Neonatal and paediatric point-of-care ultrasound review

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Abstract

Purpose: Point-of-care ultrasound (POCUS) examinations for children and newborns are different from POCUS exams for adults due to dissimilarities in size and body composition, as well as distinct surgical procedures and pathologies in the paediatric patient. This review describes the major paediatric POCUS exams and how to perform them and summarizes the current evidence-based perioperative applications of POCUS in paediatric and neonatal patients.

Method: Literature searches using PubMed and Google Scholar databases for the period from January 2000 to November 2021 that included MeSH headings of [ultrasonography] and [point of care systems] and keywords including "ultrasound" for studies involving children aged 0 to 18 years.

Results: Paediatric and neonatal POCUS exams can evaluate airway, gastric, pulmonary, cardiac, abdominal, vascular, and cerebral systems.

Discussion: POCUS is rapidly expanding in its utility and presence in the perioperative care of paediatric and neonatal patients as their anatomy and pathophysiology are uniquely suited for ultrasound imaging applications that extend beyond the standard adult POCUS exams.

Conclusions: Paediatric POCUS is a powerful adjunct that complements and augments clinical diagnostic evaluation and treatment.

Keywords: children, neonate, paediatric, POCUS, point-of-care ultrasound.

Introduction

Point-of-care ultrasound (POCUS) is rapidly expanding in its utility and presence in improving patient care across a variety of disciplines. Although much of its development has focussed on the adult patient, POCUS is slowly expanding in the paediatric practice due to decreases in the cost of equipment and advances in technology improving image quality and portability. Literature supporting paediatric and neonatal POCUS has also increased, but new applications of ultrasound for many clinical diagnoses in paediatric patients are still in development. In fact, POCUS is particularly well suited for use in the paediatric perioperative setting due to the accessibility and portability of the ultrasound machine, lack of radiation exposure, and ability to perform accurate, minimally invasive, dynamic assessments in real time. The paediatric patient offers improved visualisation of structures, often challenging to clearly depict in the adult patient, due to their smaller size and differences in body composition. The pathologies often found in neonates and young children are also well suited for ultrasound assessment.

Our aim was to systematically review the perioperative and critical care literature for evidence-based guidelines on the use of POCUS in neonates and children. The goal of this review is to examine the evidence and impart a neonatal and paediatric review of POCUS to illustrate the differences between POCUS use in adults from that of children and neonates. A summary of these differences is provided in Table 1. It is not the intention of this review to list every possible POCUS application or calculation. Rather, the focus is on providing an evidence-based clinical summary for the general practitioner as opposed to one with specialised advanced training in a particular ultrasonographic examination (*e.g.* congenital heart disease).

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Table 1: Summary of major differences between adult and paediatric/neonatal POCUS.

POCUS examination	Adult	Paediatric/Neonatal	Major differences
Airway	• Airway compression by external soft tissue mass • Vocal cord mobility* • Cricothyrotomy	• Vocal cord mobility • ETT positioning • LMA positioning • ETT sizing • Cricothyrotomy	*True vocal cord movement can be visualised in females of all ages but can be reduced in older males and patients with calcified thyroid cartilage. Direct visualisation of ETT tip in relation to carina in neonates.
Gastric	• Gastric content and volume	• Gastric content and volume • NGT/OGT & gastrostomy tube positioning	Clear liquid volume calculation is different, thus affecting aspiration risk assessment.
Pulmonary	• Pneumothorax • Pleural effusion • Pneumonia • ARDS • Extubation readiness	• Pneumothorax • Pleural effusion • Pneumonia • URI • Paediatric ARDS • Extubation readiness	Ultrasound findings can meet one of the diagnostic criteria in paediatric ARDS but not in adult ARDS
FATE	Standard FATE	Same	Congenital cardiac disease requires more advanced examination
FAST	Standard FAST • Volume status and responsiveness is based on absolute IVC size	Same • Volume status and responsiveness is based on IVC to descending aorta ratio	Paediatric IVC examination focusses on the size of IVC in relation to the descending aorta in paediatrics rather than absolute IVC size
Lines, drains, devices, and other applications	• Routine placement of peripheral intravenous lines (PIVs), arterial lines, central lines • Aspiration and biopsy of fluid collections	Same • Umbilical venous catheter or PICC positioning • Intraventricular haemorrhage (IVH) severity	Smaller margin of error for placement of lines and drains in paediatric patients. Deeper structure visualisation possible in paediatric patients.

ARDS, acute respiratory distress syndrome; ETT, endotracheal tube; FAST, Focused Assessment with Sonography for Trauma; FATE, Focused Assessed Transthoracic Echocardiography; IVC, inferior vena cava; LMA, laryngeal mask airway; NGT/OGT, nasogastric tube/orogastric tube; PICC, peripherally inserted central catheter; POCUS, Point-of-care ultrasound; URI, upper respir.

Methods

Literature searches using PubMed databases for the period from January 2000 to present were performed during November 2021. The PubMed search initially used a combination of the medical subject (MeSH) headings [ultrasonography] and [point-of-care systems] with the limits of publication date (as previously mentioned), humans, and all children aged 0–18 years. Subsequent searches utilised PubMed and Google scholar by combining the key word 'ultrasound' with one of the following: 'airway', 'gastric', 'lung', 'pulmonary', 'diaphragm', 'cardiac', 'Focused Assessed Transthoracic Echocardiography (FATE)', 'Inferior Vena Cava (IVC)', 'Rapid Assessment of the Neonate with Sonography (RANS)', 'cerebral', 'paediatric', and 'neonatal'. These searches were limited to humans and children (0–18 years). To broaden the search on the topic, bibliographies within identified publications, reviews, and guidelines were also manually reviewed and included.

Airway ultrasound

Introduction/Indications

The paediatric airway is well suited for ultrasound evaluation. Differences in body composition such as increased water content, decreased adipose tissue and muscle mass, and lack of calcification of cartilaginous structures, alongside an overall smaller size and more superficial anatomy, result in better visualisation of the laryngeal structures in children.

