Seminars in Cardiothoracic and Vascular Anesthesia
15(1) 25–39

DOI: 10.1177/1089253211411734
http://scv.sagepub.com
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Echocardiography in the Intensive Care Unit

Larry C. Field, MD[1], George J. Guldan III, MD[1], and Alan C. Finley, MD[1]

Abstract

As ultrasound technology improves and ultrasound availability increases, echocardiography utilization is growing within intensive care units. Although not replacing the often-needed comprehensive echocardiographic evaluation, limited bedside echocardiography promises to provide intensivists with enhanced diagnostic ability and improved hemodynamic understanding of individual patients. Routine and emergency echocardiography within the intensive care unit focuses on identifying and optimizing medically treatable conditions in a timely manner. Methods for such goal-directed assessments are presented.

Keywords

echocardiography, intensive care, critical care, bedside cardiac ultrasonography, hand-carried ultrasound, hemodynamics

Introduction

Over the past several years, both transthoracic and transesophageal echocardiography have become more common within the intensive care unit (ICU) but the usefulness of echocardiography for the bedside clinician has been recognized for more than 35 years.[1] Roelandt et al[2] published on the first portable "ultrasonic cardioscope" in 1978. Recent technological advancements have made ultrasound and echocardiography machines more powerful, more portable, cheaper, and easier to use. The presence of multipurpose ultrasound units, including hand-carried units, dedicated to and residing within ICUs has made bedside echocardiography readily available to intensivists. As the utility of indirect preload pressure measurements continues to be heavily scrutinized, fewer invasive pulmonary artery catheters are placed.[3] Instead, many intensivists are learning to incorporate echocardiography into their bedside exam. The heart is no longer merely auscultated with a standard stethoscope. Sophisticated tools now follow blood flow and tissue movement by ultrasound reflections to peer noninvasively into the chest.

Currently, broad ultrasound skills are routinely taught in critical care fellowships, and intensivists are increasingly expected to have some ability to perform and interpret bedside echocardiography. Prospective critical care trainees seek programs that can provide them with this appropriate skill set. Virtually all critical care training programs have access to portable ultrasound machines capable of basic goal-directed transthoracic echocardiography (TTE), and many intensivists advocate that focused TTE training should be taught to all critical care trainees.[4] Whereas some intensivists develop these skills to an advanced level, most acquire only basic skills appropriate for screening obvious abnormalities and gross causes of hemodynamic instability common to the ICU patient population.

Incorporation of echocardiography into critical care practice after limited training has been described. Melamed et al[5] reported 77% sensitivity and 94% specificity for left ventricular (LV) dysfunction detection by TTE by medical intensivists using hand-carried units, compared with TTE by cardiologists using full-sized units. In this study, the intensivists underwent 2 hours of didactic training and 4 hours of hands-on training.[5] Manasia et al[6] reported that after 10 one-hour sessions of formal training, intensivists in a surgical ICU were able to perform a limited TTE, without M-mode or Doppler interrogation, in 94% of patients with 84% accuracy compared to the cardiologist's interpretation. Furthermore, TTE findings changed management in 37% of patients.[6] Croft et al[7] demonstrated that medical residents could be trained in 20 hours over 2 weeks

[1]Medical University of South Carolina, Charleston, SC, USA

Corresponding Author:
Larry C. Field, Department of Anesthesia & Perioperative Medicine, Medical University of South Carolina, 25 Courtenay Drive, STE 4200, MSC 240, Charleston, SC 29425-9120, USA
Email: field@musc.edu

to obtain diagnostic TTE images in 94% of medical clinic cases and interpret them correctly 93% of the time. Such goal-directed TTE exams can typically be performed in 5 to 10 minutes.

Similarly, intensivists with limited transesophageal echocardiography (TEE) training are able to successfully perform a focused TEE examination to guide goal directed therapy. Benjamin et al[8] reported that surgical intensivists with no previous echocardiography experience were able to perform and interpret limited TEE with a pediatric monoplane probe with 93% accuracy after 1 didactic session and 10 supervised exams. These goal-directed TEE exams were completed in 12 (±7) minutes. When Charron et al[9] prospectively scored and validated skills of new TEE learners, they suggested it takes 30 personally performed TEE examinations to reach acceptable (88% and 94%, respectively) accuracies for qualitative and semiquantitive interpretations. The French Society of Cardiology and the American College of Cardiology/American Heart Association recommend that 25 TEE examinations need to be performed and another 25 interpreted for a physician to be deemed minimally competent.[10,11] Intensivists with limited echocardiography training will clearly still need to rely on advanced echocardiographers to perform comprehensive echocardiography exams.

Acknowledging the different levels of expertise needed in clinical practice, the National Board of Echocardiography now offers 2 levels of TEE certification for anesthesiologists. Basic perioperative TEE certification requires board certification in anesthesiology, a passing grade on the examination of special competence in *basic* TEE (Basic PTEeXAM) or on the examination of special competence in *advanced* TEE (PTEeXAM), and supervised review of 150 TEE exams, including personal performance of 50 TEE exams in a training program supported by The Accreditation Council for Graduate Medical Education (ACGME). Advanced perioperative TEE certification requires ACGME fellowship training in perioperative care of surgical patient with cardiovascular disease (usually cardiothoracic anesthesiology or critical care anesthesiology, but other core specialties and subspecialties are permitted), a passing grade on the advanced PTEeXAM, and supervised review of 300 TEE exams, including personal performance of 150 TEE exams during fellowship. Alternative practice experience pathways exist but are only offered to those physicians who have completed their residency prior to June 2009 and as such this pathway is being phased out. Formal TTE certification, intended for cardiologists with at least 2 years of fellowship training, requires passing the Special Competence in Adult Echocardiography Exam (ASEeXAM) and reviewing of 300 TTE exams, including personal performance of 150 TTE exams.

A comprehensive review of TTE and TEE image acquisition and interpretation is beyond the scope of this article. This review will focus on the use of echocardiography for routine optimization of hemodynamics and for the urgent/emergent assessment of hemodynamic instability in the ICU.

Choice of Modality

For routine use in the ICU, TTE provides an easily portable and noninvasive modality that may be used as a tool to extend the intensivist's physical exam. However, for many critically ill patients, adequate transthoracic images are difficult to acquire. Inability to position the patient in the left lateral decubitus position, obesity, surgical wounds, surgical dressings, chronic obstructive pulmonary disease, and mechanical ventilation (especially with high airway pressures) all reduce the ability to reliably obtain adequate transthoracic images. Accordingly, the ICU echocardiographer needs to use multiple acoustic windows in an attempt to acquire suitable images for meaningful interpretation in these very sick patients. Alternatively, TEE may be needed if a comprehensive diagnostic exam is desired. If the focus of the exam requires detailed imaging of the thoracic aorta, prosthetic valves, or possible thrombus/vegetation, TEE is the preferred modality.

