



Diagnostic Utility of Point-of-Care Ultrasound in the Pediatric Cardiac Intensive Care Unit

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Abstract

Purpose of Review This review summarizes the diverse uses of point-of-care ultrasound (POCUS) in critically ill children with congenital and acquired heart disease. Diagnostic utility and practicality of POCUS is reviewed. Importantly, the role of POCUS in the medical management of children in the cardiac intensive care unit is highlighted.

Recent Findings The use of POCUS in critically ill pediatric patients has emerged as an essential diagnostic tool that enhances the physical examination and influences delivery of care. Assessment of a wide range of body systems and pathologies has been impacted by the use of POCUS. Recent studies have demonstrated the use of POCUS for evaluation of cardiac tamponade, pneumonia, vocal cord function, and loss of muscle mass in critically

ill children (Hamilton et al. *Pediatr Crit Care Med* 22(10):e532-e539, 2021; Hoffmann et al. *Pediatr Crit Care Med* 22(10):889-897, 2021; Najgrodzka et al. *Ultrasound Q* 35(2):157-163, 2019; Alerhand et al. *Pediatr Ann* 50(10):e424-e431, 2021).

Summary POCUS is a non-invasive, low-risk, imaging modality that can be used to diagnose and help guide management of critically ill children in the cardiac intensive care unit. POCUS can be performed by an intensivist at the patient's bedside with real-time interpretation, leading to rapid clinical decision-making and the hope of improving patient outcomes.

Introduction

Point-of-care ultrasound (POCUS) is well established and well studied in adult critical care medicine [1, 2, 3]. Use of ultrasound to aid in diagnosis and management of critically ill children has become widespread over recent years [4, 5, 6].

Without the ionizing radiation required for conventional radiography and computerized tomography (CT), ultrasound utilizes benign, high-frequency sound waves. POCUS, specifically, is portable and can be performed at the patient's bedside, making it ideal for intensive care unit (ICU) patients. POCUS can also be used for procedural guidance of bedside procedures such as vascular access and tube thoracostomy. Important to critically ill children, POCUS does not typically require sedation given the quick, pain-free nature of image acquisition.

POCUS can be performed and interpreted in real time by the intensivist. Thus, the need for radiology

consultants, ultrasound technologists, and larger ultrasound machines is reduced. The real-time interpretation with POCUS shortens the time between diagnosis and treatment [5]. POCUS training is now commonplace in adult and pediatric critical care training programs [7, 8]. Unique to pediatric cardiac intensive care units (PCICU), many pediatric cardiac intensivists have formal echocardiography training, further enhancing their POCUS comfort level and skill.

POCUS is an important adjuvant to the diagnosis and physical examination of critically ill children that can impact medical management. In this review, we will discuss the diverse uses of POCUS in the PCICU, with focus on the diagnostic benefit and impact on treatment of disease in this vulnerable patient population. Of note, the use of POCUS for procedural guidance will not be discussed in this review.

Cardiac

Myocardium

Evaluation

Cardiac dysfunction is a common finding in pediatric ICUs, especially dedicated PCICUs [9]. Ventricular systolic function can be impaired for a variety of etiologies, ranging from congenital to acquired, in patients with and without congenital heart disease (CHD) [10, 11].

Ventricular dysfunction is most commonly diagnosed by echocardiography that is typically performed by a cardiac sonographer and interpreted by a pediatric cardiologist. Cardiac magnetic resonance (CMR) imaging and cardiac catheterization are ancillary imaging modalities that can also assess

ventricular function. However, these modalities are both time-intensive and not without risks. CMR requires a dedicated CMR imaging protocol, requires interpretation by a trained radiologist or cardiologist, and, specific for pediatric patients, often requires general anesthesia. Cardiac catheterization is an invasive procedure, is also generally performed under general anesthesia by interventional cardiologists, and exposes the patient to both contrast and ionizing radiation.

The use of POCUS to qualitatively evaluate left ventricular (LV) function in the pediatric emergency department and ICUs is well studied. Several studies demonstrated that, after a short training, assessment of LV function by non-cardiologist physicians was strongly correlated to that made by a pediatric cardiologist [6, 12, 13]. Similarly, Miller et al. [14] demonstrated that POCUS was highly sensitive and specific for LV systolic dysfunction in pediatric patients. In 2014, the American Society of Echocardiography (ASE) strongly recommended the use of cardiac POCUS in critically ill patients for specific scenarios, including evaluation of gross ventricular systolic function and cardiac arrest [15]. Importantly, these recommendations include the caveat that focused cardiac ultrasound should not replace formal echocardiography given the high risk of complex, congenital lesions in children which can complicate image interpretation [15].

To perform cardiac POCUS, the use of a phased array ultrasound transducer is recommended. Table 1 summarizes the recommended presets, transducers, and sonographic views for each organ system based on the imaging goal. While LV systolic function can be both qualitatively and quantitatively assessed by ultrasound, a qualitative assessment is the recommended method of choice for the evaluation of ventricular function in POCUS [16, 17, 18]. To evaluate a ventricular function on a qualitative basis, the thickening of the ventricular myocardium and decrease in ventricular chamber size in systole must be compared to diastole [16]. Ventricular function can be classified as hyperdynamic, normal, mildly, moderately, and severely diminished. However, POCUS has significant limitations in the evaluation of LV systolic function, specifically, precise measurements can be technically challenging to obtain via POCUS (when compared to formal echocardiography). Given the complex shape of the right ventricle, quantitative assessment is more complex than the LV, and, as a result, is not typically integrated into cardiac POCUS.

Implications for Treatment of Disease

Evaluation of LV function via POCUS by the intensivist can be instantaneously correlated with the patient's hemodynamics. Then, based on the assessment of the POCUS and the patient's clinical status, the management can be adjusted in real time (example: titration of inotropic agents). Serial re-evaluation of LV function and the patient's response to therapies can be evaluated with repeated POCUS.

