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Bedside ultrasound in pediatric critical care: A review

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Abstract

Objective—Bedside ultrasound, as performed by the intensivist, is gaining in popularity and has become a powerful tool to understand the physiological state of the critically ill patient and to decrease procedural risks. This review assesses clinical applications of bedside ultrasound in the pediatric intensive care unit.

Design—A literature review was conducted to identify English language studies in Pubmed as of June, 2010, using combinations of the following search terms: 'pediatric,' 'ultrasound,' 'critical care,' and 'intensive care.' Examination of reference lists of these studies yielded additional studies. Studies were reviewed by both authors.

Setting—Intensive care unit, emergency department, or operating rooms, as relevant to application of bedside ultrasound in the pediatric intensive care unit.

Patients/Subjects—Pediatric patients (age 0–18 yrs) with adult patients (>18 yrs) in relevant studies utilizing bedside ultrasound by the treating clinician.

Interventions—Bedside ultrasound by treating clinician.

Measurements—Variable, per individual studies.

Main Results/Conclusions—Bedside ultrasound, as practiced by the pediatric intensivist, has the potential to improve pediatric critical care medicine, but data supporting its use is limited. Further studies are needed to explore applications, with specific emphasis on the training and experience of ultrasound operators. There is a need for a standardized educational curriculum, and questions remain as to the optimal mode of education and quality assurance of ultrasound operators.

Keywords

ultrasound; intensive care; critical care; pediatric

Ultrasound, as performed at the point of care by the bedside clinician, is becoming more widely used in clinical practice. Although the technology incorporated in ultrasonography has been available for some time, recent advancements have improved image quality and capabilities while reducing overall size and bulk of the equipment. The result is that ultrasonography as a technology is more user-friendly and available to the bedside clinician (1). As a result of the greater portability of these new machines, ultrasound has been used in many locations in clinical settings, including emergency departments and intensive care units. Ultrasound has become a powerful tool for the intensivist to better understand the

physiological state of the critically ill patient (2, 3), to assist in the evaluation of traumatic injuries (4), and to decrease the morbidity associated with procedures (5).

Bedside ultrasound has traditionally been performed by technologists or physicians with extensive training such as certified ultrasonographers, cardiologists, or radiologists. However, bedside ultrasound as performed by the treating clinician (e.g., a noncardiologist or a nonradiologist) has two unique advantages: ready availability in a time-critical situation and immediate availability for serial studies assessing the response to therapeutic intervention. Other advantages of ultrasound include machine portability, lack of radiation, and low expense.

The major disadvantage to ultrasound has been the dependency on the user's skills and training. However, recent studies have demonstrated that training programs can accurately teach focused ultrasound skills, in a short time, to bedside clinicians (6–9). Recently, intensive courses as well as national guidelines have been developed to ensure the appropriate training of individuals who perform bedside ultrasound on critically ill or injured patients (4, 10).

Although the bedside clinician may not have had formal educational certification, he or she can contribute to the care of the patient using the focused ultrasound examination to augment physical examination findings or to enhance performance with procedures. In this context, the bedside point-of-care ultrasound is complementary to the routine physical examination as well as more thorough formal ultrasounds or echocardiograms done by radiology or cardiology, respectively. Indeed, focused clinician-performed ultrasounds, which can be done serially to assess the response to therapeutic interventions, provide the advantage of immediate assessment but do not negate the potential need for formal studies performed by certified ultrasonographers, radiologists, or cardiologists. As an example of a focused examination, a study by Beaulieu (11) identified left and right ventricular function, presence or absence of pericardial effusion and/or cardiac tamponade as well as volume status as distinct items to assess. A formal echocardiogram will help address a broader range of questions, including the concern for structural heart disease or pulmonary hypertension. Therefore, when contemplating the use of bedside ultrasound, the clinician must have a focused set of questions to be answered in a timely fashion as well as a clear understanding as to the limits of ultrasound technology.

