Echocardiography in the Critically Ill: An Overview

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In recent years, bedside ultrasonography has gained wide acceptance for the assessment of critically ill patients. As opposed to "blind" monitoring systems, which frequently rely on invasive techniques (e.g., pulmonary artery catheter), echocardiography Doppler allows real-time imaging of the heart and great vessels, thereby proving unparalleled anatomical and functional information. Because of its versatility, safety, and instantaneous diagnostic capability, bedside ultrasonography is ideally suited for the evaluation of unstable patients in the intensive care unit (ICU). This overview will examine the utility of critical care echocardiography and the current field of use of transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) in the ICU. Cardiac output monitoring by esophageal Doppler [1, 2] and noncardiac ultrasonography [3] are purposely excluded from this overview. Training issues are discussed elsewhere (see Chap. 21).

1.1 Historical Perspective

Whereas hemodynamic assessment of ICU patients was predominantly invasive in the 1980s and 1990s, the current approach tends to be less invasive, more functional, and to integrate heart-lung interactions in the diagnostic process. During the last decade, right heart catheterization (RHC) has been progressively supplanted by bedside echocardiography in numerous ICUs [4]. Since its introduction in 1970 [5], RHC has been utilized widely by intensivists for the management of patients with circulatory failure. Therapeutic algorithms based upon RHC rely on pressure, flow, and metabolic measurements. Concordant publications clearly showed a lack of benefit and potential

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harm associated with the routine use of RHC [6–11]. In addition, clinically relevant discrepancies between RHC and bedside echocardiography in the evaluation of patients with circulatory failure have been published [12–20] and attributed to intrinsic limitations of RHC [21]. As a result, some intensivists have come to regard bedside ultrasonography as a superior alternative to RHC for the hemodynamic assessment of ICU patients [22, 23].

The early pioneers of critical care echocardiography used TTE and emphasized the superiority of bedside echocardiography over RHC [24–26]. The development of TEE accelerated the diffusion of ultrasonography into some ICUs since surface echocardiography was often limited by inadequate image quality in the ICU environment. TEE yielded good image quality in virtually all ventilated patients and allowed assessment of deep anatomical structures, which were otherwise not accessible to TTE [27–41].

Table 1.1 Technological landmarks in echocardiography

Technological development[a]
First reported use of echocardiography in clinical practice (Edler. 1954)
Time-motion mode allows identification of cardiac condition (Joyner. 1963)
Real-time two-dimensional imaging opens window to the beating heart from the surface of the chest (Bom. 1973)
Spectral Doppler allows an assessment of hemodynamics (Hatle. 1979)
Transesophageal echocardiography yields new information and increases the diagnostic capabilities of cardiac ultrasound, especially in mechanically ventilated patients (Schluter. 1983)
Tissue Doppler provides new insights into intrinsic ventricular properties (Isaaz. 1989)
Three-dimensional echocardiography, initially based on off-line reconstructions of two-dimensional images, is progressively performed in real time, using volumetric ultrasound data acquired by matrix-array transducers
Hand-held echocardiography leads to the development of the ultrasound stethoscope and contributes to the diffusion of ultrasonography in the noncardiology community
Miniaturized full-feature imaging systems and real-time quantitative three-dimensional transesophageal echocardiography become commercially available clinical tools

[a]Years are indicative of breakthrough reports showing the clinical value of the echocardiographic tools, rather than the time of their first description

In addition, TEE became the first-line diagnostic procedure recommended officially for the assessment of circulatory failure complicating the perioperative course or occurring in ICU ventilated patients [42–44]. In the past decade, progress in machine design has allowed the development of smaller, more powerful echocardiography systems with increased TTE diagnostic capabilities (Table 1.1).

1.2 Specificities of Critical Care Echocardiography

As opposed to conventional echocardiography, which is performed by cardiologists on a consultative basis in the echocardiography laboratory, critical care echocardiography is carried out and interpreted by the intensivist at the bedside of the ICU patient. Critical care echocardiography allows the frontline clinician to establish diagnosis and guide management of hemodynamic failure. Critical care echocardiography has specific requirements that cannot be met by consultant cardiologists and that support the need for training intensivists in the use of this technique in the ICU (Table 1.2).

