POCUS in Critically-ill Children with Acute Kidney Injury

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ABSTRACT

Acute kidney injury (AKI) in children is associated with increased mortality and morbidity including the need for prolonged stay in pediatric intensive care unit (PICU) and longer duration of mechanical ventilation. Technological advancements have expanded the array of bedside tools available to clinicians for patient evaluation beyond the traditional physical examination. Point-of-care ultrasound (POCUS) has emerged as a crucial tool for clinicians to quickly diagnose kidney pathology and assess the volume status. This is especially useful in the PICU setting as clinicians seek to optimize fluid requirements, modify dialysis settings based on fluid overload status, and differentiate causes of shock. Herein, we review the role of POCUS focusing on management of critically ill children with AKI, and the improvements in technology and artificial intelligence (AI) in POCUS that allow for better outcomes.

Keywords: *Acute Kidney Injury, Kidney, Point-of-care Ultrasound*

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INTRODUCTION

Acute kidney injury (AKI) is a common complication in the pediatric intensive care unit (PICU) associated with a high morbidity and mortality [1]. In the PICU, children with AKI require optimized fluid management and are often treated with various forms of kidney replacement therapy including continuous kidney replacement therapy (CKRT), hemodialysis, sustained low efficiency dialysis (SLED) or peritoneal dialysis. Point-of-care ultrasound (POCUS) has emerged as a crucial tool for clinicians to assess the intravascular volume status, diagnose the kidney pathology and perform bedside interventions including catheter placement and kidney biopsy [2,3].

POCUS Probes and Modes

Hand-held ultrasound devices (HUDs) (not available in India) provide a portable and cost-effective alternative to traditional ultrasound machines [4]. HUDs allow single probes to operate at multiple frequencies, enhancing versatility. **Table I** describes the various ultrasound probes and modes for POCUS in children. Despite, a generally inferior image quality compared to traditional systems, HUDs are suitable for routine clinical inquiries, and the newer versions incorporate artificial intelligence for efficient tasks like bladder volume calculation. Image archiving is streamlined through compatibility with hospital systems or secure cloud servers. However, disadvantages include poorer image quality, low battery life, costs involved and privacy issues with data storage. With advances in HUD devices and image quality, the identification of detailed kidney pathologies might improve patient outcomes.

POCUS in the Clinical Setting

POCUS has grown in popularity and is slowly becoming an integral part of the medical school and residency curricula. It is likely to supplement traditional physical examination in the future and become another component of the intensivist's toolbox. With formal training and competence in kidney POCUS skills, the function of other organs like the heart, vasculature, and lungs can also be assessed [4]. This multi-organ approach is ideal in the critical care setting to evaluate fluid status and treat undifferentiated shock. One of the main advantages of POCUS is that it can be used to characterize the type of AKI into prerenal (hypovolemic), intrinsic and postrenal, in addition to guiding interventions (**Table II**) [5].

POCUS in Prerenal AKI

In children with AKI, a thorough assessment of fluid and hemodynamic status is essential for patient treatment and

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Table I Ultrasound Transducer Types and Modes in Pediatric POCUS Imaging

Transducer	*Imaging depth*	*Application*	*Pediatric version available*
Linear[a]	9 cm	Visualizes superficial structures	Yes
Phased array	35 cm	Primarily used for cardiac ultrasound	Yes
Curvilinear	30 cm	Deep penetration of tissues, useful for abdominal imaging as it provides a wide view	No

Mode	*Description*
Amplitude (A)	No spatial relationship of structures, limited to ophthalmology.
Brightness (B)	Regular 2-dimensional gray-scale display.
Motion (M)	Plotting the movement of a structure such as cardiac valves, pleural sliding, inferior vena cava (IVC) variation with respiration, over time.
Color Doppler	Detection of blood flow and its direction. Red color denotes flow towards transducer. Blue color denotes flow away from transducer.
Power Doppler	A form of color doppler that is more sensitive than regular color doppler to blood flow. It cannot discriminate blood flow direction.
Pulsed wave Doppler	A form of spectral doppler that allows measurement of blood velocity. Can calculate blood flow velocity, resistive index, pulsatility index, acceleration time, etc.
Continuous wave Doppler	A form of spectral doppler that allows measurement of peak velocity across cardiac valves, used mainly in echocardiography.