Studies investigating the use of point-of-care bedside ultrasound in pediatrics are limited and are focused mainly on the use of ultrasound in obtaining vascular access. Certainly for the bedside clinician, this is an important consideration, but there are many more potential applications that have yet to be explored. This review focuses on the evidence, mainly in adult patients, describing the potential applications for the use of bedside ultrasound by a pediatric intensivist in the intensive care unit, including the following: use in assessment of hemodynamic status; monitoring of intracranial pressure; assessment of pneumothorax; drainage of pleural effusions; assistance with vascular access; and use in other procedures, including lumbar puncture and paracentesis. Although pertinent literature from emergency room settings is cited, full discussion of ultrasound use in pediatric trauma is beyond the scope of this review.

METHODS

We conducted a search of the medical literature with the last search being performed in June 2010. Searches were limited to English language using several combinations of the following search terms: “pediatric,” “ultrasound,” “critical care,” and “intensive care.” We limited the articles to those with the primary purpose to describe the use of bedside

ultrasound in a clinical situation on humans. Additional articles were included after examination of reference lists of these studies included studies we had not collected. Twenty-one studies were identified. Both authors reviewed all studies individually. A joint summary of each article was compiled before inclusion in this review.

Vascular Access

Central Venous Catheter Placement—Ultrasound-guided placement of central venous lines (CVLs) in adult patients is one of the most frequently studied indications for bedside use of ultrasound by the treating clinician (Fig. 1 for an example of ultrasound visualization of the internal jugular vein and carotid artery). In 2001, the Agency for Healthcare Research and Quality recommended use of dynamic, real-time ultrasound guidance for placement of central venous lines to improve patient safety (12). Subsequently, in 2002, the National Institute for Clinical Excellence in the United Kingdom recommended that two-dimensional imaging ultrasound guidance be used in elective situations for insertion when inserting of internal jugular (IJ) CVLs in both adults and children (13). Similarly, the American College of Emergency Physicians stated that use of ultrasound for CVL placement has a Level I recommendation (14). These recommendations are based on a significant amount of data in adult patients. A meta-analysis of 18 adult trials (15) found that ultrasound use for IJ cannulation was associated with a lower overall failure rate (relative risk 0.14) as well as lower failure rate on the first attempt (relative risk 0.59). Fewer complications were seen with ultrasound use for IJ cannulation. There was more limited evidence supporting the use of ultrasound for subclavian and femoral vein cannulation.

Notably, the recommendations from the Agency for Healthcare Research and Quality in 2001 recommended dynamic, real-time ultrasound guidance during cannulation (“watching the needle puncture the vessel”) as opposed to static “quick look” for guidance before cannulation (12). This distinction was evaluated in a randomized controlled trial of 201 adults. IJ cannulation was improved with both static (82%) and dynamic ultrasound (98%) compared with landmark methods (64%). Dynamic ultrasound improved overall cannulation success (98% vs. 82%), first-attempt success rates (62% vs. 50%), mean number of attempts (2.3 vs. 2.9 attempts), and mean time to cannulation (109 vs. 126 secs) when compared with static ultrasound. The authors’ final conclusion of their data are that dynamic ultrasound should be used whenever the operator is appropriately trained; however, using static ultrasound may be necessary when the personnel have limited training (16).

For pediatric patients, fewer studies are available investigating the use of static or dynamic ultrasound guidance (Table 1). Two studies have used static ultrasound assistance for IJ cannulation. In the first study (17), 40 infants <2 yrs old were randomly assigned to IJ localization through static ultrasound by cardiac anesthetists precannulation or IJ localization through landmark techniques. The degree of training in the use of ultrasound by the users was not mentioned, but the group using ultrasound had greater success rate (100% vs. 80%), required less time to cannulation (mean, 23 vs. 56.4 secs), and fewer attempts (mean, 1.35 vs. two attempts). In the second study (18), 62 infants were randomly assigned to the IJ localization group through static ultrasound precannulation localization or the IJ localization group through landmarks. The group using ultrasound had improved cannulation rate (100% vs. 80%), decreased carotid puncture rate (3.1% vs. 26.7%), and a decreased number of attempts (mean, 1.57 vs. 2.55 attempts). No mention was made of the operators’ prior experience or training.