Equipment

Like the adult airway examination, a linear transducer is used for the paediatric airway ultrasound evaluation given the superficial depth of the relevant structures. The 'hockey stick' transducer is best for manoeuvring tight neck spaces, especially in neonates. The small planar linear transducer is ideal for infants or small children, while the large planar linear transducer is more suitable for the larger surfaces of older children and teenagers.

Vocal cord mobility

The gold standard for the assessment of vocal cord mobility is through direct visualisation with awake flexible nasolaryngoscopy. In adults, this procedure is tolerable with topicalisation. Paediatric patients often require sedation, which can decrease the dynamic movements of the vocal cords. Ultrasound assessment can be used reliably in place of an awake flexible nasolaryngoscopy as a non-invasive test causes less trauma and agitation and does not require sedation. In patients older than 12 months, the concordance rate between the two modalities is about 90%.[1] Ultrasound use to diagnose vocal cord dysfunction demonstrates high sensitivity (92.3%) and specificity (100%).[2]

To assess vocal cord mobility by ultrasound, the transducer is positioned transversely on the neck at the level of the cricoid. Once the thyroid cartilage is identified, the transducer is moved caudally until the vocal cords are seen (Figure 1a). The false vocal cords are more prominent with a larger hyperechoic area due to their fat content. The true visual cords can be found more caudally.[3]

Endotracheal tube position

There are two steps to assessing appropriate endotracheal tube placement by ultrasound. The first step is to rule out an oesophageal intubation by placing the transducer horizontally across the anterior neck to visualise the trachea. In an endotracheal intubation, a hyperechoic shadow can be seen within the hyperechoic cartilage of the trachea creating parallel hyperechoic arcs, or the 'railroad sign' (Figure 1b). In an oesophageal intubation, a hyperechoic circular structure can be seen adjacent to the trachea, often with a hyperechoic shadow within the lumen of the oesophagus ('double trachea sign').

The second step is to determine the presence of an endotracheal vs. endobronchial intubation. This method involves scanning the bilateral anterior lungs to assess for pleural sliding. Unilateral pleural sliding (usually on the right side) indicates an endobronchial intubation. Bilateral pleural sliding demonstrates an endotracheal intubation.

The sensitivity and specificity of oesophageal *versus* tracheal intubation were both 100%, whereas for endobronchial mainstem intubation vs. tracheal intubation, the sensitivity and specificity were 85.7% and 98.3%, respectively.[4] There are limitations to the two-step determination of ETT placement, especially in patients who have had pleurodesis or other pleural adhesion pathologies and in patients with induced pneumothorax such as in thoracoscopy.

Endotracheal size estimation

Appropriate endotracheal tube size selection in the paediatric patient minimises the need for multiple intubations that can lead to laryngeal trauma and swelling. Although age-based calculations for ETT size are commonly used, ultrasound measurement provides a more accurate estimation of airway size

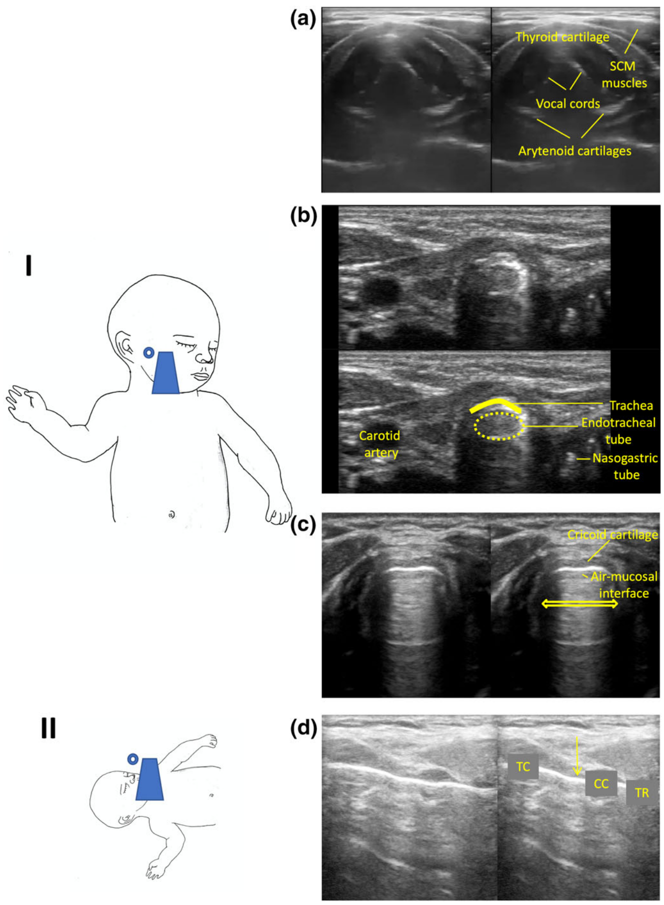

Figure 1: Airway ultrasound. (I) The patient is supine. Placement of the ultrasound transducer with the orientation marker (o) towards the patient's right side with the neck in extension for the transverse views of the airway examination such as (a) vocal cord assessment, (b) endotracheal tube placement assessment to assess for the 'railroad sign', and (c) measurement of the tracheal diameter for appropriate endotracheal tube size. (II) The patient is supine. Placement of the ultrasound transducer with the orientation marker (o) towards the patient's head with the neck in extension for the longitudinal view of the airway examination such as (d) in cricothyrotomy to view the 'string of pearls' where the arrow designates the cricothyroid mem. (Colour figure can be viewed at wileyonlinelibrary.com)

(27.5% accuracy in age-based calculation vs. 87.8% accuracy with ultrasound) with lower frequencies of tube exchange (52% in age-based calculation vs. 12% in ultrasound).[5,6]

To estimate the size of the appropriate ETT with ultrasound, extend the child's head. With the linear transducer in the transverse position across the midline of the neck, identify the vocal cords. Slide the transducer caudally until the cricoid cartilage comes into view. Measure the transverse air-column diameter at the level of the cricoid cartilage to estimate the maximum size for the outer diameter of the ETT (Figure 1c).[7] The transverse diameter is used because it is smaller than the anteroposterior diameter and acoustic air shadowing often obscures the posterior wall of the trachea.