Procedural Risk

Although more invasive than TTE, TEE has been shown to be very safe. Relatively minor and major complications (such as esophageal perforation) occur with approximately a 0.001 incidence or 0.0001 incidence, respectively.[12-16] Most of the reported complications occurred in nonintubated patients and involved cardiopulmonary compromise during moderate sedation by nonanesthesiologists. Many ICU patients are already intubated and ventilated, further reducing sedative and cardiopulmonary risks; however, these heavily sedated patients are at slightly higher risk of oropharyngeal and mucosal injuries associated with more difficult TEE probe placements. Esophageal pathology such as varices is a relative contraindication to TEE, whereas known esophageal cancer and certain esophageal surgical procedures should be considered strict contraindications. It is important to use proper insertion technique and avoid forcing the TEE probe during insertion. If necessary, laryngoscopy can aid in probe placement. Although rare, it is important to remember esophageal perforation can be a source of late sepsis or hemorrhage.[17] The intensivist must consider iatrogenic transesophageal perforation in the differential diagnosis of critically ill patients (especially if a new pleural effusion is noted hours to days after TEE). Intensivists must weigh the risks/benefits ratio for each patient based on the examination focus and individual patient characteristics.

Despite their shortfalls, central venous catheters and pulmonary artery catheters (PACs) are still routinely used for the initial assessment of cardiac preload. Several studies have compared TEE findings to indwelling PAC evaluation. TEE data disagreed with PAC volume assessment in up to 55% of patients, and the TEE findings significantly altered medical management in 32% to 44% of medical and surgical ICU patients.[8,18-20] Assuming that the TEE management is correct, which is a big assumption since no randomized trials have been performed to show outcome benefit, these studies suggests the PAC is misleading almost half of the time. A review of 21 studies of TEE in mixed ICUs suggests that TEE was diagnostic in 67% of cases (44% to 99%), changed the direction of medical therapy in 36% of cases (10% to 69%), and had a surgical impact in 14.1% of cases (2% to 29%).[14]

Although advancements in digital contrast and harmonics may decrease the failure rate of TTE, previous reports show that TTE image quality is inadequate in 30% to 38% of cases, and that TEE reveals findings not appreciated by previous TTE 39% of the time.[21-23] Additionally, based on their finding of inadequate TTE images in 38% of cases, Cook et al[23] calculated a resource and cost benefit of initial TEE rather than TTE in ventilated ICU patients. Accordingly, TEE is now recommended by the 2007 Appropriateness Criteria for Transthoracic and Transesophageal Echocardiography as the initial echocardiographic exam for critically ill patients in a number of circumstances, as listed in Table 1.[24,25]

Table 1. Indications for Primary TEE in the ICU[a]

Acute hemodynamic instability
Image quality of specific structures requires TEE
Assessment for aortic dissection
Assessment for endocarditis
Assessment for intracardiac thrombus
Assessment of prosthetic valves
Patient conditions that prevent sufficient TTE image clarity
Severe obesity
Emphysema
Mechanical ventilation with high positive end-expiratory pressure
Presence of surgical drains and dressings

Abbreviations: TEE, transesophageal echocardiography; ICU, intensive care unit.
[a]Adapted from Beaulieu.[25]

Utility of Echocardiography for Cardiac Volume and Function

Assessment of cardiac preload is performed daily by intensivists, but the imprecise nature of this assessment has long been unsatisfactory. In the past, intensivists have relied heavily upon the surrogate measures of filling pressures (central venous pressure [CVP] and pulmonary artery occlusion pressure [PAOP]) as there was no convenient bedside method to directly measure and/or monitor cardiac volumes. End-diastolic ventricular volume is, by definition, the gold standard for preload assessment. These preload surrogates do not provide a reliable assessment of end diastolic ventricular volume[26,27] and cannot discern systolic from diastolic dysfunction. Without an ability to compensate for the unknown quantity of diastolic dysfunction, filling pressures are fraught with error. However, echocardiography allows a convenient method for intensivists to directly visualize LV volume.

In patients already being monitored by CVP or PAOP, echocardiography can be used to correlate filling pressures with LV end-diastolic volumes (LVEDV). By titrating volume during the echocardiographic evaluation, the pressure (CVP, PAOP)–volume (LVEDV) relationship can be established for each particular patient. This will result in a more accurate surrogate filling pressure to be maintained after the echocardiographic exam is completed. It is important to keep in mind that if any echocardiographic finding suggests diastolic dysfunction, aggressive fluid resuscitation beyond "normal" filling pressures is often necessary to obtain appropriate LVEDV. Since most ICUs do not have continuous echocardiographic monitoring capability, repeated echocardiography exams may be necessary to adjust or verify the pressure–volume relationship as compliance changes over time.

When a limited exam is performed, the intensivist often estimates global LV function via visual assessment of LV ejection fraction (LVEF) alone. For experienced echocardiographers, this visual estimation often correlates well with the calculated ejection fraction.[28] However, if time permits, a more quantitative assessment is still desirable. Comparison between the ventricular diameters, areas, or volumes at end-systole with those at end-diastole allows the intensivist to calculate the fractional shortening (FS), fractional area change (FAC), or ejection fraction (EF), respectively:

$$\text{FS} = \frac{(\text{end-diastolic diameter} - \text{end-systolic diameter})}{\text{end-diastolic dimension}}$$

(normal 30% to 42%)[29]

$$\text{FAC} = \frac{(\text{end-diastolic area} - \text{end-systolic area})}{\text{end-systolic area}}$$

(normal 36% to 64%)[30]

$$\text{EF} = \frac{(\text{end-diasystolic volume} - \text{end-systolic volume})}{\text{end-diastolic volume}}$$

(normal 55% to 75%)[30]

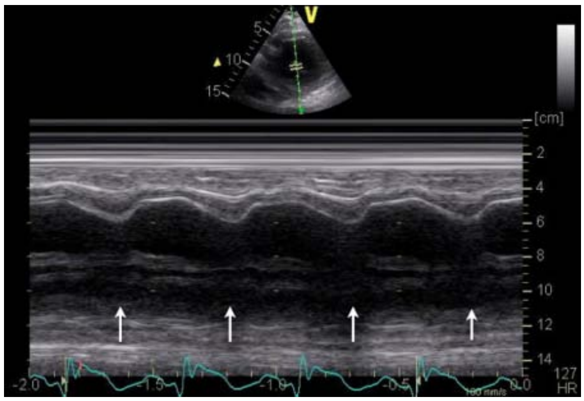

Figure 1. M-mode interrogation of a transthoracic echocardiography short-axis view
This view can be used to accurately calculate fractional shortening (FS), as end-diastolic diameters can be measured in both systole and diastole. However, this patient has a severe wall motion abnormality of the inferior wall, with neither thickening nor inward movement of the inferior wall complicating the FS measurement. Arrows indicate where the inferior wall should be seen thickening (contracting). Note the marked thickening of the opposite anterior wall.

Table 2. Qualitative Findings Associated With Categories of Shock[a]

ESD or ESA or ESV	EDD or EDA or EDV	FS or FAC or EF	Diagnosis
Very low	Low	High	Hypovolemic shock
High	High	Low	Cardiogenic shock
Very low	Normal or high	High	Distributive shock

Abbreviations: ESD, end-systolic diameter; ESA, end-systolic area; ESV, end-systolic volume; EDD, end-diastolic diameter; EDA, end-diastolic area; EDV, end-diastolic volume; FS, fractional shortening; FAC, fractional area change; EF = ejection fraction.
[a]ESV is very low, often with obliteration of the left ventricle (LV) cavity and "kissing" ventricular walls, in both hypovolemic and distributive shock. The EDV must then be used to differentiate hypovolemic from distributive shock, with relative hypovolemia assumed until fluid resuscitation normalizes EDV.

Ventricular asymmetry, as in severe regional wall motion abnormalities, makes FS and FAC less accurate measures of global contractility (Figure 1).