Studies by Verghese et al (19, 20) investigated the use of dynamic ultrasound imaging to place IJ CVLs in infants before scheduled cardiac surgery. In their first study of 95 infants (19), they found that the use of ultrasound imaging reduced the number of cannulation attempts (median attempts, one with ultrasound imaging vs. two without ultrasound

imaging), time to catheter placement (median, 3.3 mins with ultrasound imaging vs. 10 mins without ultrasound imaging), fewer carotid punctures (0% with ultrasound imaging vs. 25% without ultrasound imaging), and a higher success rate (100% with ultrasound imaging vs. 77% without ultrasound imaging). In the follow-up study of 45 infants (20), the same authors compared IJ placement using three different techniques: landmark technique, external ultrasound with image display, and an internal ultrasound technique (a continuous-wave Doppler was built into an introducer needle; this produced auditory signals to guide the user in differentiating between the IJ and the carotid). The authors found that time for cannulation was shorter with external ultrasound compared with internal ultrasound but not compared with the landmark technique. The median number of cannulation attempts was lower in the external ultrasound group (1) compared with the internal ultrasound (2) and landmark techniques (2). However, there was no significant difference in success rate or carotid puncture between groups.

A retrospective review of pediatric surgery patients undergoing IJ CVL placement noted a higher success rate with dynamic ultrasound guidance (21). However, the improvement in success was limited to children >1 yr of age and >10 kg in weight and there was no difference in the rate of traumatic complications. In contrast, in a study of 124 infants and children scheduled to undergo heart surgery, Grebenik et al (22) prospectively randomized patients to a dynamic ultrasound assisted group or a landmark groups for IJ CVL placement. The authors found a higher success rate (89% with ultrasound assistance vs. 78% in the landmark group) and a lower arterial puncture rate (6.2% with ultrasound assistance vs. 11.9% in the landmark group) with the landmark technique. The primary limitation to this study is an inadequate assessment of experience of the operators (pediatric cardiac anesthesiologists) using ultrasound in the placement of IJ CVLs. Prior experience with ultrasound assisted IJ CVL placement varied, but each physician had placed at least five CVLs with ultrasound. There is no indication of whether this number of cannulations is enough to achieve competency and how this number compares with operator experience with the landmark technique.

In a recent study, Froelich et al (23) prospectively randomized 212 patients in the pediatric intensive care unit slated for CVL placement to either the dynamic ultrasound-assisted group (93 patients) or the landmark group (119 patients). The authors found no difference in overall success rate or time to successful CVL placement. However, the need to attempt greater than one site was higher in the landmark group (21% in the landmark group vs. 6% in the ultrasound-assisted group) as was the number of attempts (40% in landmark group required four or more attempts vs. 20% in the ultrasound group). In addition, there were fewer arterial punctures in the ultrasound-assisted group (8.5% with ultrasound assistance vs. 19% in the landmark group). Further subgroup analysis showed that the time to successful placement by trainees was shorter with ultrasound, and residents required a greater number of attempts. This suggests that ultrasound assistance may benefit those with less experience in placing CVLs.

Studies in pediatric patients investigating the use of ultrasound assistance also suggest a benefit for cannulation of the subclavian and femoral veins. In a prospective feasibility assessment of dynamic ultrasound use for subclavian vein cannulation, Pirotte and Veyckemans (24) showed that the subclavian vein was cannulated with a success rate of 84% on the first attempt using a supraclavicular dynamic ultrasound-assisted approach, which improved to 100% success rate with a second attempt. There was no comparison with landmark methods. A study by Iwashima et al (25) investigated the use of dynamic ultrasound assistance for femoral vein cannulation in 87 infants with congenital heart disease who were scheduled to undergo cardiac catheterization. Success rates did not differ between the ultrasound and landmark groups, but inadvertent femoral arterial puncture did

occur more commonly in the landmark group (32% in the landmark group vs. 7% with ultrasound assistance).

