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SPECIAL ARTICLE

Critical Care Basic Ultrasound Learning Goals for American Anesthesiology Critical Care Trainees: Recommendations from an Expert Group

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OBJECTIVE: In this review, we define learning goals and recommend competencies concerning focused basic critical care ultrasound (CCUS) for critical care specialists in training.
DESIGN: The narrative review is, and the recommendations contained herein are, sponsored by the Society of Critical Care Anesthesiologists. Our recommendations are based on a structured literature review by an expert panel of anesthesiology intensivists and cardiologists with formal training in ultrasound. Published descriptions of learning and training routines from anesthesia–critical care and other specialties were identified and considered. Sections were written by groups with special expertise, with dissent included in the text.
RESULTS: Learning goals and objectives were identified for achieving competence in the use of CCUS at a specialist level (critical care fellowship training) for diagnosis and monitoring of vital organ dysfunction in the critical care environment. The ultrasound examination was divided into vascular, abdominal, thoracic, and cardiac components. For each component, learning goals and specific skills were presented. Suggestions for teaching and training methods were described.
DISCUSSION: Immediate bedside availability of ultrasound resources can dramatically improve the ability of critical care physicians to care for critically ill patients. Anesthesia–critical care medicine training should have definitive expectations and performance standards for basic CCUS interpretation by anesthesiology–critical care specialists. The learning goals in this review reflect current trends in the multispecialty critical care environment where ultrasound-based diagnostic strategies are already frequently applied. These competencies should be formally taught as part of an established anesthesiology-critical care medicine graduate medical education programs. (Anesth Analg 2015;120:1041–53)

Although clinical use of ultrasound was first described in the 1950s, it remained predominantly an experimental tool until the early 1970s, when it was used to detect ascites in cadavers and splenic hematomas.[1,2] Currently, ultrasound is routinely used for diagnostic work and procedural support in many health care settings, including the intensive care unit (ICU).[3] Because ultrasound technology improvements facilitate better imaging and ultrasound units have become more mobile and affordable, routine use has expanded to the bedside throughout the hospital, and especially in the ICU.[4–9]

With widespread availability in the critical care environment, ultrasound as a diagnostic device and procedural adjunct is increasingly used in critical care practice. When ultrasound devices and trained practitioners are available, they can be successfully used in immediate assessment of life-threatening cardiopulmonary or circulatory dysfunction in patients in the ICU.

Since bedside ultrasound in the ICU has become common, expectations for reliable and rapid image acquisition and interpretation have led to recognition that ultrasound competence can significantly enhance anesthesiology--critical care medicine (ACCM) training. Thus, many critical care practitioners have undergone formal ultrasound training. To meet this need for future ACCM-trained physicians, programs should facilitate systematic teaching, learning, and assessment of critical care ultrasound (CCUS). As in ultrasound training programs for other specialties, an ACCM program should incorporate formalized learning goals, practical teaching plans, and published standards for competency for CCUS.[7,10–12] Note that CCUS learning goals are distinct from those for transesophageal echocardiography (TEE) in cardiac anesthesiology. A distinct set of CCUS training and learning goals is appropriate because interpretation of a given study necessitates a previous understanding of critical illness to optimize the use of the imaging modality. To improve care,

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CCUS must be interpreted in context with other diagnostic and monitoring data that are present for critically ill patients.

The goal of this review is to describe a basic level of knowledge for all advanced ACCM trainees concerning the use of ultrasound in the management of critical illness and to define expectations for the application of CCUS competence to vascular, abdominal, thoracic, and cardiac imaging. This review has 3 specific goals. First, we aim to define the current state of CCUS training in ACCM fellowship programs. Second, we aim to present a set of standard, evidence-based clinical indications, learning goals, and competencies for the use of ultrasound in ACCM. Finally, we aim to propose general recommendations to support training and accomplishment of the prescribed learning goals.

METHODS

The Society of Critical Care Anesthesiologists (SOCCA) assembled an expert panel for this project. Criteria for invitation to the panel included formal ultrasound training (as defined by American Society of Anesthesiologists/American Society of Echocardiography/Society of Cardiovascular Anesthesiologists criteria), current involvement in the practice and teaching of critical care medicine to anesthesia fellowship trainees, and SOCCA membership. To define the current state of CCUS training in Accreditation Council for Graduate Medical Education--accredited ACCM fellowship programs, an online survey was sent to the program directors of those programs. To describe the areas of competency, a systematic literature search (MEDLINE, PubMed, and Ovid) was performed from years 1970 to 2013 for the key words: ultrasound, ultrasonography/standards, intensive care, critical care, echocardiography/standards, clinical competence/standards, critical care standards, curriculum, and education. A total of 69 relevant articles were included for analysis. From these articles, and from shared professional experience in teaching CCUS, the panelists described educational goals and expected competencies for successful ACCM fellowship-based learning for CCUS. The writing process was performed in groups, facilitated by a group leader, with dissenting viewpoints included in the text.

RESULTS

Current Ultrasound Training in ACCM Fellowship Programs

In September 2012, an online survey was sent to the fellowship program directors of each of the 51 ACCM fellowship programs in the United States. Forty programs (78.4%) responded. The size of the respondent programs varied, with 65% of respondents offering 1 to 5 fellowship positions each year, and 35% of respondents offering >5 (3 programs offered ≥9 positions each year). Thirty-nine other programs (97.5%) reported that other Accreditation Council for Graduate Medical Education critical care fellowships (medicine, surgery) were also offered at their institution. All 39 of those institutions offered pulmonary critical care training, and 32 had surgery critical care programs as well. With respect to ultrasound training before ACCM fellowship, 40% of program directors reported an embedded curricular element on ultrasound practice in the associated residency. Most centers (60%) did offer such training to residents, with or without embedded curricular elements. Of the 40 respondents, only 4 (10%) currently offered no CCUS training to their fellows. Of the 36 ACCM programs that offered CCUS training, nearly all incorporated both didactic and hands-on components. Twelve (33.3%) of these programs mandated that a specific number of ultrasound examinations be performed and reviewed with an attending intensivist. The responses to the questions regarding the number of required examinations were 11 to 20 examinations (1 program), between 20 and 50 (5 programs), and >50 examinations (6 programs). With regard to attending intensivist practice, 33 programs (82.5%) reported that ≤50% of the faculty frequently use CCUS to help guide therapy. All 40 programs reported that their fellows have immediate access to an ultrasound machine with both vascular and cardiac probes, with 36 programs (90%) reporting that the ultrasound machine is stored in the ICU.