Newer user-friendly systems allow parameters to be automatically measured by the echocardiography machine as long as the appropriate images are acquired. By examining these measures of systolic function (FS, FAC, or EF) and preload (EDA or EDV), one can quickly distinguish between the broader categories of shock that may be causing hypotension (Table 2). An EDD < 25 mm or an EDA $< 55\ \text{cm}^2$ is diagnostic of hypovolemia.[31]

Complex patients are likely to simultaneously experience more than one category of shock, and the primary dysfunction may appear to change with resuscitation and/or time. For instance, echocardiographic findings of septic shock may initially indicate hypovolemia alone until adequate volume resuscitation has been achieved. Even then, the low afterload can mask depressed contractility until the distributive shock is treated with vasopressors. In such a case, global myocardial depression may only become apparent as hypovolemia and afterload are adequately treated. Work by Vieillard-Baron et al[32] suggests global hypokinesis with an EF $< 45\%$ may be present or develop in 60% of septic adult patients, and can be successfully treated with inotropic support. Therefore, if hypotension persists despite ongoing treatments, repeated echocardiography is encouraged.

Because of marketing of newer less-invasive technologies and disenchantment with the usefulness of the pressure surrogates of preload, measures of the dynamic heart–lung interaction are increasingly utilized. Many modern monitors measure the distal effects of stroke volume variation by analyzing the arterial waveform or plethysmograph, and these have proven quite useful in predicting fluid responsiveness in ventilated patients.[33,34] With bedside echocardiography, the respiratory variation of aortic blood flow velocity through the LV outflow tract (LVOT) can be measured, and a threshold value of >12% variation provides a 91% positive predictive value and a 100% negative predictive value for a 15% increase in cardiac output after a fluid challenge in septic patients.[35] By measuring the diameter of the LV outflow tract, as well as the LVOT blood flow velocity-time integral (VTI_{LVOT}), cardiac output (CO) can be calculated.

$$\text{CO} = \text{heart rate} \times \pi(\text{LVOT diameter}/2)^2 \times \text{VTI}_{\text{LVOT}},$$

where LVOT diameter is measured from a 2-dimensional image in the same location as the pulsed-wave Doppler (PWD) measures flow through the LVOT. The PWD beam should be parallel to the flow through the LVOT to avoid underestimating the blood flow VTI. The VTI is easily and automatically calculated on the ultrasound machine by tracing the PWD spectral display.

More commonly, intensivists now routinely measure the respiratory variation of the vena cava diameter in ventilated patients:

$$\text{IVC distensibility index} = \frac{(\text{max IVC diameter} - \text{min IVC diameter})}{\text{min IVC diameter}},$$

$$\text{SVC collapsibility index} = \frac{(\text{max SVC diameter} - \text{min SVC diameter})}{\text{max SVC diameter}},$$

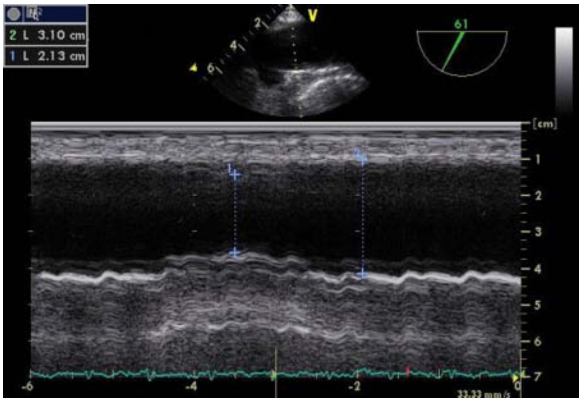

Figure 2. M-mode interrogation of superior vena cava (SVC) by transesophageal echocardiography
The measured SVC collapsibility index is (3.10 – 2.13)/3.10 = 31%, suggesting that this patient has adequate cardiac preload.

where IVC is inferior vena cava and SVC is superior vena cava.

The intra-abdominal IVC can be easily visualized from a subcostal view and measured even by intensivists with little echocardiography skills. In the absence of high intra-abdominal pressures, positive pressure inspiration impedes venous return from the abdomen, resulting in cyclic engorgement of the abdominal IVC. This IVC distention increases as ventilatory pressures increase relative to the IVC volume. In 20 septic patients, Barbier et al[36] found that an IVC distensibility index >18% discriminated responders (those who responded to fluid administration) from nonresponders with both a sensitivity and specificity of 90%. Vena cava measurements should ideally be obtained via M-mode with the transducer perpendicular to the IVC.

Furthermore, Vieillard-Baron et al[37] found that a SVC collapsibility index >36% separated fluid responders from nonresponders with a sensitivity of 90% and a specificity of 87% in 66 septic patients. Figure 2 demonstrates the quantification of the SVC collapsibility index using M-mode by TEE. For any of these measurements to be useful to predict fluid responsiveness, the patient must be in a regular, continuous passive positive pressure ventilatory mode and have a regular cardiac rhythm.

In contrast to the mechanically ventilated patients described above, in spontaneously breathing patients, the IVC collapses as flow is augmented with negative pressure inspiration. A respiratory variation of the IVC of >50% corresponds to a CVP < 10 mm Hg, suggesting the patient may respond to fluid resuscitation. It is important, however, to remember that a prediction of fluid responsiveness from any of these measures does not necessarily indicate that the patient needs the additional fluid. The intensivist must decide if the patient would substantially benefit from the expected increase in cardiac output.

Approach to the Hemodynamically Unstable Patient

Hemodynamic instability is a category 1 indication for either TTE or TEE and is the most common indication for echocardiography in the ICU.[14] Patient characteristics, operator familiarity, availability of equipment, and urgency of the examination will factor into the initial choice for TTE versus TEE. Regardless of the exam modality, the immediate differential to guide therapy generally includes hypovolemia, cardiac tamponade, ventricular failure, pulmonary embolism, acute valvular dysfunction, and (if applicable) complications from cardiothoracic surgery. Although a comprehensive exam is always the best approach to avoid missing an unexpected diagnosis, a focused evaluation to rapidly assess these common causes is often initially performed. An algorithm summarizing an initial approach is presented in Figure 3.

Most intensivists prefer to begin their assessment from the transgastric mid papillary short-axis view. This initial view allows for a quick qualitative assessment of volume status and global LV systolic function while identifying any pericardial fluid that may prompt a further evaluation for cardiac tamponade. End-systolic area (ESA) should be assessed immediately, even if this assessment is a gross evaluation. If the ESA appears small, then assessment of end-diastolic area (EDA) may allow differentiation of hypovolemia from distributive shock. Inadequate LV EDA, indicating hypovolemia, should cause the clinician to begin aggressive fluid administration while a more comprehensive echocardiographic examination continues. The right ventricular size and wall motion should then be assessed. An acutely dilated and hypocontractile right ventricle (RV) would suggests right heart failure (most likely pulmonary embolus or inferior myocardial infarct) as the cause of LV underfilling.

On the other hand, if adaquate or generous LV end-systolic volume is noted, the focus of the exam can shift toward evaluating global LV and RV systolic function, wall motion abnormalities, and valvular function. A combination of 2- and 4-chamber views is then obtained to evaluate both ventricles for regional wall motion abnormalities and valvular function (Figure 4).