Taken together, these studies in children suggest possible benefit for ultrasound assistance in CVL placement but also indicate the complexities of studying ultrasound use for CVL placement. Operator experience in placing CVLs through landmark methods is important as is the experience with using ultrasound assistance. Training and documentation of training in ultrasound modalities will be important in future studies. In addition, size and weight of the child may play a role as well as the hemodynamic status of the child when the CVL was placed. Finally, most of the data examines IJ CVL placement, although femoral vein CVL placement, particularly in emergent situations needs to be assessed.

Radial Arterial Catheter Placement—Placement of a radial arterial catheter in some cases can be accomplished easily through palpation techniques. However, in many situations, radial artery catheterization can be more difficult than expected. The use of ultrasound to aid radial artery catheterization has been studied in adults and children.

In a study of adult patients undergoing elective surgery, Levin et al (26) randomized 69 patients to either radial artery cannulation with ultrasound guidance or through a classic palpation technique; ultrasound guidance led to a higher success rate of cannulation (62% in the ultrasound assisted group vs. 34% in the landmark group) with fewer attempts required in the ultrasound assisted group (mean, 1.6 attempts with ultrasound assistance vs. 3.1 attempts in the landmark group). Similarly, ultrasound use for radial artery cannulation in the emergency department was associated with significantly fewer placement attempts (mean, 1.2 attempts with ultrasound assistance vs. 2.2 attempts with palpation method) and decreased time for cannulation (mean, 107 secs with ultrasound assistance vs. 314 secs with palpation method) (27).

Two studies investigated the use of ultrasound-guided arterial cannulation in pediatric patients. In the first study, Schwemmer et al (28) prospectively randomized 30 children to radial artery cannulation with ultrasound guidance vs. traditional palpation method. They found that the use of ultrasound increased success rate (100% success with ultrasound guidance vs. 80% success with palpation method) and decreased attempts at radial artery cannulation (mean, 1.3 attempts with ultrasound guidance vs. 2.3 attempts with palpation method). However, in a prospective randomized study of 152 children in the operating room, Ganesh et al (29) found that use of ultrasound did not change the success rate, time, or attempts for radial artery cannulation. Again the experience of operators with the ultrasound technique vs. landmark technique is a limitation of this study. All cannulations were performed by pediatric subspecialty trainee anesthesiologists or consultant anesthesiologists. None had done more than ten ultrasound-guided radial artery cannulations; operators may have been more familiar with traditional palpation techniques.

Therefore, it is unclear if ultrasound guidance will aid radial artery cannulation in pediatric patients. Such procedures are often quite difficult given the small size of the radial artery, especially in infants. However, the size of the ultrasound probe and requisite hand-eye coordination may also make the use of the ultrasound more difficult.

Difficult Peripheral Venous Access—Similar to arterial catheterization, placement of a peripheral intravenous catheter (PIV) is often straightforward but can be difficult in specific cases. A study by Costantino et al (30) found that ultrasound assistance performed by emergency medicine residents and faculty to place a PIV in adult patients with difficult venous access significantly improves success rates, decreases time and attempts, and was associated with greater patient satisfaction. In a subsequent study by Costantino et al (31)

investigating the optimal approach to obtaining a PIV in adults with difficult venous access, the use of ultrasound as performed by emergency medicine residents to place peripheral intravenous catheters was compared with placement of a PIV in the external jugular vein through nonultrasound-based methods. Ultrasound-guided PIV placement was found superior to placement of an external jugular PIV in terms of success rate (84% for PIV placement with ultrasound guidance vs. 50% for external jugular PIV placement without ultrasound guidance). However, when an external jugular was clearly visible, there was no difference in success rate between the two techniques.