Using the transverse subglottic diameter as the outer diameter of the ETT without any conversion factors assumes that the cricoid is the narrowest portion of the airway even though the narrowest portion of the paediatric larynx actually occurs at the level of the vocal cords, followed by the sub-vocal cords and the cricoid.[8] To reflect this anatomical difference, Shibasaki *et al.*[9] proposed a conversion factor between the outer diameter of an optimally sized ETT (in mm) and the transverse subglottic diameter (also in mm) with a 98% success rate. For cuffed ETTs, the outer ETT diameter = 0.46 × (subglottic diameter) + 1.56, $R^2 = 0.90$.[9] Others have subsequently followed in the pursuit of more accurate transverse diameter measurements and conversions with varying success.[10–14] This ultrasound technique is also not suitable for ETT sizing in adults due to laryngeal calcification.

Gastric ultrasound

Introduction/Indications

Bedside gastric ultrasound is highly sensitive and specific to detect a full stomach and pre-operative fasting status (sensitivity of 1.0 and specificity of 0.98).[15] Gastric ultrasound can also determine the nature and volume of the gastric contents and be used to confirm the appropriate placement of nasogastric and orogastric tubes.

Equipment

The type of transducer depends on the size of the patient and the depth of the stomach. We recommend a high-frequency linear transducer for children <40 kg and a low-frequency curvilinear transducer for children 40 kg and greater.

Positioning

Positioning is important for the gastric ultrasound examination. The patient can be positioned in (1) right lateral decubitus, which is the most sensitive for accurate assessment; (2) sitting, which is the second best option and may be more feasible in younger children, especially when utilising distraction techniques; and (3) supine, although this may lead to a higher rate of 'false-negative' findings for diagnosing an empty stomach.[16,17] Ideally, two positions should be evaluated to decrease false-negative findings. To obtain visualisation of the stomach antrum, the ultrasound probe is placed along the sagittal plane in the epigastric midline.

Interpretation of gastric contents

Bedside gastric ultrasound focusses on the antrum due to its more consistent and superficial location and its lower proportion of air content. The appearance of an empty stomach vs. a stomach with either clear fluid or thick fluid or solid contents is similar to that in adults. The empty stomach usually appears as a small, collapsed 'bull's eye' and carries a low risk for aspiration (Figure 2a). A stomach with thick fluid (such as milk) or solid contents appears hyperechoic and homogenous like 'frosted glass' (Figure 2b) and carries a high risk for aspiration. At times, solid contents can even appear as heterogenous particulates with occasional solid/fluid interfaces.[18]

The main difference between the paediatric and adult gastric ultrasound examinations is the risk stratification of gastric clear fluid volume associated with the potential for aspiration. Fasted patients will have either an empty stomach or appreciable gastric secretions at baseline.

These gastric secretions appear similar to ingested clear fluids under ultrasound visualisation – hypoechoic and homogenous (Figure 2c). In general, gastric volumes equal to or less than 1.25 mL/kg in children and 1.5 mL/kg in adults are considered a low aspiration risk. Gastric volumes greater than 1.25 mL/kg in children and 1.5 mL/kg in adults are associated with a high risk for aspiration.[15,19]

To measure the volume of clear gastric fluid, two separate calculations are available using either the child's age in months

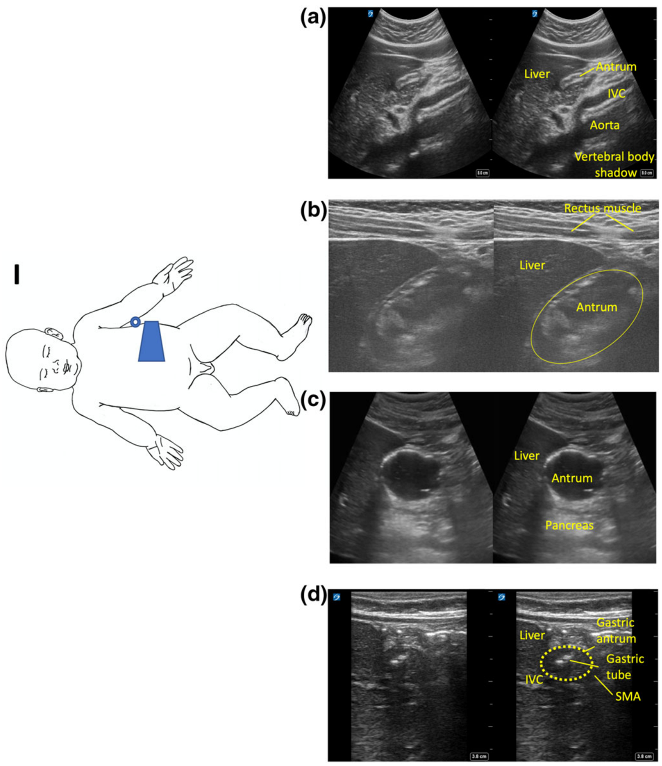

Figure 2: Gastric ultrasound. (I) The patient is either in the sitting position, right lateral decubitus position, or supine. Placement of the ultrasound transducer with the orientation marker towards the head. The transducer is placed below the xiphoid in the midline with a slight tilt towards the patient's left side. (a) Empty antrum. (b) Antrum filled with solid or thick fluid. (c) Antrum filled with clear fluid. (d) Nasogastric tube present within an empty antrum. (Colour figure can be viewed at wileyonlinelibrary.com)

or their age in years:

$$\text{Volume (mL/kg)} = -7.8 + (3.5 \times \text{CAS}) + 0.127\left(\frac{\text{age (months)}}{\text{body weight (kg)}}\right)$$

$$\text{Volume (mL)} = 27.0 + (1.46 \times \text{CSA}) - (1.28 \times \text{age})$$

The R^2 value for the first calculation is 0.6 using the right lateral decubitus position. The R^2 value becomes lower when gastric volume measurements are derived from the supine or sitting positions.[19] The second calculation can also be used in adults.

