Fifteen-minute consultation: Point of care ultrasound in the management of paediatric shock

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ABSTRACT

The use of point of care ultrasound (POCUS) in the assessment of the acutely shocked adult patient has been well established for over a decade. Comparatively, its use in paediatrics has been limited, but this is starting to change with the recent introduction of Children's Acute Ultrasound training. This article highlights the pathophysiology of shock in children and demonstrates how bedside ultrasound can be used to assist decision making in the clinical assessment of the neonate, infant or older child presenting with undifferentiated shock. We discuss a structured protocol to use when performing the POCUS examination and explain how this could lead to a more rapid correlation of the ultrasound findings with the underlying cause of shock.

INTRODUCTION

Shock is a complex clinical syndrome that is often present to varying degrees in children with critical illness. When we take account of the multiple aetiologies of shock, it is recognised as the primary mechanism leading to paediatric mortality worldwide.[1] If a child's clinical presentation is consistent with shock, then a clinician should try to ascertain its type before tailoring the management to specifically treat the underlying pathology.

In adults, point of care ultrasound (POCUS) has long been used at the patients' bedside to perform procedures and to aid in the timely diagnosis and management of life threatening pathologies.[2 3] In this article, we will describe how POCUS can be used, allowing rapid assessment of the child in shock using a suggested POCUS protocol. POCUS uses a predefined sequence of focused scans to answer specific questions often with binary answers. This allows the trained clinician to better differentiate between the causes of paediatric shock in a timely manner, and subsequent reassessment can provide information about the patients response to treatment.

SHOCK

Shock pathophysiology

The pathophysiology of shock can be summarised as an acute state of energy failure, which prevents the metabolic demands of cells from being met. This primarily results from failure of the cardiovascular system to deliver adequate oxygen and/or glucose to the cells; however, mitochondrial dysfunction can also produce the same effect through failure of adenosine triphosphate (ATP) production.[4] If shock is left untreated, it will progress through three stages:[5]

1. *Compensatory stage*: Neurohumoral mechanisms act to maintain blood pressure (BP), tissue perfusion and metabolic state.
2. *Progressive stage*: The compensatory mechanisms become overwhelmed and pathophysiological derangements worsen.
3. *Refractory stage*: Severe organ and tissue injury develops, which culminates in multi-organ failure and death.

The compensatory cardiovascular responses of the child differ from those of adults.[6]

In the paediatric patient, cardiac output (CO) is more dependent on heart rate (HR) than on stroke volume (SV) due to the lack of ventricular muscle mass and decreased ventricular elastance (ie, 1/Compliance).[6] Consequently, tachycardia is the child's principal means of compensating to maintain an adequate CO. As shock progresses, a further increase in HR may no longer be beneficial due to reduced ventricular diastolic filling time. Consequently, there is an increase in systemic vascular resistance through peripheral vasoconstriction mechanisms which are mediated by the sympathetic nervous system and the Renin-Angiotensin-Aldosterone system.[7] CO has now been maintained by

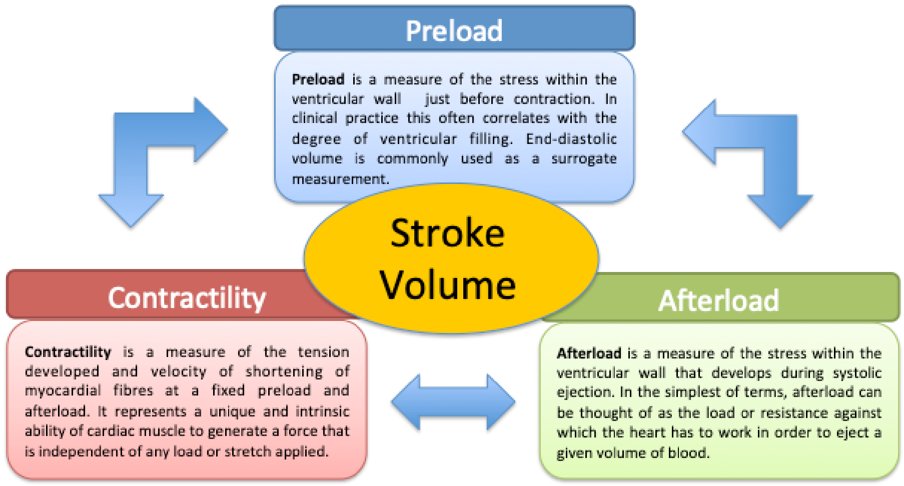

Figure 1 Determinants of stroke volume: preload, contractility and afterload.[8 27]

optimising preload, contractility and afterload, which are the determinants of SV (figure 1).[8]

