

Guidelines for the Use of Echocardiography as a Monitor for Therapeutic Intervention in Adults: A Report from the American Society of Echocardiography

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GENERAL CONSIDERATIONS

Recent guidelines have been published providing detailed guidance on specific echocardiographic diagnostic criteria for measurements of diastolic function, chamber dimensions, right ventricular (RV) function, and Doppler measurements. Also, guidelines have been published with respect to requirements for competence in basic and advanced perioperative transesophageal echocardiography (TEE), as well as focused cardiac ultrasound examinations. Increasingly, however, transthoracic echocardiography (TTE) and

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Abbreviations
ASE = American Society of Echocardiography
CO = Cardiac output
DT = Deceleration time
FAC = Fractional area change
4C = Four-chamber
IVC = Inferior vena cava
LA = Left atrial
LAP = Left atrial pressure
LAX = Long-axis
LV = Left ventricular
LVAD = Left ventricular assist device
LVIDD = Left ventricular internal diameter at end-diastole
LVIDS = Left ventricular internal diameter at end-systole
LVOT = Left ventricular outflow tract
ME = Midesophageal
MV = Mitral valve
PA = Pulmonary artery
PW = Pulsed-wave
RAP = Right atrial pressure
RV = Right ventricular
RVIDD = Right ventricular internal diameter in diastole
RVOT = Right ventricular outflow tract
SAX = Short-axis
SVR = Systemic vascular resistance
TAPSE = Tricuspid annular plane systolic excursion
TDI = Tissue Doppler imaging
TEE = Transesophageal echocardiography
TTE = Transthoracic echocardiography
2D = Two-dimensional
VTI = Velocity-time integral

TEE are being used to monitor hemodynamics and direct therapy in critically ill patients. Case reports, observational studies, and state-of-the-art literature reviews have demonstrated the potential role of echocardiography in care and decision making for medical and surgical patients. Intensivists, trauma physicians, cardiologists, and anesthesiologists are now using TTE and TEE to provide hemodynamic assessments in patients with life-threatening illnesses such as sepsis, respiratory failure, congestive heart failure (CHF), shock, and traumatic injuries, as well as patients with significant respiratory and cardiac diseases undergoing noncardiac surgery and high-risk noncardiac procedures.¹⁻¹⁰ Ramp tests and weaning protocols using echocardiographic monitoring are used in left ventricular (LV) assist device (LVAD) optimization and to guide the removal of assist devices.^{11,12} The clinical impact on diagnosis, decision making, and management has led governing bodies to address the potential value of echocardiography in unstable medical and noncardiac surgical patients. The recent consensus statement by the American Society of Echocardiography (ASE) on focused echocardiography¹³ and the standardization of the basic perioperative transesophageal echocardiographic examination⁸ have led to the need for guidelines regarding when, and how, to use echocardiography as a quantitative monitoring tool. By definition, we propose that echocardiography is being used as a monitoring tool if, after a diagnostic assessment, repetitive hemodynamic or anatomic assessments are being made over a period of minutes, hours, or days in the same patient to guide management. In this context, this covers all areas in which echocardiography is

SCOPE OF WORK

Multidisciplinary guidelines published by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists in 2010 recommend the use of TEE in patients who are undergoing noncardiac surgery and exhibit persistent hypotension or hypoxia despite intervention (category B2 and B3 evidence).¹ Clinical data exist on the usefulness of TEE and TTE in adult patients in critical care units or emergency departments who are hemodynamically unstable or who need noninvasive hemodynamic monitoring.^{9,10} However, prospective, randomized clinical trials are lacking on the morbidity, mortality, and cost-effectiveness of echocardiography in this population. Because of the ethical and logistic challenges in conducting randomized clinical trials on patients who are hemodynamically compromised, expert opinion is heavily relied on for criteria and guidelines. Although expert opinion and a significant body of literature support the use of echocardiography as a tool to guide therapy in patients who are critically ill, standard guidelines that define when and how echocardiography can be used to guide medical and surgical therapy have not been published.³ This document summarizes the literature that supports the use of echocardiography as a monitoring tool in specific clinical settings. The specific parameters that are used are discussed first, followed by guidelines for their use in specific clinical scenarios.