Table 1.2 Specifics of critical care echocardiography

Requirements
Availability of a trained operator and a dedicated platform on a 24-h basis (the intensivist performs and interprets the echocardiographic examination at bedside)
Background in critical care medicine including the use of echocardiography as an adjunct to sound medical reasoning
Integration of heart–lung interactions in the interpretation of echocardiographic studies[a]
Integration of the ventilator settings in the interpretation of echocardiographic studies[b]
Specific diagnostic algorithms based on validated echocardiographic indices to assess central hemodynamic status
Presentation of echocardiographic findings in the clinical scenario to evaluate their relevance
Online interpretation of echocardiographic studies to optimize direct therapeutic impact, including reintervention after cardiac surgery
Immediate evaluation of the efficacy and tolerance of acute therapy (monitoring tool)

[a]Especially in mechanically ventilated patients
[b]Especially in patients ventilated for acute respiratory distress syndrome

Critically ill patients require nonscheduled management and care. Critical care echocardiography must therefore be available on a 24-h basis. A key requirement is that a capable machine be immediately available to the intensivist in the ICU. By definition, critical care echocardiography is performed personally by the frontline intensivist, the study is interpreted at the bedside of the critically ill patient, and the results are used for immediate diagnosis and management. In contrast to conventional echocardiography performed in stable patients presenting with chronic cardiac disease, critical care echocardiography has optimal diagnostic ability when performed at the time of the clinical deterioration. When performed after the initiation of a treatment that rapidly alters the hemodynamic profile (e.g., diuretics in decompensated congestive heart failure, afterload reduction in mitral regurgitation), echocardiography may be less informative [45].

The current approach to hemodynamic assessment using bedside echocardiography has to integrate heart and lung interactions [46, 47]. This requires a specific background in critical care medicine [48]. Whereas positive-pressure ventilation has long been recognized as a potential confounding factor for hemodynamic assessment using RHC [21, 49], Doppler echocardiography allows a better understanding of the complex effects of volume-controlled ventilation on central hemodynamics [47]. Over the last decade, several echocardiographic indices using heart-lung interactions produced by positive-pressure ventilation in the presence of a clinically relevant hypovolemia have been validated for predicting fluid responsiveness [50–54]. Recently, passive leg-raising has allowed echocardiographic indices to predict responders to a fluid challenge in patients with spontaneous breathing activity [55, 56]. These simple yet robust indices of fluid responsiveness allow intensivists to use echocardiography routinely in deciding when to proceed with volume resuscitation.

Heart-lung interactions are influenced not only by the volume status of the mechanically ventilated patient, but also by the lung compliance and ventilator settings [57]. This is especially relevant in patients who are on ventilatory support for acute respiratory distress syndrome (ARDS). Specifically, inappropriate ventilator settings may directly impede right ventricular ejection and contribute to the development of circulatory failure [58]. Early recognition of the negative effects of mechanical ventilation on central hemodynamics is crucial as circulatory failure is a leading cause of death with ARDS [59].

The findings provided by an imaging modality have to be interpreted in light of the clinical scenario and patient history. Accordingly, critical care echocardiography results always need to be interpreted within the clinical context. The intensivist who is directly in charge of the management of a case is best equipped to do this. Operator experience is crucial in order to integrate echocardiography results correctly with the clinical presentation. The results of critical care echocardiography are immediately interpreted by the attending intensivist, and so they may often substantially alter workup and therapy.

1.3 Indications and Safety of Echocardiography in ICU Patients

1.3.1 Indications for Critical Care Echocardiography

Indications for echocardiography have long been defined in the cardiology community [43, 44]. According to these guidelines, hemodynamically unstable patients and patients sustaining severe chest or multisystem trauma represent the main indications for performing echocardiography in the ICU setting. Societies of anesthesiologists have also defined specific indications of TEE in the perioperative period [42]. In contrast, indications for performing Doppler echocardiography in ICU patients have not yet been established by critical care societies. Recent recommendations describe echocardiography as an alternative to right-heart catheterization for the measurement of cardiac output in septic patients [60]. There is compelling evidence that leads us to propose bedside ultrasonography as the first-line diagnostic tool in the ICU for the assessment of patients presenting with circulatory failure (i.e., hypotension, shock), respiratory failure, or both [12–41, 61, 62].