In cases of cardiac arrest, the 2010 International Liaison Committee on Resuscitation Pediatric Task Force recommended consideration of POCUS to identify potentially reversible causes, such as cardiac tamponade and pneumothorax—both of which will be discussed later in this review [28]. However, cardiac POCUS in adult cardiac arrest has been associated with prolonged

Table 1 Ultrasound views by body system

Body system	Imaging goal	Transducer	Views
Cardiac	Ventricular function	Low frequency, phased array; cardiac preset	PSLA; PSSA; A4C; subcostal view [17]
Pulmonary	Pericardial effusion		Subcostal view; A4C; PSLA; PSSA [17]
	Parenchyma	High frequency in neonates and infants, low frequency in older children; linear probe [19]	Transverse and longitudinal planes:
	Pleural effusions		<ul style="list-style-type: none"> • Mid-clavicular line on anterior and posterior chest • Mid-axillary line from axilla to diaphragm [20•]
	Pneumothorax		Subcostal transverse view; longitudinal, posterior axillary line view [21]
Diaphragm	Diaphragm movement	High frequency in neonates and infants, low frequency in older children; linear or phased array probe [21, 22, 23]	Transverse view over thyroid or cricoid cartilage with tilt cephalad [24•]
Vocal cords	Vocal cord movement	Linear transducer [24•]	Subcostal long-axis view of IVC [17]; subcostal transverse view of IVC and aorta [25]
Fluid status	Intravascular volume status (IVC)	Low frequency, phased array	Perpendicular to skin [26]
Muscle	Extravascular volume status (subcutaneous edema)	Linear transducer	
	Quadriceps femoris muscle thickness	Linear transducer [27•]	Short-axis view (perpendicular to femur); long-axis view (parallel to femur) [27•]

Legend: PSLA, parasternal long axis; PSSA, parasternal short axis; A4C, apical 4 chamber; IVC, inferior vena cava

pulse checks, so if utilized in pediatric arrests, interruption of chest compressions must be mitigated [5, 28, 29].

In patients with shock, POCUS leads to earlier and more frequent recognition of LV dysfunction, thereby, affecting subsequent management (example: less fluid administration) [30, 31, 32]. Given these implications, POCUS is recommended in children with shock [30]. In adults with shock, international guidelines recommend POCUS as a first-line modality for non-invasive hemodynamic monitoring [33, 34]. A study by Arnoldi and colleagues [35] concluded that the use of cardiac POCUS in children with septic shock changed the physician's hemodynamic assessment in $\sim 2/3$ of patients. The ability to accurately characterize a patient's physiology leads to targeted therapeutic interventions and, as a result, improved patient outcomes [36, 36].

Pericardium

Evaluation

Pericardial effusion is a common finding by echocardiography in the PICU. Post-operative pericardial effusions occur in about 10–15% of all pediatric patients undergoing cardiac surgery [37, 38]. Given the risk of cardiac tamponade, early recognition and treatment of pericardial effusions are crucial.

Cardiac POCUS is commonly utilized to determine the presence or absence of pericardial effusions in critically ill children. Adult and pediatric studies have consistently demonstrated the accuracy by which non-cardiologists can identify pericardial effusions and cardiac tamponade by cardiac ultrasound [12, 13, 39, 40]. Miller et al. [14] demonstrated that cardiac POCUS was highly sensitive and specific for pericardial effusions in pediatric patients after a focused ultrasound training. In fact, the ASE strongly recommended the use of cardiac POCUS to assess for pericardial effusions in children [15].

The same echocardiographic views used to determine ventricular function are used to evaluate a pericardial effusion (Table 1). By 2-dimensional ultrasound imaging, a pericardial effusion will appear as a black (anechoic) space between the echogenic epicardium and pericardium (Fig. 1; Video 1). The effusion can be circumferential or localized. If a pericardial effusion is seen, the size is subjectively quantified as trivial, small, moderate, or large, and, importantly, cardiac tamponade must be excluded. Findings of cardiac tamponade by cardiac POCUS include pericardial effusion of any size, right atrial collapse in systole, right ventricular collapse in diastole, and/or distended inferior vena cava (IVC) with minimal respiratory variation [41••, 33].

Implications for Treatment of Disease

Cardiac tamponade is a life-threatening, but treatable condition. While cardiac tamponade is rare in the general pediatric population, it is more often seen in critically ill children, commonly following cardiac surgery. Concerningly, pediatric patients with small-sized, post-operative pericardial effusions

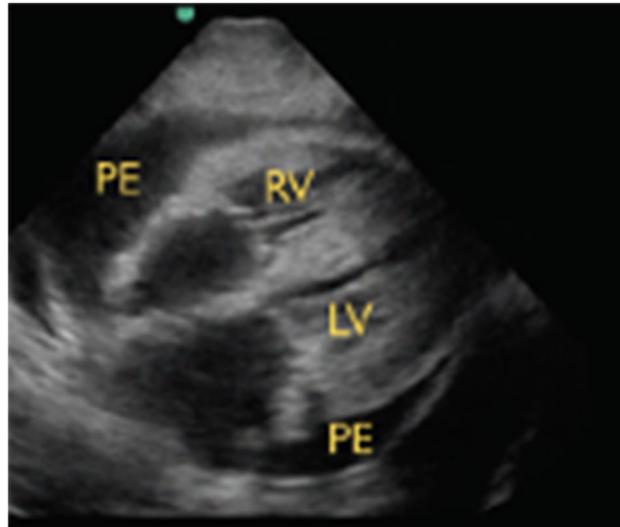


Fig. 1 Pericardial effusion (PE) shown in subcostal cardiac POCUS view. RV=right ventricle; LV=left ventricle [32]

are often asymptomatic, which can lead to a delayed diagnosis [37, 4]. Therefore, cardiac POCUS complements the physical examination of critically ill patients and can reveal undiagnosed pericardial effusions. Recognition of a pericardial effusion with or without cardiac tamponade can defer non-urgent procedures and potentially accelerate life-saving interventions (example: pericardiocentesis or surgical re-exploration) [38].

Chest

Lung

Evaluation

Lung conditions make up a large component of pediatric ICU admission as well as reasons for ongoing admission, particularly in PCICUs. Pathologies of the lung can involve the lung parenchyma as well as the pleural space. Numerous imaging modalities, including chest radiography, chest CT, and lung ultrasound are used. Lung ultrasound is favorable given the lack of ionizing radiation and the ability to identify disorders of both the lung parenchyma and pleural spaces. In pediatric pneumonia, POCUS is an effective alternative imaging modality to chest radiography [42, 43, 20]. In fact, numerous studies have demonstrated increased sensitivity of lung POCUS for the diagnosis of pneumonia compared to chest radiography [42, 44, 44].