Careful evaluation of the RV is important and should not be overlooked. For example, the RV/LV ratio and RV free wall motion are commonly assessed by the intensivist. A RV/LV ratio <0.6 is normal, but 25% of severely ill patients on mechanical ventilation for acute respiratory distress syndrome may exhibit cor pulmonale with a ratio

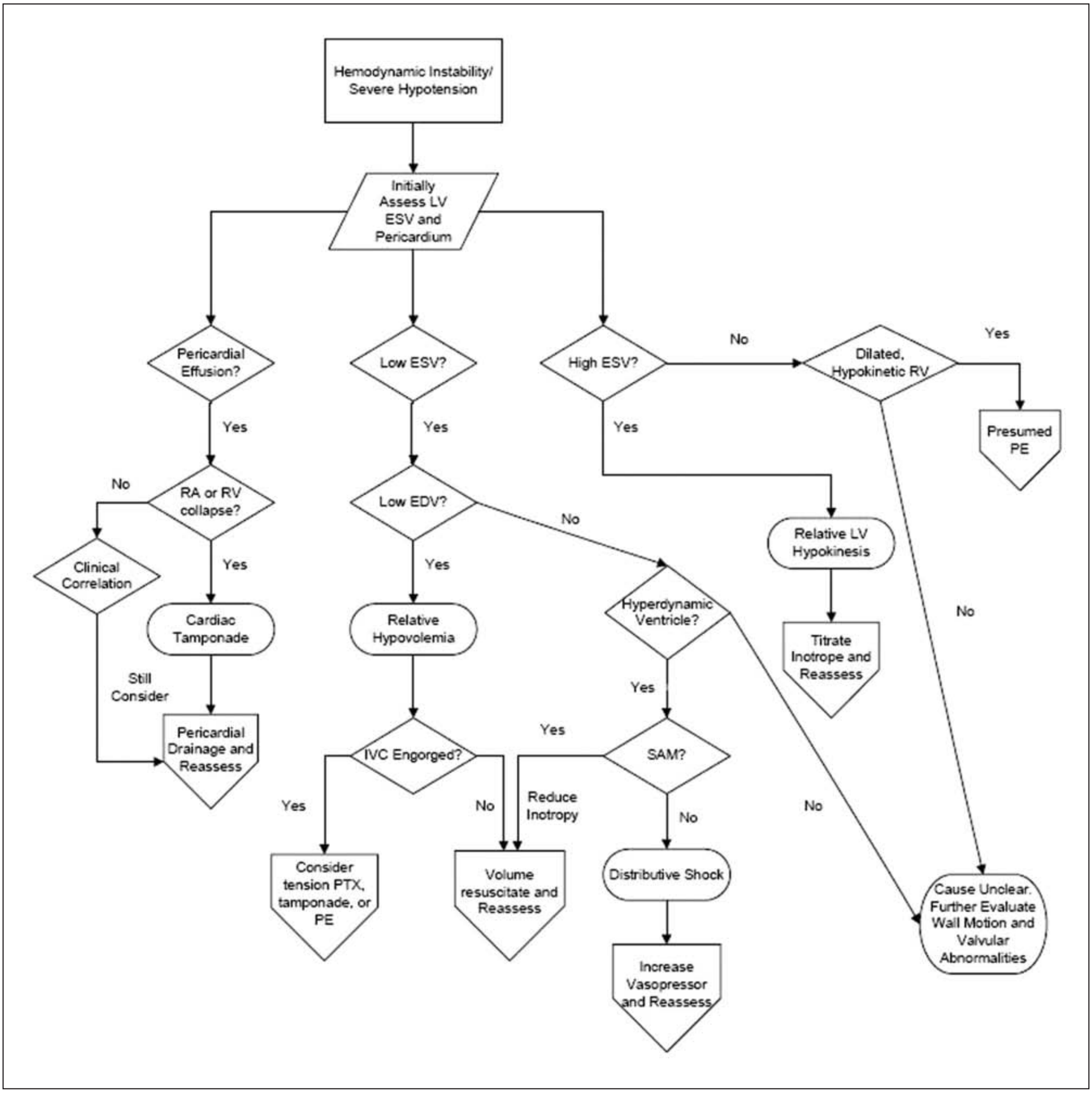

Figure 3. An approach to quickly qualitatively evaluate the hemodynamically unstable intensive care unit patient.
Abbreviations: LV, left ventricule; ESV, end-systolic volume; RV, right ventricle; PE, pulmonary embolism; IVC, inferior vena cava; SAM, systolic anterior motion.

>0.6 (Figures 5 and 6).[38] Most critically ill patients have sufficient tricuspid regurgitation to allow estimation of pulmonary artery systolic pressure (PASP) by continuous wave Doppler. Although less frequently reported, the pulmonary artery diastolic pressure (PADP) can also be obtained if pulmonary regurgitation is present. Parallel alignment of the ultrasound beam with the regurgitant jet is necessary in order to avoid underestimation of the corresponding velocities.

$$\text{PASP} = 4 \times (\text{tricuspid regurg peak velocity})^2 + \text{right atrial pressure},$$

$$\text{PADP} = 4 \times (\text{pulmonic regurg end-diastolic velocity})^2 + \text{right atrial pressure}.$$

In the acutely hypotensive patient, pulmonary embolism is often a concern, especially when oxygenation is significantly and disproportionally impaired. Visualization

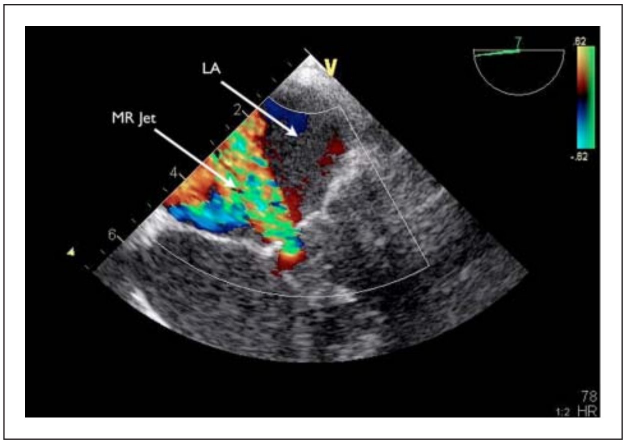

Figure 4. Mid-esophageal transesophageal echocardiography color Doppler interrogation of the mitral valve
Severe mitral regurgitation (MR) is seen in this patient with acute left ventricular ischemia. LA, left atrium.