Shock has recently been defined by an international consensus conference as clinical evidence and/or a biological marker of inadequate tissue perfusion – e.g., decreased central venous oxygen saturation ($ScvO_2$) or mixed venous oxygen saturation (SvO_2), increased blood lactate, increased base deficit, and low pH – considering that hypotension could be inconsistent [63]. Respiratory failure usually refers to the conjunction of dyspnea and potential muscular fatigue, hypoxemia, and radiographic infiltrates. In these clinical settings, Doppler echocardiography provides rapid and comprehensive evaluation of the hemodynamics (e.g., hypovolemia, left or right ventricular failure, vasoplegia, elevated filling pressures) and also allows for immediate critical diagnoses (e.g., severe valve failure, central pulmonary embolus, thrombus in transit, pericardial effusion). When compared with blind and more invasive traditional monitoring techniques, echocardiography has the unparalleled advantage of directly depicting certain mechanisms of hemodynamic embarrassment that otherwise would be undetectable, including ventricular interdependence, pericardial constraints, regional wall-motion abnormalities, impaired relaxation, dynamic left ventricular outflow obstruction, and acute valvular regurgitation. In addition to the major indication for echocardiography in the ICU, which is cardiopulmonary failure, other standard indications apply, such as assessment of blunt chest trauma patients at high risk of cardiovascular injury, searching for a cardiac embolic source, endocarditis [64], and intracardiac shunt (Table 1.3).

1.3.2 TTE Versus TEE

Traditionally, it is assumed that TTE is the first-line approach owing to its versatility, tolerance, and availability [44, 62]. TTE has certain advantages over TEE, including a better Doppler beam alignment with intracardiac flows and a broader field of examination of relatively superficial anatomical structures (Table 1.4). In general, TEE is appropriately used as an adjunct or subsequent test to TTE when surface examination is nondiagnostic (e.g., poor imaging quality, inaccessibility of deep anatomical structures). ICU patients present challenges when assessed by means of TTE since hyperinflation related to mechanical ventilation or chronic obstructive pulmonary disease, obesity, edema, chest wall wounds or dressings, tubings, or surgical emphysema frequently interfere with ultrasound transmission and result in inadequate image quality [43, 62]. This explains why previous studies conducted in the ICU consistently reported a superior diagnostic capability of TEE compared with TTE [12, 15, 28, 30, 32, 33, 36]. When serial hemodynamic assessment is required to monitor acute therapeutic changes in unstable patients, reproducible tomographic imaging planes are frequently more easily obtained with TEE than with TTE. Although recent-generation miniaturized echocardiography machines have excellent image quality and surface echocardiography may be diagnostic in hemodynamically unstable patients [65], TTE remains difficult to perform in certain patient populations. In these cases, TEE may be required. Visualization of specific anatomical structures for accurate diagnoses and assessment of ventilated patients in perioperative settings are other main indications for performing a primary TEE examination [44, 62] (Table 1.4). In North America, TEE is not yet widely performed by intensivists, whereas it is routinely used by frontline intensivists in several European countries.

1.3.3 Tolerance of TEE

TEE can be performed safely in patients with critical illness. The rate of serious complication is very low. Patients are generally on mechanical ventilatory support, with the airway secured by tracheal intubation. Respiratory complications are therefore very rare. Injury to the esophagus (esophageal abrasion, perforation, or bleeding) is always a possibility. This can be avoided by appropriate patient selection and by minimizing rotational movement of the endoscope tip while it is under flexion. A full history has to be obtained that addresses the risk of esophageal injury from TEE. TEE is contraindicated in the setting of esophageal varices, strictures, bleeding, recent surgery, tumors, diverticuli, or other significant esophageal pathology. Coagulopathy or thrombocytopenia are relative contraindications to TEE. Risks associated with sedation, such as airway compromise and transient hypotension, are similar to those with other endoscopic procedures.