In lung POCUS, a linear transducer is recommended [19]. Probe frequency is dependent on the age (and size) of the patient with high-frequency probes best for neonates and infants and lower-frequency probes more effective for older patients (Table 1) [19]. Per Lichtenstein et al. [45], the principles of

lung ultrasound include the following: all signs arise from the pleural line and findings are typically based on artifacts seen by ultrasound. Findings of normal lung POCUS include A-lines (hyperechoic, horizontal, linear artifact structures) and the “seashore sign” (M-mode finding of normal lung sliding) (Fig. 2) [45].

Lung POCUS can be used to diagnose lung consolidation (pneumonia), atelectasis, and pulmonary edema [3]. Diagnostic POCUS findings for pneumonia include hepatization of lung parenchyma (heterogenous,

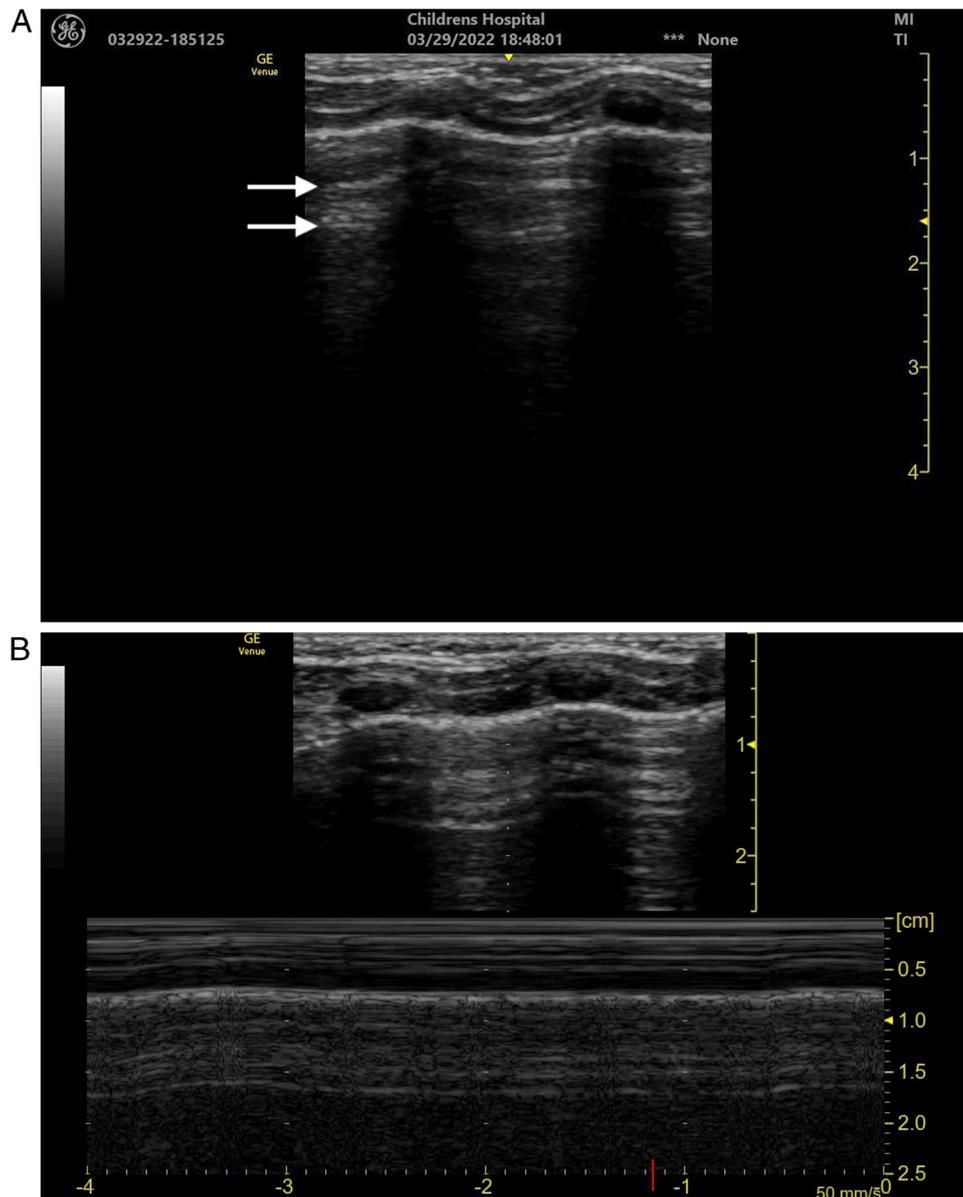


Fig. 2 Normal lung POCUS findings. **A** A-lines (white arrows). **B** Seashore sign in M-mode



Fig. 3 Abnormal lung POCUS findings. **A** Lung hepatization (white asterisk) and air bronchograms (white arrows). **B** B-lines (white arrows)

hypoechoogenicity akin to the liver) and air bronchograms (bright, focal linear structures) (Fig. 3A) [19, 20]. The air bronchograms seen in pneumonia are typically dynamic and change with respiration [20, 43]. Atelectasis appears similar to pneumonia by ultrasound but is differentiated by static air bronchograms [45, 45]. Focal B-lines are seen in pneumonia and atelectasis,

whereas multiple, diffuse B-lines indicate pulmonary edema [46]. B-lines are “comet-tail” shaped, hyperechoic, vertical artifact structures that arise from the pleural line (Fig. 47B) [47].

Implications for Treatment of Disease

Lung POCUS serves as a diagnostic tool in critically ill children, enriching the physical examination, to aid in the diagnosis of parenchymal lung conditions including pneumonia, atelectasis, and pulmonary edema [43]. The ability to identify these conditions via POCUS can decrease the utilization of other imaging tests, reduce the patient’s radiation exposure, and influence patient care [43]. Studies suggest that ultrasound paired with or without chest radiography reduced the need for chest CT in children with pneumonia [46, 48].

Management of patients with parenchymal lung problems can be guided by POCUS, especially when performed recurrently over time. In one study, trending the number of B-lines seen on serial POCUS was effective in recognizing pulmonary edema [49]. Musolino [50] found that repeat ultrasound 48 h after initiation of antibiotics for pediatric community-acquired pneumonia was a better early predictor of complicated pneumonia as compared to clinical and laboratory data. Recognizing the development of complicated pneumonia, for example, by POCUS as soon as possible may lead to earlier therapeutic interventions and better outcomes.

