

Emerging Clinical Applications of Point-of-Care Ultrasonography in Newborn Infants

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Point-of-care ultrasound (POCUS) is a bedside technology with multiple emerging applications that can complement what is clinically suspected, thereby offering novel physiological insight into disease processes (Figure 1). POCUS has been used by nonradiologists for over 30 years in adult and pediatric care but has been slower to evolve in newborn medicine (Miller et al., 2019) even though critically ill neonates are some of the most vulnerable patients that cannot be easily transported out of the neonatal intensive care unit (NICU). Thus, POCUS provides real-time diagnostic information at the crib side regarding clinical pathology and response to intervention, thereby enabling providers to more easily integrate the clinical examination findings with rapid and serial sonographic imaging (Conlon et al., 2019). POCUS is now being used by neonatologists for bedside assessment of lung pathology, heart function, intestinal health, brain bleeds, procedural guidance, and rapid identification for the etiology of acute clinical change. With a growing recognition of the clinical utility of POCUS in the NICU (Miller et al., 2019), it is imperative to have a complete understanding of this technology. Accordingly, in this review, we discuss the physics of POCUS, the applications of POCUS in the critically ill neonate, and guidelines and limitations for wide use of this modality (Figure 1).

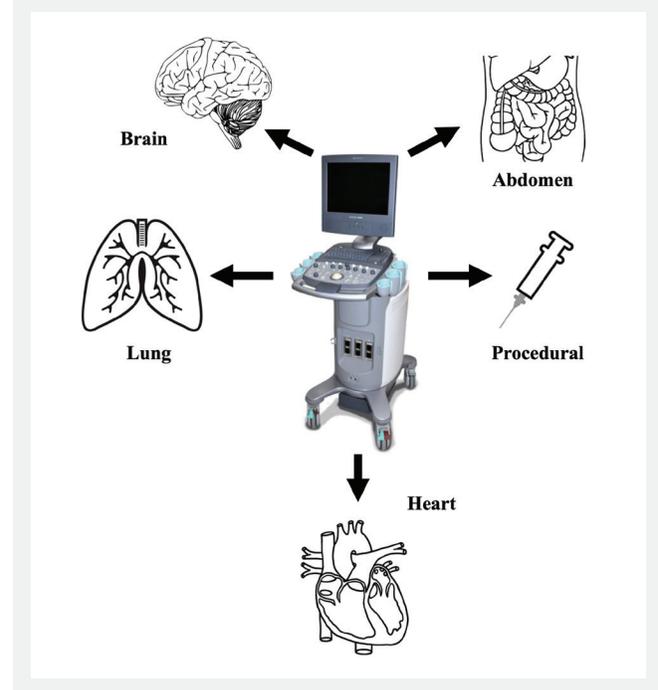
Physics of Ultrasonography

Understanding the basic physics principles of ultrasonography as they relate to POCUS, including sound wave characteristics, ultrasound transducer mechanics, image optimization, and artifact recognition, is a prerequisite to enhancing image quality, improving diagnosis, and avoiding common errors. In this section, we review the common terminology and physics behind the guiding principles of ultrasonography.

Image Production

Medical ultrasound consists of using high-pitched sound (ultrasound) bouncing off tissues to generate images of internal body structures. Ultrasound pulses are longitudinal waves commonly described by their frequency, wavelength, amplitude, and velocity. In medical imaging, there are two types of sound waves: (1) continuous, which is used in Doppler ultrasound and do not contribute to formation of an image, and (2) pulse, which generates images. Transducers equipped with polarized material inside the core, known as piezoelectric crystals, convert electrical current signals into mechanical vibrations through a tissue medium (such as tissue, fluid,

Figure 1. Medical applications of point-of-care ultrasound in neonates.



bone, or air) and compress when sound waves return from the tissue to the probe, changing the mechanical vibrations into an electrical signal to create an image (Groves et al., 2018).

There are three basic modes of electronic representation of pulse-wave sound that are generated with returning signals and displayed on a monitor.