In both the paediatric and adult models, calculating an accurate cross-sectional area (CSA) is essential for an accurate volume assessment. The CSA can be calculated by free tracing the outer border of the gastric wall and using the ultrasound's internal software capabilities to derive the area. Alternatively, CSA is calculated by (π*D1*D2)/4 where D1 is the longitudinal diameter and D2 is the anteroposterior diameter of the gastric cross section.

A three-point grading system can be used to qualitatively estimate gastric volume and therefore aspiration risk.[20,21] The presence of fluid is assessed in both the supine and right lateral decubitus positions. If no fluid is visible in both positions, then the clear fluid volume present is negligible (grade 0) and the risk for aspiration is low. However, if fluid is visible in both positions, then the fluid volume present is greater than 100 mL (grade 2) and the risk for aspiration is high. If fluid is only visualised when the patient is in the right lateral decubitus position, then the fluid volume is likely <100 mL (grade 1) in which case the risk for aspiration is intermediate. This method is primarily utilised in adults. Although different gastric volumes have been found in children for different positions, age- and weight-specific cut-off ranges have not been validated in children.[22]

It is important to understand the patient's medical history before initiating a gastric ultrasound assessment. Findings may be unreliable in patients with a history of previous gastric surgery, large hiatal hernias, and congenital diaphragmatic hernia.

Nasogastric tube/orogastric tube placement and gastrostomy tube placement

Bedside ultrasound can be used to help confirm proper nasogastric tube (NGT) or orogastric tube (OGT) placement in infants utilising the same high-frequency linear transducer.[23,24] Ultrasound use can decrease repetitive radiation exposure, especially with repeated NGT/OGT dislodgment, and has a sensitivity of 92.2–98% with a positive predictive value of 0.99–1.[25] Ideally, the tip of the NGT/OGT should be visualised in the body or the antrum of the stomach for proper placement.

While the patient is in the supine position, the transducer is horizontally oriented at the midline to locate the antrum of the stomach. The gastric tube is seen as a hyperechoic line or parallel hyperechoic lines (Figure 2d). Once the gastric tube is identified, tilt or slide the transducer towards the patient's right to assess for the presence of the gastric tube through the pylorus. If the gastric tube is not initially seen in the antrum, tilt or slide the transducer towards the patient's left to assess for the presence of the gastric tube in the body of the stomach. Alternatively, the transducer can be rotated 90° in a longitudinal direction with a slight tilt towards the patient's left side for better visualisation of the gastric tube through the EGJ into the stomach.

Pulmonary ultrasound

Introduction/Indications

The diagnostic capabilities of pulmonary ultrasound demonstrate excellent sensitivity and specificity (*e.g.* pneumothorax, pleural effusion, and interstitial disease) compared with chest X-ray and chest CT in all age groups while avoiding radiation exposure.[26,27] Its portability allows assessments to be made without transporting or positioning unstable patients while allowing for direct comparisons between pre-operative and intraoperative assessments.

Equipment

Depending on the size of the patient and the goal of the examination, different transducers can be used for the pulmonary ultrasound assessment. The microconvex transducer (4–7 MHz) is ideal for scanning between the ribs in the intercostal space with good penetration. The curvilinear transducer (2–5 MHz) is better suited for patients with thicker chest walls such as teenagers and adults. The linear transducer (6.5–14 MHz) is optimal for visualising the pleura and for imaging multiple rib levels in neonates and infants.

Positioning

The patient is placed in the supine position if the focus of the examination is on the anterior and lateral chest such as for pneumothorax or pleural effusion. Examination of the posterior lung fields for paediatric ARDS or pulmonary oedema necessitates repositioning the patient into the sitting or lateral decubitus position.

Normal lung

The normal sonographic findings (e.g. 'lung sliding' and A lines) are similar in both adult and paediatric patients. In fact, the anatomy in paediatric patients can produce higher quality images when visualising deeper pulmonary parenchyma. The 'bat sign' is often used as a reference point in pulmonary ultrasound. It represents the contour of two ribs with hyperechoic pleura in between. In the paediatric patient, it is not uncommon to see the pleura as a contiguous structure beneath the rib shadows as the ribs in paediatric patients are less calcified (Figure 3 top panel).

