Bedside echocardiography in the assessment of the critically ill

Yanick Beaulieu, MD, FRCPC

Advances in ultrasound technology continue to enhance its diagnostic applications in daily medical practice. Bedside echocardiographic examination has become useful to properly trained cardiologists, anesthesiologists, intensivists, surgeons, and emergency room physicians. Cardiac ultrasound can permit rapid, accurate, and noninvasive diagnosis of a broad range of acute cardiovascular pathologies. Although transesophageal echocardiography was once the principal diagnostic approach using ultrasound to evaluate intensive care unit patients, advances in ultrasound imaging, including harmonic imaging, digital acquisition, and contrast for endocardial enhancement, has improved the diagnostic yield of transthoracic echocardiography. Ultrasound devices continue to become more portable, and hand-carried devices are now readily available for bedside applications. This article discusses the application of bedside echocardiography in the intensive care unit. The emphasis is on echocardiography and cardiovascular diagnostics, specifically on goal-directed bedside cardiac ultrasonography. (Crit Care Med 2007; 35[Suppl.]:S235–S249)

KEY WORDS: bedside ultrasonography; hand-carried ultrasound; transthoracic echocardiography; transesophageal echocardiography; cardiac function

Echocardiography can noninvasively provide diagnostic information regarding cardiac structure and mechanical function. The supplementary information provided by this technique can help determine the cause of hypotension refractory to inotropic support or vasopressor infusions (1). It can also help in the diagnosis of a wide spectrum of other cardiovascular abnormalities and guide therapeutic management. An adequate understanding of the proper use of echocardiography is thus a prerequisite for the intensivist. General indications for performance of an echocardiographic examination in the intensive care unit (ICU) are listed in Table 1.

TRANSTHORACIC VS. TRANSESOPHAGEAL ECHOCARDIOGRAPHY IN THE CRITICALLY ILL PATIENT

Accurate and prompt diagnosis is crucial in the ICU. The easiest and least invasive way to image cardiac structures is echocardiography using the transthoracic approach (1). This noninvasive imaging modality is of great value in the critical care setting because of its portability, widespread availability, and rapid diagnostic capability. In the ICU, transthoracic echocardiography (TTE) may, in certain cases, fail to provide adequate image quality because of different factors that can potentially hinder the quality of the ultrasound signal, be it air, bone, calcium, a foreign body, or any other type of interposed structure. The failure rate (partial or complete) of the transthoracic approach in the ICU setting has been reported to be between 30% and 40% (2, 3). However, improvements have been made in transthoracic imaging (e.g., harmonics and contrast and digital technologies), resulting in a lower failure rate of TTE in the ICU (10–15% in our institution; unreported data).

Transesophageal echocardiography (TEE) is particularly useful for evaluation of suspected aortic dissection, prosthetic heart valves (especially in the mitral position), source of cardiac emboli, valvular vegetations, possible intracardiac shunts, and unexplained hypotension. This modality allows better visualization of the heart in general and especially the posterior structures, owing to the proximity of the probe and favorable acoustic transmission (4). As a result of the significantly improved technical quality of TTE imaging, the majority of ICU patients can be satisfactorily studied with this modality. In a recent study by Joseph et al. (5), bedside TTE imaging identified the great majority of cardiac causes of shock in a general critical care population of patients (excluding cardiac surgery patients). TTE image quality was adequate in 99% of cases. The authors concluded that TTE should be considered not only the initial but also the principal echocardiographic test in the critical care environment. However, immediate TEE is still preferable in certain specific clinical situations in which TTE is likely to fail or be suboptimal (3). Even when TEE is necessary, data from the TTE examination is often essential for the final clinical interpretation. The major indications for primary TEE in the ICU (6, 7) are listed in Table 2. The most common transthoracic acoustic windows used for performance of a goal-directed cardiac ultrasound examination are illustrated in Figure 1.

HEMODYNAMIC EVALUATION

Ventricular Function

Left Ventricular Systolic Function. Accurate and timely assessment of systolic function should be an integral part of the medical management of hemodynamically unstable critically ill patients. Global ventricular function will often be qualitatively assessed by visual inspection alone. This method has been found to be very reliable when used by experienced clinicians (8). Real-time visualization of the kinetics and size of the cardiac cavities by an experienced critical care intensivist with sufficient echocardiographic

From the Hôpital Sacré-Coeur de Montréal, Université de Montréal, Montréal, Québec, Canada.

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For information regarding this article, E-mail: ybeaulieu@iccuimaging.com.

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Table 1. General indications for performance of an echocardiographic examination in the intensive care unit

Hemodynamic instability
Ventricular failure
Hypovolemia
Pulmonary embolism
Acute valvular dysfunction
Cardiac tamponade
Complications after cardiothoracic surgery
Infective endocarditis
Aortic dissection and rupture
Unexplained hypoxemia
Source of embolus

Table 2. Major indications for performance of a primary transesophageal echocardiographic study in the intensive care unit

Diagnosis of conditions in which a high image quality is vital
Aortic dissection
Assessment of endocarditis
Intracardiac thrombus
Imaging of structures that may be inadequately seen by transthoracic echocardiography
Thoracic aorta
Left atrial appendage
Prosthetic valves
Echocardiographic examinations of patients with conditions that prevent image clarity with transthoracic echocardiography
Severe obesity
Emphysema
Mechanical ventilation with high-level positive end-expiratory pressure
Presence of surgical drains, surgical incisions, dressings
Acute perioperative hemodynamic derangements

background will allow an immediate functional diagnosis.

If the TTE examination is technically difficult and the endocardium is poorly visualized, harmonic imaging and possibly contrast, if needed, can dramatically improve endocardial border visualization and subsequent evaluation of global systolic function (9–13). For the remaining minority of technically challenging cases with suboptimal transthoracic imaging, performance of a TEE will allow for a more precise evaluation of ventricular function in most critically ill patients because of the higher image quality that can be obtained with this echographic modality.

Left Ventricular Failure in the ICU. Clinical examination and invasive hemodynamic monitoring often fail to provide an adequate assessment of ventricular function in the ICU setting. Assessment of biventricular function is thus one of the most important indications for performance of an echographic study in the ICU. In a study by Bruch et al. (14), 115 critically ill patients were studied by TEE. The most common indication for TEE study was hemodynamic instability (67% of patients). Of these hemodynamically unstable patients, 20 (26%) were found to have significant left ventricular (LV) dysfunction (LV ejection fraction [EF] of <30%). In a study by Vignon et al. (15), TTE allowed adequate evaluation of global LV function in 77% of mechanically ventilated ICU patients. Although TEE was needed for most other indications, TTE was shown to be an excellent diagnostic tool for assessment of LV function in the ICU, even when positive end-expiratory pressure was present.

