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REVIEW ARTICLE/BRIEF REVIEW

Point-of-care ultrasound in pediatric anesthesiology and critical care medicine

Échographie au point d'intervention en anesthésiologie et soins intensifs pédiatriques

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Abstract *Ultrasound has increasingly become a clinical asset in the hands of the anesthesiologist and intensivist who cares for children. Though many applications for ultrasound parallel adult modalities, children as always are not simply small adults and benefit from the application of ultrasound to their management in various ways. Body composition and size are important factors that affect ultrasound performance in the child, as are the pathologies that may uniquely afflict children and aspects of procedures unique to this patient population. Ultrasound simplifies vascular access and other procedures by visualizing structures smaller than those in adults. Maturation of the thoracic cage presents challenges for the clinician performing pulmonary ultrasound though a greater proportion of the thorax can be seen. Moreover, ultrasound may provide unique solutions to sizing the airway and assessing it for cricothyroidotomy. Though cardiac ultrasound and neurosonology have historically been performed by well-developed diagnostic imaging services, emerging literature stresses the utility of clinician ultrasound in screening for pathology and providing serial observations for monitoring clinical status. Use of ultrasound is growing in clinical areas where time and diagnostic accuracy are crucial. Implementation of ultrasound at the bedside will require institutional support of education and credentialing. It is only natural that the pediatric anesthesiologist and intensivist will lead the incorporation of ultrasound in the future practice of these specialties.*

Résumé *L'échographie est devenue de plus en plus un outil clinique dans les mains des anesthésiologistes et des intensivistes qui prennent soin d'enfants. Bien que de nombreuses applications échographiques suivent le modèle des modalités pour adultes, les enfants ne sont pas simplement de petits adultes et bénéficient d'applications échographiques propres à la gestion de leur situation. La composition et la taille de leur corps sont des facteurs importants qui affectent la performance de l'échographie, de même que les maladies des enfants ainsi que les procédures qui sont uniques à cette population. L'échographie simplifie l'accès vasculaire et d'autres procédures en visualisant des structures qui sont plus petites que celle des adultes. La maturation de la cage thoracique présente des défis pour le clinicien effectuant une échographie pulmonaire bien qu'il puisse voir une plus grande proportion du thorax. De plus, l'échographie peut fournir des réponses uniques aux dimensions des voies respiratoires et à leur évaluation en vue d'une cricothyroïdotomie. Historiquement, les échographies cardiaques et neurologiques ont été réalisées par des services d'imagerie diagnostique bien développés, mais des publications de plus en plus nombreuses soulignent la pertinence de la pratique de l'échographie par des cliniciens pour dépister des troubles et fournir des observations répétées dans le cadre d'une surveillance clinique. L'utilisation de l'échographie est en progression dans des domaines cliniques où le temps et l'exactitude diagnostique sont essentiels. La mise en œuvre de*

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l'échographie au point d'intervention nécessitera un soutien institutionnel en matière de formation et de reconnaissance des compétences. Il est tout à fait naturel que les anesthésiologistes et Intensivistes pédiatriques soient à la tête de l'incorporation de l'échographie dans la pratique future de ces spécialités.

Ultrasound has become a mainstay of clinical practice in the pediatric operating room and intensive care unit. Its use in preoperative, intraoperative, and postsurgical management has burgeoned, mirroring its rapid expansion in adult anesthesiology and critical care management.

In many ways the implementation of ultrasound in pediatric care areas is analogous to adult methods, with caveats pertinent for the care of infants and children (Table). Imaging in children is somewhat facilitated by their higher relative body water content than adults[1] and the fact that target structures are closer to the probe by virtue of patient size. These attributes facilitate the use of higher frequency ultrasound of upwards of 15 MHz for higher resolution imaging of tissues at 2-6 cm depth. Though not recommended for routine cardiac imaging, a linear transducer can even generate clinically useful data for procedures[2] (Fig. 1). Size also matters in children in terms of thermal losses from exposure while scanning. Since lung and abdominal ultrasound can involve scanning over large areas, an operator should consider removing the gel as able while scanning because of convective and evaporative thermal losses from gel exposure.[3]

The purpose of this narrative review is to summarize the use of ultrasound for vascular access, assessment of the airway, lungs, and circulation in children. Imaging of the abdominal cavity, gastric contents, and the central nervous system will also be discussed. This review will conclude with a brief discussion of training and certification issues unique to providers caring for children.

Vascular access

Internal jugular vein catheterization

Use of ultrasound in improving first-attempt success and reduction in complications is well described in the anesthesiology and critical care literature. It has been

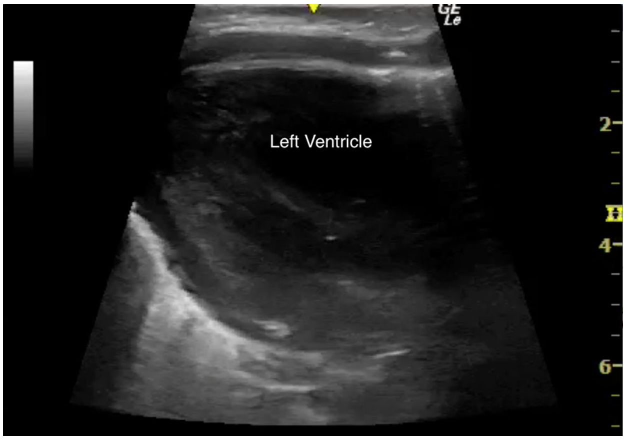

Fig. 1 Linear transducer used to visualize heart in long-axis in the parasternal window

Table Suggestions for probe selection in various pediatric point-of-care applications

Application	Newborn-2 yr	2-12 yr	Adolescent/adult
Airway linear	Linear 2.5 cm in length, shorter recommended	Linear 2.5 cm in length or shorter	Any linear
Pulmonary pleural	Any linear, curvilinear, microconvex	Any linear, curvilinear	Any linear, curvilinear
Pulmonary sector	Phased array, microconvex	Phased array, microconvex, curvilinear	Phased array, curvilinear
Cardiac	Phased array 6-12 MHz	Phased array 1-5 MHz, 2-6 MHz	Phased array 1-5 MHz
Vascular (venous and arterial) access and procedural	Linear 12 MHz and higher (>18 MHz if possible)	Any linear	Linear 4 cm length recommended
Gastrointestinal sector	Phased array, microconvex	Any sector probe	Any sector probe
Neurosonology/TCD	Microconvex, TCD through fontanelles *or* phased array 1-5 MHz through temporal windows	Phased array 1-5 MHz (TCD)	Phased array 1-5 MHz (TCD)
Ophthalmic	Linear 12 MHz and higher (>18 MHz if possible)	Linear 12 MHz and higher (>18 MHz if possible)	Linear 12 MHz and higher (>18 MHz if possible)