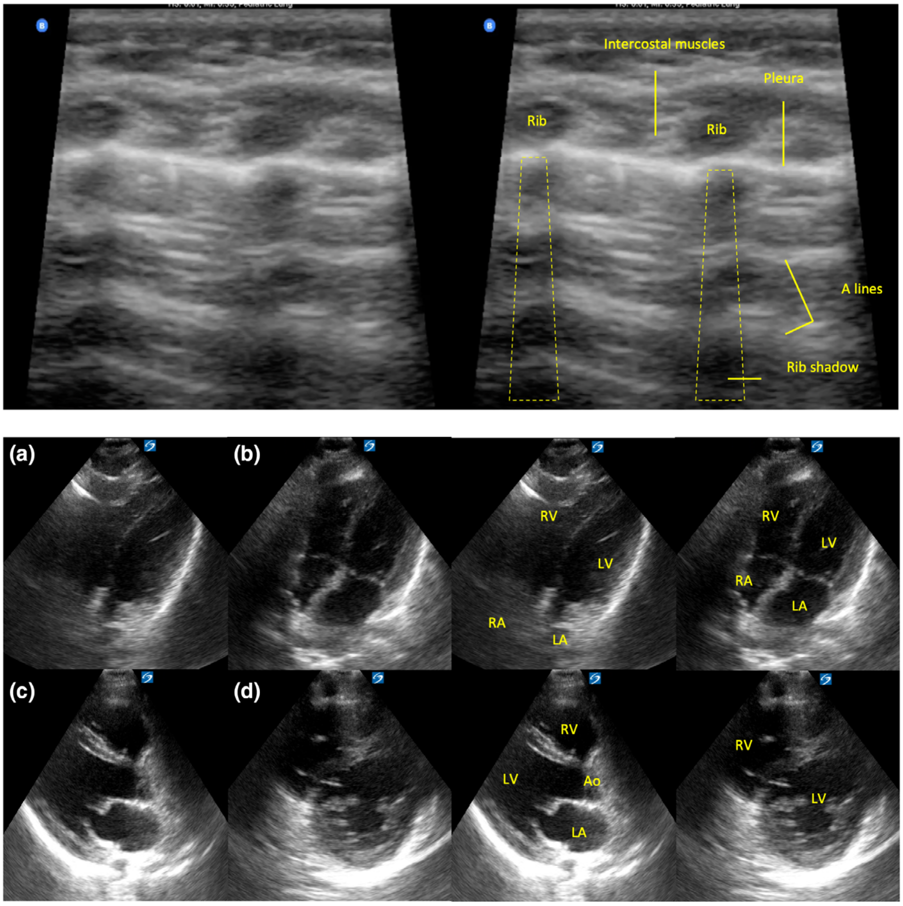

Figure 3: Pulmonary ultrasound and focussed assessed transthoracic echocardiography (FATE) examination. The top panel shows the pulmonary examination for a healthy infant without B lines. Note the almost continuous pleural line beneath the ribs that have not developed complete ossification yet. The bottom panel shows the FATE examination for a healthy infant. The basic views of the FATE examination can be seen as follows: (a) subcostal four-chamber view through the liver, (b) apical four-chamber, (c) parasternal long axis, and (d) parasternal short axis. (Colour figure can be viewed at wileyonlinelibrary.com)

Pneumothorax

Pulmonary ultrasound is fairly good at identifying pneumothorax (especially compared with chest X-ray, which fails to diagnose a pneumothorax 30–60% of the time).[28] The ultrasound examination is the same in both adult and paediatric patients, though it is generally faster in paediatric patients as they have less overall surface area to examine in relation to the size of the transducer. Although the absence of pleural sliding or the presence of a lung pulse is sign of a possible pneumothorax, the diagnosis of pneumothorax cannot be made without confirmation of a 'lung point', the interface between the pneumothorax space and the partially collapsed lung. Lung sliding may be absent due to pleural adhesions, apnoea, or large lung bullae. M-mode lung examination, a one-dimensional time recording along a single ultrasound beam, can also be used in paediatric patients as an alternative method to visualise a pneumothorax.

Pleural effusion

Ultrasound is excellent at identifying the presence of a pleural effusion and is able to detect amounts of fluid as small as 5 mL.[29] By comparison, chest X-ray is insensitive at detecting fluid volumes <150 mL.[30] The ultrasound technique used to diagnose a pleural effusion is the same in children as it is for adults. The two signs (the 'curtain sign' and the 'spine sign') can be used while the patient is in the supine position. In fact, the 'spine sign' may be easier to visualise in the paediatric patient given their smaller overall size. Unlike adults, there has been no validated method to estimate the size of a pleural effusion through ultrasound examination for paediatric patients.[31]

Paediatric acute respiratory distress syndrome

Unlike adult acute respiratory distress syndrome (ARDS), the Paediatric Acute Lung Injury Consensus Conference (PALICC) does not mention the preferred modality of imaging to diagnose paediatric acute respiratory distress syndrome (PARDS).[32] Therefore, lung ultrasound can be used to help diagnose PARDS.

The sonographic signs often found in PARDS include numerous B lines in multiple lung sections bilaterally, disrupted and thickened pleura, consolidated lung tissue, and air bronchograms. These findings are usually seen in the supine position although visualisation of the posterior areas may yield improved diagnostic sensitivity. Because these sonographic signs can be found in other diagnoses such as cardiogenic and non-cardiogenic pulmonary oedema, upper respiratory infection, or pneumonia,[33] Saigal *et al.*[34] developed a classification system based on combined lung and cardiac ultrasound findings with arterial blood gas analysis to improve diagnostic clarity with a patient's clinical history.

Pulmonary ultrasound can also be helpful in distinguishing between PARDS and transient tachypnoea of the neonate (TTN), which can present very similarly. Although TTN will have areas of sonographic findings similar to PARDS (*e.g.* numerous B lines and consolidated lung tissue), it will also have areas of near-normal lung findings (*e.g.* A lines).[35] Thus, it is important to scan several lung regions before coming to any diagnostic conclusion.

As one of the recognised causes of neonatal ARDS, meconium aspiration syndrome (MAS) shares the same lung ultrasound findings as PARDS. However, the lung ultrasound findings for MAS are dynamic due to changes in the spread of meconium plugs from mechanical ventilation.[36] Serial images in multiple lung regions are therefore required.

Hemidiaphragmatic paralysis

Ultrasonography can detect hemidiaphragmatic paralysis in both adult and paediatric patients by visualising diaphragmatic motion and thickening through M-mode scanning. Diaphragmatic visualisation through the zone of apposition by using hepatic and splenic acoustic windows can be challenging, especially through the spleen.[37] The ACBD approach is an alternative method that relies on a more systematic approach and uses basic visualisation of the pleura without hepatic or splenic windows.[38,39] The accuracy of the ACBD approach can be enhanced with an additional sniff test.[40] The sniff test however is difficult to implement in young children who may not understand the command.

Focused assessed transthoracic echocardiography examination

The cardiac POCUS examination, better known as the FATE examination, is similar in adults and paediatrics. The FATE examination is a rapid transthoracic evaluation of the heart to identify cardiovascular causes of hypotension by checking for diminished systolic function, pericardial effusion, and valvular dysfunction.