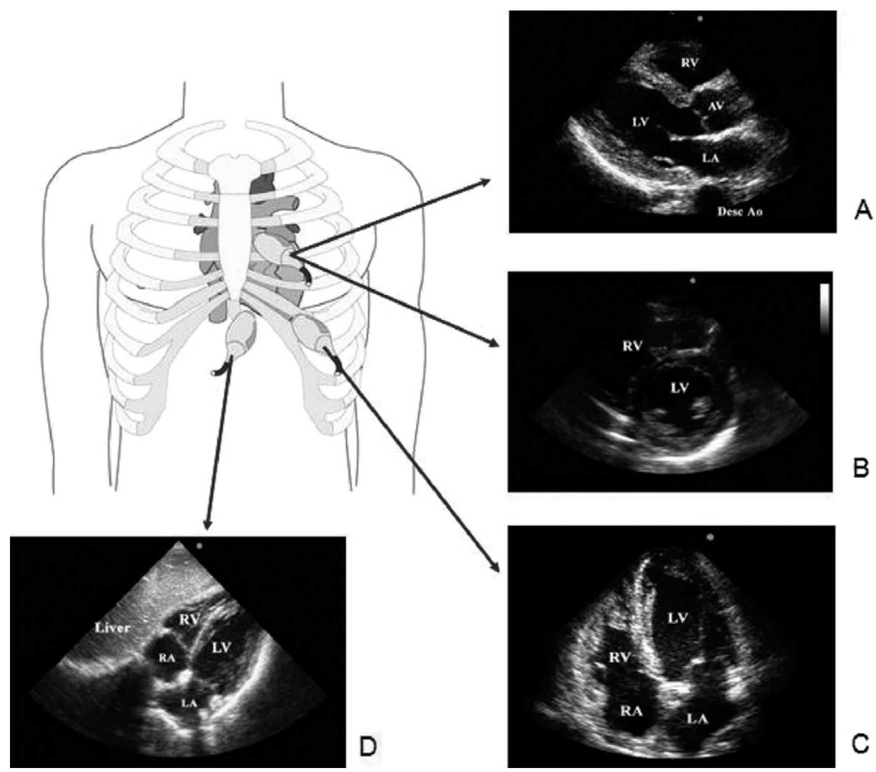

Figure 1. Illustrated above are the most common transthoracic acoustic windows (and corresponding echocardiographic images) used for performance of goal-directed cardiac ultrasound examination. Parasternal long-axis (*A*) and short-axis (*B*) views; apical four-chamber view (*C*); subcostal four-chamber view (*D*). *AV*, aortic valve; *Desc Ao*, descending thoracic aorta; *LA*, left atrium; *LV*, left ventricle; *RA*, right atrium; *RV*, right ventricle.

Several important points should be emphasized: 1) significant LV dysfunction is common in critically ill patients; 2) ventricular function should be assessed in all patients with unexplained hemodynamic instability, as this information is particularly important for guiding resuscitation and informing decisions management; 3) it is now possible to obtain adequate information about ventricular function in most ICU patients using TTE, but TEE provides better accuracy in patients with suboptimal imaging by TTE.

Sepsis-Related Cardiomyopathy. Classically, septic shock has been considered a hyperdynamic state characterized by normal or high cardiac output (CO). But echocardiographic studies indicate that ventricular performance is often markedly impaired in patients with sepsis (16, 17). Parker et al. (18) were the first to describe LV hypokinesis in septic shock. They reported that survivors manifested severely depressed LVEF but that adequate LV stroke output was maintained as a result of acute LV dilation (19). LVEF might not be a reliable index of LV systolic function in patients with early septic shock, as this is a state characterized by low systemic vascular resistance that unloads the left ventricle (16). Therefore, normal or supranormal EF in early sepsis might lead clinicians to make the wrong inference about cardiac reserve because LVEF might decrease if afterload is increased by the administration of vasopressor agents.

In the septic patient, bedside echocardiography is valuable for identification of the cause of hemodynamic instability (which may be of hypovolemic, cardiogenic, or distributive origin) and for the subsequent optimization of therapy (i.e., fluid administration, inotropic or vasoconstrictor agent infusion, or various combinations of the above) (20). The ability to perform repeat bedside examination is vital in assessing the adequacy and efficacy of therapy (20).

Cardiac Arrest

In patients presenting with cardiac arrest (either from in-hospital or out-of-hospital cardiac arrest), the advanced cardiac life support algorithm should always be rigorously followed, and assessment of airway-breathing-circulation and hunt for defibrillation must be aggressively pursued (an A-B-C-D sequence). When assessing for the presence or absence of signs of circulation in such patients, peripheral pulses are usually taken. The ultimate goal of pulse assessment is to detect the presence of an underlying cardiac activity and the associated CO generated. But there are situations in which a pulse is absent, despite the presence of a cardiac rhythm on the monitor. These situations are typically called *pulseless electrical activity* and are often equated with an *electromechanical dissociation* (EMD) condition. Not infrequently, when an urgent bedside echocardiographic study is performed in patients who are thought to have EMD, many of these cases are found to have some degree of cardiac activity and thus present pseudo-EMD and not full-blown EMD. Making the diagnosis of pseudo-EMD in such acutely sick patients can be of tremendous diagnostic and prognostic importance because patients in cardiac arrest who are found to have a residual cardiac function (varying from severe dysfunction as seen in cases of acute myocardial infarction to hyperdynamic cardiac activity as seen in cases of extreme volume depletion), have a better prognosis than patients who are in true EMD (21). Echocardiography can also be used for confirmation of asystole and even ventricular fibrillation in patients in whom the cardiac monitor may seem unreliable or difficult to assess.

The optimal resuscitation sequence to follow in a code situation should thus become A (airway), B (breathing), C (circulation), D (defibrillation), and E (for goal-directed bedside echocardiography).

Bedside echocardiography can thus be of tremendous help in the assessment of "circulation" in patients presenting with cardiac arrest (22). Despite the usefulness of echocardiography in such acute situations, there exists no clear recommendations on how to use the information obtained from a goal-directed cardiac examination during a code. It is not yet clear how, when, and which information should be used in such situation to continue or terminate resuscitation maneuvers.

LV Diastolic Function. In the ICU, diastolic dysfunction should be suspected when ventricular filling pressure (pulmonary artery occlusion pressure) is elevated and EF is normal or supranormal (4). The filling patterns related to the intrinsic diastolic properties of the myocardium are influenced by many different factors, particularly left atrial pressure, heart rate, ischemia, ventricular hypertrophy, and valvular pathologies. Only modest correlation has been found between Doppler indices of diastolic function and variables measured using more invasive means (23). Interpretation of diastolic function must be done with caution when caring for critically ill patients, given the many different factors that can acutely influence flow patterns in this population of patients (24).

Right Ventricular Function and Ventricular Interaction

In the critical care setting, right ventricular (RV) function can be altered by massive pulmonary embolism (PE) and acute respiratory distress syndrome, the two main causes of acute cor pulmonale in adults (25–28). Any other perturbations that increase RV afterload, such as positive end-expiratory pressure or increased pulmonary vascular resistance (from vascular, cardiac, metabolic, or pulmonary causes), will also have a significant effect on RV function. Depressed RV systolic function is also often associated with RV infarction, most commonly in the setting of inferior myocardial infarction. Acute sickle-cell crisis, air or fat embolism, myocardial contusion, and sepsis are other causes of acute RV dysfunction.

In unstable critically ill patients, specifically those with massive PE and acute respiratory distress syndrome, a diagnosis of concomitant significant RV dysfunction may alter therapy (e.g., fluid loading, use of vasopressors, use of thrombolytics) and provide information about prognosis (28, 29). Echocardiographic examination of the right ventricle requires primarily an assessment of the *size* and *kinetics* of the cavity and septum (30, 31). RV size and function generally are evaluated by visual comparison with the left ventricle. RV diastolic dimensions can be obtained by measuring RV end-diastolic area from an apical four-chamber view, using either TTE or TEE. Because pericardial constraint necessarily results in LV restriction when the right ventricle acutely dilates (i.e., there is ventricular interaction), one of the best ways to quantify RV dilation is to measure the *ratio* between the RV and LV end-diastolic areas, an approach that cancels out individual variations in cardiac size (30, 31). Moderate RV dilation corresponds to a diastolic ventricular ratio of 0.6–1.0; severe RV dilation corresponds to a ratio ≥ 1 (30, 31). RV diastolic enlargement is usually associated with right atrial dilation, inferior vena caval dilation, and tricuspid regurgitation. When pressure in the right atrium exceeds pressure in the left atrium, the foramen ovale may open. Pressure and volume overload of the right ventricle can lead to distortion of LV geometry and abnormal motion of the interventricular septum. With conditions of high strain imposed on the RV (volume or pressure overload), the interventricular septum flattens and the LV appears to have a D shape (30, 31). This "paradoxic" septum motion will also be seen at the interatrial level.