Pleura

Evaluation

POCUS plays an important role in the assessment of the pleural space. POCUS can diagnose pneumothoraces and pleural effusions [19, 45]. In fact, ultrasound is superior to chest radiography in the diagnosis of pleural effusions [51]. Chest CT is not ideal due to the ionizing radiation and the need for transport away from the ICU. Ultrasound can serve as a safer diagnostic tool with high sensitivity for diagnosing pneumothorax (~92%) when compared to chest radiography in both children and adults [52].

The same linear transducer is recommended for use in POCUS of the pleural spaces as with the lung parenchyma and the principles are the same (Table 1) [19]. Hypoechoic (black) space between the parietal and visceral pleura identifies a pleural effusion (Fig. 4A; Video 2) [2]. Effusions can be simple (free) or complex (loculated). Free effusions demonstrate anechoic space between parietal and visceral pleura as well as respiratory movement of the lung within the effusion, called the “sinusoid sign” [43]. The sinusoid sign is best seen by M-mode and demonstrates the variation in the interpleural distance with respiration between the visceral and parietal pleura when an effusion is present [51]. Complex effusions will typically have internal echogenicity that can appear mobile or septated.

Loss of the typical lung artifacts seen by POCUS suggests the presence of a pneumothorax [19]. Ultrasound findings of pneumothorax include absence

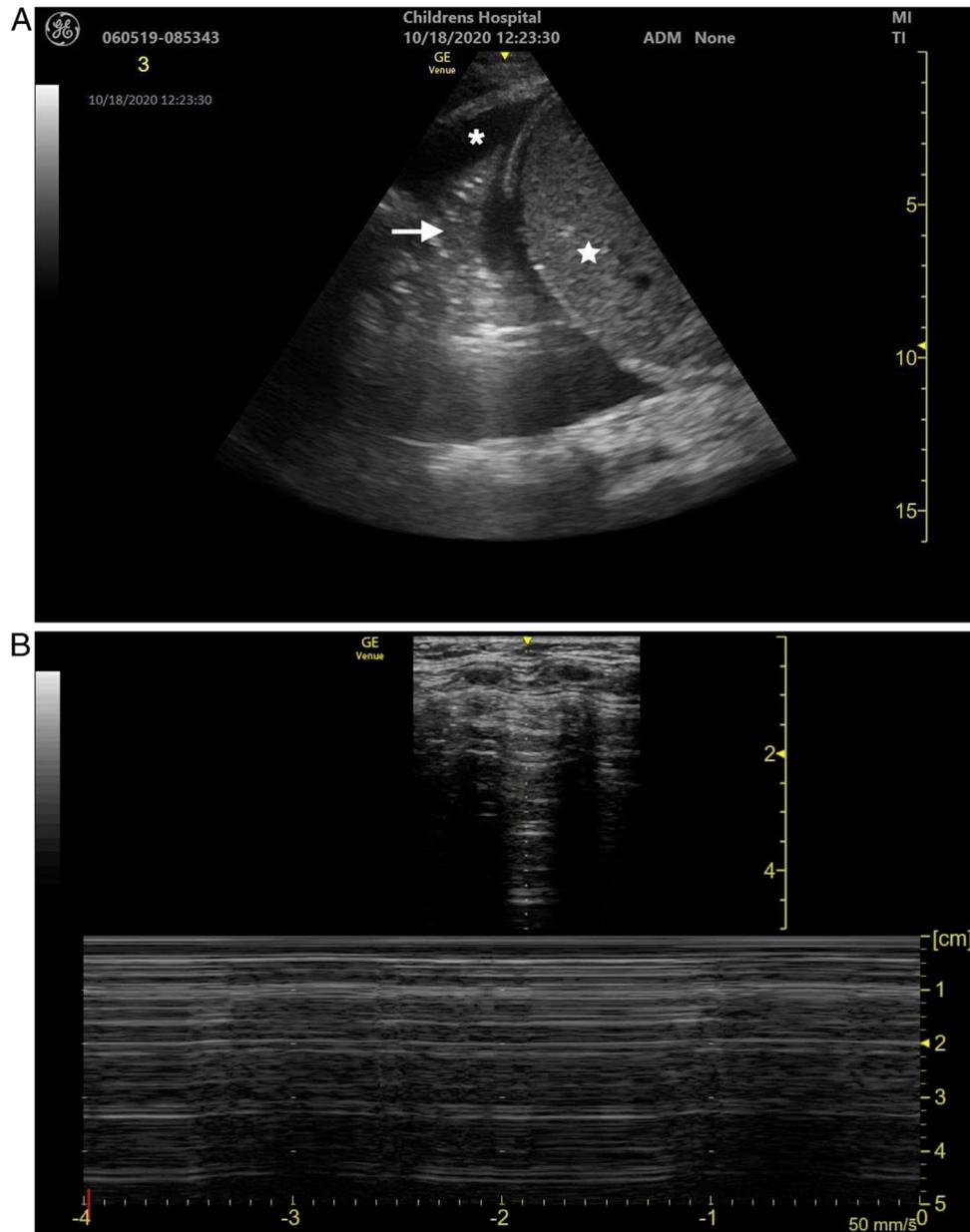


Fig. 4 POCUS images of pleura. **A** Pleural effusion (white asterisk) with lung hepatization (white arrow) and liver (white star) is shown. **B** Stratosphere sign of pneumothorax via M-mode

of normal lung sliding against the chest wall, absence of B-lines, as well as detection of the “lung point” (Video 3) [2]. The lack of normal lung sliding leads to the “stratosphere sign” by M-mode and is both sensitive and specific for the diagnosis of pneumothorax (Fig. 4B) [45, 45, 45]. In fact, lung ultrasound of a pneumothorax will only demonstrate A-lines, so the presence of any B-lines rules out the presence of a pneumothorax [52, 52]. Lastly, the lung

point is an abrupt loss of lung tissue in contact with the pleural line seen by M-mode and is also specific for a pneumothorax [53].

Implications for Treatment of Disease

Pneumothoraces and pleural effusions are treatable, yet life-threatening, causes of respiratory failure in children and are not uncommon following cardiac surgery. POCUS is a non-invasive, bedside tool that can be used to rapidly evaluate a patient with respiratory failure without delaying diagnosis or treatment [54, 55]. Krishnan [56] confirmed high accuracy in ruling out pneumothorax via lung POCUS after completion of a short online training.

Xirouchaki et al. [57] reported that clinical decision-making and management were altered in about 50% of adult ICU patients and new diagnoses unsuspected by the primary physician were identified in 20% of cases. Similarly, lung POCUS can impact patient management and lead to higher quality treatment in children [48].