I. ECHOCARDIOGRAPHIC MONITORING TOOLS

Echocardiography has the ability to noninvasively evaluate and track both RV and LV hemodynamic status.^{14,15} In the following section, we discuss echocardiography-based hemodynamic measurements that can be used to serially measure the response to medical interventions such as fluid and drug therapy.

Echocardiography can be used to manage the response to fluid resuscitation in critically ill patients who are at risk for heart failure or tissue hypoperfusion.¹⁶⁻¹⁸ Traditional monitors, such as central venous catheters or pulmonary artery (PA) catheters, have not been found to improve survival or decrease length of stay in hospitalized patients.¹⁹ PA catheters, when used to estimate left atrial (LA) pressure (LAP), can cause PA rupture. They are typically calibrated with saline-filled transducers at the bedside and therefore can be inaccurate in the assessment of LV filling pressures because of waveform artifacts, damping, and airway pressure, especially in ventilated patients.^{19,20} Furthermore, PA catheters and central venous catheters do not accurately measure LV diastolic dysfunction, which is more predictive of mortality in hospitalized patients.²¹⁻²⁵ Echocardiography has the potential to noninvasively measure left-sided filling pressures and guide volume assessments in hospitalized patients who may be at risk for both systolic and diastolic heart failure.¹⁷ Serial examination of two-dimensional (2D) and Doppler indices can be used to monitor stroke volume (SV) and overall volume status. Several studies have recently shown the benefits of goal-directed fluid therapy in surgical patients.²⁶⁻³⁰ In this setting, 2D echocardiography with Doppler can measure changes in SV in response to either a fluid bolus or the administration of a diuretic, while monitoring LAP with transmitral and tissue Doppler imaging (TDI) as well as right atrial pressure (RAP) using vena cava respiratory dynamics. The limitation of echocardiography in this setting is that it cannot perform continuous monitoring, and it requires meticulous attention to sample volume

monitoring a therapeutic cardiac or noncardiac intervention, whether it is fluid resuscitation, pericardial effusion monitoring, ramp or weaning protocols in LVAD cases, or during perioperative care.

Table 1 Specific echocardiographic monitoring parameters and monitoring values

Monitoring parameter Role Reference	System requirements	Important technical features	Specific values to use while guiding interventions
Transmitral E/e' for LAP Nagueh <i>et al.</i> ¹⁵	Pulsed Doppler Tissue Doppler	Doppler alignment End-expiratory acquisition	E/e' < 8; normal LVEF = normal LAP E/e' ≥ 13; normal LVEF = increased LAP E/A > 2; DT < 150 msec; depressed LVEF = increased LAP E/A < 1 and E < 50 cm/sec; depressed LVEF = normal LAP
IVC size /collapsibility, for RAP Rudski <i>et al.</i> ³¹ , Brennan <i>et al.</i> ³²	2D harmonic	Visualization throughout the respiratory cycle	Size ≤ 2.1 cm; collapses >50% during sniff = RAP 0–5 mm Hg Size > 2.1 cm; collapses >50% during sniff = 5–10 mm Hg Size > 2.1; collapses <50% during sniff = 10–20 mm Hg
LV and RV chamber size, areas, and volumes for intravascular volume status and function Lang <i>et al.</i> ³³	2D harmonic	Optimal alignment; endocardial border visualization*; avoiding foreshortening	Normal ranges: LVIDD men 4.2–5.9 cm* LVIDD women 3.9–5.3 cm* LVEDV 46–106 mL women LVEDV 62–150 mL men LVESV 14–42 mL women LVESV 21–61 mL men RV FAC ≥ 35%
LVOT stroke distance for intravascular volume status Ristow <i>et al.</i> ³⁴	2D harmonic; pulsed Doppler	Optimal Doppler alignment; visualization of aortic valve leaflet opening	Normal values VTI > 18 cm
PASP for right-sided hemodynamics Lahm <i>et al.</i> ⁵	Pulsed Doppler Continuous-wave Doppler	Optimal Doppler alignment	Normal value: PASP < 35 mm Hg
TAPSE RV s' for RV function during fluid administration Rudski <i>et al.</i> ³¹	M-mode (TAPSE) Tissue Doppler (RV s')	Optimal standard 4C view and alignment with TV annulus and right ventricle	Normal value: TAPSE ≥ 16 mm RV s' ≥ 10 cm/sec