Pulmonary Embolism. Hemodynamic instability from acute cor pulmonale as a consequence of massive PE is a relatively common occurrence in critically ill patients. Echocardiography is well suited for diagnosis of PE because it can be done within minutes at the bedside. The diagnosis of acute cor pulmonale at the bedside with TTE has good positive predictive value for the indirect diagnosis of massive PE (32, 33). The diagnosis is indirect in the sense that, in most situations, it is the acute RV dilation and dysfunction resulting from a large PE that is visualized and not the emboli itself (seldom seen). Thus, it is important to stress that echocardiography may not be sensitive enough for smaller PEs and that in a situation in which the clinical suspicion of a PE is moderate to high, one must not exclude PE solely based on a normal RV size and function on echocardiography. The finding of RV dilation and dysfunction is not specific for PE, as these findings may be observed with a variety of other conditions associated with increased RV strain. In a study by McConnel et al. (34), patients with acute PE were found to have a distinct *regional* pattern of RV dysfunction, with akinesia of the mid-free wall but normal motion at the apex by TTE. These findings contrasted with those obtained in patients with primary pulmonary hypertension, who had abnormal wall motion in *all* regions. Regional RV dysfunction had a sensitivity of 77% and a specificity of 94% for the diagnosis of acute PE; positive predictive value was 71% and negative predictive value was 96%. The presence of regional RV dysfunction that spares the apex should raise the level of clinical suspicion for the diagnosis of acute PE.

Central pulmonary emboli are present in half of patients with symptoms of PE and acute cor pulmonale on TTE (35). Emboli lodged in the proximal pulmonary arteries usually cannot be visualized using TTE (35). As other clinical conditions can produce acute cor pulmonale in the ICU, better visualization of the pulmonary arteries is needed to achieve high accuracy for the diagnosis of PE. This goal can be achieved by using TEE. TEE has a good sensitivity for detecting emboli that are lodged in the main and right pulmonary arteries but is limited for the detection of more distal or left pulmonary emboli (35–37). If an embolus is visualized, the diagnosis is made, but if the study is negative when the index of suspicion for PE is high, then TEE must be followed up by a more definitive test, such as angiography or helical computed tomography. Also, when there is high clinical suspicion for PE but no emboli are visualized using TEE, the potential for nonthrombotic causes of PE, such as air or fat emboli, must be kept in mind.

The demonstration of acute cor pulmonale with echocardiography has important prognostic and therapeutic implications (38–41). The presence of cor pulmonale with massive PE is associated with increased mortality, whereas the absence of RV dysfunction is associated with a better prognosis (29).

Assessment of CO

Measurement of CO remains a cornerstone in the hemodynamic assessment of critically ill patients. Several methods for determining CO have been described using both two-dimensional and Doppler echocardiography (42–45). With this technique, stroke volume and CO can be determined directly by combining Doppler-derived measurements of instantaneous blood flow velocity through a conduit with the cross-sectional area of the conduit. Of these methods, the one using the left ventricular outflow tract and aortic valve as the conduit is probably the most reliable and most commonly used. There is excellent agreement with thermodilution in most situations (45–49).

Another ultrasound-based technology to noninvasively estimate CO in adults uses a small transesophageal Doppler probe to measure blood flow velocity waveforms in the descending aorta combined with a nomogram (based on height, weight, and age) for estimation of aortic cross-sectional area. This minimally invasive esophageal probe can be inserted easily in sedated patients and left in place safely for several days to provide continuous monitoring of cardiac function (50, 51). However, several technical problems can limit the accuracy of CO measurements by esophageal Doppler monitoring (50), and although initial results are promising (52–54), more studies are needed to make a decision regarding the accuracy of this technique in critically ill patients.

Assessment of Filling Pressures and Volume Status

Adequate determination of preload and volume status is important for proper management of critically ill patients. Invasive pressure measurements to assess LV filling are commonly used at the bedside to make inferences regarding LV preload. These pressure measurements, however, only weakly correlate with LV volume (55). Data from invasive monitoring using a pulmonary artery catheter (PAC) may be misleading because ventricular compliance is altered by numerous factors (56, 57). Differences in diastolic compliance among patients may account for the weak correlation between pressure and volume and may limit the ability to use pressure measurements alone to derive information concerning LV preload (58). Echocardiography can be of great help for adequately assessing preload. Variables that can be measured using two-dimensional imaging are LV end-diastolic volume and LV end-diastolic area (EDA). Using Doppler interrogation, additional information, mainly transmitral diastolic filling pattern and pulmonary venous flow, can be obtained.

Two-Dimensional Imaging. Echocardiography has been validated for LV volume measurements (59). Subjective assessment of LV volume by estimating the size of the LV cavity in the short- and long-axis views is often adequate to guide fluid volume therapy at the extreme ends of cardiac filling and function, but more precise, quantitative values are desirable and can be obtained by tracing the inner contour of the endocardium of the LV cavity (endocardial border tracing). LVEDA measured in the left parasternal short-axis view at the level of the mid-papillary muscle is commonly used to estimate volume status. Two-dimensional TTE evaluation of ventricular dimensions has been found to be useful in assessing preload and in optimizing therapy of ICU patients (16, 60). Nevertheless, image quality may be suboptimal and preclude adequate visualization of the endocardial border by TTE. This potential limitation of TTE has partly been circumvented in recent years with the advent of harmonic imaging and contrast echocardiography, but in cases in which endocardial border visualization remains suboptimal, TEE is the modality of choice. With TEE, LV volume can be rapidly estimated by subjective assessment of the LV size. Quantitatively, it is most often estimated by determining LV cross-sectional area at the end of diastole, most commonly using the transgastric short-axis view at the level of the mid-papillary muscle. This section is used because of the reproducibility of the view and because changes in LV volume affect the short axis of the ventricle to a greater degree than the long axis (58). The EDA must be measured consistently from the same reference section. EDA measured with TEE correlates with LV volume determined by radionuclide studies (60).

Systolic obliteration (dynamic obstruction) of the LV cavity accompanies decreased EDA and is considered to be a sign of severe hypovolemia. Although a small EDA generally indicates hypovolemia, a large EDA does not necessarily indicate adequate preload in patients with LV dysfunction. Also, when systemic vascular resistance is low, as in early sepsis, LV emptying is improved because of the lowered afterload. In these situations, it may be difficult to differentiate hypovolemia from low systemic vascular resistance by echocardiography alone, as both conditions are associated with decreased EDA.

Knowledge of LV end-diastolic volume or absolute preload does not necessarily allow for accurate prediction of the hemodynamic response to alterations in preload (61). Tousignant et al. (62) investigated the relationship between LV stroke volume and LVEDA in a cohort of ICU patients and found only a modest correlation (r = .60) between single-point estimates of LVEDA and responses to fluid loading. Based on the assumption that changes in EDA occur because of changes in LV volume, the determination of this area and its subsequent degree of variation after a fluid challenge could help better assess preload responsiveness. Studies have demonstrated that changes in EDA measured by TEE using endocardial border tracing are closely related to changes in CO and are superior to measurements of pulmonary artery occlusion pressure for predicting the ventricular preload associated with maximum CO (63).

Circulating volume status also can be assessed by two-dimensional echocardiography by indirectly estimating right atrial pressure. This is often done by assessing the diameter and change in caliber with inspiration of the inferior vena cava. This method has been shown to discriminate reliably between right atrial pressures of <10 or >10 mm Hg (64). A dilated vena cava (diameter of >20 mm) without a normal inspiratory decrease in caliber (>50% with gentle sniffing) usually indicates elevated right atrial pressure. In mechanically ventilated patients, this measure is less specific because of a high prevalence of inferior vena cava dilation (65–67). A small vena cava reliably excludes the presence of elevated right atrial pressure in these patients (65–67).

Variation of the diameter of the inferior vena cava with respiration (Fig. 2) has also recently been demonstrated to be a reliable guide to fluid therapy. Feissel et al. (68) studied 39 patients on mechanical ventilation with septic shock in whom they assessed CO and change in inferior vena cava diameter (by echocardiography) before and immediately after administering a volume load (8 mL/kg 6% hydroxyethylstarch over 20 mins). They found that in patients who responded to volume loading (increase in CO by >15%), the variation in the IVC diameter before the fluid challenge was greater than in nonresponders. A 12% cutoff value in IVC diameter variation before volume loading identified those patients who would respond to a fluid challenge, with positive and negative predictive values of 93% and 92%, respectively.