- (1) Amplitude mode (A-mode) provides information about the depth of the structures using the amplitude of the returning echo. A-mode is most commonly utilized with ophthalmology and was initially utilized with echocardiography.
- (2) Motion mode (M-mode) is used to demonstrate motion across a single line of the ultrasound beam. It is commonly used to evaluate cardiac muscle movement to demonstrate strength of the muscle and effectiveness of the heart's ability to pump blood to the body. M-mode is also used to evaluate for normal lung movement with breathing. Neonates that rapidly develop difficulties breathing may have a life-threatening accumulation of air in the chest that can be detected by the absence of normal lung movement on M-mode (Groves et al., 2018).
- (3) Brightness mode (B-mode), the most common mode, produces a two-dimensional image where areas of different brightness (black, gray, and white) represent the sound waves (echoes) returning from the objects within the ultrasound beam. The signal returning from the body to the transducer is divided into pixels based on amplitude, ranging from black to white with ranges of gray in between (bright pixels represent high amplitude, such as bone; dark pixels represent low amplitude, such as blood).

Ultrasound Transducers

Curvilinear, linear (microlinear), and phased arrays are the most common types of transducers used in medical ultrasound in neonates (Groves et al., 2018; Corsini et al., 2020). Linear and microlinear probes are high frequency, providing better resolution at superficial depths, and are commonly used in the evaluation of lung ultrasound and obtaining vascular access. Phased-array probes are high-frequency probes with a small footprint whose signals penetrate deeper into the body than the signal from linear probes but with preserved resolution. They are utilized for head and cardiac ultrasound. Curvilinear probes are low-frequency probes with wide ultrasound beams that penetrate deep into the body and are utilized for abdominal ultrasound.

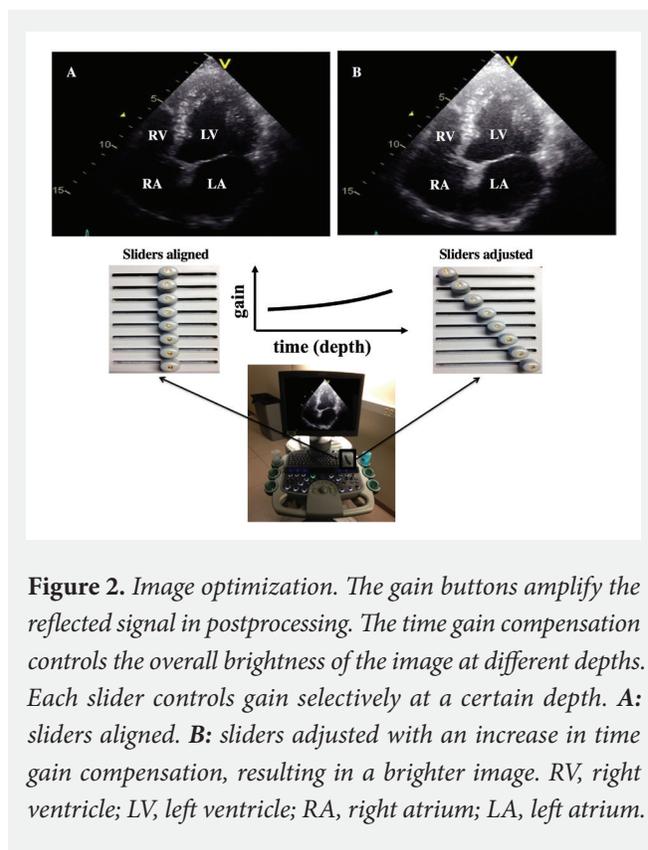


Figure 2. Image optimization. The gain buttons amplify the reflected signal in postprocessing. The time gain compensation controls the overall brightness of the image at different depths. Each slider controls gain selectively at a certain depth. **A:** sliders aligned. **B:** sliders adjusted with an increase in time gain compensation, resulting in a brighter image. RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium.

Ultrasound-Tissue Interactions

Ultrasound wave interaction with the mediums encountered along its beam produces images (Gray et al., 2019). Sound energy is attenuated or lost because parts of it are absorbed, reflected, scattered, or refracted. In POCUS, the part of the scattering that does reach the transducer and generate images is called backscatter. The nature of the backscattered signal depends on the intrinsic properties of the tissue and it can be useful in evaluating a structure with different echogenicities (e.g., heart tissue). Echogenicity describes the ability of a surface to reflect an echo (sound wave) back to the transducer. In B-mode, echogenicity is represented on the image as anechoic (black), hypoechoic (gray), and hyperechoic (bright white).