LVEDV, LV end-diastolic volume; LVEF, LV ejection fraction LVESV, LV end-systolic volume; PASP, PA systolic pressure; TV, tricuspid valve.

*LV and transmitral Doppler measurements are at the plane of the MV leaflet tips. Please refer to Figure 7 in Lang *et al.*³³ for example images of biplane LVEDV and LVESV measurements and Figure 9 in Rudski *et al.*³¹ for RV FAC image measurements.

placement. Current guidelines suggest that specific parameters be used to detect pressures that are elevated or normal, and not for exact values.¹⁵ In the setting of advanced decompensated systolic heart failure, using serial TDI measurements may be inaccurate in monitoring filling pressures.¹⁶ Therefore, different recommendations exist for monitoring LAPs in patients with systolic or diastolic heart failure (Table 1^{31,32}).

Two-Dimensional Echocardiographic Monitoring Parameters

LV Chamber Dimensions. Cardiac chambers can be measured serially to look for ventricular filling during focused examination of volume status. A small LV internal diameter at end-diastole (LVIDD) can be indicative of hypovolemia; care should be taken to not mistake a low LV internal diameter at end-systole (LVIDS) with hypovolemia. Hypovolemia is best monitored using end-diastolic measurements, because a low LVIDS could also depict decreased systemic vascular resistance (SVR), increased inotropic state, or decreased ventricular filling. In hypovolemia, both LVIDD and

LVIDS are decreased, while in the setting of decreased SVR, LVIDD is normal and LVIDS is decreased. Both RV and LV internal diameters can be measured serially to monitor response to fluids. Measurements should be made in the same echocardiographic view and serially compared. LV dimensions (LVIDD and LVIDS) can be measured in the transthoracic echocardiographic parasternal short-axis (SAX) or long-axis (LAX) view using either 2D linear measurements or M-mode imaging at the LV minor axis, 1 cm distal to the mitral valve (MV) annulus at the MV valve leaflet tips.³³ The same measurements can also be obtained with 2D TEE in the midesophageal (ME) two-chamber view at the MV leaflet tips or using M-mode imaging in the transgastric LV SAX view at the midpapillary level. The SAX or LAX view can be used for LVIDD and LVIDS, and the transgastric midpapillary SAX view provides a critical view in monitoring for the development of regional wall motion abnormalities with any of the three major epicardial vessels.⁸ However, the LAX is preferred because it may be less prone to improper alignment and thus likely to detect interval changes in dimension size and fractional shortening. Reference ranges for LVIDD are 3.9 to 5.3 cm in women and 4.2 to 5.9 cm in men.³³