In a summary review of 2,504 TEE studies performed in the ICU, there was a 2.6% overall complication rate (discounting inadvertent dislodgement of a nasogastric tube), and no procedure-related deaths were reported [66]. Unsuccessful TEE probe insertion is rare when using laryngoscopic guidance in adequately sedated patients on ventilatory support. In spontaneously breathing patients, the major risk of TEE is related to the development of an acute respiratory failure secondary to the esophageal intubation [67, 68]. TEE should be

Table 1.3 Main indications of critical care echocardiography

Common indications in ICU environment	Raised clinical questions
Circulatory failure (hypotension, shock):	
Persistent shock despite initial therapy	Main mechanism(s) of shock[a]
Complicated AMI	RWMA, LV dysfunction, RV involvement, mechanical complications[b]
Complicated acute aortic syndrome	Tamponade, acute aortic regurgitation, LV dysfunction
Massive pulmonary embolism	Acute cor pulmonale, in-transit or entrapped embolus[c]
Cardiac tamponade	Circumferential compressive pericardial effusion (guidance for pericardiocentesis), compressive mediastinal hematoma
Unexplained hypotension or shock after cardiac surgery	Surgical complication requiring rapid reoperation or medical mechanism(s)[a]
Cardiac arrest (during or after successful resuscitation)	Treatable cause of cardiac arrest[d]
Acute respiratory failure:	
Cardiogenic pulmonary edema vs. ARDS	Elevated LV filling pressure, acute cor pulmonale
Weaning failure from the ventilator	Cardiac cause of weaning failure[e]
Decompensated chronic respiratory failure	Cardiac cause of decompensation, chronic cor pulmonale, pulmonary hypertension
Unexplained hypoxemia	Intracardiac shunt (patent foramen ovale)
Other clinical settings	
Severe blunt chest trauma, penetrating trauma	Cardiovascular injury
Suspected infective endocarditis	Duke criteria and functional consequences of infection-related injuries[f]
Suspected cardiovascular source of systemic embolism	Cardiac or aortic source of systemic embolism (including patent foramen ovale)
Cardiac evaluation in brain-dead patients	Evaluation of potential heart donors

[a]Includes persistent hypovolemia, right ventricular failure (e.g., acute cor pulmonale), left ventricular failure, vasoplegia, low cardiac output unrelated to decreased contractility (e.g., valvulopathy, dynamic outflow obstruction, pericardial constraints)
[b]Includes acute free-wall rupture, septal rupture, papillary muscle rupture
[c]Embolus may be entrapped in proximal pulmonary arteries or in the foramen ovale
[d]Includes tamponade, massive pulmonary embolism, and tension pneumothorax
[e]Includes elevated left ventricular filling pressure, worsened mitral regurgitation, new RWMA, dynamic LV outflow tract obstruction
[f]Duke echocardiographic major diagnostic criteria include the presence of vegetation, abscess, or new partial dehiscence of a prosthetic valve [64], and functional consequences are valvular insufficiencies or anatomical shunts with associated ventricular volume overload
Abbreviations: AMI, acute myocardial infarction; RWMA, regional wall-motion abnormality; LV, left ventricle; RV, right ventricle; ARDS, acute respiratory distress syndrome

discouraged in unstable patients who are not on ventilatory support, especially when a tamponade or a massive pulmonary embolism is suspected, because the procedure may precipitate circulatory or respiratory compromise (Table 1.5). In ambulatory patients examined in the echocardiography laboratory, a large cardiological series of over 10,000 consecutive TEE examinations reported an incidence of complications as low as 0.88% [69] and a rate of hypopharyngeal or esophageal perforation of 0.03% [70]. There are no known mechanical complications with TTE.