Three studies of pediatric patients have examined the use of ultrasound to facilitate PIV placement. In the first study of 44 children by Bair et al (32), ultrasound by pediatric emergency medicine faculty allowed visualization of PIVs, but there was no difference in overall success rates or in first-attempt success rates. A study by Schnadower et al (33) also showed that ultrasound by pediatric emergency medicine faculty allowed visualization of peripheral veins, and additionally that lack of ultrasound visualization predicted failure of PIV placement through standard non-ultrasound-based methods by individuals blinded to ultrasound results. Finally, in a prospective randomized study of patients <10 yrs old with either a history of difficult venous access or two unsuccessful attempts at PIV placement through traditional means, Doniger et al (34) showed that ultrasound improved the success rate (80% with ultrasound use vs. 64% with traditional means) of a peripheral intravenous catheter in fewer attempts (median, one attempt with ultrasound use vs. three attempts with traditional means) and less time (6.3 mins with ultrasound use vs. 14.4 mins with traditional means). In this study, pediatric emergency medicine nurses placed intravenous catheters in both groups, whereas pediatric emergency medicine fellows and faculty performed ultrasonography. Taken together, it appears that ultrasound assistance is a useful adjunct for placement of PIVs in patients with a history of difficult peripheral access.

Hemodynamic Assessment

Much has been written regarding the use of focused echocardiography by adult critical care physicians (see [35] for a complete review), but far less is known regarding the use of ultrasound for this purpose in children. As noted in a study by Bealieu (11), focused echocardiography is directed toward answering specific clinical questions and is in general much shorter in duration than formal echocardiography. Objectives should include determination of left ventricular and right ventricular function, assessment for pericardial effusion and tamponade, and assessment of volume status. Thus, focused echocardiography provides a diagnostic assessment of the current state of hemodynamics and requires a set of specific questions to guide therapeutic interventions. Diagnosis of the cause of impaired hemodynamics can lead to therapy in a timely fashion as a result of the use of bedside ultrasound by the treating clinician. For example, noninvasive focused hemodynamic assessment of a critically ill child might support clinical suspicion of low cardiac output, and inotropic support may be titrated accordingly. Similarly, respiratory variation of the inferior vena cava detected by ultrasound may indicate the need for fluid resuscitation. Serial measurements can be made as therapies are titrated, but without a focused question for the clinician to address, the advantage of immediate bedside ultrasound may be lost.

Several caveats need to be underscored. Significant user variation may be present in focused echocardiography, underscoring the importance of not relying on ultrasound data alone to make clinical decisions; such data should be integrated with the physical examination and other data elements that have traditionally been available such as central venous pressure monitoring. In addition, children may be less cooperative with the examination compared with adults and may require sedation to complete the study. Finally, there is a much wider range of structural and anatomic abnormalities in congenital heart disease than in adult heart disease. This can make interpretation difficult but can be mitigated with appropriate focus

on the clinical questions as well as referral for a formal echocardiogram when any suspicion for structural abnormalities arises during the examination.

Data supporting the use of ultrasound for hemodynamic assessment in children by bedside clinicians are limited. Two primary indications for such use are the identification of pericardial tamponade and assessing hemodynamic status by determining left ventricular function and volume status using respiratory variation of the inferior vena cava. One study showed that in 23 children, limited echocardiograms performed by pediatric critical care fellows and faculty were accurate when compared with standard echocardiograms in identifying left ventricular size (96%), left ventricular function (96%) as well as pericardial effusion (91%) (36). Training included 1 hr of focused instruction on the physics of ultrasound, applications, the ultrasound device, and standard echocardiographic views. This was then followed by 2 hrs of practical echocardiography training at the bedside under the supervision of a cardiologist. In a prospective observational study of 31 children, pediatric emergency medicine physicians were accurate in determining left ventricular shortening fraction ($r = .78$) and respiratory variation of the inferior vena cava ($r = .8$) for volume status assessment (37).

Emerging literature has suggested the incorporation of focused bedside ultrasonography in advanced life support protocols. For example, the Focused Echocardiographic Examination in Resuscitation (FEER) examination has been proposed as a ten-step procedure to be executed simultaneously and without undue interruption of cardiopulmonary resuscitation. This might help elucidate the underlying etiology of asystole or pulseless electrical activity (38). Although this has not been evaluated in detail, it may be an extremely important potential future application, because the integration of ultrasound into pediatric advanced life support algorithms may significantly contribute to diagnosis and treatment of peak endocardial acceleration, ventricular tachycardia as well as general evaluation and management of hypotension. Well-designed training and evaluation studies are necessary to fully define the role of focused bedside ultrasonography in the advanced life support algorithms.