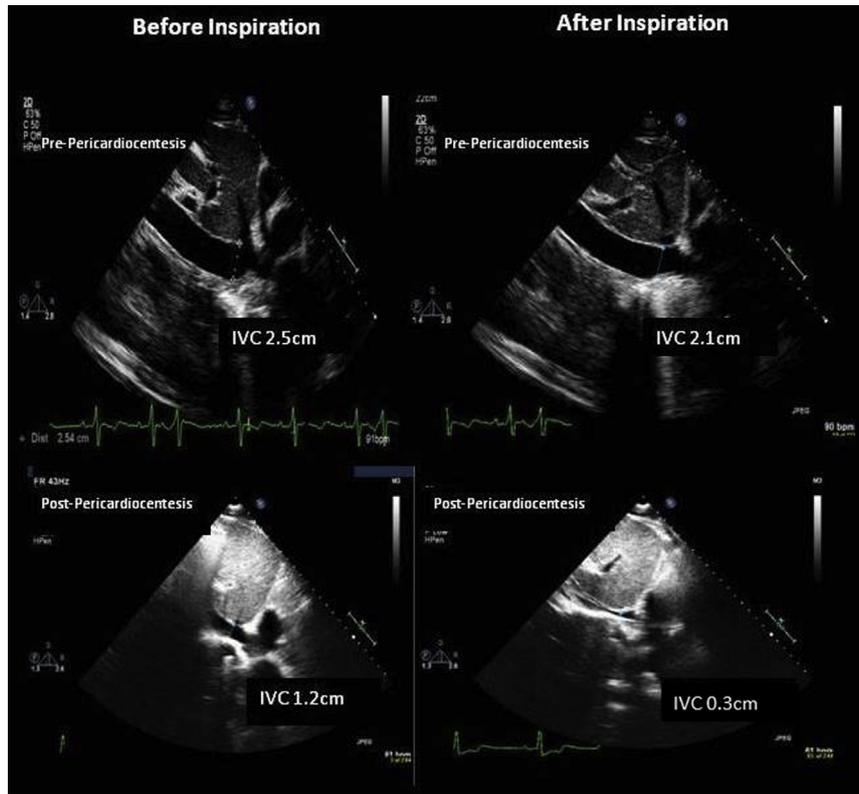


Figure 1 Change in IVC collapsibility index within 24 hours of pericardiocentesis in a patient who had increased central venous pressure (*left*) before pericardiocentesis and then improved after pericardiocentesis (*right*). A >10% change in the collapsibility index should be considered meaningful.

Inferior Vena Cava (IVC) Size and Collapsibility. Hypovolemic patients can be identified using measurement of both size and collapsibility of the IVC for estimation of RAP. Fluid responsiveness of patients can be measured using 2D or M-mode assessment of IVC parameters.²⁹⁻³¹ Inspiration in normovolemic, spontaneously breathing patients causes negative intrathoracic pressure and a decrease in IVC size. An exaggerated response in IVC collapse occurs in patients in the hypovolemic state during inspiration.³² Routine measurements in size of the IVC and collapsibility with respiration have been used in patients with shock to reliably guide fluid management decisions.³⁰ The transthoracic echocardiographic subcostal window can be used to view the IVC in the sagittal plane by angling and rotating the transducer to the left from the subcostal four-chamber (4C) view. M-mode imaging allows high-frame rate measurements of size changes throughout the respiratory cycle (Figure 1). Care must be taken to ensure that the IVC does not translate out of the imaging plane during portions of the respiratory cycle, leading to “pseudocollapse.” Because IVC collapse will not occur in patients on positive pressure ventilation due to inspiration-induced reductions in venous return, it should not be used to monitor RAP in this setting.³¹ Although isolated measurements of IVC collapsibility have been used to predict response to fluid management, there are fewer data to support serial measurements of IVC collapsibility to guide fluid management. Changes in the IVC collapsibility index of >10% have been observed with 2-kg weight reductions after hemodialysis. In this setting, collapsibility index was better than dry-weight assessments in predicting adverse outcomes associated with hemodialysis.³² Values for estimation of RAP using the IVC collapsibility index are referenced in Table 1 from the guidelines for the echocardiographic assessment of the right heart in adults.³¹