Doppler Flow Patterns. Information obtained by analysis of the Doppler signal at the level of the mitral valve and pulmonary vein offers additional information about preload (69, 70). These Doppler profiles can be obtained by either TTE or TEE. Transmitral variables that have been studied include the relation of early to late transmitral diastolic filling (E/A ratio), isovolumetric relaxation time, and the rate of deceleration of early diastolic inflow (deceleration time) (1).

Pulmonary venous flow can also be used to assess left atrial pressure (LAP). Both transmitral and pulmonary vein Doppler patterns are strongly dependent on intrinsic and external factors and are not purely affected by the loading conditions of the left ventricle. It is thus of utmost importance that interpretation of Doppler variables be done in conjunction with a global analysis of cardiac function and other available hemodynamic or anatomic variables.

Positive pressure ventilation alters stroke volume by transiently increasing intrathoracic pressure and thereby decreasing preload. This phasic variation in stroke volume results in a cyclic fluctuation in arterial pressure (63, 71). The magnitude of respiratory variation in aortic blood velocity (as recorded echocardiographically by pulsed-wave Doppler at the level of the aortic annulus) is a dynamic variable that is superior to static measurement of LVEDA (or of LV end-diastolic volume) to predict fluid responsiveness in critically ill patients (61, 72). Feissel et al. (73) demonstrated that when patients in septic shock experienced a magnitude of respiratory variation of peak aortic velocity of 12%, infusion of 500 mL of fluid increased stroke volume and CO by 15%, while decreasing proportionately the magnitude of the respiratory variation of peak aortic velocities. Although practical and reliable, use of this echocardiographic dynamic variable to assess volemic status can be applied only to patients who are receiving mechanical ventilation and who are per-

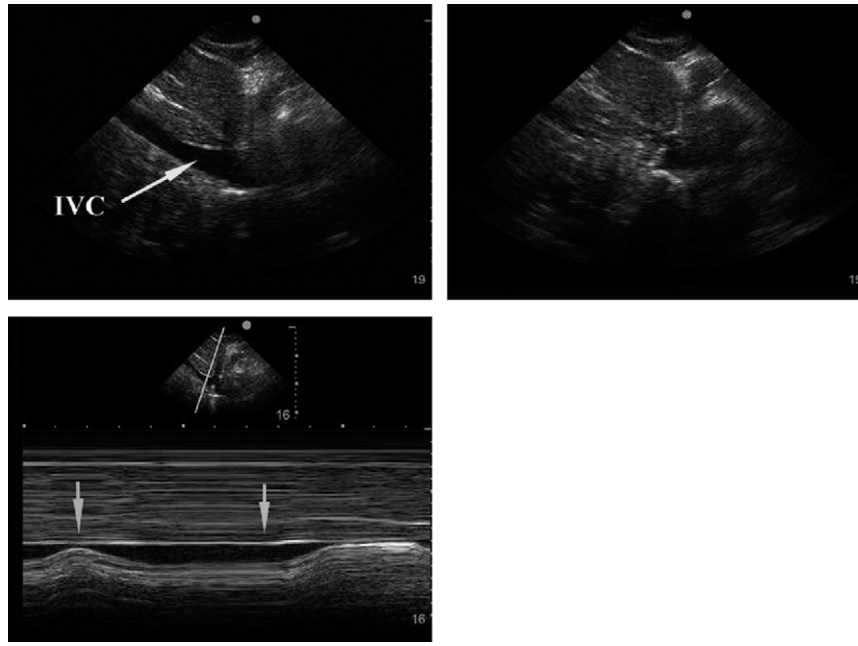

Figure 2. Variation of the diameter of the inferior vena cava with respiration has recently been demonstrated to be a reliable guide to assess fluid responsiveness in patients on mechanical ventilation. *Top left*, ultrasonographic longitudinal view of the intrahepatic segment of the inferior vena cava (*IVC*) as assessed in the subcostal area. In patients on positive pressure breathing (and synchronous with the ventilator), the maximal diameter of the IVC will be obtained at the end of inspiration. *Right*, in such a patient, the minimal IVC diameter will be found at the end of expiration (complete collapse of the IVC is illustrated). *Bottom left*, precise measurement of the IVC diameter at the end-inspiratory (*right arrow*) and end-expiratory (*left arrow*) phases can be reliably obtained by using M-mode. This will allow precise assessment of the IVC diameter variation with respiration before volume loading and help identify those patients who would respond to a fluid challenge.

fectly adapted (synchronous) to the ventilator and have no cardiac arrhythmia.

LV Dynamic Obstruction

In general, TTE has good sensitivity for diagnosing the presence of a small, hyperdynamic left ventricle, the most typical finding in severely hypovolemic patients with underlying normal cardiac function. When dynamic LV obstruction is present, CO is low, and even in the presence of marked hypovolemia, pulmonary artery occlusion pressure is high. Paradoxic worsening of hypotension after intravascular volume loading may be the first clue to dynamic LV obstruction in critically ill patients. This entity should be recognized early because inadequate management of this condition can rapidly lead to worsening of hemodynamic status and death. By two-dimensional echocardiography, the left ventricle appears to be small and hyperdynamic, and there is motion of the anterior leaflet (or chordae) toward the septum in systole. With color Doppler, a "mosaic" pattern of flow is seen in the left ventricular outflow tract due to the high velocity and turbulence. Variable degrees of asymmetric mitral regurgitation may also be present. Continuous-wave Doppler often demonstrates the presence of a significant gradient in the left ventricular outflow tract. A small, hypertrophied left ventricle (typically seen in elderly patients with chronic hypertension), reduced afterload, and significant catecholaminergic stimulation are factors that will predispose to the development or worsening of LV dynamic obstruction. Dynamic LV obstruction also has been described in patients with acute myocardial infarction, mostly in association with apical infarction (74–79).

Both TTE and TEE have been demonstrated to play a key role in making the diagnosis of hypovolemia and LV dynamic obstruction, leading to a dramatic effect on therapy (76–82).

Assessment of Pulmonary Artery Pressure

Pulmonary hypertension is common in critically ill patients and is a manifestation of various pulmonary, cardiac, and systemic processes. Pulmonary hypertension is said to be present when systolic pulmonary pressure is >35 mm Hg, diastolic pulmonary pressure is >15 mm Hg, and mean pulmonary pressure is >25 mm Hg (49). A number of echocardiographic methods have been validated for noninvasive estimation of pulmonary artery pressure (49, 83). These methods can be of great help in the ICU setting. Systolic and diastolic pulmonary artery pressures are determined from the tricuspid and pulmonary regurgitation velocities, respectively (some degree of regurgitation is essential to be able to obtain a Doppler signal and subsequently determine pulmonary artery pressure). Tricuspid regurgitation is present in >75% of the normal adult population (59) and in approximately 90% of critically ill patients (84). Approximately 70% of critically ill patients have an adequate Doppler signal of pulmonic insufficiency for this calculation (82). Tricuspid and pulmonary regurgitation are present at the same time in >85% of subjects (85).

Assessment of Valvular Function and Integrity

Attention has been drawn to the limitations of the physical examination for the detection of cardiovascular abnormalities (86, 87). This problem is enhanced in acutely ill patients in the ICU, and many cardiovascular abnormalities may be concurrent with noncardiac illness without being clinically suspected (88). Significant valvular abnormalities are a good example of such cardiovascular pathologies that can be present in the critically ill patient without being clinically recognized (88). Even in the presence of invasive monitoring, significant valvular pathologies may be missed. Precise evaluation of the valvular apparatus may thus often be warranted in the ICU. The most common indications for bedside echocardiography for evaluation of valvular apparatus in this population are for suspected endocarditis (89, 90), acute aortic or mitral valve regurgitation (91, 92), or prosthetic valve dysfunction (93). Echocardiography is uniquely suited to the evaluation of valvular heart disease because of its ability to provide information regarding the pathogenesis and severity of valvular lesions. In the ICU, TTE can provide valuable information concerning valvular integrity and function (93) but may be suboptimal and not sensitive enough to detect endocarditis, a dysfunctional mitral valve, or prosthetic valve dysfunction. Thus, TEE is often warranted.