TCD = Transcranial Doppler

well defined in a 2015 Cochrane Library review describing overall increased success in pediatric central venous catheter insertion in the internal jugular vein using dynamic ultrasound guidance.[4] Transverse (or short-axis) active (or dynamic) visualization is the primary methodology for insertion in the vast majority of published literature. One consideration is that the majority of available literature on this topic studied trainees as the primary operator in central venous catheter insertion.[5,6] This raises the question of whether or not clinicians experienced in landmark methods would necessarily benefit from ultrasound.[7] Nevertheless, since trainees place many internal jugular central venous catheters in high-volume centres, the practical question of whether trainees perform better with ultrasound remains germane. Available evidence[4] suggests that ultrasound is standard of practice for internal jugular catheterization in many pediatric environments. Anatomic issues unique to the pediatric patient including a shorter area of exposed neck, steeper angle of entry in the average patient, and closer proximity of other critical anatomic structures including the carotid artery, trachea, and spine could influence successful placement.

For the purposes of discussing the non-cardiac applications in this manuscript, indicator orientation for non-cardiac procedures and diagnostics will be towards the patient's right or head (screen indicator to the left).

Femoral and subclavian vein catheterization

Literature regarding ultrasound-guided central venous access in the pediatric femoral and subclavian vessels has been described but is insufficient to generate a summary recommendation as reflected in a parallel Cochrane Library review.[8] Multiple authors describe the utility of ultrasound in pediatric femoral venous catheter placement,[8] however with summarily modest benefits compared with internal jugular placement. Femoral catheterization is well described using again primarily transverse visualization in contrast to longitudinal under active guidance.[8] Subclavian vein catheterization is less well defined and available literature utilizes both transverse and longitudinal visualization of the needle and vessel in adults.[8] An important pediatric consideration is the tighter arc of the axillary vein as it travels medially from below the anterior axillary fold, cephalad towards the mid-clavicle as it becomes the subclavian, and then caudad as it merges with the superior vena cava (SVC) behind the sternum. Placing a probe with a 2.5-cm face length longitudinally in the infraclavicular region of an infant or small child can intersect both the subclavian vein and artery, thereby making them appear to be the same vessel (Fig. 2a-c). Authors have also described accessing the subclavian vein in the supraclavicular region of infants and children.[9-12] A potential benefit of this approach is that it achieves upper extremity access and is less confined by the length of the patient's neck than an internal jugular approach. The method uses longitudinal visualization of the brachiocephalic vein as it merges with the internal jugular vein by following the internal jugular caudally until the brachiocephalic is visualized. Available literature is retrospective and case-based and does not describe a significantly different adverse effect rate of this procedure from other types of upper extremity access. Performing the procedure, one does notice that the trajectory of the needle is aimed centrally at the mediastinum and care should be taken to monitor the needle tip.

Arterial access

The use of ultrasound to assist peripheral and central arterial access has been described in the pediatric critical care[13] and anesthesiology settings.[14-16] Though the available evidence varies, the contemporary literature suggests an improvement in first pass success and number of attempts. Notably in a study by Kantor *et al.* use of ultrasound in arterial access improved success not only in trainees who used it primarily, but also among trainees who were experienced in landmark techniques.[13] This study was performed in radial artery catheterization, and it is likely applicable to peripheral artery catheterization in other anatomic areas given the relative anatomical concerns of other vessels such as the ulnar, dorsalis pedis, and posterior tibial arteries.

Peripheral venous access

The use of ultrasound for peripheral venous access has seen increased adoption in the pediatric arena recently not only as a means to obtain access on difficult patients, but also to reduce patient discomfort and increase provider safety and satisfaction at the bedside. Using a high-frequency linear transducer, the authors have reported that use of ultrasound can reduce stick attempts to approximately 1.3 attempts per patient with an over 97% success rate in the critically ill child by a team of vascular access personnel in an academic pediatric intensive care unit.[17] A major factor in this accuracy is the use of a transducer that can achieve a 20 MHz centre frequency or higher in the point-of-care ultrasound market, which is becoming increasingly available (L40-8/12 linear array, BK Ultrasound, Peabody, MA, USA; SL3116 linear array, Esaote North America, Fishers, IN, USA; L10-22 linear array, General Electric Healthcare, Chicago, IL, USA; UHF22, UHF48, UHF70 linear arrays, Fujifilm-VisualSonics, Toronto, ON, Canada; L20-5 linear array, Mindray North America,

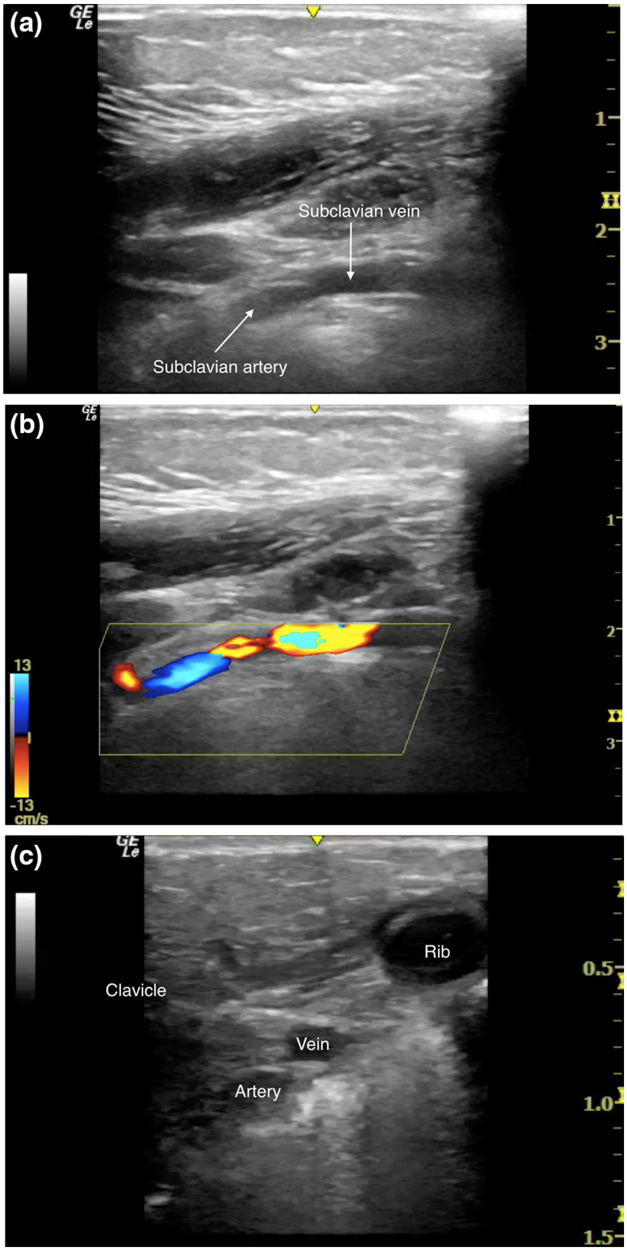

Fig. 2 a) A linear view of both the subclavian vein and artery can be seen nearly contiguously because of the arc of the vessels through the imaging plane (b) with colour-flow Doppler (c) shows a transverse view of the vessels