Doppler Monitoring Parameters

Mitral Inflow. Mitral inflow velocities, both peak early diastolic velocity (E) and late diastolic velocity (A), are commonly used to determine patterns of diastolic dysfunction and can also be used to serially monitor LAP. The mitral E wave represents the LA-LV gradient during early diastole and thus is preload dependent. The mitral A wave is the LA-LV gradient during late diastole and is affected by changes in LV diastolic function and LA compliance. Mitral inflow velocities (E wave, A wave, DT, and E/A ratio) are measured in the apical 4C view with TTE and the ME 4C view with TEE using PW Doppler (Figure 2). The sampling volume should be 1 cm distal to the MV annulus or at the leaflet tips during diastole, with a sampling gate of 1 to 3 mm.¹⁵ Comprehensive explanations of mitral inflow indices for classification of diastolic function are described in the ASE recommendations for the evaluation of LV diastolic function.¹⁵ It is the recommendation of the writing group that the E- and A-wave velocities be used in conjunction with the annular velocities when monitoring for changes in filling pressures or diastolic function. Figure 2 displays the recommended sample volume positions for monitoring the tissue Doppler measurements of e' and transmitral measurements of the E and A waves. Although pulmonary venous assessments of systolic filling fractions have proved feasible for monitoring LAP with TEE in an elective setting,¹⁴ specific cutoffs for normal and abnormal filling pressures have not been provided, and their feasibility for monitoring LV filling pressures by TTE has not been demonstrated.⁴

TDI. PW TDI is a sensitive indicator of LV diastolic function. TDI measures mitral annular velocities during both systole and diastole at end-

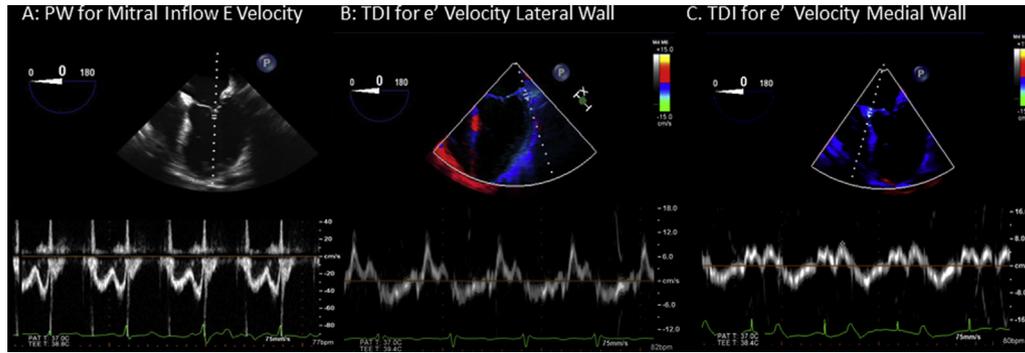


Figure 2 Transesophageal echocardiographic sampling volume position for monitoring E-, e'-, and A-wave velocities.

expiration. TDI is used to measure e' , the peak early velocity of the mitral annulus. Studies have found e' to be less load dependent than other measures of diastolic function, such as mitral inflow and pulmonary vein flow velocities.¹⁵ The measurement of E/e' , where E is the mitral inflow peak early diastolic velocity, is a reliable estimate of LAP when systolic function is normal (Table 1). Therefore, serial E/e' measurements are practical and reliable measurements that can be performed as a serial assessment of LAP to guide fluid therapy in ambulatory and hospitalized subjects at risk for heart failure.⁴ Measurement of e' is best performed in the ME 4C view on TEE or the apical 4C view on TTE, where Doppler angles are well aligned with the lateral and septal (or medial) MV annulus (Figure 2). Septal e' measurement by TEE may not be equivalent with that by TTE because of potential misalignment of the Doppler beam with the direction of tissue motion in the ME 4C view. Care should be taken to measure this within 20° of angulation of mitral annular motion. The velocity scale should be set to 20 cm/sec below and above the baseline. Both septal and lateral TDI velocities should be taken and the two averaged for the measurement of E/e' .¹⁴ Although averaging may be used for overall assessments of LAP, use of medial e' alone may be better for serial assessments of LAP.⁴ On the other hand, septal mitral annular e' measurements may not accurately reflect LV diastolic function in the setting of septal wall motion abnormalities or RV dysfunction.¹⁵