Intracranial Pressure Monitoring

Several studies in adult patients have indicated that increased optic nerve sheath diameter, as measured by ultrasound, may be correlated with increased intracranial pressure (ICP) (see [39] for a complete review). An accurate noninvasive monitor for ICP would be of great value, particularly in the pediatric population in whom signs and symptoms of increased ICP are often nonspecific and subtle. In addition, such a monitor would be useful in children with coagulopathy, in whom the risk of intracranial monitoring is outweighed by the risk of bleeding (e.g., a child with acute liver failure).

However, pediatric studies are limited with three cases reported in which the optic nerve sheath diameter measured by pediatric emergency medicine physicians correlated with opening pressure on lumbar puncture as well as clinical signs and evidence of increased ICP on cranial computed tomography scan (40). Similarly, optic nerve diameter was reported by pediatric radiologists to be increased in elevated ICP (as determined by computed tomography scan and ophthalmoscopy) compared with children without increased ICP (41). Another study assessing increased ICP showed that ultrasound by pediatric emergency medicine physicians had a sensitivity of 83%, a specificity of 38%, positive likelihood ratio 1.32, and negative likelihood ratio 0.46 (42). Each of these studies used standard multipurpose ultrasound machines (same as used for focused echocardiography, for example) with probes ranging from 7 to 15 MHz. A major limitation of all of these studies is the reliance on noninvasive tests such as computed tomography as the gold-standard for comparison rather than direct ICP monitoring. Additionally, little information is provided

regarding training and achievement of competency of the ultrasound operators. Further studies are needed to compare noninvasive ICP monitoring through optic sheath ultrasound to direct ICP measurements.

Lumbar Puncture

Few studies have examined the use of ultrasound to aid in lumbar puncture. In two adult cases in which lumbar puncture was unsuccessfully attempted using traditional landmark methods, the use of ultrasound by emergency medicine physicians was helpful in ultimately obtaining cerebrospinal fluid (43). A study by Ferre and Sweeney (44) determined that emergency medicine physicians could easily obtain ultrasound images of relevant anatomic landmarks and ultrasound assistance resulted in a 92% success rate with greater physician satisfaction with the ultrasound-based technique compared with the traditional landmark technique. In the only randomized trial comparing traditional techniques with ultrasound-based techniques, Nomura et al (45) showed that ultrasound use by emergency medicine physicians increased the overall success rate (one of 24 failure rate with ultrasound vs. six of 22 without ultrasound). No such pediatric studies comparing ultrasound assistance with no ultrasound assistance have been published; however, in infants and neonates, ultrasound by pediatric radiologists was able to facilitate difficult lumbar punctures and help diagnose the reason for the initial failure of traditional landmark methods (46) suggesting a possible use of bedside ultrasound use for lumbar punctures, particularly for difficult lumbar punctures in pediatric patients. Again, in each of these studies, there is limited information regarding training and competency of the operators.

Detection of Pneumothorax

Data from studies in adult patients have indicated the ultrasound is useful for detection of nontraumatic pneumothorax (47–51). An algorithm for adult intensivists has been proposed in a study by Lichtenstein et al (50) for detection of occult pneumothorax (not seen on chest radiograph), which shows a sensitivity of 95%, specificity of 94%, positive predictive value of 71%, and negative predictive value of 99%. This algorithm starts with evaluation of lung sliding, a “to-and-fro movement visible at the pleural line caused by the inspiratory excursion of the lung...,” and continues with evaluation of A-lines and lung point (two other artifacts seen in lung ultrasound) to generate the algorithm to detect occult pneumothorax (50). Similarly, several studies in adult trauma patients have indicated increased accuracy of ultrasound over chest radiograph for detecting pneumothorax (see [52–54] for complete reviews). One case report (55) in a neonate showed detection of pneumothorax through ultrasound performed by a radiologist, but the use of ultrasound for diagnosing pneumothorax in pediatrics remains largely unknown.