With respect to perceived difficulties in training ACCM fellows in CCUS, nearly half of the respondents ($n = 19$) reported that many of their attending intensivist colleagues were not comfortable using CCUS. Nevertheless, a majority of those programs felt that an expert faculty comprising intensivists and experts from other departments could be assembled. Eight programs reported having enough individuals within their own division to conduct formal CCUS teaching for fellows if such training became mandated. Only 1 program (3%) reported not having enough faculty members to train their fellows in CCUS, even with help from other departments. Of the remaining 31 respondent programs, 25 (63%) felt that if such a curriculum were mandated, they would need help from members of other departments, but that those departments were likely to do so. However, 6 programs (15%) noted that cardiology or radiology divisions in their institution were reluctant to train ACCM fellows. Two programs (5%) noted that cardiac ultrasound was forbidden in their ICU unless performed by a cardiologist. Sixteen programs ($n = 16$, 40%) found ≥1 impediment. The majority of programs ($n = 24$, 60%) did not see any barriers to training fellows in CCUS. With regard to competency, 28 programs (70%) felt that if CCUS training were required for ACCM fellows, successful completion of fellowship should, by definition, establish CCUS competency. Twelve respondents (30%) felt instead that a separate certification process would be useful.

Physics, Equipment, and Artifacts

An understanding of ultrasound physics is critical to the accurate interpretation of ultrasound images and artifacts.[13] As the name suggests, ultrasound imaging is generated by aiming mechanical sound waves with the frequency exceeding 20 kHz at the object in question. Diagnostic ultrasound has frequencies in the 1 to 20 MHz range. Ultrasound images are formed through interactions of ultrasound waves with tissues, fluids, air, and their interfaces.[14,15] Application of these general principles allows the clinician to anticipate and recognize potential imaging artifacts, which can occur because of excessive reflection or impairment of transmission of sound waves through tissues. Although misinterpreted artifacts can lead to misdiagnosis, imaging artifacts can also support diagnosis (as in pneumothorax, see section below).[16]

Appropriate selection of ultrasound equipment for ICU use requires an analysis of clinical needs, a survey of available local resources, and an understanding of available technology. Practitioners must be able to manage infection control and equipment storage, data transfer, and electrical and ultrasound safety. Practitioners must also thoroughly understand preprocessing and postprocessing functions and machine controls to optimize images before recording. Operator skills and understanding of anatomy are necessary to properly manipulate the transducer to obtain high-quality images.

Physics, equipment, and artifacts should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Learning goals and expected competencies for CCUS-related physics, equipment, and artifacts are shown in Table 2.

Vascular Ultrasound

Although vascular ultrasound is commonly used to support vascular access procedures,[9,17,18] current evidence suggests that real-time (dynamic) visualization of target vessels during vascular access results in fewer complications than (static) vascular mapping followed by unguided vessel puncture.[19] Indications for vascular ultrasound include real-time needle guidance during vessel cannulation for internal jugular, subclavian, axillary, and femoral venous and arterial vascular access.[17,20] Ultrasound may also be useful in securing peripheral venous access in difficult patients.[21] Diagnostically, vascular ultrasound is indicated for the diagnosis of deep venous thrombosis,[22–24] suspicion of arterial occlusion or stenosis,[25] inferior vena cava diameter and variability during the respiratory cycle (an indicator of right ventricular [RV] preload),[26–28] real-time monitoring of volume resuscitation, and diagnosis of aortic aneurysm or dissection.[29–31]

Vascular ultrasound should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Standard image planes in vascular ultrasound are represented in Figure 1. Learning goals and expected competencies for CCUS vascular ultrasound are shown in Table 3.

Abdominal Ultrasound

Indications for CCUS abdominal examination include (but are not limited to) the following: guidance for paracentesis,[32] clinical suspicion for hemoperitoneum, clinical suspicion for abdominal compartment syndrome or other hypoperfusion syndrome, clinical suspicion for retroperitoneal hematoma, clinical suspicion for abdominal aortic pathology, including aneurysm and/or dissection,[33] laboratory or clinical evidence of renal failure,[34] and laboratory or clinical evidence of hepatic failure.[35] The focused assessment with sonography for trauma examination is a structured ultrasound examination designed to identify the above elements that require immediate intervention and has been an important contribution to secondary trauma assessment.[36] It was popularized early based on the idea that the examination can be completed very quickly to support a rapid decision for immediate surgical intervention.

Abdominal ultrasound should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Standard image planes in abdominal ultrasound are represented in Figure 2. Learning goals and expected competencies for CCUS abdominal ultrasound are shown in Table 4.

Table 1. Learning Goals and Expected Competencies: Equipment and Artifacts

Correctly identifying artifacts	Application of ultrasound equipment	Application of machine settings and transducer manipulation
• Shadowing, reverberation, refraction, side lobes, range ambiguity, poor resolution, enhancement, Doppler aliasing, mirror imaging, and ghosting[37] • Improving image quality and diagnostic information when artifacts are present	• Selecting appropriate ultrasound machine for clinical needs • Safe equipment storage, maintenance, and safety • Adequate infection control • Reliable data acquisition, storage, and transfer	• Selection of appropriate ultrasound probe for specific clinical examination • Selection of appropriate mode of ultrasound and Doppler • Proper ergonomics of ultrasound scanning • Optimization of image acquisition by manipulating the transducer by rotation, rocking, sliding, tilting, and compression • Application of calculation packages appropriate for common ultrasound applications

Table 2. Learning Goals and Expected Competencies: Vascular Ultrasound

Procedural	Vascular anatomy and pathology	Diagnostics
• Implement extended barrier precautions with use of sterile sheath over ultrasound transducer • Ergonomically position ultrasound machine and other equipment • Apply cross-sectional and longitudinal views of vessels to be cannulated • Document dynamic ultrasound guidance using stored images showing vascular access, including needle entering the vessel	• Identify relevant arteries (carotid, subclavian, axillary, radial, femoral, popliteal, and dorsalis pedis) • Identify relevant veins (internal jugular, subclavian, axillary, brachial, basilic, femoral, saphenous, and popliteal) • Identify vascular pathology, including venous and arterial thrombosis, and arterial atherosclerotic disease • Identify adjacent structures, such as lymph nodes, masses, and hematomas • Ability to obtain vascular imaging with in-plane and out-of-plane technique	• Identify relevant veins and arteries • Differentiate vascular from surrounding structures; identify vascular wall dissection and hematomas • Appreciate anatomic variations • Implement sequential scanning versus 2-point ultrasonography of femoral/popliteal veins • Identify venous thrombosis using B-mode, color Doppler, and compression testing. Understand limits of 2-point examination