Image Optimization

In POCUS, image optimization can be done in several ways including, for example, with the heart changing the output power (brightness), the receiver gain (brightness), the time gain compensation (offset attenuation with enhancement of image resolution), and the harmonics (improves the signal-to-noise ratio; **Figure 2**). These maneuvers assist in improving the spatial and temporal resolutions that are impacted by the ultrasound beam properties (Abu-Zidan

et al., 2011). Spatial resolution is divided into axial, parallel to the beam; lateral, perpendicular to the beam; and elevation, reference to thickness of the slice of the images and similar to lateral resolution but in the orthogonal plane. Temporal resolution is the ability to detect a moving object and is mainly determined by the frame rate.

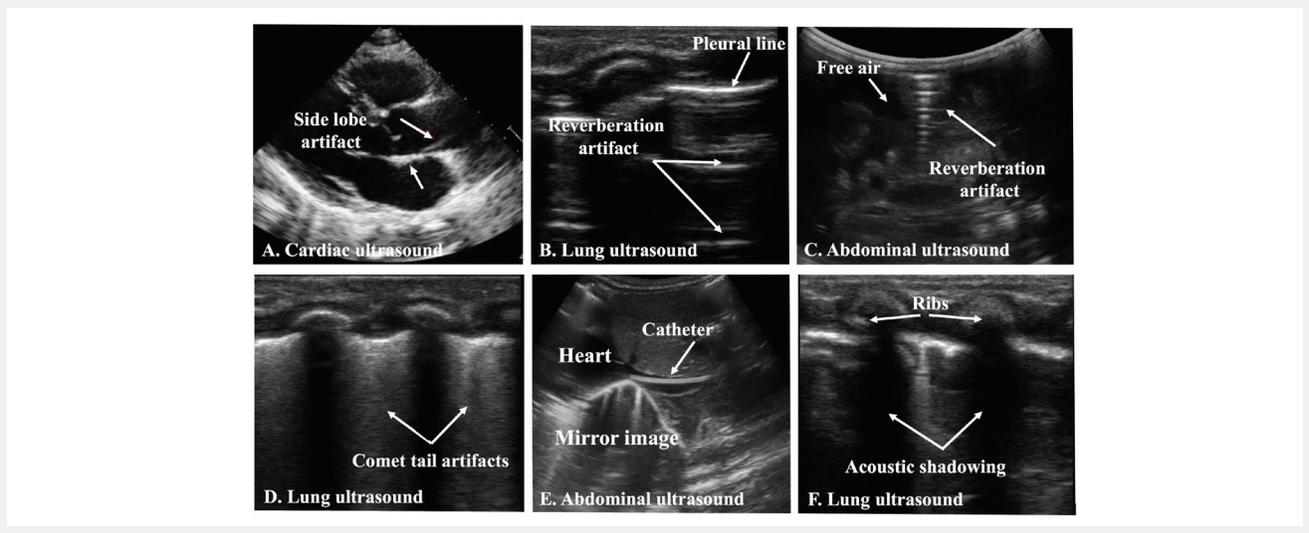
Ultrasound Artifacts

Ultrasound machines make assumptions in forming an image that does not always accurately show the structures or flow patterns being interrogated (Feldman et al., 2009). The more common artifacts in POCUS can be divided into beam artifacts, multiple echoes artifacts, velocity errors, and attenuation errors.

- (1) *Beam artifacts* occur due to the assumption that the sound waves received by the transducer are located within the beam. As a result, side-lobe artifacts occur when a strong reflector outside of the beam sends an echo back to the transducer and the machine inaccurately places a focus in the wrong location on the image (Figure 3A). A beam-width artifact occurs when the beam is wider than the object, echoes from other objects are returned, and the machine assumes these echogenicities are the same, altering the brightness of the image.
- (2) *Multiple echoes artifacts* include reverberation, comet tail, and mirror image artifacts. Reverberation occurs when multiple echoes originate from a