Evaluation of the Pericardial Space

In the ICU, the most common clinical indication for assessment of the pericardial space is suspected tamponade. The pericardium is a potential space that can become filled with fluid, blood, pus, or uncommonly, air. Presence of fluid in this space is detected as an echo-free space. Pericardial fluid is usually easily detected with TTE. The parasternal long- and short-axis and the apical views usually reveal the effusion. In many critically ill patients with suboptimal TTE image quality, the subcostal view is often the only adequate window available to detect the presence of a pericardial effusion. In these ICU patients with poor acoustic windows and in the postcardiac surgical setting, TEE may be needed to assess the pericardial space adequately.

In addition to assisting in the diagnosis of pericardial effusion and tamponade, two-dimensional echocardiography can also assist in its drainage, as pericardiocentesis can be performed safely under two-dimensional echocardiographic guidance (94, 95). By determining the depth of the effusion and its distance from the site of puncture, it is possible to optimize the needle placement. Echocardiography also can be used to immediately monitor the results of the pericardiocentesis.

Cardiac Tamponade in the ICU

The most common causes of cardiac tamponade in the ICU are listed in Table 3. Echocardiographic two-dimensional

Table 3. Most common causes of cardiac tamponade in the intensive care unit

- Myocardial or coronary perforation secondary to catheter-based interventions (i.e., after intravenous pacemaker lead insertion, central catheter placement, or percutaneous coronary interventions)
- Compressive hematoma after cardiac surgery
- Proximal ascending aortic dissection
- Blunt or penetrating chest trauma
- Complication of myocardial infarction (e.g., ventricular rupture)
- Uremic or infectious pericarditis
- Pericardial involvement by metastatic disease or other systemic processes

signs of tamponade are a direct consequence of increased pericardial pressure, leading to diastolic collapse of one or more cardiac chambers (usually on the right side first). Usually, collapse of the RV free wall is seen in early diastole and right atrial wall collapse is seen in late diastole (58). This latter sign is sensitive but not specific for tamponade. It is, however, specific for a hemodynamically significant effusion if the right atrial collapse lasts longer than one third of the R-R interval (58, 96). In the presence of a massive effusion, the heart may have a "swinging" motion in the pericardial cavity. This finding is not always present in cardiac tamponade, as the amount of fluid in the pericardial space may be small but still cause a tamponade physiology, depending on the acuity with which the effusion accumulates and the compliance of the pericardium. In poststernotomy patients, tamponade may be missed by TTE (even in cases in which imaging quality seems adequate) because hematomas causing selective cardiac chamber compression are often in the form of loculated clots, located in the far field of the ultrasound beam in the posterior heart region (even when the anterior pericardium is left open) (97). The right atrium and right ventricle may be spared in such cases secondary to postoperative adhesions or tethering of the right ventricle to the chest wall anteriorly (97).

Another (indirect) sign of a hemodynamically significant pericardial effusion on two-dimensional imaging is plethora of the inferior vena cava with blunted respiratory changes (1). The latter sign is less valuable in mechanically ventilated patients because they often have a stiff dilated inferior vena cava, even in the absence of a pericardial effusion.

Doppler findings of cardiac tamponade are based on characteristic changes in intrathoracic and intracardiac hemodynamics that occur with respiration. In critically ill patients, however, mechanical ventilation, bronchospasm, significant pleural effusion, respiratory distress, and arrhythmias make the Doppler findings difficult to interpret. In some circumstances, echocardiographic signs of tamponade may be very subtle or even absent so one must keep in mind that the diagnosis of tamponade remains a clinical one and that the echocardiographic signs must be analyzed in conjunction with the clinical findings.

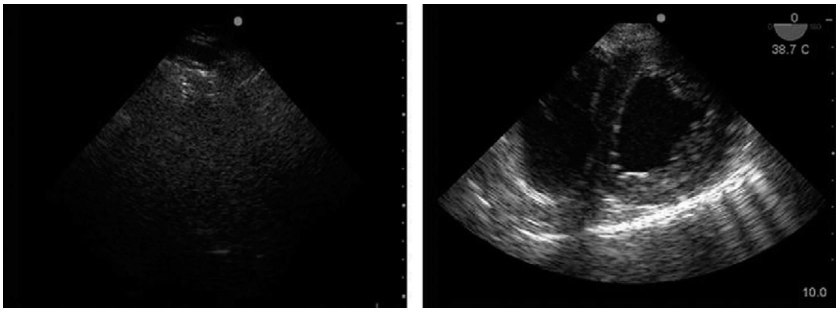

Figure 3. In certain specific clinical situations in which transthoracic echocardiography is likely to fail or be suboptimal, immediate transesophageal echocardiography will be preferable. In the above example, a 65-yr-old patient presented with hemodynamic instability after having undergone cardiac surgery. A transthoracic echocardiographic study was initially performed, but no adequate ultrasonographic window could be obtained (*left*, suboptimal parasternal short-axis view demonstrated), and cardiac function was impossible to assess with such an approach. A transesophageal echocardiographic study was then performed and a complete and reliable assessment of ventricular and valvular function was made (*right*, transesophageal short-axis view of the left and right ventricles from the transgastric plane demonstrated).

Complications After Cardiac Surgery

Bedside echocardiography has proved to be of particular value in the critical care management of patients with hemodynamic instability after cardiothoracic operations (77, 89, 98–101). TTE is often severely limited in this group of patients (35, 89) (Fig. 3). TEE is thus the modality of choice in this setting because it provides detailed information that can help determine the cause of refractory hypotension. The most frequent echocardiographic diagnoses encountered in this population of patients are LV or RV failure, tamponade, hypovolemia, and valvular dysfunction. Schmidlin et al. (102) studied 136 patients after cardiac surgery and showed that a new diagnosis was established or an important pathology was excluded in 45% of patients undergoing TEE. A therapeutic effect was found in 73% of cases. The main indications for TEE in this study were control of LV function (34%), unexplained hemodynamic deterioration (29%), suspicion of pericardial tamponade (14%), cardiac ischemia (9%), and "other" (14%). Reichert et al. (99) performed TEE in hypotensive patients after cardiac surgery. LV failure was found in 27% of patients, hypovolemia in 23%, RV failure in 18%, biventricular failure in 13%, and tamponade in 10%. Comparison with hemodynamic variables showed agreement on diagnosis (hypovolemia vs. tamponade vs. cardiac failure) in only 50% of the cases. Echocardiography identified two patients with tamponade and six with hypovolemia that were not suspected based on standard hemodynamic data. In five patients with hemodynamic findings suggestive of tamponade, unnecessary reoperation was prevented as TEE ruled out this diagnosis. Costachescu et al. (82) also demonstrated the superiority of TEE, compared with conventional monitoring with a PAC, in diagnosing and excluding significant causes of hemodynamic instability in postoperative cardiac surgical patients. Descriptions of the echocardiographic findings of LV dysfunction, tamponade, hypovolemia, and valvular dysfunction have been described in earlier sections of this article.

INFECTIVE ENDOCARDITIS

Occurrence of infective endocarditis in patients hospitalized in an ICU is not an uncommon event. It is often in the differential diagnosis of febrile patients in the ICU. Infective endocarditis was the second most common indication for performance of an echocardiogram among centers reporting their experience (35). Echocardiography is the test of choice for the noninvasive diagnosis of endocarditis. The echocardiographic features typical for infective endocarditis are a) an oscillating intracardiac mass on a valve or supporting structure or in the path of a regurgitant jet or an iatrogenic device, b) abscesses, c) new partial dehiscence of a prosthetic valve, or d) new valvular regurgitation (49, 103, 104). Sensitivity for the echographic diagnosis of endocarditis is 58–62% for TTE and 88–98% for TEE (105, 106). TEE is particularly useful for detecting small vegetations (107) and detecting vegetations on prosthetic valves.