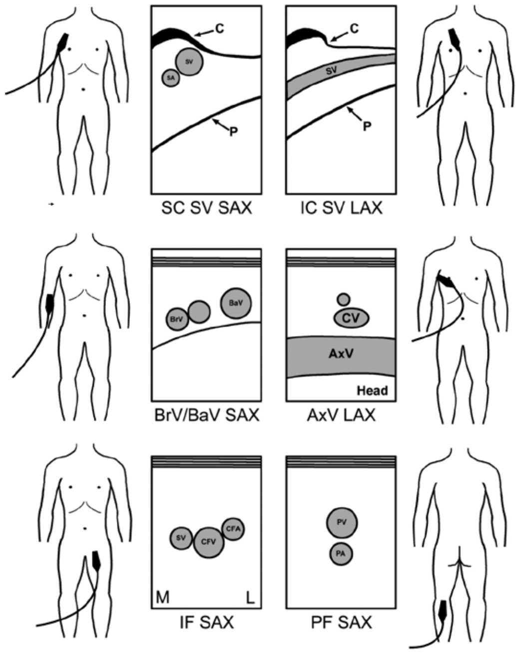

Figure 1. Vascular ultrasound views. SC SV SAX = supraclavicular long axis; IC SV LAX = infraclavicular subclavian vein long axis; BrV/BaV SAX = brachial and basilic vein short axis; AxV LAX = axillary vein long axis; IF SAX = inguinal fossa short axis; PF SAX = popliteal fossa short axis; C = clavicle; SV = subclavian vein; SA = subclavian artery; P = pleura; BrV = brachial vein; BaV = basilic vein; CV = cephalic vein; AxV = axillary vein; CFA = common femoral artery; CFV = common femoral vein; SV = saphenous vein; M = medial; L = lateral; PV = popliteal vein; PA = popliteal artery.

Thoracic/Pulmonary Ultrasound

In contrast to computed tomography scanning or chest radiograph, thoracic ultrasound (TU) can generate images in real time and may be repeated easily and without radiation exposure. As with the focused assessment with sonography for trauma examination above, in the context of hemodynamic instability, TU may help diagnose pleural effusion, pneumothorax, hemothorax, interstitial disease, or consolidation and may facilitate rapid intervention.[37] Indications for performance of TU include (but are not limited to) hemodynamic instability, anatomic guidance for thoracentesis,[5] evaluation of dyspnea,[37] and clinical evidence for pneumonia,[38] interstitial disease,[37] pulmonary edema and/or acute respiratory distress syndrome,[39] pneumothorax,[40,41] and effusion.

Thoracic/pulmonary ultrasound should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Standard image planes in thoracic/pleural ultrasound are represented in Figure 3. Learning goals and expected competencies for TU are shown in Table 5.

Transthoracic Echocardiography/TEE in Shock

Critical care knowledge provides diagnostic focus for bedside echocardiography, which in turn may guide resuscitation efforts.[42–45] Although performing and interpreting a complete echocardiographic examination requires extensive training, intensivists have been able to correctly identify normal and abnormal left ventricle (LV) function with a high degree of certainty after relatively little formal training.[43] Diagnostic information obtained from echocardiography acquired and interpreted by the intensivist may change management in half of cases, including fluid administration, use of vasoactive medications, and treatment limitations.[44] Image quality in this setting is most often sufficient for both nonventilated and ventilated patients. When not adequate, a transesophageal approach may provide better images.[44] Protocol-driven rapid or focused transthoracic echocardiogram (TTE) examination in this setting can improve patient care, especially in the setting of cardiac tamponade, code/cardiac arrest, global cardiac systolic dysfunction, ventricular enlargement, and hypovolemia.[7] Concurrent hemodynamic data analysis may corroborate diagnoses of myocardial ischemia, cardiac tamponade, isolated RV dysfunction (and pulmonary hypertension), septic shock with hyperdynamic LV and RV dysfunction, or hypovolemia.

Focused TTE examination is not meant to replace a comprehensive TTE study. Rather, TTE allows quick serial assessments of hemodynamically unstable patients and their responses to resuscitation. In the acute setting, TEE is needed infrequently for adequate image acquisition .[42] When presented with uncertain TTE and TEE findings, we recommend consultation with an expert echocardiographer, specifically a cardiologist or a cardiac anesthesiologist.[46–48]

Ultrasound in hemodynamic instability should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Standard image planes in TTE and TEE are represented in Figures 4 and 5. Learning goals and expected competencies for CCUS in the identification of causes of hemodynamic instability are shown in Tables 6–8.

LV and RV Systolic Function

In the assessment of systolic LV function, subjective estimation of LV contractility using TTE is as accurate and reproducible as calculated measures of ejection fraction, including fractional area change, fractional shortening, and Simpson's method of disks. Hypovolemic shock is associated with decreased end-diastolic and end-systolic ventricular volumes, and when severe, LV cavity obliteration. In cardiogenic shock, LV hypocontractility and dilation are often present. In distributive shock states, such as septic shock, impaired contractility can be observed with or without LV dilation.[3] A complete diagnostic evaluation for myocardial ischemia is time consuming, can be difficult because of body habitus, positioning, dressing locations, or anatomic variation in some patients, and, thus, is outside the scope of a CCUS examination. In emergency situations, an examination limited to the midpapillary short-axis (SAX) view can identify myocardial regions supplied by each of the major coronary arteries and may facilitate intervention.

The practicing intensivist should understand the structured evaluation and nomenclature of regional wall motion abnormalities. The system recommended by the American Heart Association is the 17-region model, which includes 6 basal segments assessed on the ventricular side of the mitral valve, 6 midventricular segments assessed at the midpoint of the papillary muscles, 4 apical segments assessed between the papillary muscles and the apex, and the apical cap.[49] The scoring system awards values of 1 to 5 for

Table 3. Learning Goals and Expected Competencies: Abdominal Ultrasound

Procedural views	Abdominal anatomy and pathology	Diagnostics
• Right upper quadrant (as part of FAST examination) • Right paracolic gutter • Left upper quadrant (as part of FAST examination) • Left paracolic gutter • Longitudinal and transverse pelvis (as part of FAST examination)	• Identify normal anatomic structures: abdominal wall, diaphragm, liver, gallbladder, spleen, kidney, bladder, bowel, bladder, uterus, spinal column, aorta, IVC. Recognize variations in normal relationships between anatomic structures • Assess and characterize echodense fluids (hemoperitoneum, ascites) • Assess urinary bladder size and contents[64,65] • Identify intra-abdominal fluid, as evidenced by subhepatic anechoic fluid in Morison's pouch, pelvic free fluid in the Cul de Sac (Pouch of Douglas), or a large volume of anechoic fluid surrounding loops of bowel.[66] Assess need for further imaging or consultation	• Identify hepatic congestion, IVC diameter >10 mm, or by systolic flow reversal[66] • Identify obstructive nephropathy (hydronephrosis)-marked dilation and distortion of the collecting system with thinning of the renal parenchyma[67] • Identify signs of cholecystitis, as evidenced by a thickened gallbladder wall, an enlarged, tender gallbladder, and a pericholecystic fluid collection[68] • Identify retroperitoneal hematoma, as evidenced by perirenal fluid[65,69]

FAST = focused assessment with sonography for trauma; IVC = inferior vena cava.