More specifically for septic shock, the progression of shock is often described in two phases, 'warm shock', which occurs early; and 'cold shock', which occurs late. Warm shock occurs as a result of compounds produced during the inflammatory response causing capillary leakage and vasodilation leading to a relatively warm and 'flushed' compensated patient. When these compensatory mechanisms start to fail, CO starts to fall and vasoconstriction dominates, leading the ominous later stage of cold shock.[9] A key difference in paediatric shock (of any aetiology) is that left ventricular dysfunction occurs due to the vasoconstrictive mechanisms earlier and more commonly than in adult shock, making the distinguishing of cardiogenic shock due to a primary cardiac pathology versus a non-cardiac pathology sometimes difficult.[10 11]

In paediatric patients, BP can often be preserved, so BP is often a poor indicator of cardiovascular homeostasis. The evaluation of HR and end-organ perfusion, including the quality of the peripheral pulses, mental state, urine output, skin perfusion and acid-base status is much more valuable in determining a child's circulatory status. The relationship between preload, contractility and afterload is of paramount importance, particularly when deciding whether to use volume resuscitation, vasopressors or an inotropic agent as the initial therapeutic approach to the patient in circulatory failure. Although there are an almost inexhaustible number of potential causes for circulatory shock in children, the choice narrows if the clinician uses a purely physiological classification.[7]

Aetiology of shock

The aetiology of shock can be broken down into five broad physiological categories (table 1).[4 5]

It should be noted that any one pathology may cause shock via a number of these mechanisms. For example, sepsis will initially cause a distributive shock but as increasing vascular permeability allows fluid to leave blood vessels, a hypovolaemic shock will ensue. Further progression leads to worsening acidosis and electrolyte imbalances, and eventually cardiogenic shock will ensue.[12 13] As mentioned above, this happens earlier in the younger age groups.[10 11]

POCUS IN SHOCK: ADULT EXPERIENCE

The use of POCUS in assessment of the acutely shocked adult patient has been well established for over a decade. Protocols such as 'Rapid Ultrasound in Shock' (RUSH) and 'Extended Focus Assessment with Sonography in Trauma' (eFAST) have been developed to allow the bedside user to perform a sequence of focused ultrasound scans to differentiate between the

Table 1 The five physiological categories of shock

Type of shock	Description	Examples
Hypovolaemic	Reduction in circulating volume	Haemorrhage Vomit/diarrhoea DKA Burns
Cardiogenic	Decline in cardiac output due to reduced myocardial function or cardiac damage	MI Cardiac failure Arrhythmias Septic shock Cardiac surgery
Obstructive	Mechanical obstruction that reduces cardiac output	Cardiac tamponade Pneumothorax Massive PE
Distributive	Abnormalities in blood flow distribution, despite normal or high cardiac output	Septic shock Anaphylaxis Neurogenic shock
Dissociative	Inadequate tissue oxygenation secondary to abnormal affinity for oxygen	Carbon monoxide Methemoglobin

DKA, diabetic ketoacidosis; LV, left ventricle; MI, myocardial infarction; PE, pulmonary embolism; RV, right ventricle.

adult causes of shock, many of which are the same in children. In the hands of experienced clinicians, these approaches have been proven to have a higher sensitivity compared with the chest X-ray and clinical examination in detecting certain pathologies for example, haemothorax and pneumothorax.[14] The use of these protocols has been incorporated into several training programmes for doctors, nurses and paramedics, and it has been proven that within 30–50 supervised scans a novice can be taught to identify specific pathologies and answer binary questions.[15] It is now the requirement of some training programmes that trainees must have completed basic entry-level POCUS training prior to obtaining their certificate of completion of training in the UK.[16]

POCUS IN SHOCK: PAEDIATRIC EXPERIENCE

The use of POCUS in paediatrics has thus far been limited, but it is now a rapidly growing assessment tool. Training has been developed for paediatricians in the UK with the Children's Acute Ultrasound course now being accredited by the Paediatric Intensive Care Society.[17] POCUS can be considered an extension of the bedside clinical assessment when used in conjunction with standard examination techniques. The trained clinician uses it as a supplementary diagnostic tool that can assess any body system in any setting.[18] Ultrasound is not harmful; this allows for repeated scanning of the same child to assess the impact of any intervention. While most of the literature pertains to POCUS in adults, its role in assessing the acutely ill neonate/child has been demonstrated on numerous occasions.[19 20] When children present in shock the increasing availability and portability of ultrasound machines now means that this tool can be easily brought to the bedside.