1.4 Therapeutic Impact of Critical Care Echocardiography

Owing to its excellent diagnostic capability, TEE has a therapeutic impact that is consistently superior to that of TTE when ventilated ICU patients are evaluated with both procedures [12, 15, 28, 30, 32, 33, 36]. Critical care echocardiography has documented a direct impact on therapy in up to 50% of ICU patients [12, 15, 17, 20, 28, 31, 33–37, 39–41]. TEE has been shown to prompt cardiac surgery in up to 20% of examined patients,

Table 1.4 Indications of transthoracic and transesophageal echocardiography

TTE	TEE
General screening, overall evaluation	Non-diagnostic TTE
Evaluation of cardiac function	Circulatory failure in ventilated patients[a]
Suspected pericardial disease Guidance of pericardiocentesis	Suspected extracardiac tamponade (mediastinal hematoma) or loculated compressive pericardial effusion[b]
Evaluation of left-sided valvulopathy or prosthetic valve	Mechanism and quantification of mitral regurgitation or prosthetic-valve dysfunction
Suspected LV outflow-tract obstruction	Diagnosis and management of infective endocarditis
Evaluation of pulmonary artery pressure	Identification of embolus-in-transit or proximal pulmonary embolism[c]
Suspected thrombus of LV apex	Identification of intracardiac shunt
Inferior vena cava examination	Identification of a cardiac or aortic source of systemic embolism
Penetrating chest trauma	Suspected acute condition of the thoracic aorta (e.g., spontaneous dissection, traumatic aortic injuries)
Contraindications for TEE	Guidance of invasive procedures (other than TEE during cardiac surgery)[d]

[a]Especially in the perioperative period
[b]In ventilated patients, after cardiac surgery or chest trauma
[c]In ventilated patients
[d]For example, guidance of patent foramen ovale closure or aortic stenting, assessment of mechanical circulatory assistance
Abbreviations: TTE, transthoracic echocardiography; TEE, transesophageal echocardiography

according to the type of ICU recruitment [17, 20, 27, 29, 31–35, 37–41]. By accurately identifying the mechanism of shock or acute respiratory failure, critical care echocardiography allows the intensivist to change therapeutic strategy and reduce the risk of inefficient or harmful therapy. It frequently corrects initial diagnosis derived from conventional hemodynamic monitoring [12–20]. In unstable patients, acute therapy (e.g., fluid challenge, initiation of inotropic support, ventilator settings) may result in a rapid variation of the hemodynamic profile. Accordingly, the hemodynamic assessment is best performed early in the course of organ failure and serial echocardiographic examinations provide real-time monitoring of both the efficacy and tolerance of therapeutic interventions in ICU patients. The anticipated efficacy of therapeutic changes related to critical care echocardiography is closely related to the severity of patient presentation, its benefit being maximal in the most unstable patients at the time of examination.

1.5 Conclusions

Echocardiography should be the primary diagnostic tool for the evaluation of ICU patients with circulatory or respiratory failure. Critical care echocardiography requires that a capable machine be immediately available on a 24-h basis in the ICU. The frontline intensivist who uses echocardiography to guide the management of the critically patient must be competent in image acquisition, image interpretation, and application of the results to the clinical situation. Both TTE and TEE offer strong utility in the ICU. TEE may be required where TTE image quality is inadequate to answer the clinical

Table 1.5 Tolerance of transesophageal echocardiography in critically ill patients

Good	Questionable	Contraindications
Ventilated patients	Spontaneously breathing unstable patients[b]	Esophagogastric surgery
Adequate sedation[a]	Shock potentially related to tamponade or massive pulmonary embolism in the absence of mechanical ventilation	Any relevant esophageal disease Excessive risk of bleeding Unstable neck fracture Mediastinal radiation therapy

[a]Muscle relaxation may be necessary to facilitate TEE probe insertion under laryngoscopic examination
[b]Especially when acute aortic syndrome is highly suspected

question, but the use of TEE may also be curtailed by its limited availability in some ICUs. TEE has an excellent safety record in the ICU. The intensivist should regard echocardiography as a key area in which to acquire cognitive and technical skills for optimal management of patients with cardiopulmonary failure.

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