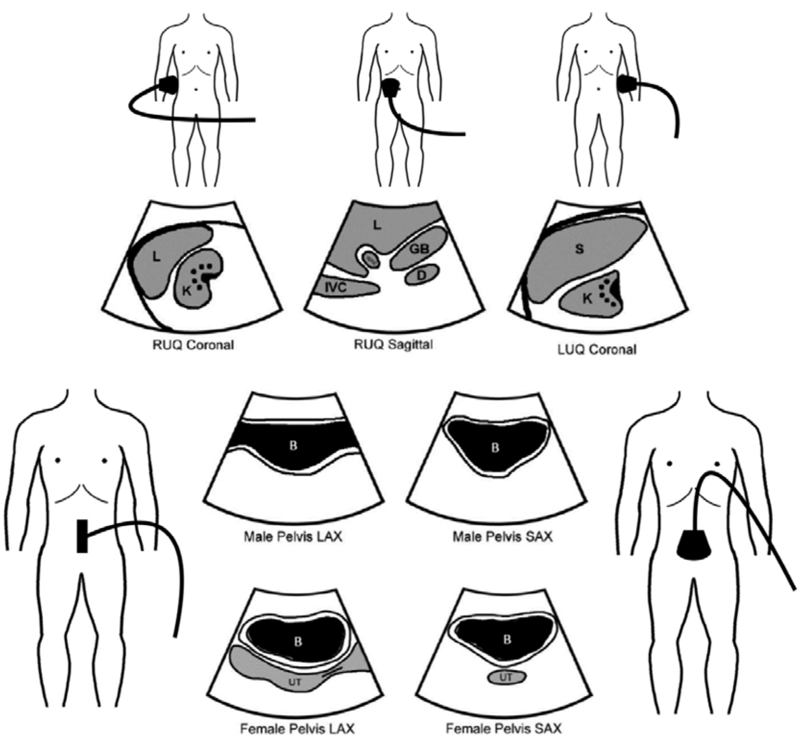

Figure 2. Abdominal ultrasound and focused assessment with sonography for trauma examination views. RUQ Coronal = right upper quadrant coronal; RUQ Sagittal = right upper quadrant sagittal; LUQ Coronal = left upper quadrant coronal; Male Pelvis LAX = male pelvis long axis; Male Pelvis SAX = male pelvis short axis; Female Pelvis LAX = female pelvis long axis; Female Pelvis SAX = female pelvis short axis; L = liver; K = kidney; HPV = hepatic portal vein; GB = gallbladder; D = duodenum; IVC = inferior vena cava; S = spleen; B = bladder; UT = uterus.

Table 4. Learning Goals and Expected Competencies: Thoracic (Lung/Pleura) Ultrasound

Procedural views	Thoracic anatomy and pathology	Diagnostics
• Interrogate lateral, nondependent aspects of pleura and lung • Use higher frequency and linear probes for identification of pathology very near probe • Use lower frequency and phased array for better tissue penetration and distance resolution	• Identify normal anatomic structures: diaphragm, chest wall, ribs, visceral pleura, and lung • Identify normal dynamic changes of anatomic structures and relationships • Identify other structures visible through transthoracic windows: liver, spleen, kidney, heart, pericardium, spinal column, aorta, IVC • Assess and characterize intrathoracic fluid collections	• Identify pleural disease: effusion or hemothorax, pneumothorax • Identify lung consolidation or interstitial edema

IVC = inferior vena cava.

each segment evaluated: 1 is normal (>30% thickening), 2 is mildly hypokinetic (10%–30% thickening), 3 is severely hypokinetic (<10% thickening), 4 is akinetic (no appreciable thickening), and 5 is dyskinetic (paradoxical motion during systole).[50] The walls are named according to their anatomic position and comprise the basal and midpapillary

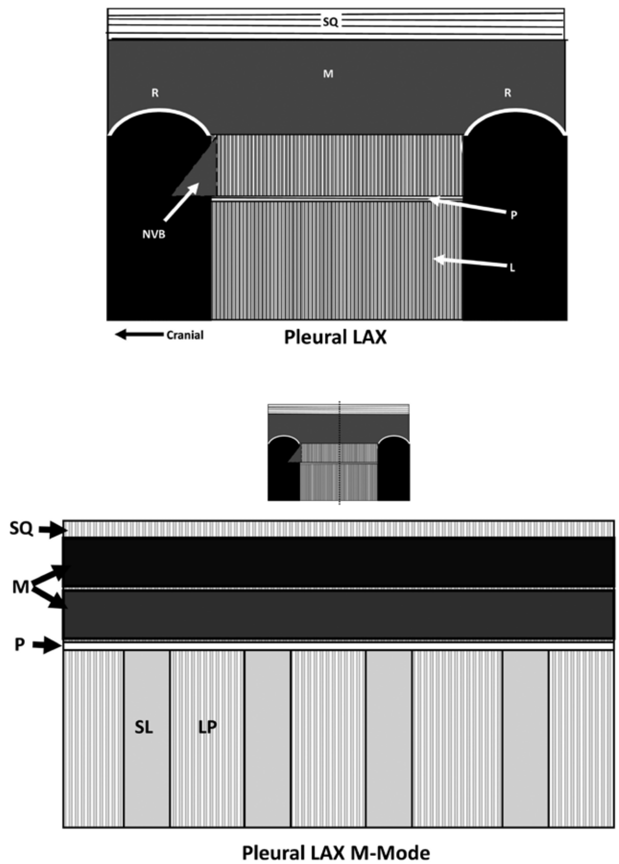

Figure 3. Pleural ultrasound views. Pleural LAX = pleural long axis; Pleural LAX M-Mode = pleural long axis M-mode; SQ = subcutaneous tissue; R = rib; M = muscle; NVB = neurovascular bundle; P = pleura; L = lung; SL = sliding lung; LP = lung parenchyma.

anteroseptal, anterior, anterolateral, inferolateral, inferior, and inferoseptal walls. In the apical LV, there are anterior, lateral, inferior, and septal segments.[49]

Global RV function and RV pressures can also be assessed using TTE. Tricuspid annular planar systolic excursion of the lateral aspect of the tricuspid valve provides a reliable estimate of RV systolic function, with an excursion distance <14 mm, indicating RV failure.[51] RV dilation is present when the basal RV diameter is >42 mm in 4-chamber views.[52] Flattening or D-shaping of the interventricular septum and akinesia of the mid-free wall of the RV in combination with a normally functioning RV apex (McConnell's sign) can also indicate acute RV dysfunction attributable to volume and/or pressure overload and may be present in pulmonary hypertension or pulmonary embolism.[53] In this way, regional LV function and global RV function can be assessed using CCUS.