TEE has also been clearly shown to be superior to TTE for diagnosing complications of endocarditis, such as aortic root abscess, fistulas, and ruptured chordae tendineae of the mitral valve (93). As concluded by Colreavy et al. (89), performance of TEE in the ICU for suspicion of infective endocarditis should be reserved a) for cases associated with a clinical likelihood of endocarditis and a negative TTE examination, b) for suspected prosthetic valve endocarditis, c) to assess complications in known cases of endocarditis, and d) for cases of *Staphylococcus aureus* bacteremia when the source is unknown or blood cultures remain positive despite antibiotic therapy.

ASSESSMENT OF THE AORTA

Suspected aortic pathologies can be encountered in different ICU settings. The aorta may need to be imaged to rule out dissection, rupture, aneurysm, aortic debris, or aortic abscess. TTE is a good initial imaging modality for evaluation of the proximal aorta (ascending aorta and arch) (49). The descending thoracic aorta, however, cannot be adequately assessed and visualized with this modality. Because of the close anatomic relationship between the thoracic aorta and the esophagus, TEE allows optimal visualization of the entire thoracic aorta.

Aortic Dissection and Rupture. Patients presenting with suspected aortic dissection need emergency diagnosis and treatment. Different noninvasive tests have been advocated for evaluation of suspected aortic dissection: TEE, computed tomography, and magnetic resonance imaging (35, 108). Nienaber et al. (108) compared all three modalities and found similar sensitivities (98%). Magnetic resonance imaging had higher specificity than TEE (98% vs. 77%). A limitation of the study was that single-plane TEE was used. With multiplane TEE, specificity is improved to >90% (109). TEE was compared with computed tomography and aortography in the multicenter European Cooperative Study (110), and it was demonstrated that TEE was superior to both modalities for the diagnosis of aortic dissection (sensitivity, 99%). Other studies have confirmed the high accuracy of TEE (110–113) (Fig. 4). A negative TEE for the diagnosis of aortic dissection, even in a high-risk population, has high negative predictive value (114).

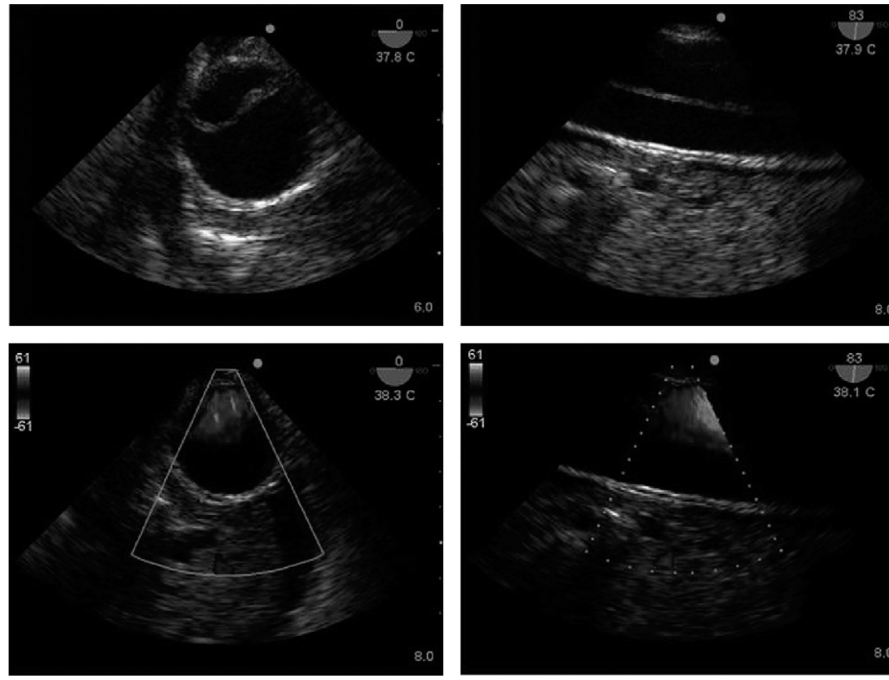

Figure 4. A 54-yr-old male patient with no medical history presented to the emergency room with severe chest pain. His electrocardiogram was within normal limits and so was an initial urgent bedside transthoracic echocardiographic examination. A subsequent bedside transesophageal echocardiographic study revealed the presence of an important dissection of the descending thoracic aorta, as can be seen from the two-dimensional images obtained in the short-axis (*top left*) and long-axis views (*top right*). A color-Doppler study performed in the same two views (*bottom left* and *bottom right*) showed the presence of flow in a severely narrowed true lumen, with no flow detected in the relatively large false lumen. The patient was urgently taken to the operating room.

Additional very helpful features of TEE in the evaluation of aortic pathologies are the ability to detect or assess: extension of dissection into the proximal coronary arteries; the presence of pericardial or mediastinal hematoma or effusion; the presence, severity, and mechanism of associated aortic valve regurgitation; the point of entry and exit between the true and false lumens; the presence of thrombus in the false lumen; and ventricular function (93).

Intraaortic Balloon Counterpulsation. Bedside TEE may be of help in different aspects of intraaortic balloon counterpulsation management. Before insertion, it can rule out the presence of significant aortic regurgitation, which would represent a contraindication to intraaortic balloon counterpulsation use. After insertion, TEE can confirm the position of the intraaortic catheter in the descending thoracic aorta, ensure correct functioning of the balloon (visualization of inflation and deflation), and rule out the presence of important complications of aortic catheter insertion like aortic dissection. TEE may also be used for monitoring of the ventricular function while separating the patient from the intraaortic balloon counterpulsation device.

ASSESSMENT FOR INTRACARDIAC AND INTRAPULMONARY SHUNTS

In critically ill patients, clinical suspicion for an intracardiac or intrapulmonary shunt will most often be raised in the context of unexplained embolic stroke or refractory hypoxemia. In such cases, the presence of a right-to-left shunt needs to be excluded. Common origins of right-to-left shunt are atrial septal defect or patent foramen ovale at the cardiac level (35) and arteriovenous fistula at the pulmonary level (35). To be able to detect the presence of such a shunt at the bedside, a contrast study is often needed, as the shunt is usually not well visualized with two-dimensional echocardiography alone. Color-flow imaging increases the detection rate of intracardiac shunt to some extent, but usually only when the shunt is large. Accordingly, a contrast study should be performed routinely as part of a TEE or TTE examination when evaluating a pa-