Calculated Monitoring Parameters

SV, Cardiac Output (CO), and SVR Calculations. Measurement of SV of both the right and left ventricles can be performed readily using PW Doppler.³⁴ These measurements can be reliably obtained using TTE and TEE. Assessment of CO is important in determining responses to medical and surgical therapies, such as administration of inotropic agents for the treatment of right and left heart failure.^{5,34} Using PW Doppler, SV through a site (such as the RV outflow tract [RVOT] or LV outflow tract [LVOT]) can be calculated using two variables: (1) the velocity-time integral (VTI), or stroke distance, and (2) the cross-sectional area of the site (using the diameter of the RVOT or LVOT).³⁵ Thus,

$$\text{Stroke volume (or flow)} = \text{Cross sectional area (cm}^2\text{)} \times \text{VTI (cm)}.$$

Because $\text{CO} = \text{SV} \times \text{heart rate}$, both right- and left-sided CO can be serially measured noninvasively before and after medical therapies. In clinical practice, RV SV is calculated by using the parasternal SAX view. PW Doppler can be used to acquire the RVOT VTI (in centimeters) in this view. Because of difficulties in measuring the RVOT diameter, it is recommended that the RVOT VTI be used as a monitor of RV SV. LV SV is calculated on TTE using the apical five-chamber or

LAX view. The deep transgastric LAX view is used in TEE, whereby the PW Doppler sample volume is placed in LVOT. Gradients across the aortic valve (in the setting of prosthetic valve thrombolysis monitoring) should be acquired with continuous-wave Doppler monitoring in this location. Measurement of the baseline LVOT diameter is best accomplished in the ME LAX view. The LVOT diameter can be used to calculate area, which when combined with the LVOT VTI and heart rate can be used to calculate SV and CO. Using IVC collapsibility indices to estimate RAP, and arm blood pressure measurements to calculate mean arterial pressure, SVR (in Wood units) can be calculated as

$$\text{SVR} = \text{MAP} - \text{RA pressure (mm Hg)} / \text{CO (L/min)}.$$

To convert this to conventional SVR units ($\text{dynes} \cdot \text{sec}/\text{cm}^5$), this value should be multiplied by 80. The limitations of echocardiographic measurements of SV, CO, and time-velocity integrals in the LVOT are that all measurements require accurate alignment with the LVOT, and consistent sampling should occur just beneath the aortic valve. The use of an LVOT diameter adds a second potentially more significant error measurement, and it was the recommendation of the committee that stroke distance (i.e., LVOT and RVOT time-velocity integrals) alone be used for serial measurements, with the assumption that LVOT diameter remains constant.

RV Systolic Function. Echocardiographic evaluation of right heart function at the bedside is critical in the management of right heart failure, a common and serious diagnosis in intensive care unit patients.⁵ Because of a lower systolic elastance, the right ventricle is more sensitive to afterload than the left ventricle.⁵ Simple, noninvasive measurements of RV function can be completed using several indices (Table 1). Tricuspid annular plane systolic excursion (TAPSE) is less preload dependent than other markers of RV function and is performed in patients using both TTE and TEE.^{36,37} TAPSE and RV s' can be measured with TTE in the apical 4C view and with TEE using the ME 4C view or transgastric view. For TAPSE, the M-mode cursor is directed through the lateral annulus of the tricuspid valve, and the distance of annular motion during systole is measured longitudinally. The view that provides optimal longitudinal alignment should be used. A TAPSE measurement of <16 mm, or $s' < 10$ cm/sec, is highly specific for RV dysfunction, and both can be used to serially monitor RV systolic function. RV internal diameter in diastole (RVIDD) and fractional area change (FAC) measurements can be measured routinely in the apical 4C view on TTE and in the ME 4C view with TEE. RVIDD and the RVIDD/LVIDD ratio should be measured at the widest point of the right ventricle in a standardized 4C plane.³¹ Although normal and abnormal values for longitudinal strain are still to be determined,

this parameter has been used to monitor RV systolic function during therapeutic interventions in pulmonary hypertension.³⁸