Diastolic Function

Assessment of LV filling pressure and diastolic function in the hemodynamically unstable patient[4] can be estimated by measurement of the early diastolic maximal transmitral flow velocity (E) and the early diastolic tissue velocity of the mitral valve annulus (e'). In an apical 4-chamber or midesophageal (ME) 4-chamber TEE view, pulsed-wave Doppler may be used to measure the transmitral flow velocity, and tissue Doppler may be used to measure the velocity of the lateral mitral annulus. The E/e' ratio is relatively independent of loading conditions. An E/e' ratio >8 is indicative of impaired ventricular relaxation, and the ratio increases with worsening diastolic dysfunction. The E/e' ratio can also be used to identify patients with high filling pressures as E/e' ratios >7 correlate well with a pulmonary capillary wedge pressure >13 mm Hg.[6] Accurate assessment of diastolic function can be challenging and should be performed only by clinicians in advanced stages of training.

Cardiac Output

The measurement of stroke volume (SV) and the derivation of cardiac output (CO) can be performed during a CCUS TTE examination. The calculation of SV and CO requires 2 different echocardiographic windows. The diameter (D_{LVOT}) of the LV outflow tract (LVOT) is measured just underneath the aortic valve (AV) in a long-axis (LAX) view. In midsystole, the cross-sectional area of the LVOT (A_{LVOT}) can be estimated using the formula for the area of a circle: $A_{LVOT} = \pi \times (D_{LVOT} / 2)$.[2] To estimate SV, pulsed-wave Doppler velocity time integral (VTI_{LVOT}) through the LVOT is measured from an apical 5-chamber view in TTE or deep transgastric view in TEE. The SV calculation is as follows: $SV = A_{LVOT} \times VTI_{LVOT}$.[7]

Pulmonary Arterial Systolic Pressure

Estimation of pulmonary artery systolic pressures should be performed routinely where tricuspid valvular regurgitation is present. Color Doppler echocardiography is used to identify any tricuspid regurgitation (TR). The TR jet maximal velocity (V_{max}) is recorded. The pressure gradient (ΔP) between the right atrium (RA) and the RV in systole is calculated using the simplified Bernoulli equation: $\Delta P = 4 \times V_{max}$.[2] This ΔP is then added to the estimated RA mean pressure or central venous pressure reading to estimate the RV systolic pressure. In the absence of pulmonic valve pathology and/or severe TR, this approach provides a good estimation of systolic pulmonary artery pressure.[54]

Assessment of Severe Valvular Dysfunction

The level of detail in the assessment of valvular dysfunction will be determined by echocardiographic operator experience and clinical context. Severe mitral stenosis (MS) or aortic stenosis (AS) and severe acute mitral or aortic insufficiency (mitral regurgitation [MR] and aortic regurgitation) may cause acute hemodynamic decompensation in the ICU. If present, severe valvular lesions should be correctly identified by the intensivist. Common chronic valvular lesions may also complicate the course of the critically ill patient. TTE assessment of the AV involves the parasternal LAX, parasternal SAX, apical 5-chamber and 3-chamber, and in some cases, subcostal SAX AV. The TEE examination involves the ME AV SAX, ME AV LAX, and deep transgastric views. TTE mitral valve assessment is performed via the parasternal LAX, parasternal SAX (basal view), apical 4 chamber, and apical 2 chamber. TEE interrogation of the mitral valve involves the ME 4-chamber, ME commissural, ME 2-chamber, ME AV LAX, and transgastric SAX (basal) views.

Table 5. Learning Goals and Expected Competencies: Cardiac Ultrasound Views and Anatomy

Procedural transthoracic echocardiogram views and anatomy to identify	Procedural transesophageal echocardiography views and anatomy to identify
• Parasternal long axis—evaluation of pericardium, anteroseptal, and posterior LV walls, right ventricle, left atrium, MV, LVOT, AV, and ascending aorta • Parasternal short axis—evaluation of pericardium, left and right ventricles, and regional LV walls • Apical 4 chamber—evaluation of lateral and septal LV walls, MV, left atrium, RV, tricuspid valve, right atrium, and pericardium • Apical 5 chamber—evaluation of LVOT and AV • Apical 2 chamber—evaluation of inferior and anterior LV walls, left atrium, MV, and pericardium • Apical 3 chamber—evaluation of inferolateral and anteroseptal LV walls, left atrium, MV, LVOT, AV, and pericardium • Subcostal 4 chamber—evaluation of pericardium, LV, MV, left atrium, RV, right atrium, and tricuspid valve • Subcostal IVC—evaluation of IVC and right atrium	• Midesophageal aortic valve short axis—evaluation of AV, left atrium, tricuspid valve, RV, and pericardium • Midesophageal AV long axis—evaluation of LVOT, AV, proximal ascending aorta, pericardium, anteroseptal and posterior LV walls, left atrium, and MV • Bicaval view—evaluation of IVC (including intrahepatic portion) right atrium, SVC, fossa ovalis, left atrium, and pericardium • Right ventricular inflow–outflow—evaluation of right atrium, tricuspid valve, RV, pulmonic valve, left atrium, AV, and pericardium • Midesophageal 4 chamber—evaluation of lateral and septal LV walls, MV, left atrium, right atrium, tricuspid valve, RV, and pericardium. • Midesophageal 2 chamber—evaluation of anterior and inferior LV walls, left atrium, left atrial appendage, MV, and pericardium • Transgastric short-axis—evaluation of pericardium and regional wall motion • Descending aorta short-axis—evaluation of thoracic descending aorta and pleural spaces • Aortic arch long-axis—evaluation of aortic arch and main PA • Pulmonary artery long-axis—evaluation of main, right, and left PA and the ascending aorta

LV = left ventricle; RV = right ventricle; MV = mitral valve; IVC = inferior vena cava; PA = popliteal artery; SVC = superior vena cava; LVOT = left ventricle outflow track; AV = aortic valve.