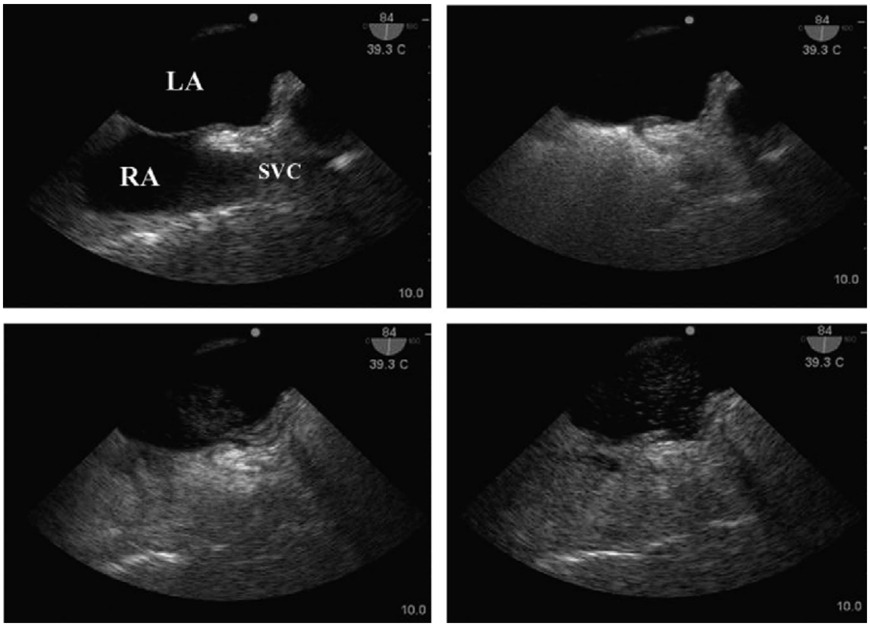

Figure 5. A 67-yr-old male patient had moderate to severe hypoxemia 2 days after a cardiac surgery. He was still on mechanical ventilation, with a high level of positive end-expiratory pressure. The chest radiograph did not show significant abnormalities. The possibility of having some degree of right-to-left shunt via a patent foramen ovale was entertained, and a transesophageal microbubble contrast study was performed at the bedside. *Top left*, an adequate TEE imaging plane to view the left atrium (*LA*), right atrium (*RA*), interatrial septum (the membrane seen between the LA and RA), and distal part of the superior vena cava (*SVC*) was obtained before injection of the microbubbles. *Top right*, microbubbles have just been injected and are seen completely opacifying the SVC and RA. *Bottom left*, within 2–3 heartbeats, the microbubbles are seen passing from the RA to the LA via a slit-like opening in the superior aspect of the interatrial septum, thus confirming the presence of a right-to-left shunt via a patent foramen ovale. *Bottom right*, a few seconds later, more of the left atrium gets filled with the bubble contrast. In such patient, the finding of a right-to-left shunt via a patent foramen ovale is of great importance, and an attempt will be made to lower the positive end-expiratory pressure and intrathoracic pressure as much as possible to decrease the degree of right-to-left shunting and associated hypoxemia.

tient with unexplained embolic stroke or refractory hypoxemia in the ICU. For this purpose, agitated saline contrast is usually used. Approximately 0.5 mL of air is mixed with 10 mL of normal saline and is then vigorously agitated back and forth between two syringes connected to the patient by a three-way stopcock. After an adequate echocardiographic view of the right and left atrial cavities has been obtained, the agitated saline is forcefully injected intravenously. After injection, the contrast is seen in the vena cava, right atrium, right ventricle, and the pulmonary artery. In the absence of a shunt, only a minimal amount of contrast should be seen in the left-sided cavities, as most of the microbubbles from the agitated saline are not able to pass through the pulmonary capillaries. If an intracardiac shunt is present, such as an atrial septal defect or patent foramen ovale, left-sided contrast will be observed immediately after right-sided opacification, and the contrast will be seen going through the interatrial septum (Fig. 5). Performance of a Valsalva maneuver by the patient during contrast injection increases the sensitivity of the bubble study to detect right-to-left shunting. Right-to-left shunting can also be caused by the presence of pulmonary arteriovenous fistulas. These are often associated with end-stage liver disease (hepatopulmonary syndrome). With this type of shunt, contrast is seen to appear in the left atrium from the pulmonary veins instead of through the atrial septum; this finding is best detected by TEE, which usually permits visualization of all four pulmonary veins. The characteristic of intrapulmonary vs. intracardiac shunt is that there is a longer delay (3–5 cardiac cycles) between the appearance of contrast from the right-sided to left-sided cavities in the presence of an intrapulmonary shunt (5). Agitated saline is a simple and easy to use contrast at the bedside. In critically ill patients, TEE is in general more useful than TTE for evaluation of patent foramen ovale, atrial septal defect, and pulmonary arteriovenous fistula (115) due to the close proximity of the lesion to the ultrasound transducer.

SOURCE OF EMBOLUS

In the setting of acute unexplained stroke, echocardiography will often be required to determine whether a potential embolic source of cardiac origin is present. TEE is the modality of choice for this purpose. Possible cardiac sources of emboli to the arterial circulation include left atrial or appendicular thrombus, LV thrombus, thoracic atheromatosis, and right-sided clots (right atrium, right ventricle, vena cava) combined with a right-to-left intracardiac shunt (leading to a paradoxic embolus). Cardiac tumors and vegetations are other potential sources of emboli of cardiac origin that need to be considered.

In the critically ill patient with atrial fibrillation or flutter in whom cardioversion is considered, performance of TEE will be very helpful for evaluating the left atrium and appendage for the presence of thrombus. If no intracardiac clots are documented, cardioversion can then be performed with minimal embolic risks.

COMPARISON BETWEEN BEDSIDE ECHOCARDIOGRAPHY AND PULMONARY ARTERY CATHETER IN THE ICU

Since its introduction into clinical practice in 1970, the PAC has been the standard hemodynamic monitoring technique for critically ill patients in the ICU (116–118). The PAC provides clinicians with indices of cardiovascular function to assist in therapeutic decision making. A PAC can be a very useful diagnostic tool, aiding in the management of critically ill patients. Nevertheless, poor interpretation of the data it provides can lead to excessive morbidity and mortality (51, 116, 119, 120). Conventional monitoring using a PAC has been shown to often be limited in the evaluation of global ventricular function (80, 81), and echocardiographic studies have established that pulmonary artery occlusion pressure often does not allow accurate assessment of LV preload (17, 57, 121). The frequent changes in ventricular compliance and loading conditions occurring in critically ill patients can affect both systolic and diastolic function. In such cases, conventional monitoring does not enable early detection of acute changes in function, and it does not allow the clinician to discern systolic from diastolic changes (80). In critically ill patients, echocardiography, particularly TEE, has the ability to clarify diagnosis and define pathophysiologic process more precisely than PAC. In a prospective study of limited-scope, goal-directed TEE, Benjamin et al. (81) found that TEE-derived data disagreed with the PAC evaluation of intracardiac volume in 55% of cases and with the PAC assessment of myocardial function in 39% of cases. These authors also demonstrated that the post-PAC therapeutic recommendations were different from the post-TEE therapeutic recommendations in 58% of patients. In a retrospective analysis of 108 critically ill patients who underwent a TEE, Poelaert et al. (122) found that of 64% of patients with a PAC, 44% underwent therapy changes after TEE (41% in the cardiac and 54% in the septic subgroup). Also, they found that in 41% of patients without a PAC, TEE led to a change in therapy. They concluded that TEE produced a change in therapy in at least one third of their ICU patients, independent of the presence of a PAC (122). Another significant advantage of echocardiography in the ICU is the speed with which it can be performed relative to PAC. In the study by Benjamin et al. (81), TEE was performed in 12 ± 7 mins vs. ≥30 mins for PAC insertion. In a study by Kaul (123), the average time required to place a PAC and record the data was 63 ± 45 mins vs. 19 ± 7 mins to perform bedside TEE. Reported complications of PAC include pneumothorax, hemothorax, bacteremia, sepsis, cardiac arrhythmias, pulmonary artery rupture, cardiac perforation, and valvular damage (81). Compared with PAC, bedside echocardiography has a better safety profile, as reported in a previous section of this article.

A major advantage of the PAC vs. TEE examination is that the catheter can more easily serve as a continuous monitoring technique to assess the response to a therapeutic intervention (81). However, this potential advantage may provide little benefit in patients in whom the information is misinterpreted or inadequate. In some ICUs, TEE has completely replaced the PAC for assessment of circulatory status of mechanically ventilated patients (28). Despite having multiple limitations, the PAC still has a role in the ICU and remains a useful diagnostic tool when used by physicians who have extensive experience with it (122, 124). A combination of invasive pressure monitoring and TEE imaging probably offers the most complete evaluation at the bedside on morphology and intracardiac hemodynamics and provides a more precise pressure–volume evaluation of both LV and RV function and filling (82, 122).