Serial lung ultrasounds can be performed to monitor the progression of the patient's pleural condition, response to therapy, and/or recurrence following treatment. Moreover, lung POCUS has been shown to decrease the number of chest radiographs performed in newborns with pneumothoraces [55]. Another advantage of POCUS is in procedural guidance for thoracentesis and thoracostomy tube placement [58].

Diaphragm

Evaluation

Phrenic nerve injury with consequent diaphragm paralysis is a known complication following pediatric cardiac surgery. Abnormal diaphragm movement is a major cause of respiratory failure in children, specifically infants, following cardiac surgery, with an incidence up to 13% [59, 60]. Fluoroscopy and ultrasound are the most common imaging modalities to evaluate diaphragm function [23]. Chest radiography can raise suspicion for diaphragm paralysis but is non-diagnostic and cannot distinguish bilateral diaphragm paralysis. POCUS is a reliable and accurate imaging modality for the diagnosis of diaphragm paralysis that does not require the ionizing radiation and patient transport needed for fluoroscopy [23, 23, 61]. Again, POCUS is favored in unstable patients as it can be performed at the patient's bedside. Sanchez de Toledo et al. [62] demonstrated that lung POCUS can be performed by an intensivist after a 4-h hands-on training course with subsequent high sensitivity (86%) and specificity (100%) of identifying an abnormality.

To evaluate the diaphragm via lung POCUS, a linear probe is recommended with transducer frequency dependent on the patient's size (Table 1) [19]. The subcostal transverse view can evaluate the symmetry of the diaphragm leaflets (normal is less than 50% difference) while the longitudinal, posterior axillary line view can assess the excursion of each hemi-diaphragm (Fig. 5) [19, 23, 63, 64]. With inspiration, the diaphragm will normally move

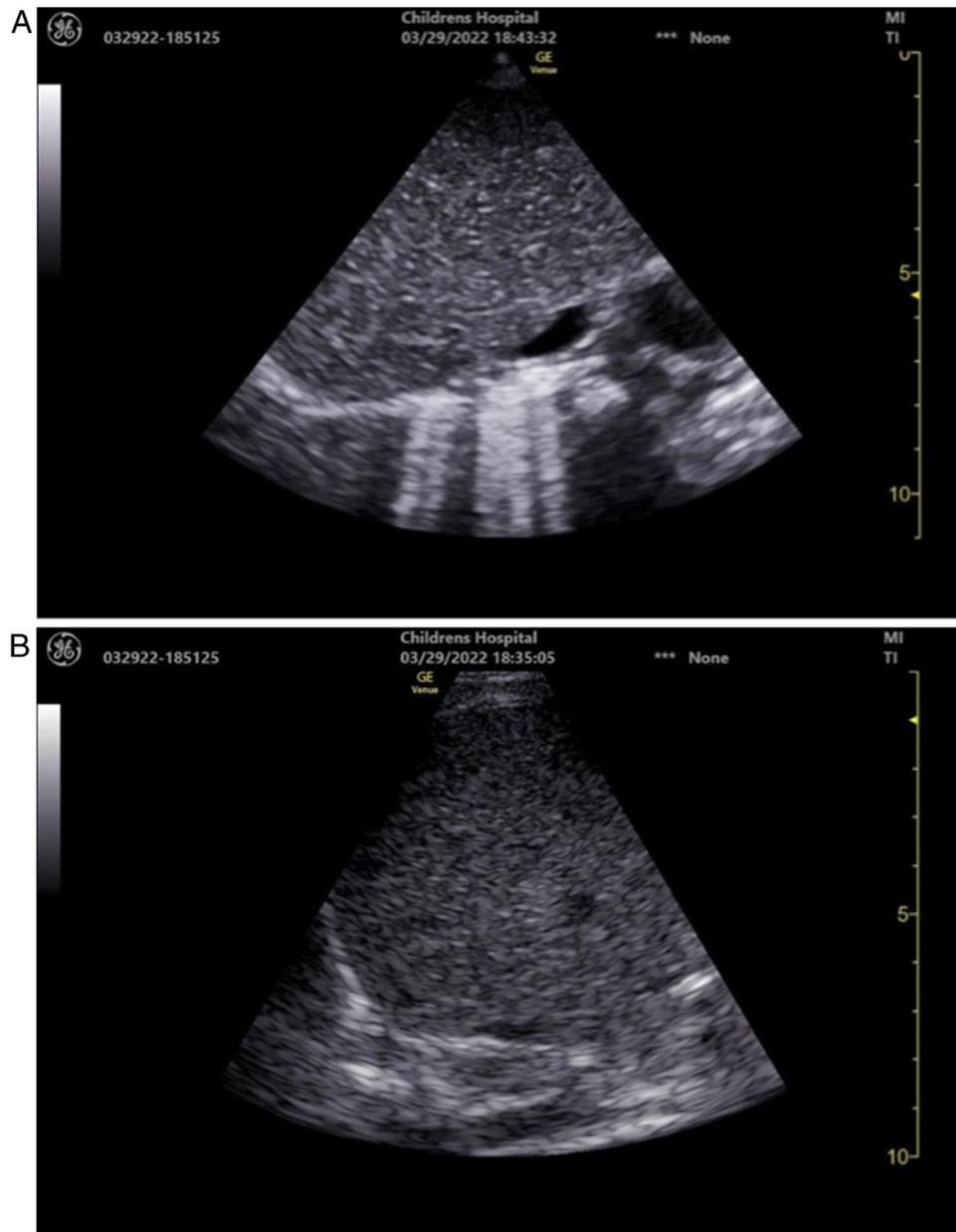


Fig. 5 POCUS views to evaluate the diaphragm (white arrow). **A** subcostal transverse view and **B** longitudinal, posterior, mid-axillary view

caudal, toward the ultrasound transducer, and can be quantified via M-mode with normal excursion measuring greater than 4 mm in children [19, 19, 22]. Based on these POCUS findings, diaphragm movement can be classified as normal, decreased, absent, or paradoxical (the latter two indicating diaphragm paralysis) [63, 63]. Additionally, Hosokawa et al. [64] identified a

new ultrasound finding in children with severe hemi-diaphragmatic paralysis. In diaphragm paralysis, by 2-dimensional imaging of the subcostal transverse view, the descending aorta can be seen sliding into the unaffected side of the diaphragm with breathing.