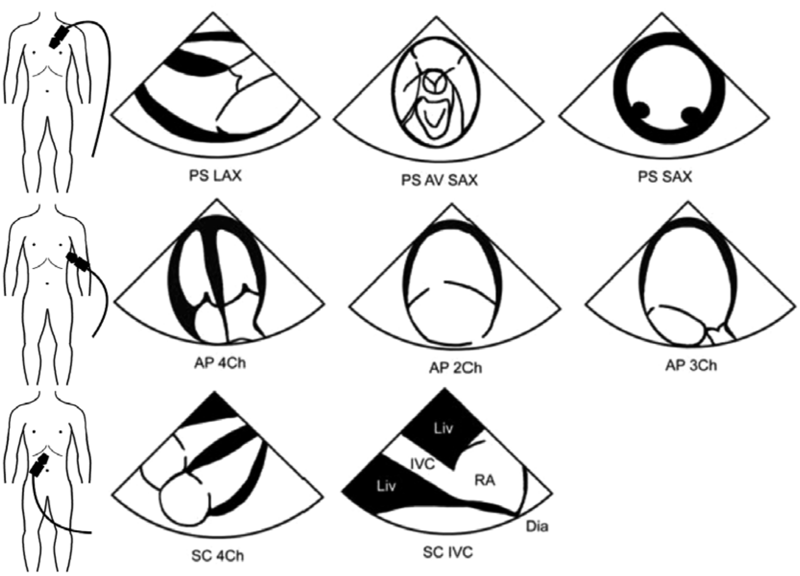

Figure 4. Critical care ultrasound transthoracic echocardiograph views. PS LAX = parasternal long axis; PS AV SAX = parasternal aortic valve short axis; PS SAX = parasternal short axis; AP 4Ch = apical 4 chamber; AP 2Ch = apical 2 chamber; AP 3Ch = apical 3 chamber; SC 4Ch = subcostal 4 chamber; SC IVC = subcostal inferior vena cava; Liv = liver; IVC = inferior vena cava; RA = right atrium; Dia = diaphragm.

Aortic Stenosis

AS is detected in LAX and SAX views by identifying calcified left, right, and noncoronary leaflets and restricted leaflet motion. Color-flow Doppler (CFD) will reveal turbulent flow from the AV into the proximal ascending aorta. Continuous-wave Doppler (CWD) velocity measurements, taken in the apical 5-chamber view by TTE or the deep transgastric view by TEE, may provide more quantitative information, with severe AS defined as peak aortic velocities >4 m/s.[55] However, in patients with low CO states, measured velocity across the AV may underrepresent the severity of AS because of reduced aortic outflow.

Aortic Insufficiency

Aortic insufficiency is assessed by CFD. Moderate-to-severe aortic insufficiency will be characterized by a vena contracta diameter larger than two-thirds of the LVOT diameter and holodiastolic flow reversal in the aortic arch.[56]

Mitral Stenosis

MS may be identified by calcification/thickening of mitral valve leaflets and restricted mitral leaflet opening. The severity of MS can be quantified by measuring the transmitral gradient in diastole with CWD. A mean transmitral diastolic gradient >10 mm Hg is indicative of severe MS. However, when severe MR is present, the transmitral gradient will be artifactually increased because of increased flow.

Mitral Regurgitation

MR or insufficiency is assessed by evaluation of anterior and posterior leaflet coaptation and by using CFD to determine the shape of the regurgitant jet. The severity of

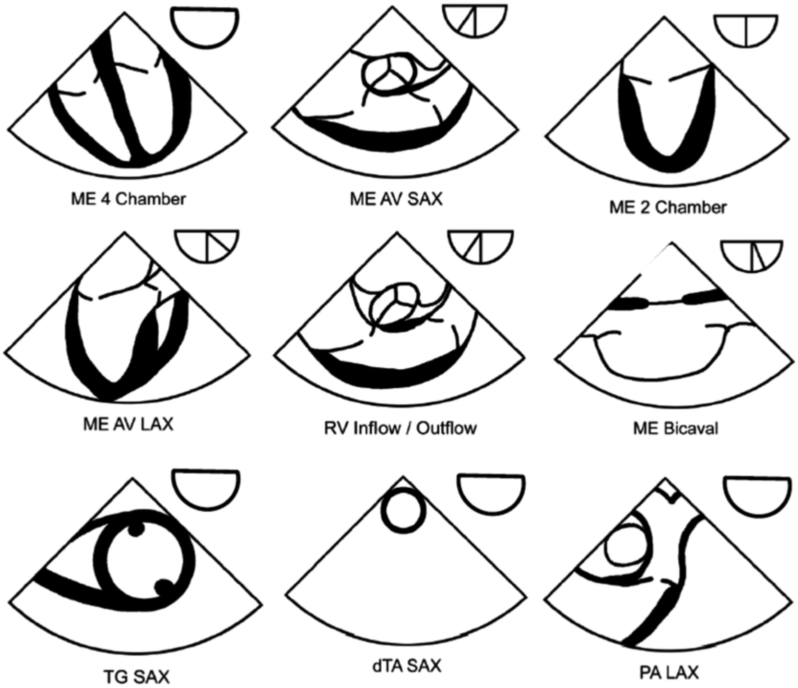

Figure 5. Critical care ultrasound transesophageal echocardiograph views. ME 4 chamber = midesophageal 4 chamber; ME AV SAX = midesophageal aortic valve short axis; ME 2 chamber = midesophageal 2 chamber; ME AV LAX = midesophageal aortic valve long axis; RV inflow/outflow = right ventricular inflow and outflow; ME bicaval = midesophageal bicaval; TG SAX = transgastric short axis; dTA SAX = descending thoracic aorta short axis; PA LAX = pulmonary artery long axis.

Table 6. Learning Goals and Expected Competencies: Cardiac Ultrasound Assessment

Procedural routine measurements	Thoracic anatomy and pathology	Diagnostics
• Identify normal anatomic structures and chamber sizes • Identify normal left and right ventricular contraction • Estimate LV and RV systolic pressures (MV inflow and TV peak regurgitation, respectively)	• Identify cardiac arrest • Identify and characterize intravascular volume abnormalities by ventricular filling and IVC size with respiratory variation • Identify significant wall motion abnormalities • Identify pericardial effusion, tamponade, and associated findings • Identify and characterize severe valvular dysfunction	• Identify LV failure and associated findings • Identify RV failure and associated findings, including RV failure from acute PE and cor pulmonale • Assess LV or RV dysfunction in septic shock • Identify traumatic aortic disruption, mediastinal hematoma, and hemopericardium

LV = left ventricle; RV = right ventricle; MV = mitral valve; TV = tricuspid valve; IVC = inferior vena cava; PE = pulmonary embolism.