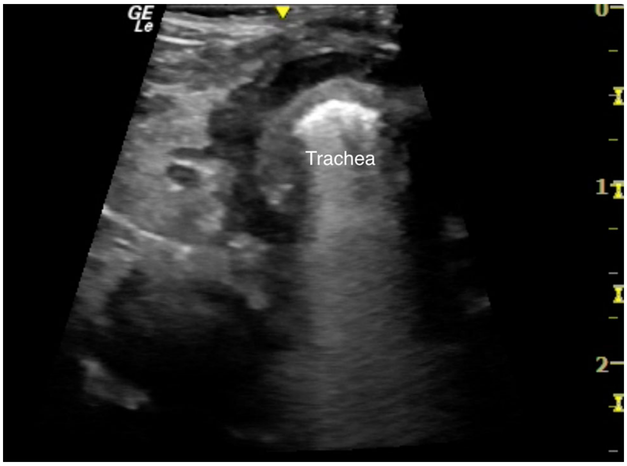

Fig. 3 Transverse image of the trachea from the anterior neck

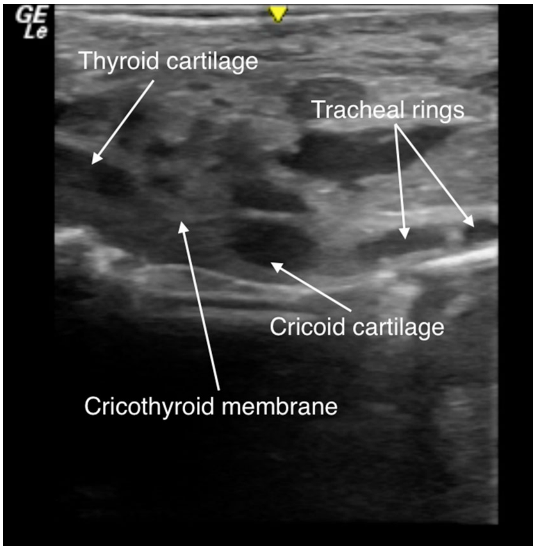

Fig. 4 Identification of the cricothyroid membrane via sagittal tracheal view

Mahwah, NJ, USA). Important considerations in ultrasound-guided peripheral vein catheterization include depth of insertion, as the technology permits visualization of veins a centimetre or deeper from the skin surface.[18] At depths of 10 mm, insertion of a 25-mm long cannula at 30° to the skin may only leave less than 3 mm of catheter in the vessel. Extravasation at these depths is also problematic because it may be diffuse and difficult to palpate, delaying detection and increasing the potential for injury. For these reasons it is recommended that intravenous catheters placed at these depths be longer than 25 mm. Colour-flow Doppler has also been described as a means of confirming intravenous placement in children and is readily implemented.[19]

Airway and pulmonary

Airway assessment

Airway ultrasound has also been used to identify tracheal diameter, with some studies describing superiority of the technique to conventional sizing methods.[20-26] With a linear transducer typically used for vascular access placed transversely on the trachea below the level of the larynx,

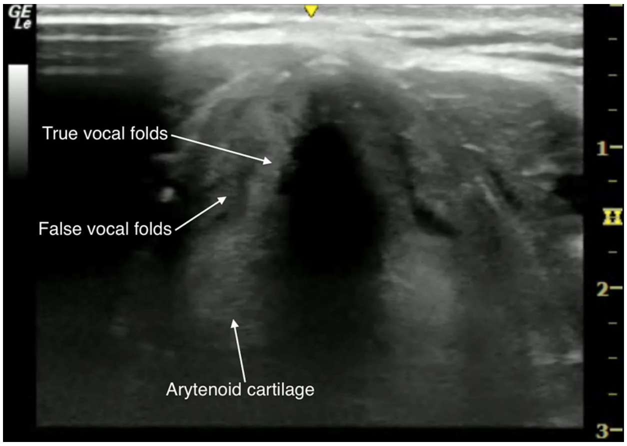

Fig. 5 Transverse view of the vocal folds from the cricothyroid membrane

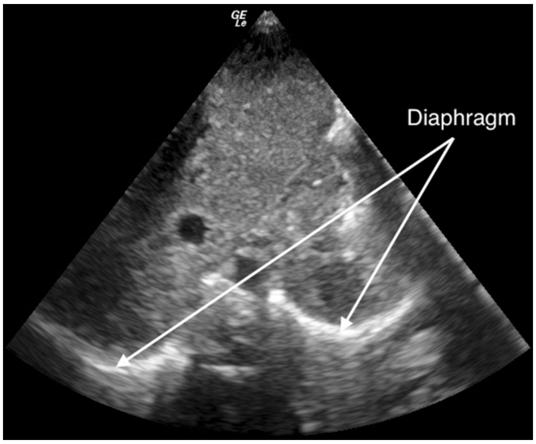

Fig. 6 View of the diaphragmatic recess axially through the liver from the subcostal position

the air shadow generated by the internal surface of the trachea is measurable for appropriate tracheal diameter (Fig. 3). Patients with irregular tracheal surfaces from subglottic stenosis or prior airway surgery may not be candidates for this technique.

Ultrasound has also been described for identifying the cricothyroid membrane[27] (Fig. 4). This may be of special importance in young children at risk for difficult intubation where the membrane may be small or nonexistent. With a linear transducer placed sagittally over the inferior border of the larynx, the cricothyroid membrane can be identified inferior to the larynx. In an anticipatory situation its position could be marked on the skin surface prior to surgery for access in the event of critical airway failure.

Vocal cord movement is also visible from the cricothyroid membrane by positioning a linear transducer transversely across the trachea at this position[27] (Fig. 5). Angling the probe such that the beam passes cephalad towards laryngeal structures, the true and false cords can be visualized. This is of potential utility in percutaneous injection procedures, and whether it is useful in identifying cord dysfunction after extubation or neck/chest surgery remains to be determined.