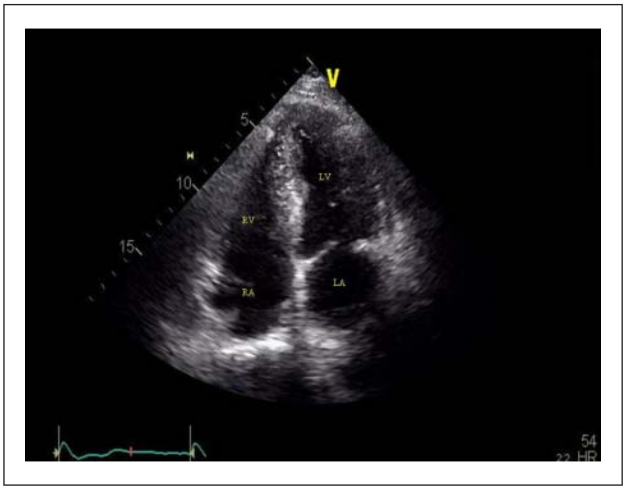

Figure 5. Apical 4-chamber transthoracic echocardiography view to compare ventricles while looking for wall motion abnormalities. The RV/LV size ration is normally <0.6, but it is often not considered significantly abnormal in critically ill patients on positive pressure ventilation until RV/LV size >1
Abbreviations: RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium.

of a thrombus in the right heart or pulmonary artery confirms the diagnosis. Nonvisualization does not necessarily exclude the diagnosis as distal thrombus is not often seen by echocardiography. With distal pulmonary thromboembolism, echocardiographic findings of severe acute cor pulmonale may support the intensivist's clinical suspicion. A RV/LV area ratio >0.6 at end-diastole, paradoxical motion of the interventricular septum, RV free wall thickness <7 mm, and diffuse hypokinesis of the RV free wall with sparing of the apex all support the diagnosis of acute

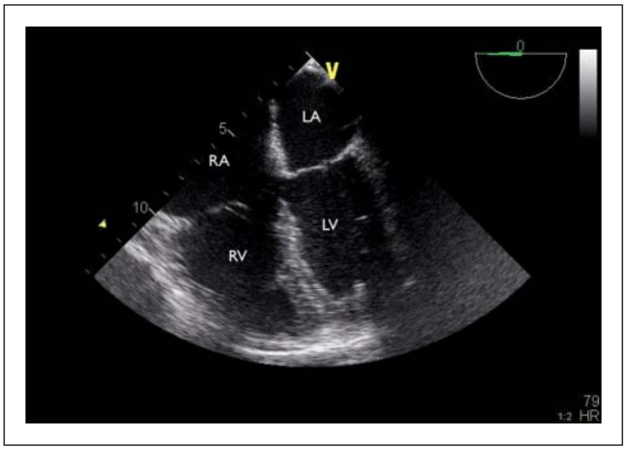

Figure 6. RV failure from mid-esophageal 4-chamber transesophageal echocardiography image. RV/LV size >1. A hypokinetic RV free wall with sparing (residual contractility) of the RV apex is suggestive of acute cor pulmonale, which is suggestive of pulmonary embolism in the appropriate clinical context
Abbreviations: RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium.

cor pulmonale and pulmonary embolism in the appropriate clinical context.[39] The normal thickness of the RV is <0.4 cm, but this width may double within only 48 hours after sudden afterload increase, and may thicken to >1 cm in chronic cor pulmonale.[40]

Echocardiography, when immediately available, is advocated during cardiac arrest.[25] Although the echocardiographic examination should never interfere with the advanced cardiac life support algorithm, it may allow additional goal-directed therapy. Echocardiography may confirm asystole or true electromechanical dissociation (EMD), but it may also reveal pseudo-EMD where mechanical activity is present but is insufficient to generate a palpable pulse. If pseudo-EMD is present, echocardiography can guide fluid, inotropic, and vasopressor needs. Breitkreutz et al[41] recommends the use of a subcostal 4-chamber view obtained during the 5- to 10-second pause of compressions for pulse and rhythm check, being careful not to interfere with the normal cardiopulmonary resuscitation algorithm in order to minimize the no-flow intervals. Ideally, a short echocardiographic loop can be recorded to allow additional review during ongoing cardiopulmonary resuscitation. During this short image acquisition time, the focus should be on identifying global, right- or left-sided heart failure, hypovolemia, or pericardial effusion.

Specific Urgent Concerns

If the patient has recently been subjected to trauma, the echocardiographic exam should be additionally focused to

Table 3. Pericardial Fluid Estimation[a]

Separation Distance of Pericardium From Epicardium	Estimated Pericardial Fluid Amount
Up to 1 cm	<300 mL
1-2 cm	400-600 mL
>2 cm	>700 mL

[a]Estimation of pericardial fluid volume based on separation of the dependent portion of the pericardium from the epicardium.

evaluate conditions specific to the underlying trauma mechanism. Whereas pericardial effusion and tamponade may be of primary concern for penetrating trauma near the heart, blunt trauma is often associated with cardiac contusions and aortic injuries. TTE and TEE may additionally identify pneumothorax or pleural fluid during the course of the exam.

Cardiac Tamponade

Assuming the traumatic effusion is not loculated, a suspected pericardial effusion may be identified from any view that includes the dependent portion of the pericardium where free flowing fluid accumulates. A subcostal TTE view is often obtained to quickly diagnose the presence of a pericardial effusion. The amount of separation of pericardial sac from the epicardium can provide a rough estimate of pericardial fluid volume (Table 3). However, cardiac tamponade physiology depends more on the acuteness of accumulation than on the total amount of fluid. The subcostal view can be also used to safely guide the placement of a pericardiocentesis needle in an unstable patient.[42] Unfortunately, in patients with a large body habitus or surgical dressings, a subcostal TTE view often cannot easily be obtained. In these circumstances, TEE is best suited to adequately evaluate these patients.

The most sensitive 2-dimensional echocardiographic manifestation of cardiac tamponade physiology is early-diastolic right ventricular collapse (Figure 7). Late-diastolic right atrial invagination is another echocardiographic sign of cardiac tamponade, and it is very specific if the collapse persists through one third of the cardiac cycle (Figure 8). Simultaneously recorded electrocardiography is very helpful for appropriately timing these findings. In the post–cardiac surgery patient, loculated effusions and clots may cause left atrial and/or LV compression.

More advanced echocardiographers may also use Doppler to further evaluate a patient with suspected effusion. In the normal patient, there is little respiratory variation of mitral inflow. However, in a spontaneously breathing patient with tamponade, inspiration will reduce early diastolic flow through the mitral valve. On exhalation the flow increases thus giving the characteristic respiratory variations in E wave velocity seen in tamponade physiology (Figure 9). Doppler evaluation of the tricuspid valve velocity reveals the opposite of mitral flow in the spontaneously ventilated patient. These Doppler correlations have been demonstrated in spontaneously ventilated patients. The opposite may apply during positive pressure ventilation. Regardless of the modality used to evaluate these patients, it is important to remember that cardiac tamponade is a clinical syndrome and the patient's clinical condition, being more important than echocardiographic findings, should always drive their care.

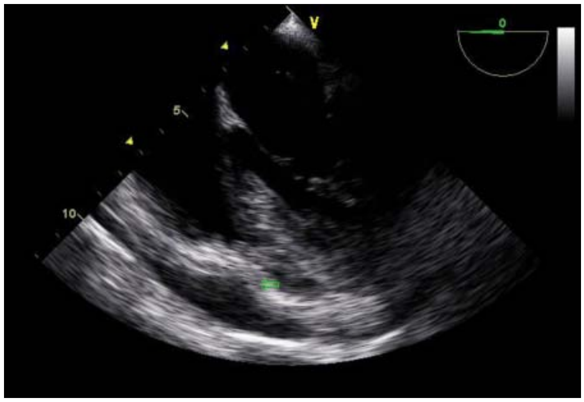

Figure 7. Mid-esophageal 4-chamber transesophageal echocardiography view of a pericardial effusion. Diastolic right ventricular collapse (arrow) is a sensitive sign of cardiac tamponade

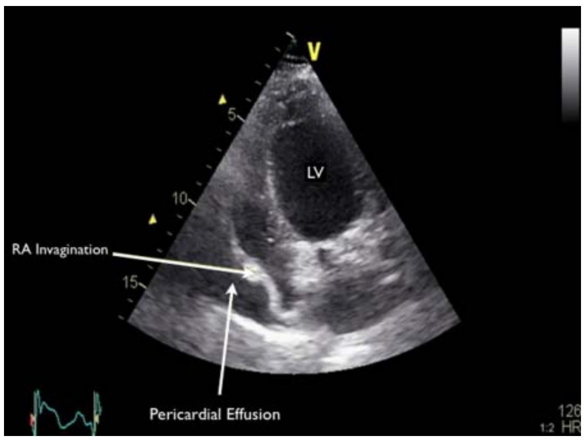

Figure 8. Transthoracic echocardiography apical 4-chamber view of a large pericardial effusion. The right atrial invagination shown here is a specific sign of cardiac tamponade
Abbreviations: RA, right atrium; LV, left ventricle.