Table 7. Learning Goals for Focused Transthoracic Ultrasound During Shock

Procedural view	To be rapidly assessed	Diagnostics
• Parasternal long axis • Parasternal short axis • Apical 4-, 2-, and 3-chamber view	• Pericardial space, right ventricular size and function, left ventricular size and function, mitral and aortic valves, and proximal aortic size • LV, RV, intraventricular septum, and pericardial space • RV and LV, right and left atrium, tricuspid valve, mitral valve, and aortic valve	• Global LV size and function • Global RV size and function • Volume status, LV and RV filling, IVC variability and size • Pericardial effusion • Pericardial tamponade • Gross valvular function • Assess LV or RV dysfunction in septic shock • Identify traumatic aortic disruption, mediastinal hematoma (TEE) and hemopericardium

LV = left ventricle; RV = right ventricle; IVC = inferior vena cava; TEE = transesophageal echocardiography.

MR is affected by LV afterload, which can vary depending on positive-pressure mechanical ventilation, positive or negative inotropic support, vasopressors, or vasodilators. Cardiogenic shock resulting from severe acute MR is usually caused by papillary muscle rupture, trauma, or endocarditis.[57] CFD is a simple means to visualize systolic regurgitation into the left atrium. Complicated mitral valve lesions may require consultation of another subspecialist with echocardiographic expertise.

Tricuspid Regurgitation

Severe TR can be associated with symptoms of venous congestion (e.g., hepatic congestion, peripheral edema, and jugular venous distention). TR can be qualitatively described

Table 8. Sample Curriculum for Critical Care Ultrasound

Title	Type	Time or no.
Equipment and artifacts	Didactic	30 min
Equipment and artifacts practical[a]	Wet lab	15 min
Vascular ultrasound	Didactic	45 min
Vascular ultrasound practical[a]	Wet lab	30 min
Vascular ultrasound study review	Exam	10
Vascular ultrasound study performance	Exam	10
Abdominal ultrasound	Didactic	90 min
Abdominal ultrasound practical[a]	Wet lab	60 min
Abdominal ultrasound study review	Exam	30
Abdominal ultrasound study performance	Exam	30
Lung and pleural ultrasound	Didactic	45 min
Lung and pleural ultrasound practical[a]	Wet lab	30 min
Lung and pleural ultrasound study review	Exam	10
Lung and pleural ultrasound study performance	Exam	10
Transthoracic echocardiographic views and anatomy	Didactic	90 min
Transthoracic echocardiographic views and anatomy[a]	Wet lab	90 min
Transesophageal echocardiographic views and anatomy[b]	Didactic	60 min
Transesophageal echocardiographic views and anatomy[ab]	Wet lab	60 min
Transthoracic and transesophageal echocardiographic pathology	Didactic	120 min
Transthoracic echocardiographic study review	Exam	50
Transthoracic echocardiographic study performance	Exam	50
Transesophageal echocardiographic study review[b]	Exam	50
Transesophageal echocardiographic study performance[b]	Exam	50
Critical care ultrasound quality assurance and quality improvement	Meeting	At least quarterly

[a]May include simulation sessions.
[b]Strongly suggested, but not required.

as severe when the regurgitant jet occupies more than two-thirds of the area of the RA.

Tricuspid Stenosis

Tricuspid stenosis can be suspected when leaflet thickening or limited leaflet opening is observed in the setting of signs and symptoms of venous congestion. Quantification by velocities and estimated pressure gradients is of limited value.

Echocardiographic Evaluation During Cardiopulmonary Arrest

During cardiac arrest and in the periarrest period, echocardiography can noninvasively and rapidly provide a large quantity of critical information that is easier to interpret than indirect measures such as direct visualization of pericardial fluid (as a sign of tamponade rather than equalization of intracardiac pressures) or acute RV dilation and McConnell's sign (as a sign of pulmonary embolism versus spiral computed tomography scan). In both scenarios, TTE may more rapidly facilitate therapeutic decision making.[25,56–58]

The first step in echocardiographic evaluation during cardiac arrest is to compare the rhythm seen on the electrocardiogram with the ventricular contraction pattern visualized by echocardiography and the presence or absence of a palpable pulse: asystole versus pulseless electrical activity versus pseudopulseless electrical activity (ventricular electrical and mechanical activity that generates no pulse).[7] The next step is to assess the cause of arrest, looking closely for evidence of conditions such as cardiac tamponade, pulmonary embolism, pneumothorax, or aortic dissection. Upon return of spontaneous circulation (ROSC), a more complete examination can further explore potential causes of ongoing shock or arrest. Valvular abnormalities causing arrest would likely be catastrophically severe. (See previous section for more information on valvular interrogation.) Acute MR from a papillary muscle rupture or acute MR and aortic regurgitation from endocarditis could result in profound shock or cardiac arrest. Severe aortic and mitral stenosis may be a rare cause of primary arrest, but it may prolong arrest or shock states that occur for nonvalvular reasons. After ROSC, the ascending and descending aorta should be examined again with TEE for aortic dissection. LV and RV dysfunction after ROSC may be the primary inciting event or postarrest or posthypoxic myocardial stunning.[58] Echocardiographic findings suggestive of acute pulmonary embolism as a cause of circulatory collapse include acute RV dysfunction (TTE and TEE) and clot in the main and right pulmonary artery (TEE).

Hypertrophic obstructive cardiomyopathy and systolic anterior motion of the mitral valve are uncommon but potentially treatable causes of circulatory collapse. Aortic outflow obstruction or turbulent subvalvular flow can be generated in patients with small hypertrophic LVs who are hypovolemic and/or tachycardic and may be assessed by a high CWD gradient in the LVOT. These high systolic flow velocities can lead to motion of the anterior mitral leaflet into the aortic outflow tract (systolic anterior motion), resulting in subaortic obstruction and severe MR. With correction of hypovolemia, discontinuation of inotropic drugs, and increased afterload, this dynamic and functional systolic outflow obstruction decreases and can be observed using CWD in LAX views through the LVOT.

One of the limitations of ultrasound assessment during cardiac arrest is the challenge of imaging the heart and lungs during chest compressions. Neither TTE nor TEE should interfere with ongoing advanced cardiovascular life support. However, the use of TEE allows fewer and shorter interruptions in cardiopulmonary resuscitation and should probably be the primary echocardiographic choice when equipment is available. Echocardiographic evaluation of circulatory arrest is appropriate as a diagnostic adjunct when treating any patient who has cardiopulmonary arrest.

Cardiac Function in Septic Shock

Myocardial depression with sepsis peaks within the first few days and resolves in survivors by 7 to 10 days. Unlike classic cardiogenic shock, it is associated with low or normal filling pressures.[55,56] Septic cardiomyopathy occurs in the majority of patients with septic shock during the first 3 days, with most cases occurring in the first 48 hours.[57] Often, sepsis-induced decreases in afterload can mask myocardial dysfunction until administration of vasoconstrictive drugs exposes a poorly contracting ventricle. Serial assessments of myocardial function are necessary because myocardial dysfunction can change rapidly in the early phases of septic shock. The relationship between ventricular function during sepsis (hyperkinetic or hypokinetic) and survival is not yet clear.[55,57,59,60] Because the ventricular dysfunction of sepsis affects both LVs and RVs, changes in chamber volumes and pressures should be closely monitored when trying to establish optimal preload.[55,56,61]

Rapid assessment of hemodynamic instability in septic shock should also be part of a complete CCUS curriculum for trainees, as shown in Table 1. Learning goals and expected competencies for rapid assessment of hemodynamic instability in septic shock are shown in Table 8.