Additionally, diaphragm atrophy is a known morbidity of critically ill children and adults [65]. Diaphragm atrophy is well associated with increased duration of mechanical ventilation, longer length of ICU stay, and higher mortality in adults [66, 67, 68]. POCUS can quantify diaphragm thickness and atrophy over time [65]. Using B-mode or M-mode, the diaphragm can be seen in the coronal plane in the mid-axillary line, between the ninth and tenth intercostal space [65, 69]. Measurement of the diaphragm thickness is performed from the outer edge of the diaphragmatic pleura to the outer edge of the peritoneal membrane, during end-expiration [65].

Implications for Treatment of Disease

Diaphragm motion abnormalities, including paralysis, can lead to persistent respiratory failure in pediatric patients, especially following cardiac surgery. These patients can struggle with separation from mechanical or non-invasive ventilation [23]. Therefore, early recognition of diaphragm paralysis is necessary to progress patient care and minimize post-operative complications [70].

The use of POCUS for the diagnosis of abnormal diaphragm movement in children after cardiac surgery has been validated [21]. POCUS in children after cardiac surgery can provide a timely and accurate assessment of diaphragm motion and, as a result, direct patient care to improve outcomes and length of stay [23]. Repeat POCUS to re-evaluate diaphragm function may be essential prior to potential surgical plication as up to nearly 60% of children can have spontaneous recovery [65]. Glau et al. [71] reported a prolonged need for non-invasive ventilation in children with diaphragm atrophy after cardiac surgery, when diagnosed via POCUS. Repeat POCUS in mechanically ventilated children can identify the development of diaphragm atrophy [72]. Therefore, post-extubation respiratory failure can potentially be prevented by identifying diaphragm atrophy prior to extubation. Changes to a patient's care (such as weaning the ventilator rate and increasing number of spontaneous breathing trials, and/or lifting neuromuscular blockage) can mitigate diaphragm atrophy [72].

Volume status

Intravascular

Evaluation

Achieving euvolemia is a primary goal in critical care medicine. Hypovolemia can compromise end-organ perfusion and lead to cardiovascular collapse. Fluid overload (FO) is associated with increased morbidity and mortality in children [73, 74, 75]. Children recovering from cardiac surgery

are at even more high risk of FO as a consequence of perioperative volume administration and resuscitation, cardiopulmonary bypass, hemodilution, fluid retention via neurohormonal pathways, and increased capillary permeability [76, 75, 77]. Unfortunately, fluid status is challenging to accurately assess in children.

There is no gold standard method to determine fluid status. Invasive and non-invasive methods for estimating fluid status do exist. Invasive options include measuring the central venous pressure (CVP) via a central venous catheter or during cardiac catheterization, both of which require vascular access, typically achieved under sedation. Non-invasive methods include trending a patient's daily weights, net fluid balance, and physical examination findings, all of which can be imprecise [78, 79]. POCUS, specifically of the inferior vena cava (IVC), is another non-invasive method for determining a patient's intravascular fluid status.

Ultrasound of the IVC to assess a patient's intravascular fluid status has been well studied in adults and children and is comparable to invasive CVP monitoring [80, 15]. The ASE strongly recommended the use of POCUS to evaluate volume status in children [81].

Specifically, POCUS evaluation of intravascular fluid status includes measurement of diameter and collapsibility of the IVC [80]. The IVC can be best visualized in the subcostal long-axis view (Table 1; Fig. 6) [17, 31]. In a patient with euvoemia and spontaneous breathing, the IVC will partially collapse with inspiration [31]. With ultrasound, IVC diameter and percent collapsibility with inspiration can be measured. In adults, normal values for IVC diameter exist, but normative values are not utilized in children. When evaluating IVC, it is also important to recognize the impact of intrathoracic pressure, respiration, and positive pressure ventilation [82].

IVC collapsibility of more than 50% with respiration in hemodynamically unstable children can be considered hypovolemia [12]. In adults, the IVC collapsibility index (IVCCI) has been correlated to CVP measurements [83]. The IVCCI is determined by measuring the maximum and minimum diameter of the hepatic IVC in the subcostal long-axis view [12]. The IVCCI equation is as follows: $[(\text{max. IVC diameter} - \text{min. IVC diameter}) / \text{max. IVC diameter}]$ [84]. In spontaneously breathing children following cardiac surgery, two studies found a strong inverse relationship between IVCCI and CVP, where an IVCCI less than or equal to 0.22–0.26 was associated with a CVP greater than or equal to 10 mmHg [82, 84]. Similarly, the IVC distensibility index (IVCDI) can also be calculated as $[(\text{max IVC diameter} - \text{min IVC diameter}) / \text{min IVC diameter}]$ [85]. The IVCDI has been correlated with fluid responsiveness in adult patients [86].

The ratio between the IVC and aortic diameters has also been studied as a surrogate of intravascular fluid status [25, 87]. This ultrasound measurement is obtained in the subcostal transverse view where both the IVC and aorta can be seen and measured [25]. A mean IVC/aorta ratio ~ 1 has been seen in healthy, euvoemic children, while a ratio < 0.8 suggests severe hypovolemia [87, 88, 87]. In a study by Chen et al. [89], lower IVC/aorta ratios were seen in children with clinical evidence of dehydration (compared to non-dehydrated matched controls) and this ratio increased with fluid administration.

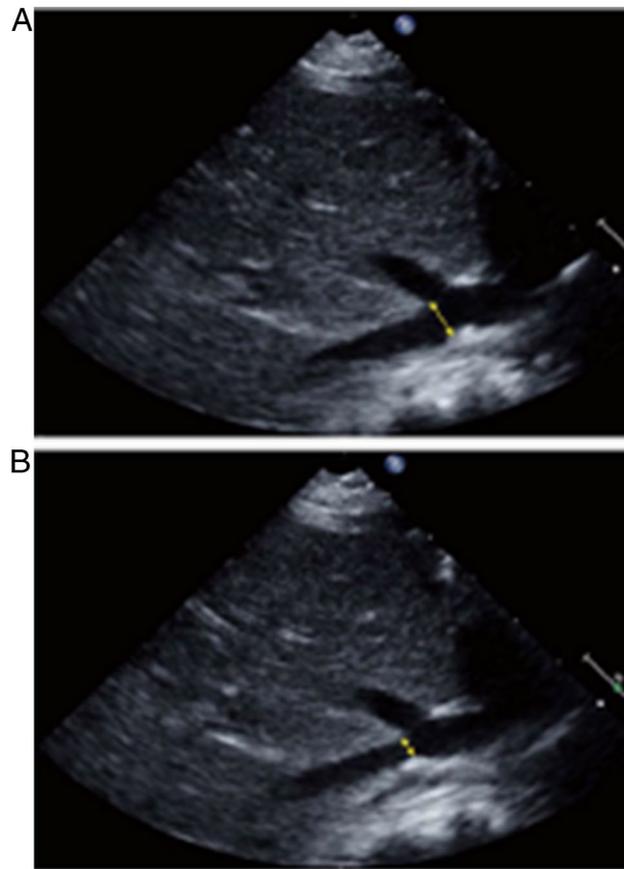


Fig. 6 IVC distention (A) and collapse (B), as depicted by yellow arrow, in subcostal, long-axis, POCUS view of the IVC [82]

