact in patient care. Defining a provider's scope of practice helps identify appropriate diagnostic applications and establish training toward competency development.

ABBREVIATIONS

FAST: focused assessment with sonography for trauma
IVC: inferior vena cava
LV: left ventricle
POCUS: point-of-care ultrasound
PPHN: persistent pulmonary hypertension of the newborn
RDS: respiratory distress syndrome
RV: right ventricle

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