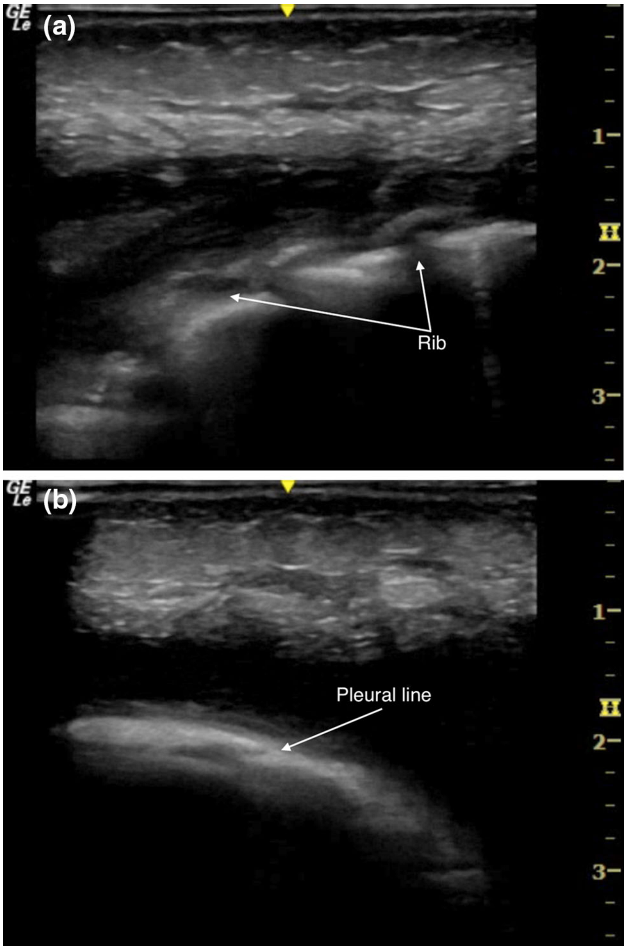

Fig. 7 a) Views of the lungs from the traditional coronal view and (b) intercostal in-plane view

Intubation

Multiple authors have described the utility of neck and lung ultrasound for confirmation of intubation in the pediatric operating room and intensive care unit (ICU).[28] Akin to adult methods, the trachea is visualized in a manner identical to that described above for endotracheal tube sizing. Placing the probe in position during intubation permits visualization of the tube as it passes through the trachea causing a sudden reduction in air column width.[29] Inadvertent esophageal intubation will be observed as passage of an air column through the esophagus instead of the trachea, posterior and slightly to the left of the patient's trachea. It should be noted that cricoid pressure cannot be readily performed in this situation as the ultrasound probe in the subglottic area and the skin will likely have gel on it.

An alternative means of intubation confirmation has been described where the diaphragm may be visualized from the subcostal margin.[30,31] Though a curvilinear, microconvex, or phased array probe has been used to assess the diaphragm, a linear probe may also be used along the patient's flank to see lung sliding as well.[32,33] In this application, the goal is to see movement of the lung with respect to pleural or diaphragmatic displacement following intubation so as to confirm tracheal placement of the tube. Differential movement of one diaphragm but not the other suggests mainstem intubation into the bronchus of the moving lung. Based on this finding, tube position can be adjusted until bilateral movement is evident. Using a curvilinear or phased array probe, movement of each hemidiaphragm can be either evaluated separately from mirrored positions under the costal margin of the chest or occasionally simultaneously when the probe is placed transverse to the aorta in the subxiphoid position, with the beam angled slightly upwards into the thorax (Fig. 6). Adequate visualization of the left hemithorax from subcostal positions benefits from *nil per os* status and may be difficult to see in emergency cases. In these instances, the left and right diaphragm leaflets can be compared from the flank position with the probe placed below the costal margin at the middle or posterior axillary line. Direct visualization of the endotracheal tube tip remains imprecise as this portion of the airway may be readily seen only in neonates.[34]

Similar to this technique, movement of the diaphragm can also be assessed by clinicians in pediatric patients at risk for failure of extubation and has been extensively described in the cardiac ICU setting. This technique in the hands of intensivists has also been found valid compared with fluoroscopy[35] and electromyography.[36] It is potentially useful in the management of the patient with potential diaphragm or phrenic injury or with muscle weakness, whether congenital or acquired.

Pulmonary assessment

In children rib ossification and the intercostal rib space can affect visualization. In the youngest patients, the immature ossification of the thorax improves visualization of intrathoracic structures. In the young child past infancy, narrow intercostal spaces and ossified ribs reduce the window for lung imaging. In this situation, the probe can be rotated to be in plane with the intercostal space to reduce obstruction from the ribs[1] (Fig. 7a-b). In this view, pleural movement can still be seen even as sliding occurs oblique to the plane of visualization.