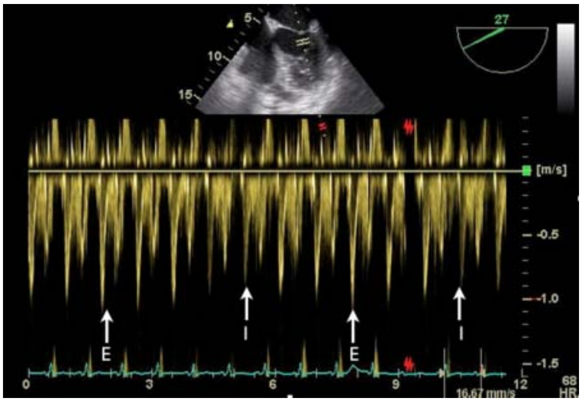

Figure 9. Transesophageal echocardiography pulsed wave Doppler evaluation of mitral inflow velocities. Respiratory variation of mitral inflow velocities >25% is indicative of tamponade physiology
Abbreviations: E, expiration; I, inspiration.

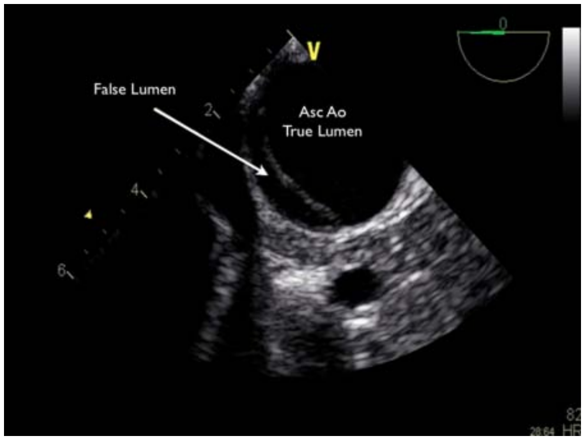

Figure 10. Transesophageal echocardiography short-axis view of an ascending thoracic aortic dissection
An intimal flap is clearly visualized between the labeled true and false lumens of this type A aortic dissection. Asc Ao = Ascending aorta.

Myocardial Contusion

If direct chest wall trauma is suspected, the diagnosis of myocardial contusion should be considered. Since the right ventricle is the most anterior structure in the chest, it is most frequently involved. The echocardiographic presentation of myocardial contusion is the presence of wall motion abnormalities occurring without evidence of transmural myocardial infarction on electrocardiogram. The clinical context is often very important, as regional wall motion abnormalities in a younger patient with blunt chest wall trauma are more likely to be the result of a myocardial contusion than an infarction. Other supportive echocardiographic findings include increased diastolic wall thickness and increased ventricular wall brightness. Chest wall ultrasound may also reveal an associated pulmonary contusion.

Aortic Dissection

Motor vehicle accidents may include sudden deceleration injuries to the aorta. Based upon mechanism of injury or the finding of another deceleration injury, the need for a thorough aortic evaluation may lead to the choice of TEE over a transthoracic approach. TEE is the preferred method of evaluating aortic dissections in the ICU bedside because of its ability to provide rapid high resolution images of the dissection, without interrupting the ongoing treatment of the patient. The goals of a TEE exam should include the following:

1. confirmation of the diagnosis,
2. localization of the intimal tear,
3. interrogation of the aortic valve to determine its viability and involvement,
4. evaluation of possible coronary artery dissection,
5. estimation of LV function, and
6. evaluation of associated conditions such as pericardial tamponade.

Although the intensivist familiar with TEE may initially establish the diagnosis of an obvious aortic dissection, advanced echocardiography experience will be required to confirm the diagnosis and complete the more comprehensive evaluation used to guide appropriate management. Vignon et al[43] suggest that the echocardiographer needs to have performed 150 TEEs examining aortic trauma in order to obtain an appropriate positive and negative predictive value for the related findings which is consistent with the National Board of Echocardiography advance certification of 150 personally performed examinations.

The echocardiographic exam of an aortic dissection is often associated with the detection of an intimal flap, seen as a thin mobile echogenic line within the aortic lumen (Figure 10). To avoid misdiagnosis from ultrasound artifacts, it is very important that the flap be seen in 2 imaging planes. The flap divides the aorta into a true and a false lumen. The true lumen tends to expand during systole and contract during diastole. The use of color Doppler to view blood flow within the true and false lumens can aid in identification as the true lumen has flow in early systole, whereas the false lumen experiences flow later in the cardiac cycle (Figure 11). Often, the false lumen becomes larger than the true lumen. Other 2-dimensional

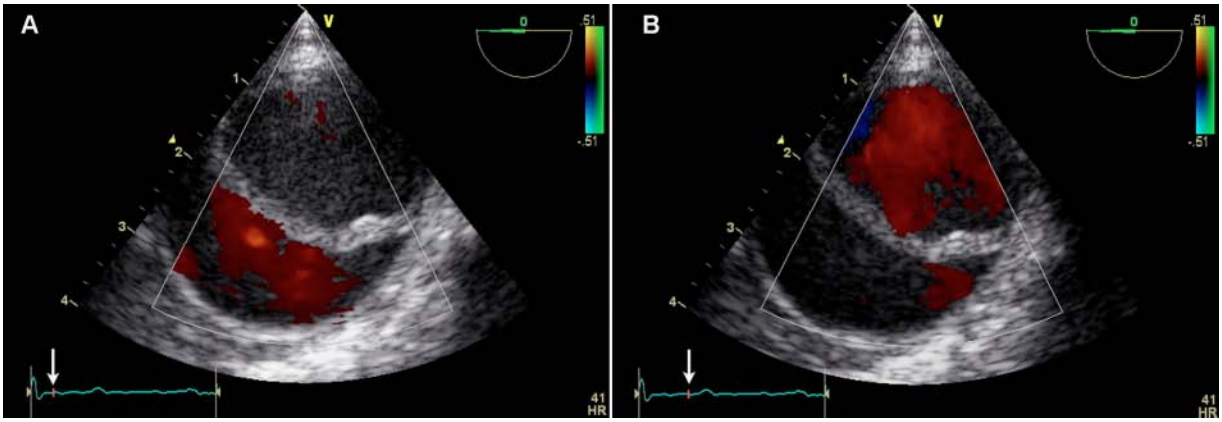

Figure 11. Transesophageal echocardiography short-axis view of a thoracic aortic dissection demonstrating the differentiation of the true lumen versus the false lumen by color flow Doppler evaluation
A, The flow in the true lumen occurs early in systole (arrow marking the timing tracer is close to the QRS) and is often smaller in size than the false lumen, especially in chronic dissections. B, The flow in the false lumen occurs late in systole (arrow marking the timing tracer is closer to T wave than to QRS).