There are no major differences between the adult and paediatric FATE examinations. Figure 3 (bottom panel) shows the four views of the basic FATE examination in a paediatric patient. Achieving certain windows may be more challenging given the smaller intercostal spaces and increased rib shadowing. The faster heart rates of younger children and infants may make the visualisation of intracardiac structures more difficult, necessitating the use of a more advanced ultrasound machine if available. For children with a history of congenital heart disease, the FATE examination is of more limited utility, but may still show physiological and haemodynamic information such as pericardial effusion or grossly altered systolic function. International evidence-based guidelines[41] do not recommend using POCUS as a screening tool for diagnosing congenital heart defects in neonates and children unless advanced echocardiography training specifically for this purpose has been achieved.

The apical five-chamber view in the extended FATE examination can be used by those with advanced POCUS skills to assess fluid responsiveness in neonates and children with preserved left ventricular systolic function. A >15% variation in the velocity–time integrals[41] (VTIs), measured at the left ventricular outflow tract, between inspiration and expiration has a high predictive value for fluid responsiveness. Although measuring VTI variation is more technically involved than measuring IVC collapsibility or IVC to descending aorta diameter ratio (described later) to determine fluid responsiveness, VTI variation measurements have a sensitivity and specificity exceeding 90% and have been validated in many studies involving mechanically ventilated children.[42,43]

Point-of-care ultrasound is also helpful in assessing pulmonary artery systolic pressures (PASP) to evaluate for pulmonary hypertension in neonates and children. In the presence of tricuspid regurgitation, the methodology is similar to that used in adults, whereby the regurgitation velocity is used to estimate the PASP using a modified Bernoulli equation. In the absence of tricuspid regurgitation, visual inspection of the foramen ovale using colour flow Doppler provides another tool to assess pulmonary arterial pressures (PAP).[44] Right-to-left flow through the foramen ovale suggests suprasystemic PASP, while left-to-right flow is reflective of a PASP that is lower than the systemic pressure. In persistent pulmonary hypertension of the newborn, flow is often bidirectional.

Focused assessment with sonography for trauma (FAST) examination

The FAST examination identifies the presence of free intraperitoneal and pericardial fluid for patients presenting with thoracoabdominal trauma. Since its introduction, the FAST examination has become the standard of care in adult trauma with utilisation by almost all adult trauma centres. It is noninvasive, easy to perform, and efficient in obtaining reproducible results and reduces repeated radiation exposure on serial examinations.

In the paediatric world, the FAST examination is controversial and utilised in only 15% of paediatric trauma centres.[45] Much of the slow adoption is due to the lack of evidence in children, especially those less than 2 years of age, the low incidence of intra-abdominal injury in children, and the fact that most children with intra-abdominal injuries are typically pretty stable.[46] Some test characteristics of the paediatric FAST examination are comparable, but for the most part inferior to many published studies in adult patients.[47,48] The accuracy and utility of the paediatric FAST examination increases with serial examinations, particularly when there is sudden clinical deterioration or hypotension from an ongoing pathophysiologic process.[47] Figure 4 (subfigure I) demonstrates the abdominal ultrasound images obtained in a paediatric patient.

More recently, abdominal ultrasound has been used to detect signs of necrotising enterocolitis (NEC) in newborns, especially when radiographs are inconclusive.[49,50] It has been shown that abdominal ultrasound outperforms conventional radiology in identifying free fluid, bowel wall thickness, pneumatosis intestinalis, portal venous gas, and vascular perfusion.[51] As a result, the International Neonatal Consortium updated their diagnostic criteria such that the presence of pneumatosis intestinalis or portal venous gas by abdominal radiograph or POCUS can be used to meet the 'two out of three' diagnosis model for NEC.[50] To visualise the bowel wall, a high-frequency linear transducer should be used for small premature infants while a curvilinear transducer should be used for larger term infants. Due to the onset of inflammation and increased blood flow and mucosal oedema at the early stages of NEC, the abdominal wall should appear thickened with increased echogenicity and increased perfusion on ultrasound.[49] To visualise portal venous gas, a curvilinear transducer should be used regardless of the infant's size to completely visualise the liver. The gas bubbles within the portal veins will appear as echogenic foci. It is important to note that these gas bubbles in portal venous gas will extend all the way to the periphery of the liver parenchyma as opposed to pneumobilia where the gas bubbles are focussed centrally near the hepatic hilum.[52] As NEC progresses, colour Doppler can be used to identify absent perfusion in a thinned bowel wall, due to compromised microvasculature over time, which is highly suggestive of impending bowel perforation.[49]

Inferior vena cava examination

Inferior vena cava size and collapsibility are correlated with volume determination and responsiveness in adults. In both non-ventilated adults and children, IVC collapse during inspiration is greater than 50% in the setting of euvolaemia and normal right atrial pressure. A dilated IVC with decreased collapsibility (<50%) is a sign of increased right atrial pressure. A collapsed IVC may be suggestive of hypovolaemia.[53] While the IVC size is measured 3–5 centimetres from the right atrial junction in adults, there is currently no standardised approach that accounts for the developmental differences in children. Figure 4d demonstrates the IVC seen in a paediatric patient with the right atrium in view.

An alternative determination of volume status and responsiveness in the paediatric patient (up to age 18 years) utilises the IVC to descending aorta (Ao) ratio (Figure 4e). Although the sizes of the IVC and descending aorta (Ao) vary in paediatric patients according to their age and size, the diameter of the descending aorta remains mostly constant in a single patient even during intravascular depletion.[54] Therefore, volume status may be estimated by the IVC:Ao ratio. An IVC:Ao ratio of approximately 1 suggests euvolaemia, while an IVC:Ao ratio of less than 0.8 is suggestive of intravascular depletion. The IVC:Ao ratio has a sensitivity of ~86% and a specificity of ~56% and should therefore be used in combination with the patient's clinical history and physical examination.

Neonatal specific ultrasound

Introduction

The adoption of point-of-care ultrasound in the care of neonates has been slow, mainly due to a lack of ultrasound equipment available and trained personnel to teach fellows and faculty. The anatomy, size, larger body content of water, and decreased calcification of osseous structures of the neonate present exceptional conditions for obtaining high-quality ultrasound visualisation. These characteristics present new avenues in which to assess the neonate.