[a]Neonatal/Pediatric Linear probe with a smaller footprint in a hockey stick configuration is also available with a 7-22 MHz frequency for a better fit in between rib spaces

Table II Use of POCUS in Diagnosis of Different Types of Acute Kidney Injury in Children

	Prerenal	*Intrinsic*	*Postrenal*
Pathology	Impaired perfusion to the kidney	Damage to kidney tissue	Obstruction
POCUS findings	- B-lines in lung ultrasound - Left ventricular tract velocity time integral <18 cm - Left ventricular ejection fraction - IVC diameter compared to aorta	- Use of renal resistive index, although nonspecific - Presence of renal infarcts on doppler	- Identification of hydronephrosis - Ureteral jets with Doppler - Bladder scan
Considerations for imaging	- Conditions such as pulmonary hypertension and liver cirrhosis can cause mixed presentations, characterized by high total body or lung fluid levels alongside low intravascular fluid levels.	Causes of intrinsic acute kidney injury are varied, with ultrasound being non-diagnostic	- Obstruction may not always cause dilation of the ureters - Hydronephrosis may be normal findings in patients on diuretics or polyuria.

management. Fluid status can be comprehensively assessed with lung ultrasound, a focused cardiac ultrasound (FoCUS), and venous excess ultrasound [1-5]. Lung ultrasound (**Web Fig. 1a-d**) is a simple method to assess extravascular lung fluid [4]. Normal lung tissue produces hyperechoic A-lines due to ultrasound reverberation **(Web Fig. 1a)**; however, abnormal B-lines signify interlobular septal thickening that is most often due to extravascular lung fluid **(Web Fig. 1b)**. B-lines in multiple scan zones most likely suggest pulmonary edema.

Ultrasound of the inferior vena cava (IVC) and internal jugular vein, when assessed in combination, is strongly correlated with central venous pressure, especially in low volume states [6]. A focused cardiac ultrasound (FoCUS) (**Web Fig. 1e**) can also be used to assess fluid and hemodynamic status, although clinical correlation is necessary for rational interpretation. Left ventricular outflow tract (LVOT) velocity time integral (VTI) measurement can be measured using a 5-chamber apical view with a pulsed-wave Doppler [5]. The left ventricular outflow tract velocity-time integral (LVOT VTI) is a crucial echo-cardiographic parameter for assessing stroke volume and cardiac output, providing vital information for managing patients with cardiac dysfunction. By measuring the distance blood travels during each cardiac cycle, LVOT VTI offers insights into overall cardiac performance. More research is needed to characterize abnormal VTIs and cutoff values in children. Assessment of left ventricular systolic function or left ventricular ejection is helpful, in children with heart failure [5]. An elevation of cardiac output or cardiac index by 15% or greater is indicative of a positive response to a fluid challenge. The aorta to IVC ratio (largest aorta diameter during systole divided by largest end expiration IVC diameter transversely) is sensitive to detect hypovolemia [7]. An IVC that is larger than the aorta shows volume intolerance (**Web Fig. 1f, 1g**). Venous Excess Doppler Ultrasound (VExUS) (**Web Fig. 1h-j**) combines IVC ultrasound with ultrasound of the hepatic vein, portal vein, and kidney parenchymal veins [8]. Comprehensive VExUS assess-ments help in fluid precision in complex cases e.g., children postcardiac surgery, and post liver transplant where a careful assessment of venous congestion can help the treating physician in tailoring fluid therapy.

POCUS in Intrinsic AKI

The usefulness of POCUS in identifying the cause of intrinsic AKI is limited [4,5]. The renal resistive index (RRI) assesses the resistance to flow, making it a valuable tool for evaluating macrovascular perfusion to the kidney [5]. It is calculated as [(peak systolic velocity – end diastolic velocity)/peak systolic velocity] at the main renal and intrarenal arteries. Normal values are around 0.6; values > 0.70 are considered abnormal in the native kidneys and > 0.8 in transplanted kidneys. Elevated levels indicate poorer renal outcomes and predict AKI. It is a common procedure in children post kidney transplant to assess perfusion. However, there are limitations with using RRI. Tachycardia can falsely decrease the RRI and be affected by factors such as intra-abdominal pressure and medications [5]. Other parameters that can affect the RRI include aortic stenosis, vascular rigidity, body mass index (BMI), and the use of vasopressors [3]. It has limited efficacy in evaluating microcirculatory perfusion relevant to AKI in sepsis. Finally, while reproducibility has been shown among experienced sonographers, novice operators may introduce intra-observer variability.