Drainage of Pleural Effusions

Pleural effusion is frequently found in critically ill patients necessitating drainage for diagnostic and/or therapeutic purposes. Iatrogenic pneumothorax is the main risk of thoracentesis with rates ranging from 2% to 30% (56, 57). Researchers have studied the use of ultrasound guidance for thoracentesis to improve success rates and decreasing iatrogenic pneumothorax (57– 62) (Fig. 2 for an example of a large pleural effusion as seen on ultrasound).

A retrospective study of 342 thoracenteses done in adult patients showed the use of ultrasound was associated with decreased pneumothorax rates (57). However, in a prospective study to determine the use of chest radiographs after thoracentesis, no differences were found in the rate of pneumothoraces with the use of ultrasound compared with the use of chest radiography alone. However, the study was not designed as a comparison of ultrasound vs. traditional methods for thoracentesis. Consequently, only 5%

of thoracentesis were done using ultrasound guidance, limiting interpretation of the study's findings (58). Similarly, a study by Petersen and Zimmerman (62) noted pneumothoraces in five of 36 (14%) thoracenteses done with ultrasound guidance as compared with 13 of 242 (5%) thoracenteses performed with ultrasound assistance. This was nonsignificant ($p = .05$), but interpretation is limited because only a small percentage of overall thoracenteses was done with ultrasound assistance (13%).

In a more recent prospective study (61), the complication rate of thoracentesis for pleural effusion performed with ultrasound assistance was 2.5%. However, no direct comparison within the study with a control group was made, and potential confounding factors of operator experience as well as selection bias may have influenced the results. A study by Barnes et al (59) directly compared ultrasound-based thoracentesis with nonultrasound-based thoracentesis and found that the routine use of ultrasound during diagnostic thoracentesis was associated with a lower rate of pneumothorax (4.9% if ultrasound was used vs. 10.3% if ultrasound was not used) and tube thoracostomy (0.7% if ultrasound was used vs. 4.1% if ultrasound was not used). Finally, implementation of a simulation-based training module (which included standard use of ultrasound) to decrease the rate of pneumothorax after thoracentesis significantly reduced the rate of iatrogenic postthoracentesis pneumothorax from 8.6% in patients in whom the treating physician received no training to 1.1% in patients in whom thoracentesis was performed by physicians after simulation training (60). Although not definitive, these studies suggest after proper training in a simulated environment, there is a benefit of ultrasound guidance for thoracentesis in adult patients. However, other factors besides the ability to visualize the lung and instruments may play a role in the rate of iatrogenic pneumothorax, including presence of loculations, size of effusion seen, volume of fluid removed, underlying patient condition, need for repeated thoracentesis, and operator experience (56, 57, 59, 61). The interaction between the use of ultrasound and these other factors remains to be determined.

No data in pediatric patients comparing use of ultrasound for thoracentesis with nonultrasound-based methods have been published, but because of the smaller size of the thorax in children compared with adults, it seems reasonable to investigate the use of bedside ultrasound in performing thoracentesis in children.

Paracentesis

Data on the use of real-time ultrasound to aid paracentesis are limited. Ultrasound is often obtained before paracentesis to identify ascites as well as to identify optimal needle insertion point and depth. In a randomized clinical trial by Nazeer et al (63), residents in the emergency department performed paracenteses either by traditional means (without the aid of ultrasound localization) or after localization and marking by bedside ultrasound. The group using ultrasound guidance had a significantly higher success rate than the nonultrasound-based group (95% with ultrasound guidance vs. 61% without ultrasound guidance). This result has not been replicated in children and there is no comparison between real-time ultrasound guidance during paracentesis with ultrasound marking before paracentesis.