Figure 12. Transesophageal echocardiography aortic valve long-axis view demonstrating dilation of the aortic annulus and destruction of annular support by a proximal aortic dissection (AV = aortic valve)

echocardiographic findings include spontaneous echo contrast and/or apparent thrombosis in the false lumen. In up to 70% of cases, the entry site of the intimal tear occurs in the ascending aorta 1 to 3 cm above the sinus of Valsalva (Figure 12). Most of the remaining cases have an intimal flap initiating at the ligamentum arteriosum in the descending thoracic aorta. Adachi et al[44] was able to show that successful location of intimal injury sites could be obtained by TEE in 90% of type B and 83% of type A dissections. This identification of the injury site is essential to the decision regarding the urgency and type of repair required.

Systolic Anterior Motion of the Mitral Valve

Systolic anterior motion (SAM) of the mitral valve is a relatively common complication of mitral valve repair (Figure 13). SAM is known to cause obstruction at the level of the LVOT. In this clinical scenario the usual escalation of inotropic support for dwindling cardiac output results in a paradoxical clinical deterioration. Echocardiography can assist in making the diagnosis and in monitoring the effect of proper therapy. In a study of 301 postoperative cardiac surgical patients, Schmidlin et al[45] reported TEE to reveal a new diagnosis such as SAM or eliminate a disease process in 45% of patients and to significantly guide therapeutic intervention in 73% of patients.

Less Urgent Concerns

Lack of time and/or experience often necessitates that the intensivist consult an advanced echocardiographer for less urgent diagnostic concerns. However, the intensivist may be able to identify some of the more obvious abnormalities during the course of their limited exam.

Patent Foramen Ovale

Diagnosis of a patent foramen ovale is an example of a somewhat obvious finding. In the clinical context of refractory hypoxemia or suspected paradoxical embolic disease, the intensivist should evaluate the possibility of a right-to-left intracardiac shunt. Using color flow Doppler, the color flow map should be adjusted to investigate relatively low velocities, which may facilitate the diagnosis of

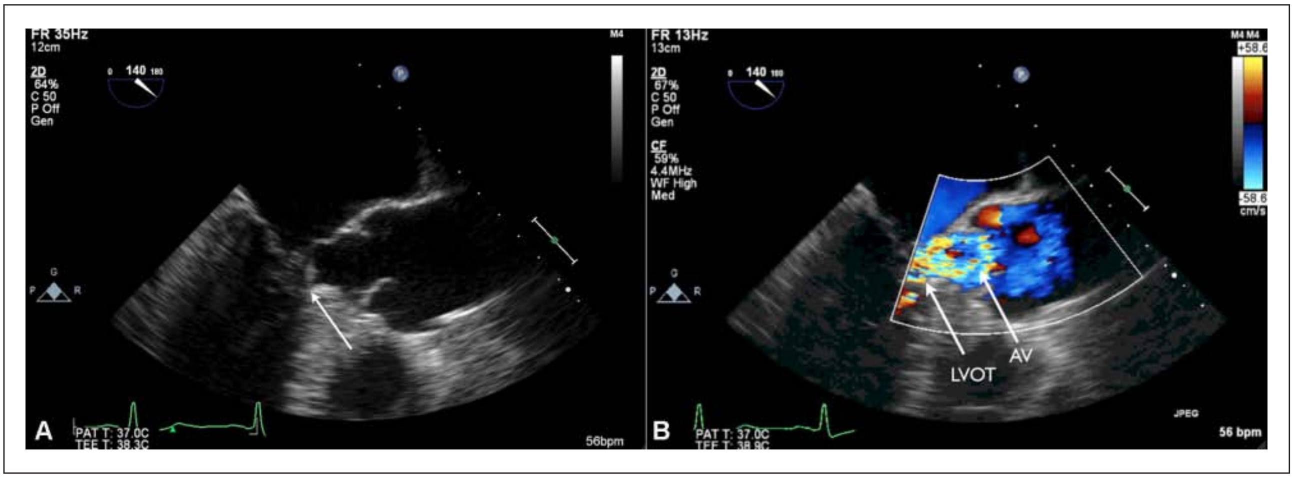

Figure 13. Transesophageal echocardiography aortic valve long-axis view
A, Arrow indicates systolic anterior motion (SAM) of the mitral valve with complete obstruction of the left ventricular outflow tract (LVOT). B, Color flow Doppler demonstrating turbulent flow in LVOT with a transition to laminar flow across the aortic valve (AV).

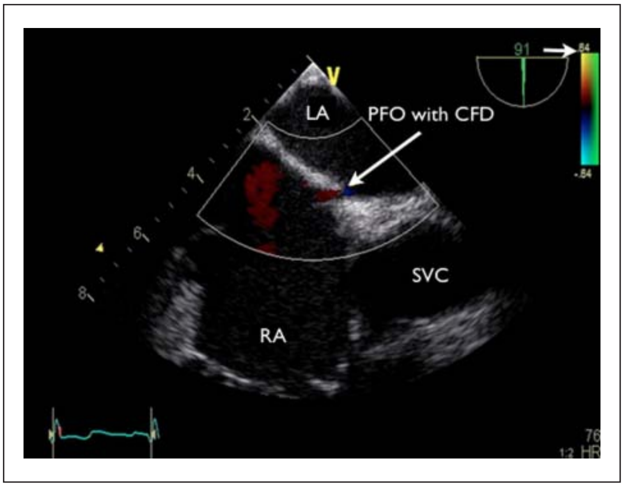

Figure 14. Transesophageal echocardiography mid-esophageal bicaval view demonstrating a patent foramen ovale (PFO) with color flow Doppler (CFD)
If a PFO is suspected, but not visualized, color Doppler velocities can be lowered to facilitate detection. Because of the size of this PFO, the defect is seen even at a high-velocity color map setting of (0.64, in top right corner). Smaller lesions typically require adjusting the velocity scale lower (0.15 to 0.25). RA, right atrium; SVC, superior vena cava.

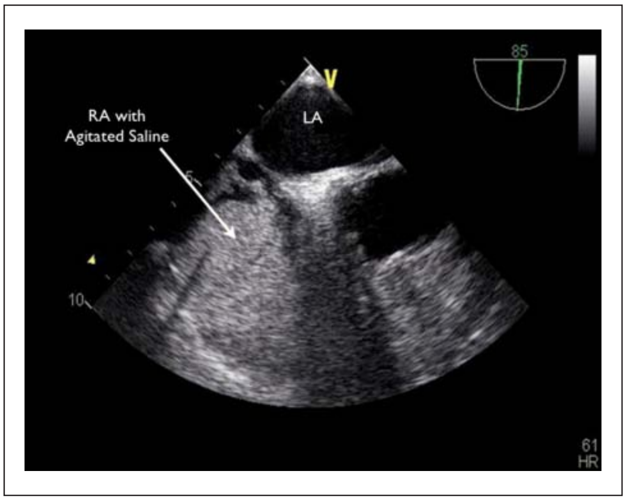

Figure 15. Transesophageal echocardiography mid-esophageal view showing opacification of the right heart by injection of agitated air–saline contrast
Following a Valsalva maneuver, lack of air–saline contrast in left atrium after 5 cardiac cycles would suggest absence of a right-to-left shunt. LA, left atrium; RA, right atrium.

more subtle septal defects (Figure 14). If a defect is still not apparent, an agitated air–saline contrast rapidly injected through a central vein into the right atrium may enhance the detection rate (Figure 15). In a patient without a shunt, the agitated saline can be expected to be nearly completely filtered by the lungs. Bubbles identified in the left atrium within 3 to 5 cardiac cycles are indicative of a right-to-left shunt (patent foramen ovale, atrial septal defect). Longer delays of more than 5 cardiac cycles indicate an intrapulmonary shunt rather than an intracardiac shunt. A Valsalva maneuver will favor right-to-left shunting to aid detection. In the ventilated patient, the sudden release of sustained airway pressure at the time of contrast bolus will similarly optimize intracardiac shunt detection.