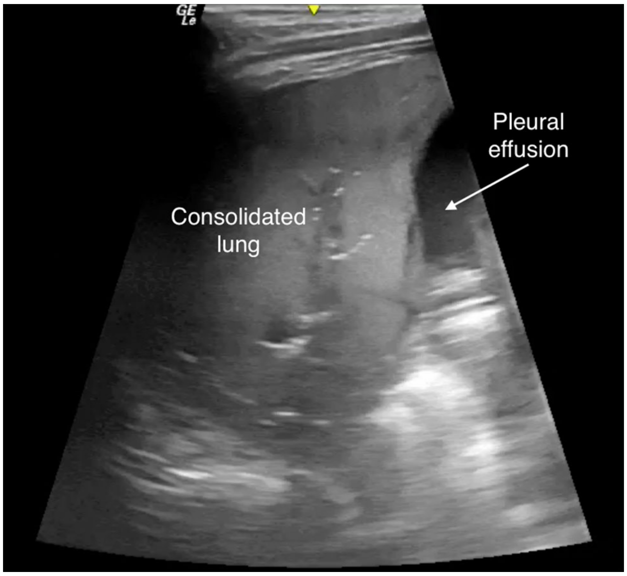

Fig. 8 Consolidated lung viewed axially from the anterior right chest

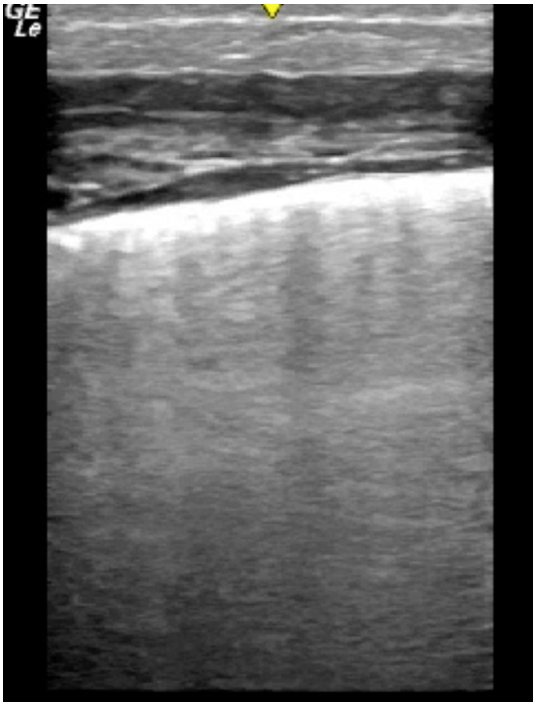

Fig. 9 B-line dense pattern consistent with interstitial pulmonary edema

Interstitial disease

Due to the effect of thermal losses from gel in the pediatric population, use of ultrasound benefits from practitioners having an index of suspicion for an area of pulmonary pathology prior to scanning to reduce the patient's exposure. Identification of an increased B-line pattern, as described in the lung ultrasound review in this issue, has

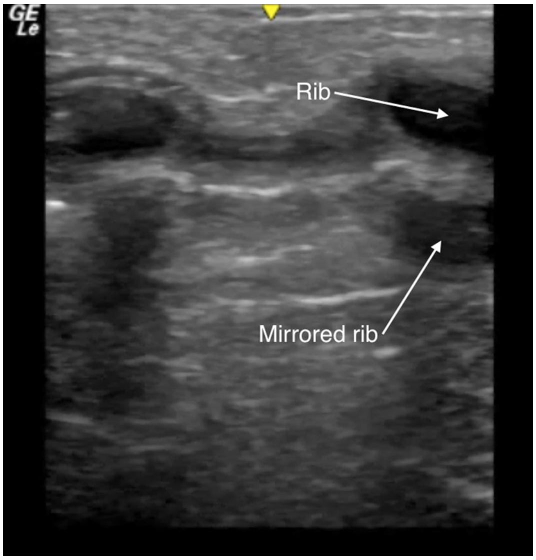

Fig. 10 Pneumothorax in an infant; figure-of-eight sign shown in ribs transparent to ultrasound mirrored across the pleural line

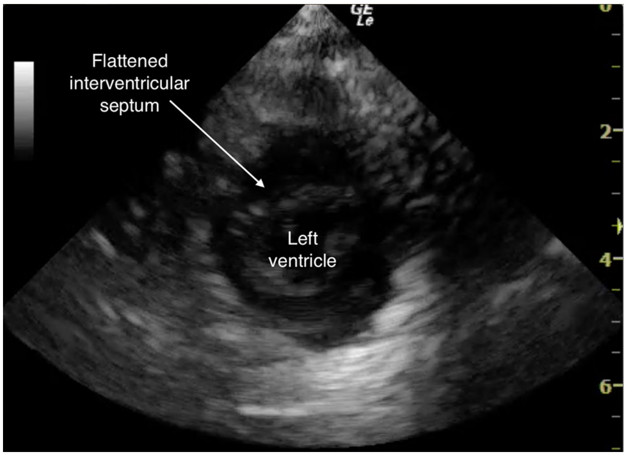

Fig. 11 Video Parasternal short-axis view at the mid-papillary level. Displacement of the interventricular septum (IVS) into the left ventricular chamber due to right ventricular pressure overload

been associated with several interstitial lung pathologies in children in addition to increased lung water and edema as described in adults. Shah *et al.* described an entirely B-line dense pattern in patients with a viral pneumonitis consistent with bronchiolitis.[37] This pattern has been described in contrast to pneumonia, which appears to be a pattern where the air spaces of the lung are less prone to artefact and appear more consolidated or "hepatized" where secretion filled alveoli no longer generate air artefact and the architecture of the diseased lung appears similar to the liver. Secretion-filled bronchi may appear anechoic, with air bronchograms appearing as bright streaks in the parenchyma (Fig. 8). Using these imaging characteristics, practitioners are able to differentiate pneumonia from bronchiolitis with 86% sensitivity and 89% specificity.

A B-line predominant pattern in the newborn (Fig. 9) has been associated with persistence of pulmonary edema and an increased need for subsequent noninvasive positive pressure ventilation[38] or even mechanical ventilation.[39] It has additionally been used to differentiate transient tachypnea of the newborn from pneumonia.[40] In this sense ultrasound likely has a role in outcome prediction and lung injury characterization.

Pleural disease

Pleural effusions in pediatric patients can be visualized using a linear array transducer in a manner similar to adults. Additionally, the size of the pediatric thorax permits identification of effusion from the subcostal position. A phased array or curvilinear probe placed transversely in the subxiphoid region and aimed up into the thorax can image pleural effusions behind the liver. This view permits a wide field view of an effusion that may capture the trajectory of thoracostomy drains and any complexity to the effusion better than is possible with the narrower field of a linear array.

Pneumothoraces in children appear largely similar to those seen in adult patients.[41] With mirroring of the chest wall structures across the pleural line, less ossified ribs that appear ovoid and do not obscure deep structures may be mirrored as well across the pleura and appear as a figure-of-eight (Fig. 10).

Cardiac

For the purposes of this cardiac discussion, view orientation will be discussed in the cardiac convention where the indicator appears to the right of the screen and is oriented towards either the patient's head or left. Though pediatric cardiology echocardiography often inverts the probe position to the bottom of the screen for subcostal or apical imaging, this discussion will maintain probe position for these views at the top of the screen as it facilitates ease of use among providers in the ICU setting. Views are obtained analogous to those described in the review of cardiac applications in this journal issue. Inferior vena cava views of the heart can be obtained from the subxiphoid position similar to those seen in adults. Given that hypovolemic shock is common in children, the calibre of the IVC in a dehydrated child can be narrow and difficult to detect.

Fig. 12 Transverse views of the abdominal inferior vena cava and aorta

Function

Head-to-head comparisons between focused cardiac ultrasound by pediatric intensivists and experienced echocardiographers are highly concordant as shown in multiple studies.[42,43] In the pediatric population it is important that operators take care not to foreshorten the small pediatric heart by passing the beam through it off axis to the left ventricle (LV), and sonographers should take care to optimize views across the largest chamber diameter visible before recording and interpreting an image. In addition to assessing motion of the left ventricle, other factors are relevant for assessment of LV function. This assessment includes consideration of the left atrial size, brisk mitral valve movement, thickening of the myocardium with contraction, and brisk opening of the aortic valve. Normal fractional shortening ranges between 25-45% of the LV diameter at the mid-papillary level, and normally the LV chamber is easily visible at the end of systole. Right ventricular (RV) dysfunction may also manifest as diminished movement of right-sided valves and myocardium. Nevertheless, given that the right heart is more compliant, dilatation of the right heart can be dramatic with compensatory chronic hypertrophy as a response to wall stress.[44] Focused cardiac ultrasound does not emphasize views of the right heart and therefore its assessment may be slightly more difficult than the left. Primary views for its evaluation in focused ultrasound include the parasternal short axis view to assess septal position (Fig. 11, Video, available as Electronic Supplementary Material), and the remainder of the views may identify RV dilatation, which is more prominent at the extremes of the disease.