It is important to note that ultrasound assessment of the IVC can be impacted by the patient's respiratory status and the potential confounders [85]. These confounders include acquired and congenital factors, such as ventricular dilation/dysfunction, valvular dysfunction, and forms of CHD [31, 84, 90].

In a similar manner, femoral vein diameter, both alone and compared to femoral artery diameter, has been associated with CVP and volume status in adults [91, 92]. Femoral vein and artery diameter can be easily seen and measured via POCUS. However, this utilization of POCUS has not yet been studied in the pediatric population.

Implications for Treatment of Disease

Ultrasound of the IVC complements the clinical assessments of a patient's fluid status. Increased IVC collapsibility and/or decreased IVC/aorta ratio is consistent with dehydration [17, 25]. In addition to determining a patient's fluid status, IVC ultrasound can be used to predict fluid responsiveness in

critically ill patients [35]. Singh et al. [35] reported that IVC collapsibility greater than 55% is predictive of fluid responsiveness. Several studies found a strong correlation between adults and children with an IVCCI greater than 0.18 and volume responsiveness [80, 85]. The 2016 Guidelines for the Appropriate Use of Bedside General and Cardiac Ultrasonography in the Evaluation of Critically-ill Patients by the Society of Critical Care Medicine recommends the use of cardiac POCUS for both the assessment of hypovolemia and determination of fluid responsiveness in children [86].

This use of ultrasound can be performed rapidly and serially after fluid administration to monitor responsiveness [4]. The ability to titrate fluid administration based on ultrasound findings can optimize a patient's fluid status while avoiding fluid overload—a known risk factor for increased morbidity and mortality [74].

Extravascular

Evaluation

As discussed above, FO, whether extra- or intravascular, worsens clinical outcomes in critically ill children [73, 74, 75]. Signs of extravascular FO include pleural effusions, pulmonary edema, ascites, and subcutaneous edema. The diagnostic tools to identify these findings can include chest radiography and physical examination. Additionally, POCUS can be used to assess for extravascular FO, with several of these signs having been discussed earlier in this review [25].

POCUS of the subcutaneous tissue can identify edema, which will appear as hypoechoic (black) space in the subcutaneous region (located between the skin and underlying muscle) (Fig. 7) [26]. To evaluate for subcutaneous edema via ultrasound, a linear transducer is placed perpendicular to the skin with care to avoid compressing the subcutaneous tissue, as this will confound the findings (Table 1) [26].

Additionally, abdominal POCUS can diagnose and subjectively quantify ascites. Using a low frequency, curvilinear transducer, the peritoneal space can be imaged [94]. Ascites will appear as an anechoic space in the abdomen, especially in dependent areas (example: peri-splenic, hepato-renal, and pelvis) [95]. The main limitation is that POCUS cannot differentiate the type of fluid in the abdomen (ascites vs blood, etc.) [94].

Implications for Treatment of Disease

Subcutaneous edema is a sign of extravascular FO. POCUS can enhance the physical examination for extravascular FO. POCUS of the subcutaneous tissue has been performed on infants following cardiac surgery, with increases in subcutaneous tissue over a short time suggestive of extravascular FO [93]. Yanagisawa et al. [26] correlated the amount of subcutaneous edema seen by ultrasound with physical examination findings of edema in pregnant women. Future research is needed to validate the findings of edema by subcutaneous

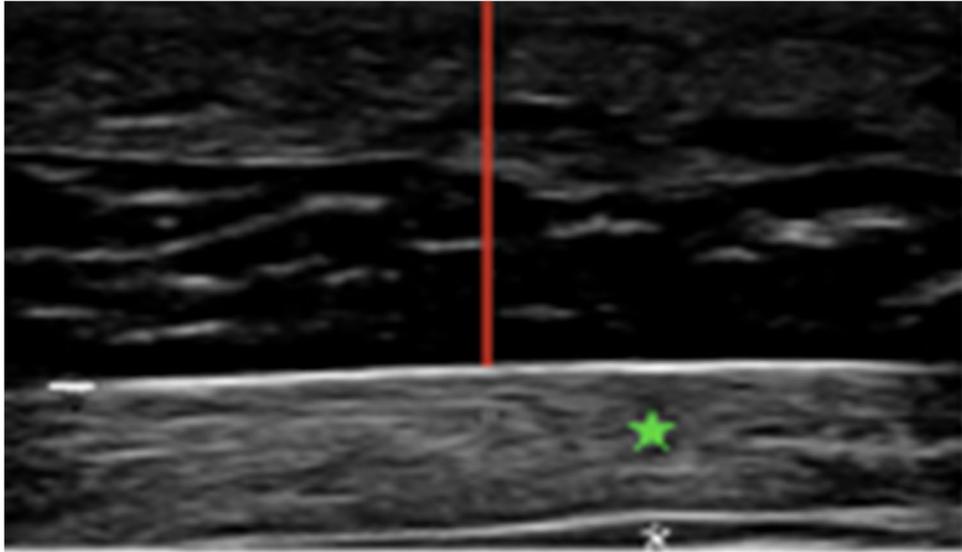


Fig. 7 Subcutaneous edema demonstrated via abdominal skin POCUS in long-axis, mid-axillary line. Red vertical line=subcutaneous edema; green star=abdominal muscle; white star=liver [93]

tissue ultrasound as a surrogate for extravascular FO. POCUS of the subcutaneous tissue, as an objective, non-invasive diagnostic tool, could lead to prompt recognition and treatment of extravascular FO.