highly reflective surface (e.g., the pleural line-tissue connection between the lungs and the chest wall). The echoes go back and forth between the transducer and reflector, and the machine assumes that these echoes are accurate and displays them as hyperechoic (white) parallel lines. Reverberation artifacts can be a normal finding as seen in lung ultrasound with reverberation from the pleural line (Figure 3B) or an abnormal finding as seen in the abdominal ultrasound, with reverberation from free air outside the intestines indicating a surgical emergency (Figure 3C). Comet tail is a type of reverberation, but instead of one reflective surface, there are two reflective surfaces. In this scenario, one echo, stuck between two reflective surfaces, bounces back and forth and is detected by the transducer as multiple echoes. This artifact is displayed as a hyperechoic triangle due to decreased attenuation of the later echoes and can be seen when fluid is in the lungs (Figure 3D). Mirror image occurs when the object being evaluated is adjacent to a highly reflective surface. The sound waves hit the reflector and then hit the nearby medium and return to the transducer. The machine displays a duplicated image on both sides of the reflector due to the assumption that echoes are from two different mediums and can be seen when doing a lung ultrasound where the mirror image of the liver is visualized instead of the lung (Figure 3E).

Figure 3. Ultrasound artifacts. **A:** beam artifacts. **B:** reverberation artifacts in lung ultrasound. **C:** reverberation artifacts in abdominal ultrasound. **D:** comet tail artifacts from lung ultrasound. **E:** mirror artifacts in lung ultrasound. **F:** attenuation artifacts with acoustic shadowing with normal lung ultrasound.



- (3) *Velocity errors* occur based on the assumption that the speed of sound is constant even though it changes in different mediums, thereby leading to errors with calculating the distance. A speed displacement artifact and refraction are examples of velocity errors where the object is displayed at the incorrect distance or incorrect location on the image.
- (4) *Attenuation errors* occur from the absorption and scattering of the beam in different mediums where the machine attempts to make the image more homogeneous as compensation for echoes that take varying times to return to the transducer. Acoustic shadowing occurs when the beam encounters a highly reflective or attenuating medium and the intensity of the beam weakens distal to this encounter, as demonstrated as rib shadowing in a normal lung ultrasound (**Figure 3F**). The machine interprets that area as having less signal than the highly reflective surface and presents it as hypoechoic or anechoic (gray or black) on the image. Increased through transmission is the opposite of acoustic shadowing in which the beam encounters a lower attenuating medium than the adjacent mediums. The machine interprets this area as having more signal and presents it as hyperechoic (white) on the image.

Applications for POCUS

POCUS can provide bedside diagnostic and procedural information with several different applications, including lung, cardiac, abdominal, head, and procedural ultrasonography (**Figure 1**).

Lung Ultrasound

Although respiratory pathology is common in neonates, the etiology and prognosis can be difficult to discern from the clinical history and plain film radiography alone. Lung ultrasound can be employed to discern the etiology of respiratory distress, predict the need for increased respiratory support and intervention, and assess the risk of long-term morbidity in neonates. Lung ultrasound has also been utilized to assess adequate fluid replacement during the management of severe infections in children and may be particularly useful to guide therapeutic options in emergencies (e.g., rapid accumulation of air or fluid between the lungs and chest wall; Lichtenstein, 2012). A recent international task force has evaluated the evidence with neonatal lung POCUS and is in agreement with its use to delineate and diagnose

lung pathology as well as to guide interventions for respiratory emergencies (Singh et al., 2020).

Lung ultrasound is based on the interpretation of artifacts rather than the direct visualization of the lung because of beam reflection between the air, pleura (tissue covering the lungs), and fluid around or within the lungs. In a normal lung ultrasound, the skin, muscle, ribs, and surface of the lung are easily identified and normal lung movement with breathing is observed. Normal lung ultrasound in B-mode (**Figure 4A**) shows reverberation artifacts from the tissue covering the lungs (pleural line). We can also see acoustic shadowing from the ribs that is displayed as hyperechoic, equally displaced, horizontal lines. The pleura slides back and forth as the patient breathes. This process is known as “lung sliding” (see **Multimedia 1** at acousticstoday.org/ruosmm). In M-mode, normal lung movement with breathing appears as a stratosphere sign (waves on a beach) where absent lung movement is displayed as a barcode (**Figure 4B**). Although the presence of lung movement with breathing is not the equivalent of a healthy lung, its absence is always pathological. Comet tail artifacts are from increased fluid in the lungs and, as previously described, are vertical, hyperechoic (white), triangular shapes that extend from the pleural line to bottom of the image and move with normal lung movement with breathing. In the neonate, a small number of comet tails can be normal, such as immediately after birth when the lungs still have fluid. However, an increasing number and size of comet tails correlate with disease pathology and severity, with coalesced comet tails being the most severe as in the lung disease seen in premature neonates (**Figure 4C**).