PA Systolic Pressure. Besides serial quantification of RV function, pulmonary pressures can also be evaluated by calculating the RV-RA gradient using the modified Bernoulli equation ($4V^2$). Using the peak tricuspid regurgitant jet velocity as V , the RV-RA gradient can be calculated.³⁵ Because RAP can be determined by assessing IVC size and collapsibility, PA systolic pressure can be estimated as RAP + RV-RA gradient, where RV-RA gradient is $4 \times$ (peak tricuspid regurgitant jet velocity). The peak tricuspid regurgitant jet velocity is measured using continuous-wave Doppler parallel to the tricuspid regurgitant jet. This can be performed with TTE in the apical 4C view, parasternal SAX view, or RV inflow view. Doppler through the tricuspid valve in TEE is best performed in either the ME 4C view or the RV inflow view obtained from transducer angles that align the Doppler cursor parallel to the color Doppler jet. An additional transesophageal view that is useful for Doppler alignment is obtained by rotating the viewing angle to 130° to 145° to obtain an apical LAX plane and then rotating clockwise to visualize the tricuspid valve regurgitant jet using current guidelines.³⁹ Although measurements are taken in multiple views with both TTE and TEE, the highest velocity signal should be used for serial measurements (as this represents the most parallel alignment).

II. ADVANTAGES, DISADVANTAGES, AND RECOMMENDATIONS OF ECHOCARDIOGRAPHY AS A MONITORING TOOL

Patient monitoring is currently performed in most critical care and intraoperative settings with serial measurements of vital signs, oxygen saturation, end-tidal carbon dioxide monitoring, and occasionally PA catheters. The use of echocardiographic monitoring is a new concept that has emerged in several different fields that include cardiology, emergency medicine, anesthesiology, and critical care. As echocardiography becomes more portable, monitoring with echocardiographic techniques will be used to greater degrees in patient management decisions. Although echocardiographic monitoring has proved useful in several specific areas outlined in this review, the technique is heavily operator dependent and demands that continuous quality improvement measures be implemented for all practicing echocardiographers within an institution, to ensure that Doppler and anatomic measurements are following established technical guidelines that have been published. Second, the data presented in this document derive for the most part from single-center experiences and were not rigorously evaluated in prospective studies examining differences in patient outcome as a result of echocardiographic monitoring. The writing committee has developed a “level of data support” that displays the number of studies that have been performed for each of the proposed clinical scenarios in which echocardiographic monitoring may be useful (Table 2). Note that in the setting of trauma, there are no clinical comparative studies published, despite numerous reviews suggesting that echocardiographic monitoring would be useful.

III. CLINICAL SCENARIOS

Expert opinion supports the use of primarily TTE to guide the management of patients in specific clinical settings in which monitoring

Table 2 Summary of clinical scenarios in which echocardiographic monitoring is considered helpful and the level of support on the basis of a number of clinical studies examining utility in this setting

Clinical scenario	Predominant monitoring tool	Level of data support*
Acute CHF/LVAD	TTE	B2
Critical care	TTE	B2
Trauma	TTE/TEE	D1
Tamponade monitoring	TTE	B2
Pulmonary embolism	TTE	B2
Prosthetic valve thrombus	TTE/TEE	B2
Kidney/liver/lung transplantation	TEE	Kidney-B3 Liver-B2 Lung-B2
Major vascular surgery	TEE	B2
Orthopedic/spinal surgery	TEE	B2
Neurosurgery/sitting position	TEE	B2

B2, observational studies permit inference of benefit of the guiding tools listed in Table 3 and clinical outcomes on the basis of noncomparative observational studies with associative (e.g. relative risk, correlation) or descriptive statistics; B3, observational studies permit inference of benefit of the monitoring tools in Table 3 on the basis of case reports only; D1, lack of scientific evidence in the literature to address whether the monitoring tools in Table 2 affect outcomes. *Please refer to Thys *et al.*¹ for reference to the entire level-of-support classification.

of fluid management or drug interventions needs to be assessed rapidly. These are listed in Table 3. Despite this expert opinion, the writing group could find no formal clinical studies in which monitoring of echocardiographic Doppler parameters was compared with other monitoring modalities in the setting of sepsis, respiratory failure, or trauma. Monitoring in CHF, pulmonary embolism, and pericardial tamponade are discussed separately.