Paediatric shock POCUS protocol

Whatever protocol is used to assess the child in shock, POCUS is designed to help answer specific questions, as shown in box 1:

The adult RUSH protocol provides a framework for the attending clinician to perform a series of scans to obtain this information and help them determine the aetiology and subsequent management of the shock. Given that the majority of causes of shock are age independent, the adult RUSH protocol can be adapted for paediatric and neonatal practice. Figure 2 demonstrates a flow chart used by the authors at Southampton Children's Hospital Paediatric Intensive Care Unit as a checklist for POCUS assessment of undifferentiated shock.

At each stage of the POCUS examination, more information is gained, and the positive ultrasound features can then be used to determine which component of CO is contributing to the shocked state; is it preload, contractility or afterload?

Box 1 Key questions to answer with POCUS when dealing with a shocked child

Is there a preload problem?
- Is there evidence of pulmonary oedema?
- Is the heart full or empty? Is the IVC distended or collapsible?
- Are there signs of fluid loss (eg, effusions, bleeds)?

Is there a contractility problem?
- Are the ventricles ejecting blood adequately?
- Are the atria and/or ventricles dilated?

Is there an obstructive problem?
- Cardiac tamponade?
- Tension pneumothorax?
- Pleural effusions?

IVC, inferior vena cava; POCUS, point of care ultrasound.

Interpreting POCUS findings

The management of the patient can be tailored to more specifically address the underlying cause when the component of the CO leading to the shock is identified. For instance, in a shocked child with signs of pulmonary oedema (bilateral B lines on lung ultrasound with normal pleura) and a distended poorly contracting left ventricle, then impaired contractility is the likely cause. The Advanced Paediatric Life Support guidelines would initially suggest volume resuscitation for undifferentiated shock; however, now the management of this shocked child differs and earlier intervention with inotropes and ventilation may be indicated, with less or no fluid given. Following any intervention, the POCUS examination can be repeated, and this reassessment helps confirm the selected management strategy is correct. Table 2 provides a summary of how the POCUS findings can be used to identify the aetiology of shock.

Cardiorespiratory POCUS

A full detailed description of how to obtain the respiratory ultrasound views and interpret the findings relevant to shock has previously been discussed in this journal.[18] The key respiratory pathologies to exclude in a shocked child include pulmonary oedema (suggestive cardiac impairment or overfilled circulation), tension pneumothorax or pleural effusions (both of which can cause a reduction in CO). Finding signs of consolidation may suggest a primary pneumonia as a source of sepsis.

Ultrasound assessment of cardiac function and ventricular filling for critical care purposes is best done by a global visual assessment of the heart. Descriptions of how to obtain key cardiac POCUS views are well documented.[21 22] Assessment of cardiac filling/function should always be done in more than one view to ensure the findings are validated. For example, apical 4 chamber and parasternal long and short axis views are