Lung ultrasound is performed utilizing a high-frequency linear probe with a small footprint (e.g., microlinear). Lung ultrasound has been used to discern the difference between common respiratory illnesses in neonates (Raimondi et al., 2019) and has been demonstrated to be a reliable diagnostic tool with high concordance with chest plain film radiography (X-ray) and may be able to predict the need for interventions in neonates born early (Corsini et al., 2020). Lung ultrasound findings in neonates born early include abnormalities of the pleural line (thickened, irregular) resulting in abnormal or absent reverberation artifacts, some comet tails in moderate cases, and “white lung” appearance in severe cases (Copetti et al., 2008).

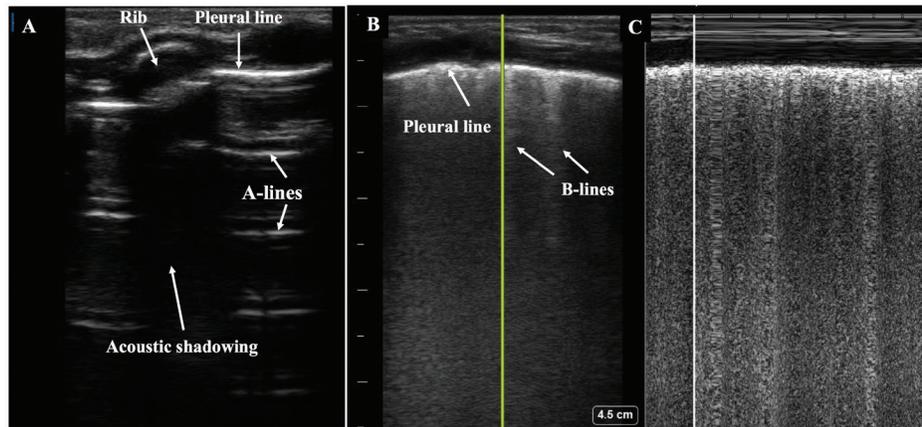


Figure 4. Lung ultrasound. **A:** normal lung in brightness mode (B-mode), showing acoustic shadowing from the ribs and a reverberation artifact from the pleural line. **B:** severe lung disease of prematurity, showing a rough appearing pleural line and coalesced comet tail artifacts. (B-mode). **C:** normal lung movement with breathing in motion mode (M-mode).

Lung ultrasound in neonates with delayed transition after birth consist of a normal pleural line, reverberation artifacts from the pleural line, few thin comet tails in the superior lung field (front of the chest), and increased compacted comet tails in the posterior lung field (back of the chest) (Raimondi et al., 2019).

Head Ultrasound

Head ultrasound is utilized for a noninvasive interrogation of structures within the skull through open fontanels (soft spot or spaces between areas of the skull) in newborn infants. Evaluation of the brain requires higher frequency transducers and the use of a far-field, wide-view sector transducer (Konofagou 2017). Occasionally, near-field evaluation is required, and a linear-array probe can be utilized. Indications to perform head ultrasound in a neonate include serial evaluation for bleeds around and within the brain and fluid collection within the brain. Intraventricular hemorrhage, which is bleeding within the ventricles or central areas of the brain that contain spinal fluid, is a cause of significant morbidity in neonates that are born early. As a greater proportion of extremely preterm infants are surviving in the NICU, there is an increasing need for technologies to evaluate and monitor the evolution of these brain bleeds. The prompt identification of severe brain bleeding in the setting of acute clinical change can help guide management and modify decision making.