EFFECT OF BEDSIDE ECHOCARDIOGRAPHY IN THE CRITICALLY ILL PATIENT ON DIAGNOSIS AND MANAGEMENT

Several studies have examined the effect of bedside echocardiography, particularly TEE, on the management of critically ill patients. Published studies have reported changes in management after TEE in 30–60% of patients, (15, 122, 125, 126) leading to surgical interventions in 7–30% (15, 92, 126, 127). Effect varies depending on the type of ICU population being studied. Several studies have reported the clinical effect of urgent TEE in hemodynamically unstable patients (126, 128, 129). In a prospective study of surgical ICU patients by Bruch et al. (14), echocardiography altered management in 50 of 115 patients (43%). Alterations in medical management induced by TEE included administration of fluids and initiation or discontinuation of inotropic agents, anticoagulants, or antibiotics. These findings are similar to those reported in patients in medical or coronary care ICUs (2, 127). In a retrospective study done by Colreavy et al. (89) of a mixed medical and surgical ICU population, TEE findings led to a significant change in management in 32% of all studies performed. In a prospective study by Heidenreich et al. (130) of 61 critically ill patients with unexplained hypotension, new diagnoses were made in 17 patients (28%), leading to surgical intervention in 12 (20%). Prospective randomized trials to study the ultimate effect of bedside echocardiography on mortality and morbidity in the ICU are needed. Such studies will be difficult to perform, however, given the growing use and importance of this technology in the critical care setting.

HAND-CARRIED ULTRASOUND

Hand-carried ultrasound (HCU) devices are a new generation of portable ultrasound machines that are lightweight (6–10 lbs), battery powered, and less expensive ($15,000–50,000) than the sophisticated high-end machines. The tremendous potential of HCU to immediately provide diagnostic information at the bedside not assessable by the physical examination alone has been increasingly demonstrated and recognized in the last few years (131–139). These devices may facilitate the full clinical potential of ultrasound imaging in the ICU, with true portability, ease of use, and lower cost (Fig. 6). They are especially powerful when used as an adjunct to the physical examination (136, 137).

An examination using HCU is usually directed toward a specific clinical question and is in general significantly shorter in duration (<6 mins in some studies) than one using traditional echocardiography (133, 135, 140–144). The disadvantage of such directed examina-

Figure 6. Hand-carried ultrasound is a new generation of portable ultrasound machine that is lightweight (6–10 lbs), battery powered, and much less expensive than the sophisticated high-end machines. The small size is a tremendous advantage in the acute care environment because space is often significantly limited, as shown in this picture of an intensive care unit patient receiving mechanical ventilation and continuous renal replacement therapy.

tions with hand-carried devices is that they are not as comprehensive and can potentially miss some findings compared with traditional echocardiographic examinations. However, the HCU devices should not be compared with the yield or quality of the high-end machines. The HCU should be viewed more as an extension to the physical examination (133, 136, 142–144). In general, accuracy of images created by these devices has shown good agreement when compared with standard echocardiogram machines with respect to two-dimensional findings (133, 142, 145). Studies have shown HCU sensitivity of two-dimensional imaging for finding abnormal LV function to range from 76% to 96%, with lower sensitivity for color-Doppler assessment of valvular regurgitation (52% to 96%) (133, 142, 145). Most studies comparing HCU with standard echocardiography were done in the inpatient ward or outpatient practice setting (133, 136). A recent study done by Gorcsan et al. (135) investigated the utility of HCU when specifically used as an extension of the physical examination on consultative cardiology rounds (n = 235). The HCU demonstrated an excellent close overall agreement (92–100%, $r = .91–.96$) for estimation of EF, LV hypertrophy, regional wall motion abnormalities, and pericardial effusion (as assessed by two-dimensional imaging) when compared with an echocardiographic study using a full-size echocardiographic system. The goal-directed HCU study was performed in <10 mins and was focused on the above-mentioned diagnoses. HCU data influenced treatment decisions in 149 patients (63%); 50% had a change in medical therapy, and 22% had a change in their diagnostic workup. In all, 12 patients (5%) had an immediate change in the decision for cardiac catheterization or pericardiocentesis. The authors of this study concluded that use of "goal-directed HCU has the potential to influence bedside patient treatment decisions and expedite health care" (135). Concerns have been raised that HCU devices may compare less favorably with standard echocardiography when performed in critically ill patients because of the more frequent occurrence of a limited acoustic window. In a study of 80 critically ill patients that compared HCU vs. standard echocardiography, 85% of clinical questions could be addressed by the HCU device (146). HCU failed to detect a clinically significant finding in 31% of patients; however, the majority of these missed findings were Doppler-based diagnoses (e.g., valvular regurgitation). A more recent study by Vignon et al. (138) compared the diagnostic capability of HCU and of conventional TTE (used as a gold standard) in a population of 106 critically ill patients on mechanical ventilation. In this study, the HCU exams were performed by echocardiography-trained intensivists and the TTE exams were reviewed by a cardiologist experienced in echocardiography. They showed that the number of acoustic windows was comparable when using the HCU and conventional TTE in this population of patients. HCU had a lower overall diagnostic capacity than TTE (199 of 251 vs. 223 of 251 clinical questions solved, $p = .005$), mainly due to its lack of spectral Doppler capability. However, diagnostic capacity based on two-dimensional imaging was comparable for both approaches (129 of 155 vs. 125 of 155 clinical questions solved, $p = .4$). Also, HCU and TTE had a similar therapeutic effect. Results from these studies suggest that the accuracy of HCU with respect to two-dimensional imaging remains very good in the critically ill patient when compared with standard ultrasound machines but that information derived from HCU color-Doppler imaging should be interpreted cautiously in this patient population.

It should be emphasized that the goal of using HCU in the ICU should not be to replace high-end machines but to provide diagnostic data not detected on physical examination. HCU should allow critical care physicians to diagnose certain cardiopulmonary pathologies more rapidly than with standard echocardiography (which is often performed with a variable delay after having been requested). Provided that physicians performing point-of-care examinations with the HCU have adequate training (133, 143, 147), have realistic expectations, and understand the limitations of the device, then the HCU has the potential to create a tremendous advantage for bedside assessment and treatment of the ICU patient.

PERFORMANCE OF BEDSIDE ECHOCARDIOGRAPHY BY THE INTENSIVIST

It is usually not feasible to have a cardiologist or sonographer available on immediate call on a 24-hr basis to perform bedside ultrasonographic examinations in the ICU. The value of immediate bedside echocardiography for aiding in diagnosis and management of acute hemodynamic disturbances has been well demonstrated in both the ICU and the emergency room (24, 148, 149–151). It is recognized that ultrasound technologies are not exclusive to the radiologist or cardiologist. Appropriately trained emergency room physicians, surgeons, anesthesiologists, and intensive care specialists have been performing echocardiographic examinations with great success. Anesthesiologists were instrumental in many of the pioneering studies of TEE in the operating room and ICU (152–154). Successful performance of bedside echocardiography by noncardiologist intensivists has also been well demonstrated in the literature (137, 138, 143). A recent study by Manasia et al. (155) demonstrated that after a brief (10 hrs) formal training in using a handheld echocardiographic system, intensivists were able to successfully perform a limited TTE in 94% of patients and interpreted their studies correctly in 84%. Limited TTE provided new cardiac information and changed management in 37% of patients. This study supports the concept that intensivist-performed goal-directed TTE can be easily feasible and have significant clinical effect. However, adequate training is essential, and this must be individualized and tailored to the specific needs and applications of the user (156). With expert backup, focused bedside ultrasonography by intensivists is not only feasible but can also be done safely and rapidly and yield information pertinent to the management of critically ill patients. However, inappropriate interpretation or application of data gained by a poorly skilled user may have adverse consequences (156). To avoid misusing this technology, adequate training is essential.

The importance of adequate training and subsequent maintenance of competence cannot be overemphasized, as inappropriate use or misapplication could potentially temper the acceptance of intensivist-performed bedside ultrasound. Performance of emergency bedside ultrasound should provide rapid answers to clinical questions that may profoundly affect medical and surgical management decisions. Training in goal-directed echocardiography and general ultrasonography should be incorporated in the critical care fellowship as part of the training program of intensivists. The era of a technology-extended physical examination (136) seems to have arrived, and there seems to be a role for user-specific, focused ultrasound examinations (156, 157).

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