Doppler ultrasound can show renal infarction which presents as echo-free areas with swollen parenchyma with doppler assessment showing the absence of flow to the affected region [6]. This differs from cortical necrosis, characterized by a dark hypoechogenic kidney cortex, typically secondary to severe ischemia caused by vascular abnormalities.

POCUS in Postrenal AKI

Clinicians skilled in POCUS can easily identify urinary obstruction through bedside POCUS. POCUS can be used to identify hydronephrosis [4]. To prevent misdiagnosis of other pathologies that appear like hydronephrosis, the most straightforward approach involves acquiring color doppler images to reveal blood flow in the renal pelvis area if vessels are present. To ensure an accurate diagnosis, it is advisable to compare with previous imaging studies, obtain color doppler images, and, when necessary, pursue additional imaging. With proper training, physicians can diagnose hydronephrosis with a high degree of sensitivity. In an emergency setting study, emergency physicians exhibited an overall sensitivity (95% CI) of 85.7% (84.3%, 87.0%), specificity (95% CI) of 65.9% (63.1%, 68.7%), a positive likelihood ratio (95% CI) of 2.5 (2.3, 2.7), and a negative likelihood ratio (95% CI) of 0.22 (0.19, 0.24) when compared to the reference radiology interpretation for the detection of hydronephrosis [7]. Within the bladder, color doppler ultrasound can identify ureteral jets which can help distinguish functional (presence of jets) and non-functional (absence of jets) obstruction.

POCUS for Assessment of Volume Status

Dialysis (Peritoneal dialysis, Hemodialysis and Continuous Renal Replacement Therapy) is commonly used in children with AKI. There are currently significant variations in the management of volume status in the treatment of AKI [2]. POCUS could be used to supplement clinical findings to identify patients who would likely benefit from fluid removal (**Table III**). Detecting lung congestion at the bedside in critically ill patients undergoing dialysis may allow prompt removal of fluid and consequently, improvement in respiratory status [4]. Identifying venous congestion with IVC collapsibility loosely correlates with CVP and serves as a static measure of volume status, which may indicate another finding of fluid overload. The IVC distends with mechanical breathing and thus assesses vessel compliance in addition to right atrial pressures in ventilated patients [5]. A detailed VExUS also helps in comprehensive fluid assessment in children with right ventricular dysfunction. Increased weight, increased pressor requirements, and the presence of peripheral edema could be correlated with POCUS findings of abnormal venous doppler, B lines, and plethoric IVC to make the decision for fluid removal. Findings of right ventricle dilatation, septal bowing, and portal and renal vein doppler can also support the decision for fluid removal. However, B-lines can be found in mutiple pathologies like pneumonia and pulmonary congestion. Many of the findings may be non-specific and shared by several conditions. Parapelvic cysts, extra renal pelvis and vascular malformations need additional imaging.

Other Applications of POCUS in Pediatric Nephrology

The implementation of real-time ultrasound guidance has markedly reduced complications in kidney biopsies and improved the probability of successful sampling [4]. Integration of ultrasound technology enables immediate visualization of the biopsy needle track and provides an accurate evaluation of the kidney's depth relative to the skin surface. POCUS also allows clinicians to place hemodialysis catheters in the central veins, peritoneal dialysis catheters, monitor complications like thrombosis or bleeding, and evaluate blood flow in arteriovenous fistulas using similar techniques.

POCUS in Education and Research

POCUS is emerging as a vital skill which needs to be acquired by medical trainees. In a recent survey of pediatric nephrology trainees, specialists, and faculty, 87% of respondents stated that formal POCUS training in pediatric nephrology programs is very important and should be mandatory [8]. However, 85% of survey respondents stated that their training program did not have a formalized program. There are online platforms such as *https://www.picunephrologyvideos.com/* that clinicians can use for training. Guidelines for POCUS in pediatric nephrology are undergoing development in this emerging field and have been published by the PCRRT-ICONIC group [8]. The goal is to enable clinicians to competently perform multiorgan POCUS in order to manage complex patients and clinical situations [9]. For instance, a diffuse B-line pattern on lung ultrasound with reduced left ventricular ejection on FoCUS suggests heart failure, necessitating fluid removal and/or inotropic therapy. A B-line pattern adjacent to subpleural consolidation on lung ultrasound and a hyperdynamic left ventricle on FoCUS would suggest the need for fluid resuscitation. This is especially beneficial in cases of undifferentiated shock, allowing clinicians to rapidly categorize the etiology as distributive, cardiogenic, or hypovolemic shock for prompt intervention and improved patient outcomes.