Abdominal Ultrasound

The rapid assessment for abdominal pathology with ultrasound is recognized as a critical tool in adult and pediatric trauma patients and has recently become more widely utilized in neonates (Lynch et al., 2018). High-frequency linear or low-frequency curvilinear probes are utilized for abdominal ultrasound, with the choice being based on the depth of structure and resolution needed. Plain film abdominal radiography (X-ray) is still the initial tool employed for evaluation of intestinal pathology and bowel health in neonates (van Druuten et al., 2019), but it is limited by its inability to assess for malrotation (twisting of the bowel), bowel health, and abnormal fluid collections. Abdominal ultrasound can interrogate for normal bowel health (Figure 5A) by evaluating for absence of intestinal movement or good blood flow, bowel wall thinning and thickening, fluid filled intestines, and echogenicity of free fluid (Figure 5B; Cuna et al., 2018). Recent experts and international consensus task forces have recommended abdominal ultrasound as a diagnostic modality for several abdominal emergencies in neonates and POCUS-guided paracentesis (bedside needle drainage of free fluid in the abdomen; Singh et al., 2020).

Abdominal ultrasound has been shown to be more sensitive in the early detection of necrotizing enterocolitis (van Druuten et al., 2019), a severe life-threatening complication of preterm birth that causes bowel death (Figure 5C). Similar

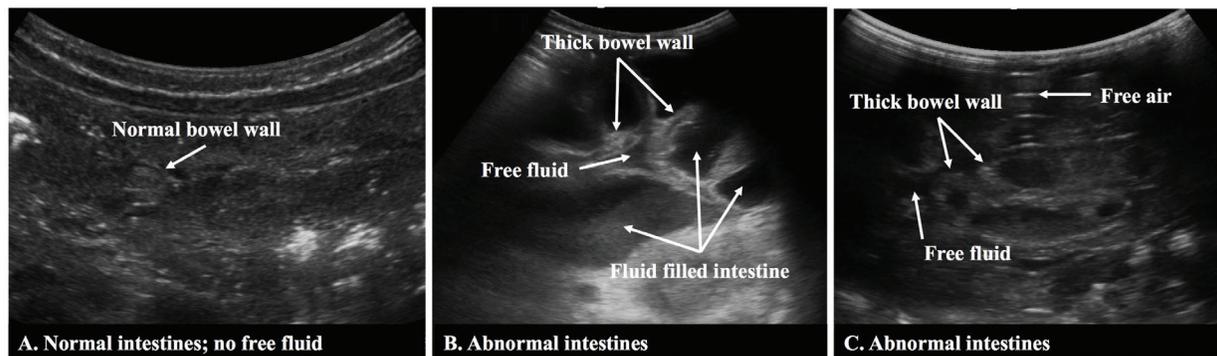


Figure 5. Abdominal ultrasound. **A:** normal bowel. **B:** abnormal bowel with fluid-filled intestines and echogenicity of free fluid. **C:** abnormal bowel showing thickened bowel wall and edema (fluid) of the affected bowel.

to adults, neonates can suffer from complications of intestinal malrotation (abnormal twisting of the intestines), which, in some cases, is a surgical emergency requiring quick diagnosis and surgical intervention. The gold standard for diagnosis of malrotation is a study that requires transport to the radiology suite, liquid contrast placed in the stomach, and multiple plain film radiographies, all of which have inherent risks in the small and premature neonates. The pediatric literature has demonstrated the utility for ultrasound in the diagnosis of malrotation with high sensitivity and specificity through evaluation of the blood flow and orientation of blood vessels to the intestines (Garcia et al., 2019). Abdominal ultrasound is also used to interrogate for free fluid and provide information on whether this fluid is anechoic (e.g., clear fluid), hypoechoic and nonhomogeneous (e.g., blood or presence of stool indicating a tear in the intestine), or loculated fluid (e.g., abscess or blood within the lining around the liver).

Cardiac (Echocardiography)

The use of bedside cardiac ultrasound to characterize cardiovascular health and guide care of the sick newborn has now become the standard of care in many NICUs (El-Khuffash and McNamara, 2011). The recognized limitations of clinical and laboratory measures of normal blood flow out of the heart and adequate blood flow to the body has supported the need for an extensive approach to the monitoring of the neonatal cardiovascular system. Cardiac ultrasound provides detailed information regarding the function of the heart that cannot be obtained by clinical assessment alone. Echocardiography must include

an initial evaluation confirming normal anatomy, followed by an appraisal of blood flow to the lungs and body and assessment of the cardiac muscle health (see **Multimedia 2** at acousticstoday.org/ruosmm). Three main uses of cardiac ultrasound in neonates include evaluation and management of neonatal cardiac transition from in utero to postbirth, elevated blood pressure in the lungs, and cardiac dysfunction due to infection or poor oxygen and blood flow to the heart. Utilization of emerging and serial physiological assessment by cardiac ultrasound may help identify cardiovascular compromise earlier and guide therapeutic intervention, thereby improving outcomes in neonates. The cardiac ultrasound serves to complement the clinical examination, with serial imaging offering insights into therapeutic response.