Rapid assessment of the neonate with sonography examination

The rapid assessement of neonates with sonography (RANS), introduced by Safarulla *et al*,[55] provides a quick and organised method to diagnose a decompensating neonate. The RANS scan uses a single microconvex (5–8 MHz) transducer and looks for the presence of four problems: pericardial effusion, pneumothorax and pleural effusion, central venous line malposition, and severe intraventricular haemorrhage (IVH).

The assessment for pericardial effusion is similar to the subcostal view of the FATE examination where the transducer is placed in the subxiphoid position and angled about 30 degrees towards the patient's head. A pericardial effusion, if present, will present as anechoic fluid between the heart and the pericardial sac. The detection of a pneumothorax and pleural effusion is similar to the paediatric and adult pulmonary ultrasound examinations as well.

To assess the position of an umbilical venous catheter, the IVC is visualised by placing the transducer inferior to the xiphoid process in the sagittal plane. The transducer is held at a 90-degree angle to the longitudinal axis and angled slightly towards the patient's right side, similar to the IVC examination in the extended FATE examination. The central venous line is seen as a linear, hyperechoic structure within the IVC lumen. If

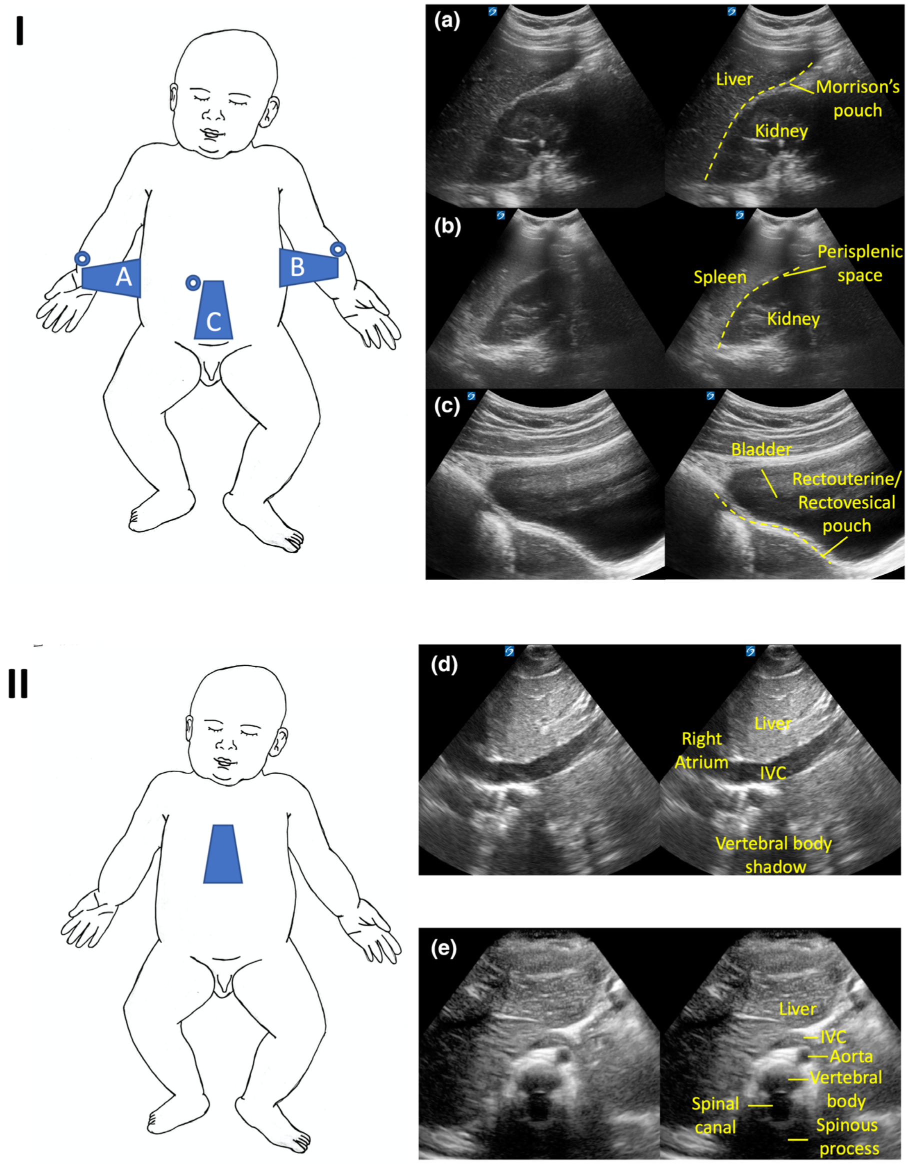

Figure 4: Focussed assessment with sonography for trauma (FAST) examination and inferior vena cava (IVC) examination. (I) The patient is supine. Placement of the transducer, with orientation marker (o) either towards the patient's head or to the patient's right, can be seen in the three positions for the FAST examination as follows: (a) right upper quadrant to assess Morrison's pouch or the hepatorenal recess, the liver tip or right paracolic gutter, and the lower right thorax; (b) left upper quadrant to assess the subphrenic space, splenorenal recess, spleen tip or left paracolic gutter, and the lower left thorax; (c) pelvis to assess the rectovesical pouch in males and rectouterine or pouch of Douglas in females. (II) The patient is supine. Placement of the transducer in the transverse position below the xiphoid process in the midline. (d) IVC examination in a teenager, which is similar to an adult examination where the IVC is measured about 3–5 cm from the right atrial junction. (e) IVC examination in an infant where the IVC to descending aorta (Ao) ratio allows for a more accurate volume estimation. (Colour figure can be viewed at wileyonlinelibrary.com)

the tip is visualised at the junction of the IVC and the right atrium, correct positioning is confirmed.