More research is needed for determining reference cut-off values and imaging findings for the POCUS examination in the neonatal and pediatric population. It is important for clinicians to not rely on a single POCUS view and instead image multiple organs to reliably assess volume status in children with AKI [9].

Artificial Intelligence in POCUS

Artificial intelligence (AI) has increased in popularity with AI tools in POCUS helping clinicians identify abnormalities in imaging as well as improve the accuracy of measurements made. For example, in cardiac views, the Venue (GE) system was found to be equal to a POCUS expert in identifying ejection fraction, velocity time integral, and inferior vena cava (IVC) measurements [10]. More recently, AI tools have assisted clinicians with image acquisition and calculations. In pediatric lung ultrasound, AI tools allow the examiner to note if there is a complete pleural profile of lung parenchyma [11]. In echocardiograms, a novel AI algorithm was able to guide novices with no experience in echocardiography to obtain all ten views of the echocardiogram which is expected to be performed by a sonographer after a 9-month training [12]. AI POCUS tools have been shown to be able to calculate the left ventricular outflow velocity time integral, as well as IVC assessment [13, 14]. AI tools can provide clinicians with accurate measurements and interpretations, but still depends on the operator to have the proper training to acquire the optimal image. With the improvements made in AI tools, both experienced clinicians and trainees will benefit from the improved accuracy of the acquired ultrasound images. AI tools simplify the process for estimating volume status for clinicians when treating children with AKI, as identification of B-lines or calculation of ejection fraction are becoming within the capabilities of AI.

Limitations and Ethical Considerations

The accuracy and reliability of POCUS are highly dependent on the clinician's expertise and experience. The technique also has a limited field of view, which can lead to incomplete assessments. Additionally, POCUS images may be affected by patient factors like obesity or subcutaneous emphysema, which can degrade image quality, and the level of technical complexities of hand-held ultrasound devices (not available in India), which may not always replace the conventional ultrasound machines. Furthermore, POCUS is not a substitute for comprehensive imaging modalities, and its interpretation can sometimes lead to misdiagnosis if not correlated with other clinical findings.

Ethical concerns surrounding POCUS in the PICU include the risk of misdiagnosis due to operator variability and limited training. This emphasizes the need for centralized governing and credential authorities to monitor and standardize the process and protocol of POCUS in the PICU setting. Ensuring informed consent is challenging, as patients may not fully understand the limitations of POCUS, raising concerns about transparency and patient autonomy.

CONCLUSIONS

In critically sick children with AKI, integration of POCUS with the physical examination can help the clinicians

Table III POCUS Examination to Assess Volume Depletion or Overload

Organ being scanned	*Volume depletion signs*	*Volume overload signs*
Lung ultrasound	• A lines (artifact) in healthy/dry lung • Pleural effusion	• B lines (especially bilaterally)
Cardiac ultrasound	• Hyperdynamic left ventricle • Low stroke volume and ejection fraction • Dilated right ventricle • Low right atrial pressure and central venous pressure (estimated by small, collapsible IVC)	• Decreased left ventricle systolic motion • Higher stroke volume • Interventricular septal flattening • High right atrial pressure (seen by plethoric IVC) • E/e' >15 with pulse wave Doppler over
VeXUS	• Normal in volume depletion (hepatic S wave larger than D wave) • Hepatic vein doppler with fusion of S and D waves	• Hepatic vein pulsed wave Doppler changes (D wave larger than S wave due to increased right atrial pressure) • With severe overload, there will be reversal of flow with a retrograde S wave on hepatic vein pulse wave Doppler • Increased pulsatility of portal vein and renal parenchymal vein

IVC Inferior vena cava, VExUS Venous Excess Doppler Ultrasound

rapidly identify underlying kidney pathology, differentiate the etiology of shock, and assess fluid status in their patients. While being able to rapidly give a diagnosis, disadvantages of POCUS include the need for training to reliably acquire and interpret the images. POCUS advances in the form of HUDs (not available in India), and AI have increased accessibility to more clinicians of varying skill levels. The next step for widespread adoption for POCUS in the treatment of critically ill children with AKI is for the adoption of guidelines for its use and standardization of training. As POCUS use becomes more common in the critical care setting by well-trained intensivists, there is a potential for improved outcomes in critically ill children with AKI.