Future Directions

An important consideration underlying all of the studies cited is the level of training of the operator(s). Traditionally, ultrasound has been seen as quite "user-dependent" compared with other forms of imaging, although inter-operator reliability for each ultrasound application has not been routinely reported in studies. Future studies need to explicitly detail the level of training of the operators. As the use of bedside ultrasound continues to increase, the need for a standardized educational curriculum also increases. The greatest strides in this

direction have been made through the guidelines from the American College of Emergency Physicians (10). However, understanding both the overlap and differences between the emergency department and intensive care unit, other intensive care unit organizations have recently proposed curricular guidelines (6, 64), yet another step is needed to begin to generate a pediatric intensive care unit-specific curriculum.

Many questions surface regarding optimal education to achieve competency in bedside ultrasound. One of the most important is whether competency should be based on a specific number of ultrasounds or on ultrasound acquisition quality. If we decide on quality as a measure of competency, how then do we define ultrasound quality? How can we facilitate achievement of that requisite ultrasound quality and what educational methods are best suited to teaching bedside ultrasound? These questions and more remain to be answered, both separate from and yet integral to evaluating the data behind clinical applications of bedside ultrasound to the critically ill pediatric population.

Literature concerning ultrasound use in adult critical care is informative, but significant deficits exist in the data for ultrasound use in pediatric patients. Bedside ultrasound, as practiced by the pediatric intensivist, has the potential to revolutionize pediatric critical care medicine only if careful studies as to the use of the technology as well as clear guidelines addressing the appropriate training necessary to become competent in the use of bedside ultrasound are developed.

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Figure 1.
Ultrasound showing the internal jugular vein and carotid artery in a child.

Figure 2.
Ultrasound showing large pleural effusion.

Characteristics of studies comparing ultrasound assistance with landmark methods for central venous line placement in pediatric patients

Table 1

Study	Location	Type of Study	Patient	Dynamic/Static	Operator Experience	Specifics of Ultrasound Training	Findings
Alderson et al (1993)	Internal jugular	Prospective, randomized	40, precardiac surgery, <2 yrs	Static	Cardiac anesthesiologists	Not discussed	US group had significantly better cannulation success rate and fewer attempts
Verghese et al (1999)	Internal jugular	Prospective, randomized	95 infants precardiac surgery	Dynamic	Pediatric anesthesia fellows	Trained in US techniques using five patients not included in the protocol	US group had significantly better cannulation success rate, less time to cannulation, fewer carotid artery punctures, and fewer number of attempts
Verghese et al (2000)	Internal jugular	Prospective, randomized	45 infants precardiac surgery	Dynamic	Pediatric anesthesia fellows	Trained in US techniques using five patients not included in the protocol	No difference in rate of carotid artery puncture or cannulation success rate, but US group required significantly less time for cannulation and fewer attempts
Grebenik et al (2004)	Internal jugular	Prospective, randomized	124 precardiac surgery	Dynamic	Consultant pediatric anesthesiologists	Five or more US-guided cannulations before start of study	US group had significantly worse cannulation success rate and more carotid artery punctures; no difference in time to cannulation
Chaun et al (2005)	Internal jugular	Prospective, randomized	62 infants precardiac surgery	Static	Not discussed	Not discussed	US group had significantly better cannulation success rate, fewer carotid artery punctures, and fewer attempts
Leyvi et al (2005)	Internal jugular	Retrospective	149 precardiac surgery	Dynamic	Anesthesia residents	Not discussed	US group had significantly better cannulation success rate, but only in those >1 year and >10 kg; no differences in carotid artery punctures
Iwashima et al (2008)	Femoral	Prospective	87 precardiac catheterization	Dynamic	Not discussed	Not discussed	No difference in cannulation success rate, or time to cannulation, but US group had fewer carotid artery punctures

Study	Location	Type of Study	Patient	Dynamic/Static	Operator Experience	Specifics of Ultrasound Training	Findings
Froehlich et al (2009)	Internal jugular	Prospective Cohort	212 pediatric intensive care unit patients	Dynamic	Pediatric intensive care unit residents, fellows, attendings, and nurse practitioners	Not discussed	No overall difference in cannulation success rate, or time to cannulation, but US group had fewer attempts and arterial punctures

US, ultrasound.