Severe Intraventricular haemorrhage (IVH) severity (grade 3 and 4 IVHs) can cause blood loss and metabolic acidosis in neonates, especially in those with extremely low birth weights. The transducer is placed transversely on the anterior fontanelle with the orientation marker pointing towards the patient's right side. The transducer is then slowly tilted towards the patient's nose to evaluate the frontal horns of the lateral ventricles. Normal ventricles are seen as narrow hypoechoic slits (Figure 5a). Haemorrhage in the ventricles appears as a hyperechoic mass within the ventricles. In a grade 2 IVH, hyperechoic heme can

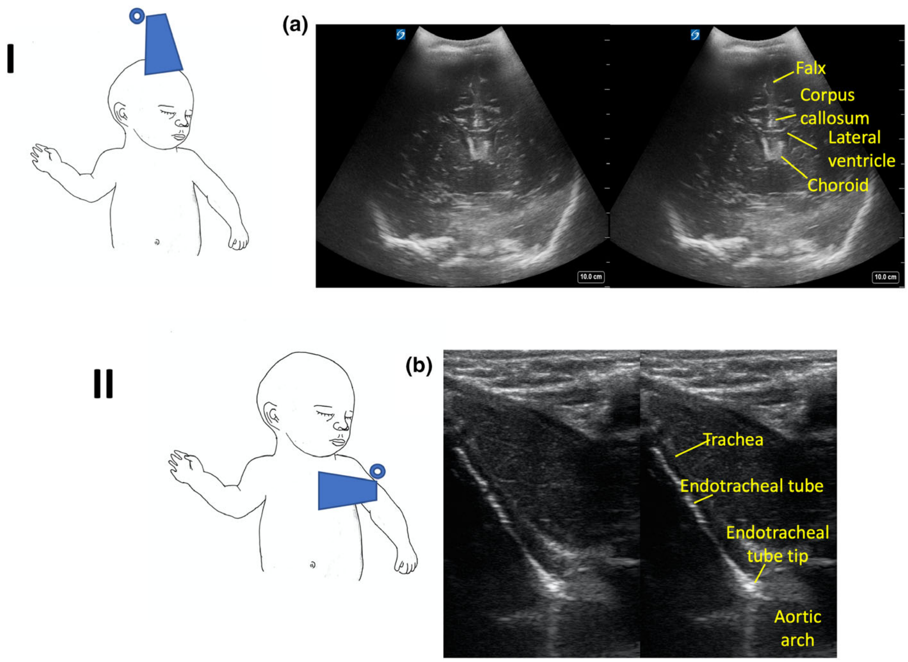

Figure 5: Neonatal examinations. (I) The patient is supine. The ultrasound transducer is placed transversely on the anterior fontanelle with the orientation marker pointing towards the patient's right side. The transducer is then slowly tilted towards the patient's nose to evaluate the (a) frontal horns of the lateral ventricles. (II) The patient is supine. The linear ultrasound transducer is placed in the midsagittal position over the upper sternum with the baby's head rotated slightly to one side. (b) The hypoechoic aorta and trachea can be very similar in their appearance and artifactually contiguous. Visualisation of the hyperechoic endotracheal tube and utilisation of colour Doppler can help to discriminate the aortic arch from the trachea, as well as demarcate their anatomical locations. The carina will be located inferior and caudal to that demarcation. (Colour figure can be viewed at wileyonlinelibrary.com)

be seen in the ventricles, but the ventricles are not enlarged. When the ventricles are enlarged with blood, a grade 3 IVH is considered unless there is haemorrhagic extension into the brain parenchyma (grade 4 IVH).

Cerebral examination

Although there is strong evidence for the use of cerebral POCUS to detect germinal matrix and IVHs in neonates, caution must be used when applying POCUS to other neonatal cerebral pathologies due to insufficient data. For example, estimations of flow velocities and calculations of pulsatility and resistance indices have been performed but there are no neonatal data to support its use, especially since there are no neonatal data to help interpret results yet.[56] An alternative assessment for raised intracranial pressure utilises POCUS to detect changes in the optic nerve sheath diameter. Increased optic nerve sheath diameter is suggestive of papilloedema and increased intracranial pressure. Caution should be used when implementing a published threshold measurement[57,58] as many of these studies have different recommended thresholds, some of which conflict with each other and others that have very narrow margins of error between a pathological and normal diagnosis.

Endotracheal tube placement

Unlike in adult and larger paediatric patients, the tip of the endotracheal tube above the carina can be directly visualised in neonates with ultrasound.[59,60] To perform this examination, place a linear transducer in the midsagittal position over the upper sternum with the baby's head rotated slightly to one side. The hypoechoic aorta and trachea can be very similar in their appearance and artifactually contiguous. Visualisation of the hyperechoic ETT and utilisation of colour Doppler can help to discriminate the aortic arch from the trachea, as well as demarcate their anatomical locations. The carina will be located inferior and caudal to that demarcation (Figure 5b). The cross section of the right pulmonary artery can be another landmark to locate the slightly cephalad location of the carina. Note that excessive rotation of the head may result in an endobronchial intubation once the head is straightened.

Conclusion

Point-of-care ultrasound (POCUS) is rapidly expanding in its utility and presence in the perioperative care of paediatric and neonatal patients as their anatomy and pathophysiology are uniquely suited for ultrasound uses that extend beyond the standard adult POCUS examinations. Paediatric POCUS is a powerful tool to complement our clinical assessment, but it augments rather than replaces much of the clinical examination. Formal imaging evaluations still play a large role in standard-of-care practice. As ultrasound machines become increasingly available and our knowledge and use of ultrasound in the paediatric patient evolves, we are optimistic that paediatric POCUS will improve the quality of care, time to intervention, and overall outcomes in patients.

Authorship statement

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Author contributions

Stephanie Pan: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Carole Lin:** Data curation (supporting); writing – review and editing (supporting). **Ban Ban Tsui:** Conceptualization (lead); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); validation (equal); visualization (equal); writing – review and editing (equal).

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