Endocarditis

Suspicion of infective endocarditis is the second most common indication for echocardiography in the ICU.[14] In

Table 4. Modified Duke Criteria for Infective Endocarditis (IE)[a]

Major criteria
Positive blood culture with typical IE microorganism, defined as one of the following:
Typical microorganism consistent with IE from 2 separate blood cultures, as noted below:
Viridans-group streptococci, or
Streptococcus bovis, including nutritional variant strains, or
HACEK group,[b] or
Staphylococcus aureus, or
Community-acquired enterococci, in the absence of a primary focus
Microorganisms consistent with IE from persistently positive blood cultures defined as:
Two positive cultures of blood samples drawn >12 hours apart, or
All of 3 or a majority of 4 separate cultures of blood (with first and last sample drawn 1 hour apart)
Coxiella burnetti detected by at least one positive blood culture or antiphase I IgG antibody titer >1:800
Evidence of endocardial involvement with positive echocardiogram defined as one of the following:
Oscillating intracardiac mass on valve or supporting structures, in the path of regurgitant jets, or on implanted material in the absence of an alternative anatomic explanation, or
Abscess, or
New partial dehiscence of prosthetic valve or new valvular regurgitation (worsening or changing of preexisting murmur not sufficient)
Minor criteria
Predisposing factor: known cardiac lesion, recreational drug injection, fever >38°C
Evidence of embolism: arterial emboli, pulmonary infarcts, Janeway lesions, conjunctival hemorrhage
Immunological problems: glomerulonephritis, Osler's nodes
Positive blood culture (that does not meet a major criterion) or serologic evidence of infection with organism consistent with IE but not satisfying major criterion

[a]Adapted from Li et al.[47] Two major criteria, 1 major and 3 minor criteria, or 5 minor criteria are required to establish the diagnosis of endocarditis.
[b]HACEK group = *Haemophilus* (*Haemophilus parainfulenzae*), *Aggregatibacter* (*Aggregatibacter actinoycetemcomitans*, *Aggregatibacter aphrophilus*), *Cardiobacteroim hominus*, *Eikenella corrodens*, *Kingella* (*Kingella kingea*).

a study by Thangaroopan et al,[46] fever and positive blood cultures were present in 100% of patients with evidence of endocarditis by TEE, but they were not specific enough to have a high positive predictive value in and of themselves. A new regurgitant murmur, peripheral manifestations, and/or persistently positive blood cultures were more specific for endocarditis while still having 57%, 65%, and 71% sensitivity, respectively.[46] Without one of these additional findings, persistent fever, even without a source, is usually not a sufficient indication for TEE for endocarditis evaluation. However, the risk may be sufficiently high in the context of recent staphylococcus, streptococcus, or fungal bloodstream infection and/or intracardiac prosthetics. The most frequently quoted criteria for the diagnosis of endocarditis, listed in Table 4, are a modified version of those originally developed at Duke University.[47]

Although a basic-level echocardiographer may recognize obvious vegetations (Figure 16), a TEE exam by an advanced-level echocardiographer is required to fully

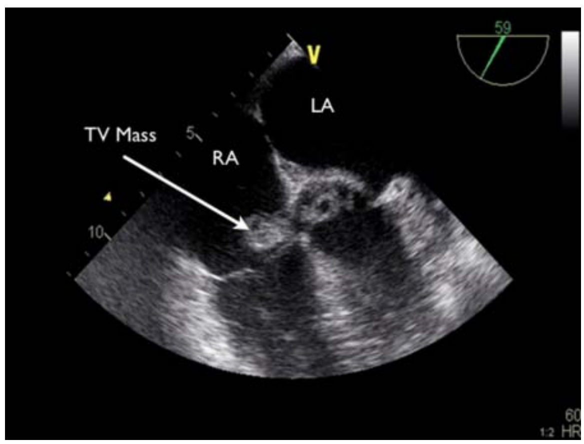

Figure 16. Transesophageal echocardiography mid-esophageal image demonstrating a large vegetation associated with the tricuspid valve (TV)
Abbreviations: RA, right atrium; LA, left atrium.

evaluate for associated lesions and more subtle findings. With TEE's superior resolution and the likelihood of poor TTE image quality in critically ill patients, TEE is more sensitive for detection of vegetations and associated perivalvular findings. The sensitivity of TTE and TEE for endocarditis detection is 58% to 62% and 88% to 98%, respectively.[48,49] Therefore, if there is significant clinical suspicion of endocarditis and the TTE examination is nondiagnostic, a TEE is indicated. Because of prosthetic valve acoustic shadowing, TEE is usually required to obtain sufficient resolution in patients with prosthetic valves.

Thromboembolic Sources

Similarly, because TEE is uniquely suited to view the atria and the left atrial appendage, a comprehensive advanced-level TEE is also required to obtain a high negative predictive value for a thromboembolic source. TEE also allows imaging of the thoracic aorta as another possible source of emboli. An echocardiogram may be requested as the result of clinical evidence of embolic disease (eg, stroke or peripheral infarctions) or in preparation of cardioversion from atrial fibrillation lasting longer than 24 hours. It follows that if the primary purpose of the study is to evaluate for a thromboembolic source, it is most efficient to have an advanced-level echocardiographer perform the definitive TEE as the initial test.

Conclusion

Cardiac anesthesiologists have long appreciated the invaluable information that may be provided by TEE, and training of new cardiac anesthesiologists now includes training in advanced transesophageal echocardiography. Complex critical care patients also appear to benefit from the additional information echocardiography provides, and more intensivists are beginning to incorporate echocardiography into their training and practice. Although intensivists with limited experience may not be able to acquire and correctly interpret images with the same skill as an advanced echocardiographer, intensivists have shown that they can successfully incorporate echocardiography into their clinical practice. Even a quick, goal-directed bedside echocardiographic examination can aid the intensivists' understanding of the hemodynamics of a critically ill patient. This appears to be a significant improvement over, and an adjunct to, current CVP and PAOP monitoring. No other bedside tool can currently provide the amount and quality of information obtained by echocardiography.

As intensivists become more familiar with echocardiography and the technology becomes cheaper and more portable, echocardiographic monitoring will become even more commonplace. Serial TTEs or TEEs allow for monitoring on a frequent basis. Monoplane disposable TEE probes, approximately the size of a nasogastric tube, are already commercially available for continuous monitoring. Advancements in image processing and user interfaces will most likely result in more user-friendly echocardiography devices that will continue to encourage increased use. Although no diagnostic or monitoring device can improve patient outcomes without being coupled to proper therapeutic intervention, the increased information provided by low-risk echocardiography should allow physicians a significant opportunity to improve outcomes by properly targeting their therapeutic efforts. Future studies of echocardiography in the ICU should seek to establish these expected outcome benefits.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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