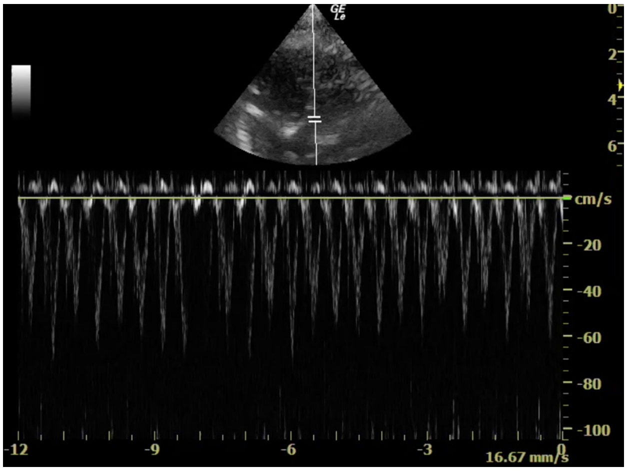

Fig. 13 Pulsed-wave Doppler spectra illustrating assessment of peak systolic flow across the left ventricular outflow tract through the respiratory cycle

Intravascular volume status

Though visualization and measurement of the IVC has been well described in the adult setting for both intubated and spontaneously breathing patients,[45] its use in children is less supported by the literature. It has been clearly shown in the operating room (OR) that induction and intubation markedly change the IVC calibre and respiratory variability even at low airway pressures such that these measures are not reliable as a determinant of intravascular volume status.[46] Even if they were to be used, available adult data suggesting that 12-16% variability in the IVC calibre through respiration indicate volume responsiveness is exceedingly difficult to determine in infants where the calibre of the IVC may only be 4 mm or less.[47] In the pediatric emergency department Chen *et al.* found that using a transverse view of the IVC and aorta to calculate an IVC:aortic ratio generated findings consistent with dehydration when the ratio was less than 0.8:1[48] (Fig. 12), and it has also been found that a ratio in excess of 1.2:1 was consistent with fluid overload in a population of children with renal failure.[49] Nevertheless, this index has not been evaluated as a measure of volume responsiveness and would expectedly also vary with intrathoracic pressure. Further examination is warranted into use of the technique to guide management.

Within the OR, the use of LV outflow tract (LVOT) Doppler has been described in the neurosurgery and cardiac surgery patient. The methodology for this is analogous to an adult technique for derivation of the cardiac output or aortic valve orifice area via the apical five-chamber view. In this calculation, a measurement of LVOT flow velocity is traced using pulsed wave Doppler with the probe cursor placed proximal to the aortic valve in the LVOT. On the Doppler spectra, running the tracing at a slow sweep speed (Fig. 13) ensures a maximal number of systolic stroke volumes captured for comparison over the respiratory cycle. In children care must be taken to place the cursor in the LVOT flow away from the chamber walls. Variability in peak LVOT velocity greater than 15% suggests volume responsiveness in these pediatric surgical populations.

Pericardial effusion

As in adults, pericardial effusion is readily identified in the subcostal view with the patient resting with the head inclined to 15° or more. Similarly, in the presence of shock and vital sign abnormalities such as pulsus parodoxus and tachycardia, identification of RV collapse in early diastole, collapse of the right atrium in mid systole, IVC plethora, and alteration in mitral valve inflow velocity of more than 25% through the respiratory cycle as determined using pulsed wave Doppler are indicative of tamponade physiology.[50]

Pericardiocentesis in pediatric patients can be assisted using cardiac ultrasound by placing the transducer in the region of the percutaneous needle insertion and identifying its track with the transducer to determine the depth of insertion to effusion. Usually this is performed in the subxiphoid position but can also be performed in the apical position depending on the insertion position. Monitoring the procedure performed with puncture at the subcostal position from the apical position is also possible; however, direct visualization of the needle on insertion is difficult and rare. Rather, confirmation of pericardial puncture can be determined by visualization of a Seldinger wire, injection of agitated saline or contrast, or watching drainage of the effusion though crude. Recently methods for pericardiocentesis have been described using a linear transducer placed longitudinally over the needle in the subxiphoid position.[2] With this arrangement the advancement of the needle into the effusion is dynamically monitored under direct visualization and the authors describe no complications of the technique.

Cardiac arrest

Use of ultrasound in the determination of reversible causes of cardiac arrest has been described in the medical literature, though infrequently.[51] The use of focused cardiac ultrasound is limited by practical constraints of attempting views within the ten seconds allotted for pulse checks. It is arguable that the greatest utility of the technique is early in an arrest when determination of a reversible cause could have the greatest impact on outcome. Potential reversible causes of arrest ultrasound could help identify include pericardial tamponade, hypovolemia, cardiogenic shock, RV failure, and pneumothorax. Aside from pneumothorax, the remaining four causes require cardiac views in between compression cycles. During a cardiac arrest it is important that ultrasound gel is wiped from the patient in between uses because of the potential for it to conduct electricity. At the authors' institution[52] cardiac arrest ultrasound is performed by a dedicated operator not responsible for other aspects of the code and focuses on image acquisition and recording during a ten-second pulse check clearly requested during the process of the arrest. The operator or team leader clearly counts down the amount of time hands are off of the chest for compressions, and if the operator cannot get the image or ten seconds are reached compressions are reinstated and the gel is wiped off. During compressions the data are reviewed and shared with the code team. By and large, only a single subcostal view is usually used because of the presence of defibrillator pads obstructing the parasternal and apical views. It is only in the cases of hypovolemia and pneumothorax that ultrasound is used to titrate therapies, as tamponade is remedied in cardiac arrest with pericardial drainage and therapies for RV or LV failure do not necessarily lead to rapid changes in cardiac ultrasound unless the loading conditions of the heart change significantly. A sonographic finding of an akinetic heart, known as cardiac standstill in the adult-focused cardiac ultrasound literature, has been associated with failure to achieve return of spontaneous circulation. Though in adults in some populations this has been implemented as an indicator to cease resuscitative efforts, the experience at the authors' institution has been that if patients are otherwise potential candidates for veno-arterial extracorporeal membranous oxygenation therapy, cardiac function can recover on this support.[53]