Levels of Training

A practical understanding of ultrasound physics, choice of appropriate images, and image interpretation in the context of differential diagnosis are the requirements for CCUS competency.

The components of any curriculum that focuses on image acquisition and interpretation should include fundamentals of ultrasound physics, cardiac anatomy, and physiology in addition to recognition of normal versus abnormal findings. These topics can be taught via didactic sessions attended locally,[62–64] attendance at external courses,[65] certification through online courses, or taught using ultrasound simulators.[66]

Teaching in the home department should be conducted using a combination of lectures, bedside demonstration with trainee participation and supervisor oversight, frequent repetition of specific predetermined teaching points, case presentations, and grouped review of archived video recordings of ICU ultrasound examinations. All sessions should be supervised by an experienced intensivist or group of intensivists with responsibility for teaching, patient documentation, and quality assurance for ultrasound diagnostics. This type of ICU-based ultrasound teaching/learning system requires several elements, such as well-maintained and easily accessible ultrasound machines in the ICU, a robust system for recording and archiving examinations, and a reading station, where a senior intensive care specialist, who is an experienced supervisor for ultrasound learners, can review all the archived ultrasound studies together with the individuals who performed them, provide feedback and encouragement, support optimal interpretation, and review and endorse the documentation in the patients' records.

The amount of didactic teaching time that is recommended by most groups to provide new trainees with an appropriate introduction to CCUS ranges from 4 to 10 hours for echocardiography. The recommended times take into consideration the depth of the training, which ranges from basic 2D assessment[63–65] to semiquantitative evaluation using CFD, CWD, and pulse Doppler.[11,67,68] Given the scope of focused echocardiography proposed in these suggestions, we recommend a total didactic time of no <10 hours for goal-directed echocardiography. Our recommendation is in line with previous proposals and also with the recent guidelines for vascular ultrasound and TU.[65,67–70]

Mastering Interpretation Skills

To acquire the skills necessary for interpreting transthoracic or transesophageal ultrasound examinations, repetition and exposure to a wide range of normal and pathologic anatomy are necessary. To achieve facility within a reasonable amount of time, supervised performance and review of many patient examples are needed, both of which can be provided in different forms and are most efficiently delivered when an experienced supervisor instructs multiple trainees at one time. These high-volume sessions should review a number of archived studies, with and without pathology, conducted in a quiet private room to encourage discussion. These supervised reading sessions will serve the dual purpose of facilitating the interpretation and journal documentation of the ultrasound studies and as quality assurance. The didactic and case review sessions should be organized and scheduled on a regular basis.

Mastering Technical Skills

During the initial phase of training, learners should perform a series of ultrasound examinations under direct supervision of an experienced clinical ultrasound supervisor. There is evidence to support that 12 hours spent with an expert sonographer during this initial phase is sufficient.[71] In the second phase, the learner can perform examinations and record images with less oversight, but they should continue to record their examinations and review the images (both for quality and interpretation) with a senior colleague at a later time. They should also continue to participate in quality assurance discussions that specifically address aspects of ultrasound image acquisition and analysis. The numbers of studies that are needed until a learner can perform, record, and interpret a CCUS examination independently will vary greatly from learner to learner. It typically takes between 30 and 50 independently performed examinations before learners feel as though they have some mastery of simple image acquisition. Practicing on normal volunteers can be useful at the beginning of ultrasound training although the majority of examinations in the training phase should be performed on critically ill patients. Although not necessary, an echocardiography simulator can be useful in helping learners understand the anatomy, spatial reasoning, and equipment manipulation.

A critical care fellow should perform ≥50 examinations during their training, each reviewed with a local expert in

CCUS or a surrogate supervisor. If considered necessary by the supervisor, >50 studies may be required in the training phase to acquire technical mastery. Each trainee should maintain a log of all supervised and independent examinations, including the final diagnosis for each examination. The log should include a number of normal examinations as well as a wide range of abnormal findings. Final proficiency should be identified and documented by the person responsible for the ACCM training program in their institution.

Instructors

Once a CCUS teaching curriculum is established, bedside teaching can be provided by instructor(s) with a critical care background from anesthesiology, cardiology, surgery, emergency medicine, or internal medicine. The instructor should have experience with focused examinations and should be familiar with critical care interventions in response to abnormal findings. It is ultimately the responsibility of the ACCM faculty, rather than other potential teachers of ultrasound, to ensure both optimal patient care and optimal training of ACCM fellows. Therefore, as with the introduction of any new diagnostic or treatment modality into the ICU, 1 or more members of the ACCM physician staff will need to prepare themselves to serve as supervisors for the basic aspects of ultrasound signal acquisition and interpretation in the ICU.

Equipment

Necessary equipment for the successful incorporation of CCUS into an ICU includes: the ultrasound machines themselves; appropriate transducers for vascular, cardiac, and transesophageal examinations; an image archiving system; and ready access to archived examinations in a location amenable to teaching. All CCUS examinations should be interpreted and their results reported in a standardized manner. A preliminary report may be completed by the trainee but should be finalized with expert review. The report should be archived with the examination images.

DISCUSSION

As with other aspects of ACCM practice and teaching in the ICU, CCUS practice and teaching should be multidisciplinary and include local experts from anesthesiology, internal medicine critical care, surgery critical care, cardiology, vascular surgery, and emergency medicine according to their formal supervisory and teaching roles for ACCM fellows. The final responsibility for this aspect of ACCM training resides with those responsible for the ACCM fellowship in each institution. This responsibility includes assuring availability of training material and equipment in the workplace. Communicating expectations, clear learning goals for trainees, and provision of means to achieve those goals are the responsibilities of the ACCM fellowship program directors and departmental leadership.

In this review, a SOCCA expert group proposed a set of learning goals and expectations for both ACCM trainees and fellowship programs concerning modern CCUS. These goals are based on published literature and are similar to those proposed by other acute medical specialties. ACCM practice and training has seen the widespread introduction of informal diagnostic ultrasound use in ICUs. We conclude that for future ACCM practitioners to be recognized as experts in the diagnosis and treatment of acute critical illness, ultrasound diagnostic techniques should be included in the formal ACCM learning goals for training programs. Improving and standardizing CCUS training and practice are matters of both patient safety and professional development.

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