Ascites can suggest extravascular FO, especially in critically ill children following cardiac surgery. Identification and quantification of ascites can guide the selection of appropriate therapies, such as diuretics or peritoneal drain insertion.

Airway

Vocal cords

Evaluation

Vocal cord immobility or paralysis is a known complication following pediatric cardiac surgery. The incidence of vocal cord immobility can be as high as ~35% after aortic arch repairs in children [96]. The gold standard to evaluate vocal cord function is flexible nasolaryngoscopy, which is invasive and can be uncomfortable, especially in unsedated patients. Laryngeal ultrasound is a relatively new, but effective, alternative imaging modality. As compared to laryngoscopy, ultrasound is highly sensitive and specific for diagnosing abnormal vocal cord motion in children [24•]. As usual, laryngeal ultrasound has the advantages of being non-invasive and pain-free. Additionally, during the COVID-19 pandemic, laryngeal ultrasound was preferred over laryngoscopy as it is not aerosol-generating [97].

While laryngeal ultrasound is typically performed by otolaryngologists, one study demonstrated that pediatric cardiac intensivists can successfully diagnose vocal cord paralysis via laryngeal ultrasound with good reliability compared to laryngoscopy [98]. Laryngeal ultrasound is best performed using a linear probe positioned over the thyroid or cricoid cartilage in a transverse orientation with the patient's neck extended (Table 1) [24•]. Vocal cord mobility is qualified as normal, impaired, or paralyzed [99]. While measurement of anatomic angles, such as the vocal fold-arytenoid angle, can also be used to evaluate vocal cord mobility, this is likely best reserved for formal laryngeal ultrasound as opposed to laryngeal POCUS [100].

Implications for Treatment of Disease

Vocal cord immobility prolongs hospitalizations in children following cardiac surgery [96]. The risk of aspiration is notably higher in children with vocal cord immobility, so the sooner the diagnosis is made, the sooner the patient can be screened for aspiration which may then alter their management and discharge plan, including the long-term feeding method [101]. Laryngeal ultrasound is a reliable diagnostic tool for vocal cord impairment [24]. The use of laryngeal ultrasound in the PCICU may improve widespread screening in patients at high risk for vocal cord impairment [100•].

Musculoskeletal

Muscle

Evaluation

Critically ill patients are at risk for suboptimal nutrition and muscle wasting, which is associated with poor clinical outcomes and long-term impairment [102, 103]. Infants with CHD, especially those with single ventricle physiology, are at particularly high risk of growth failure while in the PCICU [27]. Current recommendations for assessing the nutritional status of critically ill children include trending weights, anthropometric measurements, and indirect calorimetry [104]. Recently, the use of ultrasound to measure muscle thickness has been studied in both critically ill children and adults as a novel tool to assess muscle mass and serve as a surrogate for nutritional status [105•, 106].

To perform an ultrasound of the muscle, a linear probe is recommended. Images are obtained in B-mode with the transducer positioned over the muscle. Hoffmann et al. [27•] studied the use of ultrasound to measure the thickness of the quadriceps femoris muscle in critically ill children. In these patients, the ultrasound probe was placed on the proximal third of the anterior thigh with the hip and leg extended. Ultrasound views are obtained with the transducer perpendicular to the femur (short-axis) and parallel to the femur (long-axis) (Table 1; Fig. 8). The muscle thickness

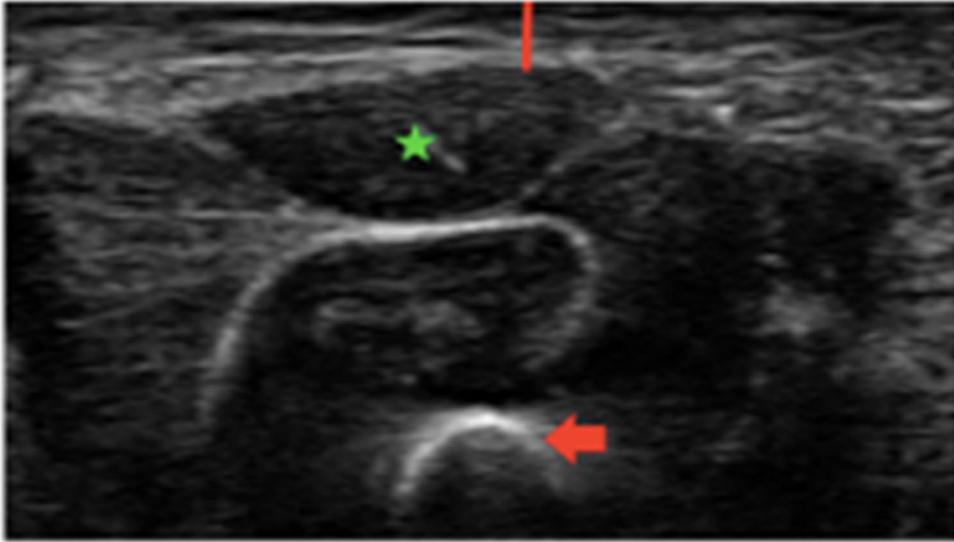


Fig. 8 Short-axis POCUS view of quadriceps femoris muscle. Red line – subcutaneous tissue. Green star – rectus femoris muscle. Red arrow – femur [93]

can be trended over time. Hoffmann et al. [27•] reported that this can be successfully performed by pediatric intensivists and is an innovative, reliable tool for measuring muscle thickness, and does not appear to be confounded by fluid overload.

Implications for Treatment of Disease

Ultrasound of the muscle can be used to identify early muscle mass loss. Measurements can be repeated over time to assess for response to interventions, such as nutrition optimization [27•]. Further study and validation of this novel use of ultrasound are recommended [27•, 27]. This non-invasive and objective tool can guide nutrition optimization and, as a result, lead to improved clinical outcomes [106•, 107].

Conclusion

POCUS is a non-invasive, low-risk, imaging modality that can be used to diagnose and help guide the management of critically ill children in the cardiac intensive care unit. POCUS can be performed by an intensivist at the patient's bedside with real-time interpretation, leading to rapid clinical decision-making and the hope of improving patient outcomes.

Declarations

Conflict of Interest

Jessica N. Persson declares that she has no conflict of interest. John S. Kim declares that he has no conflict of interest. Ryan J. Good declares that he has no conflict of interest.

Human and Animal Rights and Informed Consent

this article does not contain any studies with human or animal subjects performed by any of the authors.

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