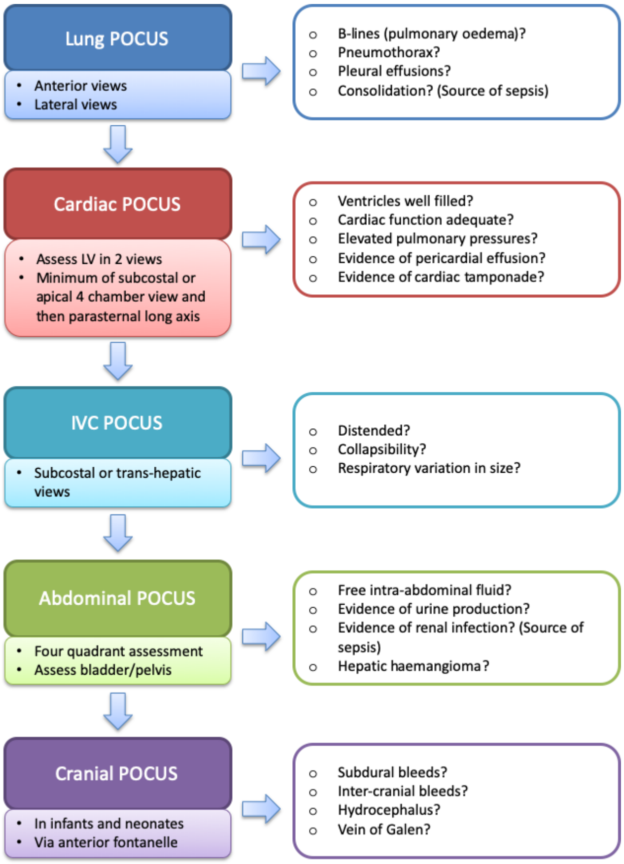

Figure 2 Ultrasound examination approach to the child with undifferentiated shock. IVC, inferior vena cava; POCUS, point of care ultrasound.

helpful together. Assessment of the LV should include a visual assessment of the size of the chamber, the wall movements and the interactions with the RV. Cardiac POCUS is very different to the detailed echocardiography assessment looking for congenital heart disease; cardiac POCUS is a brief functional assessment only to help guide immediate resuscitation.

Assessment of IVC

The use of the subcostal view to assess inferior vena cava (IVC) collapsibility and respiratory variation is thought to be a potential predictor of fluid responsiveness, if performed under the right conditions. To obtain the images, the probe should be placed to acquire the subcostal view of the heart, then the probe is moved progressively to the right to visualise the IVC/right atrium in the centre of the field. The probe is then rotated by 90° anticlockwise to obtain the IVC in its longitudinal plane.[23] In a spontaneously breathing child, a variation in IVC diameter during respiration of >50% combined with an easily collapsible vessel suggests a low-volume state (figure 3A). Conversely, a variation of <50% with a distended or minimally collapsible IVC suggests a high-volume state or potential tamponade/obstructive physiology (figure 3B).[22] The heterogeneity of studies performed in both adults and children have failed to fully support or refute the concept of IVC variability and fluid responsiveness.[24 25] It is the view of the authors that the IVC POCUS assessment should not be used in isolation,

Table 2 POCUS features that can help determine the pathophysiology and aetiology of shock

Component of cardiac output		Example diagnoses	Helpful POCUS features
Preload pathology	Reduced	▶ Sepsis ▶ Haemorrhage ▶ Fluid loss (eg, Gastroenteritis, third space)	✓IVC variability ✓Absent B lines ✓Empty left ventricle ✓Hyperdynamic heart ✓Evidence of fluid loss (eg, free fluid in abdomen) ✓Evidence of source of sepsis (eg, consolidation)
	Excessive	▶ Iatrogenic volume overload ▶ Heart failure	✓Distended IVC ✓Multiple B lines ✓Well filled ventricle
Contractility pathology	Reduced	▶ Sepsis induced LV dysfunction ▶ Myocarditis ▶ Cardiomyopathy ▶ Congenital heart disease ▶ Pulmonary hypertension ▶ Myocardial ischaemia	✓Dilated ventricle(s) ✓Reduced movement of ventricle walls ✓B-lines and other signs of volume overload ✓Evidence of valve regurgitation ✓Structural defect
	Hyperdynamic	▶ Sepsis ▶ Reduced preload	✓Signs of reduced preload ✓Good ventricular function
Afterload pathology	Increased/obstructive	▶ Pneumothorax ▶ Pericardial effusion ▶ Pleural effusions ▶ Pulmonary embolus	✓Distended IVC ✓POCUS features of pneumothorax or effusions ✓Features of thrombosis
	Reduced/vasodilated	▶ Sepsis ▶ Inflammatory response (eg, postcardiopulmonary bypass)	✓Signs of reduced preload ✓Good ventricular function ✓Evidence of source of sepsis (eg, consolidation)

IVC, inferior vena cava; POCUS, point of care ultrasound.