Gastrointestinal tract

Imaging of the stomach for gastric contents can be performed in a manner analogous to that seen in adults.[54,55] Use of ultrasound to identify peritoneal fluid has been described in pediatric abdominal trauma. Accuracy is affected by operator skill and some series describe dismal performance of focused assessment with sonography for trauma (FAST) in identifying bleeding in the trauma setting.[56] The presence of free fluid is suspicious for intraabdominal blood loss; however, lack of an anechoic fluid-filled area does not necessarily exclude injury. In a large-scale prospective evaluation of the efficacy of the FAST examination in the emergency room setting it was not found to improve outcomes or resource utilization.[57] Its effect in the OR and ICU in terms of detection of free abdominal fluid of non-trauma etiologies

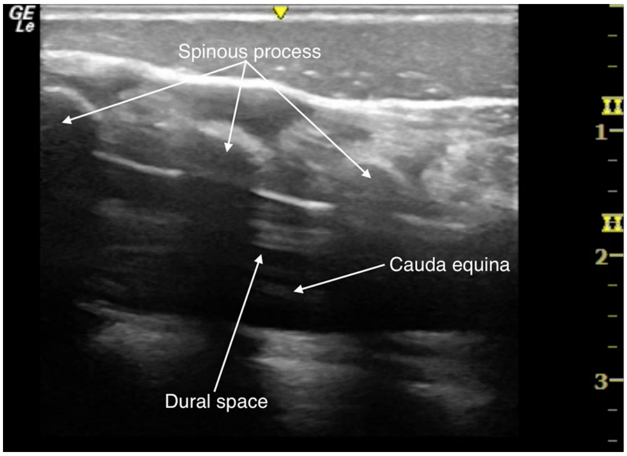

Fig. 14 View of the cauda equina and filum terminale in sagittal views for lumbar puncture in an infant

is undetermined however. Techniques described for abdominal ultrasound in trauma can also be used in patients with ascites in the evaluation of pathology and planning for paracentesis. Though Morison's pouch and the retrovesical space are common areas where fluid is seen in trauma, it is important to consider that the patient is typically flat in this setting similar to the OR. In the inpatient setting, the inclined inpatient may show fluid pooling in the lower abdominal quadrants instead.

Neurological

Regional anesthesia and lumbar puncture

The practice of regional anesthesia in children is affected by the frequent need for sedation to accommodate the procedure. Developmental age is also relevant to determine adequacy of the block and whether any sensory or motor deficits persist after the block. Otherwise techniques are largely analogous for specific blocks.

Regarding lumbar puncture, the procedure can also be facilitated by pre-procedure ultrasound marking of the site, measurement of the insertion angle, and estimation of depth. In infants the dura and its contents may be visible including the spinal fluid and cauda equina and filum terminale. After successive attempts, at times hematoma and obliteration of the dural space can be identified precluding further attempts as well[1] (Fig. 14).

Neurosonology

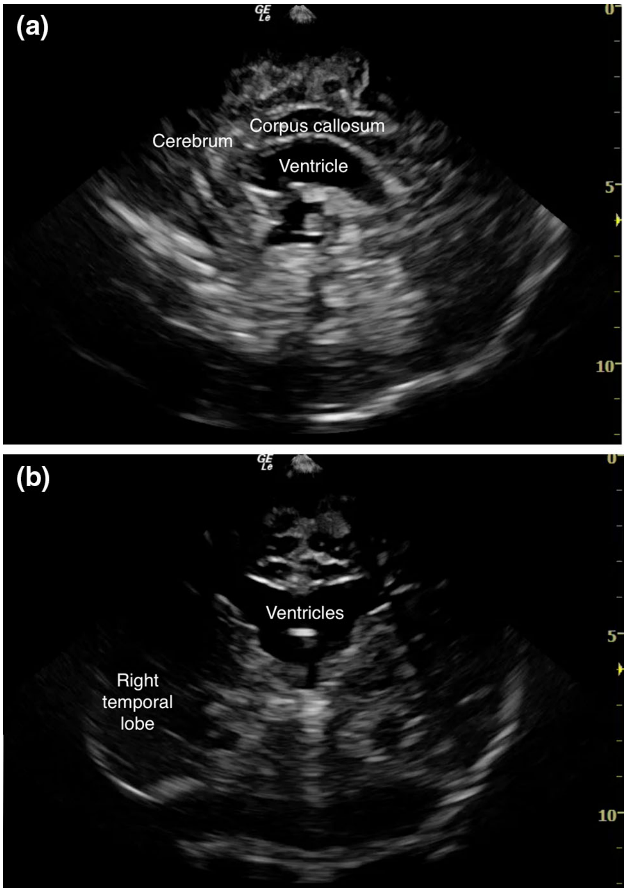

Fig. 15 a) Sagittal view of the head from the anterior fontanelle in an infant; b) coronal view

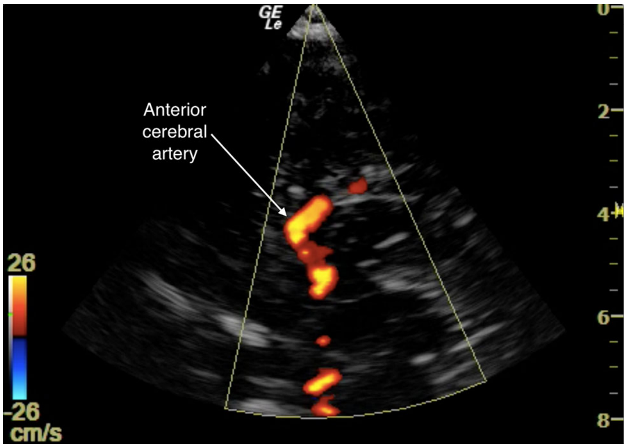

Fig. 16 Transcranial Doppler of the anterior cerebral artery

Use of ultrasound for visualization of the brain through the fontanelles of the immature skull has been well defined in pediatric radiology as a modality introduced in the neonatal setting when 2D obstetrical ultrasound was used to image the neonatal brain. Neonatal brain imaging is routinely practiced by neonatologists in some institutions around the globe, though education and clinical implementation vary significantly.[58] Views of the brain are typically obtained in sagittal (Fig. 15a) and coronal sweeps (Fig. 15b) of the brain obtained from the anterior fontanelle in infants. A posterior fontanelle can also be used if it is open as well. With ultrasound, intraventricular pathology tends to be most clear. Extra-axial blood, as seen in subdural hemorrhage, may be difficult to see from the fontanelles. Additionally, stroke may be very difficult to see as the ischemic changes do not generate significant sonographic contrast early in the process.