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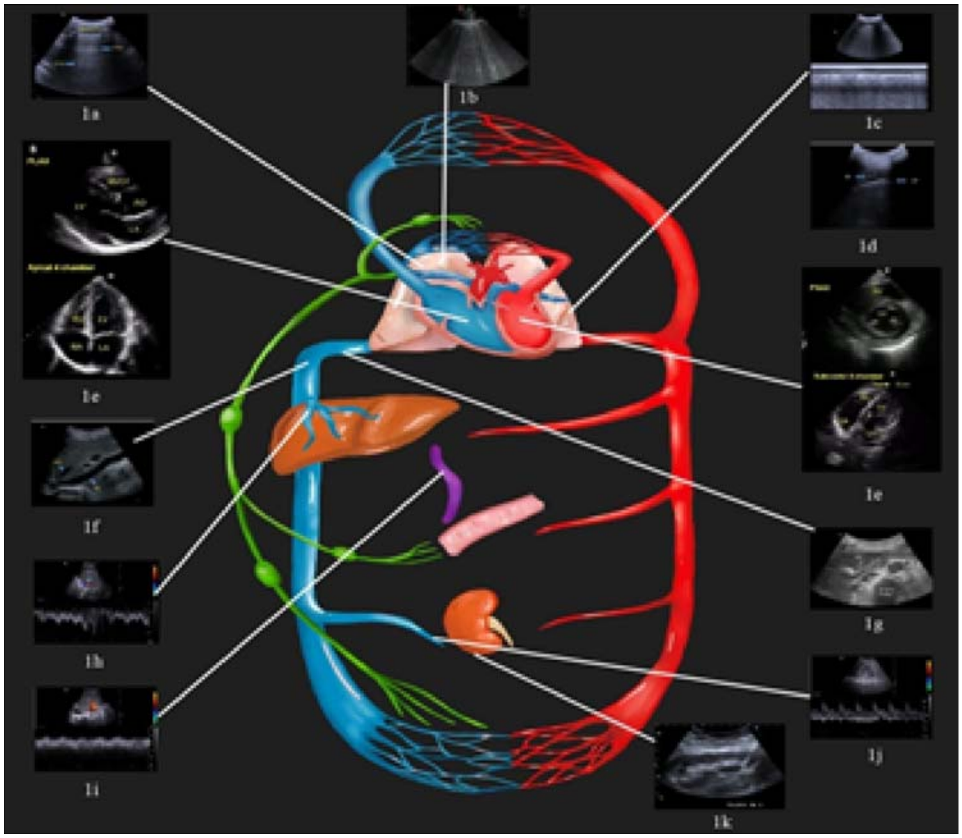

Web Fig. 1a to 1j: Essential POCUS Applications for evaluating children with acute kidney injury **1a** Normal lung ultrasound demonstrating A lines; **1b** Sonographic image of the lung demonstrating B lines; **1c** M mode ultrasound image demonstrating 'the seashore sign': a normal finding on a lung ultrasound that indicates lung sliding. It appears as a pattern of horizontal lines and a grainy texture, similar to a seashore; **1d** Lung ultrasound demonstrating pleural effusion separating visceral and parietal pleura; **1e** Focused cardiac ultrasound views: parasternal long axis, apical 4 chamber, parasternal long axis and subcostal 4 chamber view; **1f** Sagittal view of intrahepatic IVC at the level of middle hepatic vein (MHV) entering it; **1g** Cross section showing retroperitoneal structures at the level of kidneys, with liver above, aorta (seen as a round structure) to the left, IVC (seen as an oval structure) to the right and vertebral body posteriorly; **1h** Hepatic vein doppler showing triphasic waveform; **1i** Portal venous doppler showing respiratory variations ; **1j** Normal intrarenal artery doppler waveform **1k** Ultrasound demonstrating a real-time kidney biopsy of the lower pole of the kidney