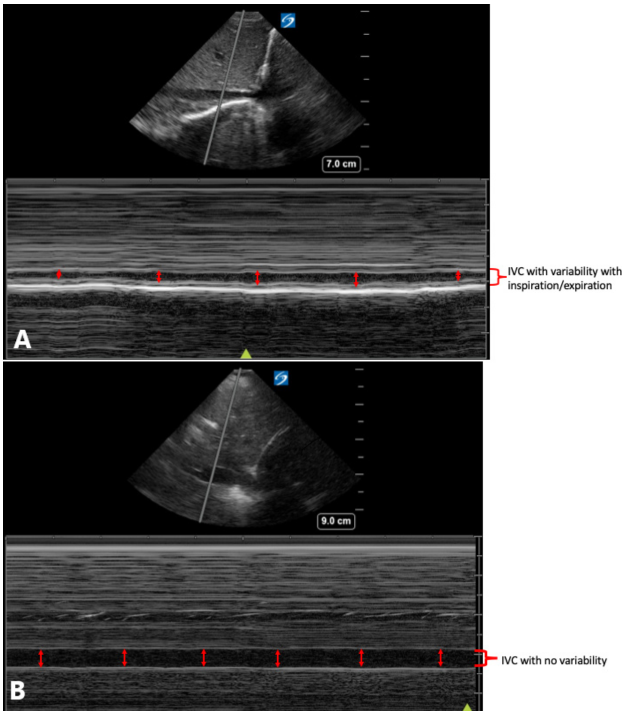

Figure 3 Subcostal view of the IVC in Motion (M)-mode. The upper image shows the liver with a scan line, passing through the IVC. The lower image shows the movements of structures along that line and displays them against time. (A) shows significant variability in change of the IVC diameter and (B) shows no variability in IVC diameter. IVC, inferior vena cava.

and it must always be correlated with the patients history, examination and additional POCUS findings.

Abdominal POCUS

Abdominal POCUS users should be trained to identify intra-abdominal and pelvic free fluid and major organ abnormalities (eg, large hepatic haemangioma causing high output cardiac failure); it is not intended to replace a formal departmental abdominal ultrasound. The ability to perform an abdominal POCUS provides us with a useful tool at the bedside to help determine the type of shock; however, it should be recognised that POCUS trained clinicians have a very limited diagnostic capability. If the clinician is not confident of the findings at any point in the POCUS assessment, then more specialised imaging may be indicated.

Cranial POCUS

Cranial ultrasound can be performed through any open fontanelle to obtain images of the brain. It remains a useful tool at identifying major intracranial pathology until these fontanelles start to close (perhaps up to 1 year of age).[26] Many paediatric trainees are exposed to this during neonatal intensive care placements. Key pathologies to identify include hydrocephalus, extra/subdural/intraventricular blood or vein of Galen malformations.

Test your knowledge

1. In the compensatory phase of shock, what are the primary mechanisms by which a child maintains their cardiac output?
   A. Reduced afterload
   B. Increased heart rate
   C. Increased systemic vascular resistance
   D. Increased left ventricular end-diastolic pressure
   E. All of the above
2. Which underlying pathology would cause a child to primarily develop distributive shock?
   A. Spinal cord injury
   B. Burns
   C. Diabetic ketoacidosis
   D. Sepsis
   E. Anaphylaxis
3. Which features seen on POCUS would suggest a reduced preload as a cause of the shock in a child?
   A. Multiple B-lines
   B. Inferior vena cava variability >50%
   C. Empty left ventricle
   D. Reduced movement of ventricle walls
   E. Free fluid in the abdomen
4. Which of the following are features of a pneumothorax on lung POCUS?
   A. Presence of pleural sliding
   B. QUAD sign
   C. Sea-shore sign
   D. Lung point
   E. Tissue-like sign
5. An 8-week-old infant presents with shortness of breath during the winter months. He is initially diagnosed with bronchiolitis. Over the next 24 hours, he becomes increasingly tachycardic and tachypnoeic. POCUS demonstrates normal pleura bilaterally with extensive B lines in all zones. His IVC is distended with no variability from respiration. His cardiac POCUS demonstrates dilated left and right ventricles with reduced wall movements. What are the possible differential diagnoses?
   A. Cardiomyopathy
   B. Kawasaki's disease
   C. Myocarditis
   D. Pericarditis
   E. Pneumonia

Answers to the quiz are at the end of the references.

CONCLUSION

POCUS is an excellent clinical tool for use at the bedside to supplement diagnosis and monitor the response to treatment. POCUS has regular use within adult emergency medicine and critical care in the shock process, and we would suggest the same for paediatrics. In our experience, the development of a POCUS protocol to assess the child with undifferentiated shock has improved the diagnostic certainty of the shock aetiology. We believe it can lead to a reduced number of unnecessary interventions and reduce the time to diagnosis and initiation of more specific management. However, as POCUS is used to examine the child presenting with undifferentiated shock, a solid understanding of the shock pathophysiology is important.

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Answers to the multiple choice questions

1. B and C.
2. A, D and E.
3. B, C and E.
4. D.
5. A and C.