Transcranial Doppler

Use of ultrasound for transcranial Doppler is also commonly performed in infants via the anterior fontanelle under direct imaging. Applications for transcranial Doppler are primarily for monitoring of vasospasm in the cerebral arteries related to subarachnoid hemorrhage and stroke,[59] and some explorations have been made into its use in determination of intracranial pressure (ICP), though evidence suggests that this method is imprecise.[60,61] Traditional transcranial Doppler can be performed with either a two-dimensional (2D) ultrasound machine with pulsed wave Doppler functionality (Fig. 16) or a dedicated transcranial Doppler machine with Doppler functionality but no 2D imaging capability.[62] In the absence of a 2D image, the architecture of the cerebral vessels is directly visualized and is instead inferred from the Doppler velocities and probe position. In adult transcranial Doppler,[63] standard depths are used, though this is not practical in children because of child development. The methodology has been shown to suggest an association between increased cerebral vessel velocity and the eventual development of intracranial hemorrhage in pediatric extracorporeal membrane oxygenation patients.[64] Further development of this monitoring application is ongoing.

Optic nerve sheath diameter

This application has been an area of intense interest in recent years as a noninvasive quantifiable metric for papilledema and increased ICP. It has been described in children and an enlarged sheath diameter has been associated with increased ICP in children with neurological pathology in some series.[65] Studies have also shown persistently increased sheath diameter in patients with chronically elevated ICP in the setting of shunted hydrocephalus even after it has normalized.[66] This phenomenon is also well described in craniosynostosis patients with persistence of papilledema findings after resolution of intracranial hypertension.[67] As such, interpretation of results should be performed within the context of the patient's neurological history. The technique may also be prone to foreshortening error and depends on alignment of the probe across the centre of the optic nerve to ensure accurate measurement of the widest point of the optic nerve sheath. Ophthalmic ultrasound requires a reduction in ultrasound power to protect the retina from injury. Some machines have ophthalmic settings, and others permit reduction such that the mechanical index of the ultrasound beam is less than 0.4 and the thermal index is less than 0.5, though as low as is reasonable to permit imaging is best.[68] Measures should be taken to protect the eye from gel and some practitioners use a transparent adhesive dressing to prevent gel from entering the eye. Others might use a well-cleaned transducer and ophthalmic lubricant gel. The probe is placed transversely (axially) across the upper eyelid and aimed medially towards the centre of the head to capture the path of the optic nerve sheath (Fig. 17), and measurements are typically performed 3 mm behind the optic disc for standardization.

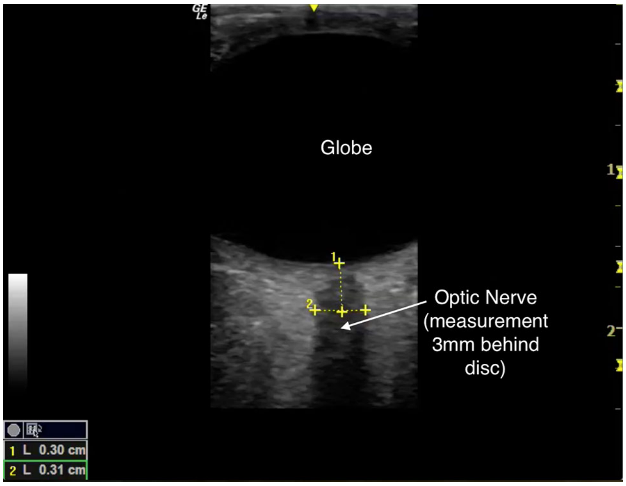

Fig. 17 Optic nerve sheath view for measurement via axial view of the left eye through the optic disc

Education, credentialing, and certification

Limited literature is available regarding the education of anesthesiologists and intensivists on pediatric point-of-care ultrasound. The pathway for education leading to credentialing has typically taken a two-pronged approach similar to that used in adult emergency medicine.[69] Experienced practitioners who have completed training are asked to participate in a brief dedicated course and then complete a program of image acquisition and review with a mentor. Trainees are asked to participate in a system of residency or fellowship didactics and practical experiences. Conlon *et al.* described feasibility in the pediatric ICU setting in a 2015 article detailing the construction of the program at the Children's Hospital of Philadelphia,[70] and ongoing curriculum development is occurring in various institutions worldwide as equipment becomes increasingly approachable and economical. Recommendations also exist in neonatology for the practice of targeted neonatal echocardiography with somewhat more extensive criteria given the increased potential for undiagnosed congenital heart disease.[71] At the present time ultrasound education and practice in the pediatric anesthesia setting are lacking and would benefit greatly from ongoing development of airway and regional anesthesia methods such that the impact of ultrasound's diagnostic and procedural performance in these areas is better understood.

Certification for practitioners to perform ultrasound independently in the pediatric setting has been largely limited to fellowship experiences in diagnostic specialties, with the exception of ultrasound fellowships in pediatric emergency medicine. One route for certification through testing is pursuit of a pediatric registered diagnostic sonographer certificate in a practitioner's country of practice. In Canada, this is administered by Sonography Canada (Échocardiographie Canada) and in the United States this is the American Registry of Diagnostic Medical Sonographers. Others have pursued the board examinations of the National Board of Echocardiography (NBE) in the United States; however, there are no pediatric certificates offered by this organization. In 2019, it is anticipated that the NBE will offer an examination of Critical Care Echocardiography for clinicians of all specialties to seek certification in clinical applications of ultrasound largely focusing on the heart and lungs.[72] Though this will be targeted at adult providers, it is anticipated that the substance of the examination will have broad applicability to the pediatric setting.[73]

Conclusions

In summary, ultrasound has seen broad and meaningful inroads into clinical practice for the anesthesiologist and intensivist who cares for infants and children. An ongoing interest in its application has yielded meaningful advancements in procedural performance and the assessment and management of pulmonary and hemodynamic conditions among others in the intra- and perioperative settings. That said, much remains to be elucidated in terms of the technology's performance in its expanding role in the pediatric setting. One must be wary of extrapolating evidence regarding adult modalities to their use in children. These issues will be clarified if anesthesiologists and intensivists who care for children pursue evaluation of point-of-care ultrasound with the same enthusiasm that surrounds the use of this technology at the bedside.

Conflicts of interest Dr. Erik Su has a research project on catheter associated thrombosis supported with loaned ultrasound equipment by General Electric Corporation.

Editorial responsibility This submission was handled by Dr. Gregory L. Bryson, Deputy Editor-in-Chief, *Canadian Journal of Anesthesia.*

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