Procedural Ultrasound

The use of POCUS to guide invasive procedure in neonates has grown significantly over the past decade, and includes obtaining vascular access and drainage of fluid or air from the abdomen, heart, or chest. Additional procedure, such as monitoring of endotracheal (breathing) tube placement and removal of fluid from the spinal canal (also known as a lumbar puncture) are beyond the scope of this review.

Vascular Access

Placement of peripheral and central access into arteries or veins for close monitoring of blood pressure, lab draws, and medication administration is a common practice in neonatology. Ultrasound-guided vascular access has been shown to decrease placement time, with fewer

manipulations, and a decrease in the number of required radiographs to confirm placement. Linear array or micro-linear probes with high-frequency transducers (up to 25 MHz) are most often utilized in the placement and evaluation of these superficial structures. Radiographs have been shown to have a low sensitivity in identifying the tip of the line compared with ultrasound evaluation (see **Multimedia 3** at acousticstoday.org/ruosmm; Miller et al., 2019).

Evacuation of Life-Threatening Abnormal Fluid Collections

POCUS is strongly recommended for needle-assisted drainage of fluid around the heart (pericardiocentesis), from the chest (thoracentesis), and from the abdomen (paracentesis). Fluid, blood, or air can surround and compress the heart, resulting in cardiac failure and death. POCUS can rapidly confirm the diagnosis before other clinical features appear and can be used to guide emergent pericardiocentesis (see **Multimedia 4** at acousticstoday.org/ruosmm). Accumulation of fluid or air between the chest wall and lungs can cause severe issues with breathing and death if not there is no intervention. Fluid is characterized by hypoechoic or anechoic signals below the pleural line with absent reverberation artifacts in the area of the fluid collection, and, in some cases, the lung is collapsed and can be visualized as a hyperechoic object moving in the anechoic area (see **Multimedia 5** at acousticstoday.org/ruosmm). Accumulation of air in the chest cavity is displayed as absent lung movement with preserved reverberation artifacts from the pleural line in B-mode and a barcode sign in M-mode. Ultrasound can identify smaller amounts of fluid than plain film radiography and can be used to guide needle drainage of the fluid or air collection while avoiding an unintended injury to organs in close proximity. Evacuation of peritoneal fluid (fluid in the abdominal cavity) for emergent or diagnostic purposes with POCUS improves the efficacy of the procedure (Singh et al., 2020).

Establishment of Point-of-Care Ultrasound Programs

The establishment of a neonatal-focused POCUS program requires multidisciplinary collaboration between neonatology, radiology, and cardiology. Evidence and an international multidisciplinary pediatric and neonatal group consensus support that POCUS has a diagnostics and procedural role in the NICU (Singh et al., 2020). POCUS aims to enable nonradiologists to use bedside ultrasound to answer specific questions in real time,

assist in procedures, and decrease radiation exposure in neonates. Although the need for POCUS differs between NICUs depending on the availability of pediatric-trained subspecialists and technologists, there are multiple common barriers (cost, training, and quality improvement) to developing a program. Finally, clinicians need to be aware of the technique limitations, their own limitations, and the scope of their practice when using POCUS, with continued referral to radiology or cardiology for more detailed and comprehensive assessments.

Conclusion

POCUS applications in newborn medicine are growing, with increasing evidence to support its use for a variety of neonatal applications. Comprehensive understanding of the diagnostic and procedural implications as well as the limitations and considerations is a prerequisite to widespread implementation of POCUS in critically ill neonates. It is now imperative to further define the scope of POCUS in the NICU through formal training, accreditation guidelines, and a close multidisciplinary collaboration within pediatrics. Neonatologists should be honest with families about the advantages and limitations of POCUS in the NICU and adopt a culture of research that will support development and labeling of new precision diagnostics and therapeutic interventions.

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