Acute CHF Monitoring

In the setting of heart failure, most monitoring applications have dealt with situations in which Doppler has been used to assess the effects of therapeutic interventions that will eventually be used for longer term therapy. Transmitral E- and A-wave velocity ratios, combined with E-wave DT, have been used to assess responsiveness to nitroprusside infusion and carvedilol therapy, which may also predict prognosis.⁴⁰ Patients with heart failure and depressed ejection fractions who had E/A ratios > 1, combined with EDTs < 130 msec, and who did not reverse these parameters with nitroprusside infusion, had the worst prognosis. Changes in mitral filling parameters after leg lifting or nitroprusside infusion were predictive of tolerance to carvedilol therapy and patient outcome. More recently, studies have evaluated E/e' to monitor LAP in response to interventions in patients with symptomatic heart failure (New York Heart Association classes II and III) in an outpatient setting and have demonstrated that the E/medial e' ratio most accurately reflects changes in LAP.⁴

Although E/e' monitoring has been shown to reflect changes in pulmonary capillary wedge pressure in small numbers of patients

Table 3 Specific clinical settings in which echocardiographic monitoring could potentially guide therapeutic interventions

	Specific clinical scenario	Recommended monitoring parameters
Critical Care	Hypotension	IVC collapsibility index Regional wall motion LVOT VTI response to passive leg raising
	CHF	IVC collapsibility index Transmitral E/e' E/A ratio with EDT RV s' TAPSE Regional wall motion
	Sepsis*	IVC collapsibility index LVIDD, LVIDS Regional wall motion
	Respiratory failure* Possible pulmonary embolus	IVC collapsibility index RV s' TAPSE Doppler PASP RVOT VTI Regional wall motion RVIDD/LVIDD ratio
	Pericardial effusion/tamponade	Pericardial effusion size Right ventricular diastolic collapse IVC collapsibility index
	Prosthetic valve dysfunction	Transvalvular gradient
Trauma*	Blunt trauma Aortic trauma Myocardial contusion	IVC collapsibility LVIDD, LVIDS Pericardial effusion size Regional wall motion
	Burns	IVC collapsibility LVIDD, LVIDS Transmitral E/A ratio, E/e'
Perioperative	Thoracoabdominal cross-clamping	Regional wall motion LVIDD, LVIDS
	Liver transplantation	LV regional wall motion LVIDD, LVIDS RV s' TAPSE RV cavity monitoring for emboli
	Renal transplantation	LV regional wall motion LVIDD, LVIDS RV s' TAPSE Transmitral E/e' and E/A ratio RV cavity monitoring for emboli
	Orthopedic/spinal/neurologic surgery	RV s' TAPSE Transmitral E/e' RV cavity monitoring for emboli

PASP, PA systolic pressure.

*Although potentially useful and used clinically in this setting, no clinical studies have been published examining these echocardiographic parameters in monitoring patients in this setting.

with acute decompensated heart failure,^{41,42} the writing committee currently recommends that E/e' not be used in monitoring LAP of patients with decompensated heart failure with depressed systolic function ("cold and wet patients"), as others have shown that these parameters do not predict LAPs or guide management in this clinical setting.¹⁶ The primary focus of these studies was to use E/e' to predict initial pressures, not on E/e' as a monitoring tool. As a result,

only small subsets of the study population had serial E/e' measurements compared with serial changes in LAPs.

One evolving area in which echocardiographic guidance has become helpful in CHF is assessing responsiveness to LVAD therapy. Echocardiographic parameters have been used to serially monitor ramped interventions and determine whether patients can be weaned from LVAD therapy. Ramp protocols are defined as dynamic assessments

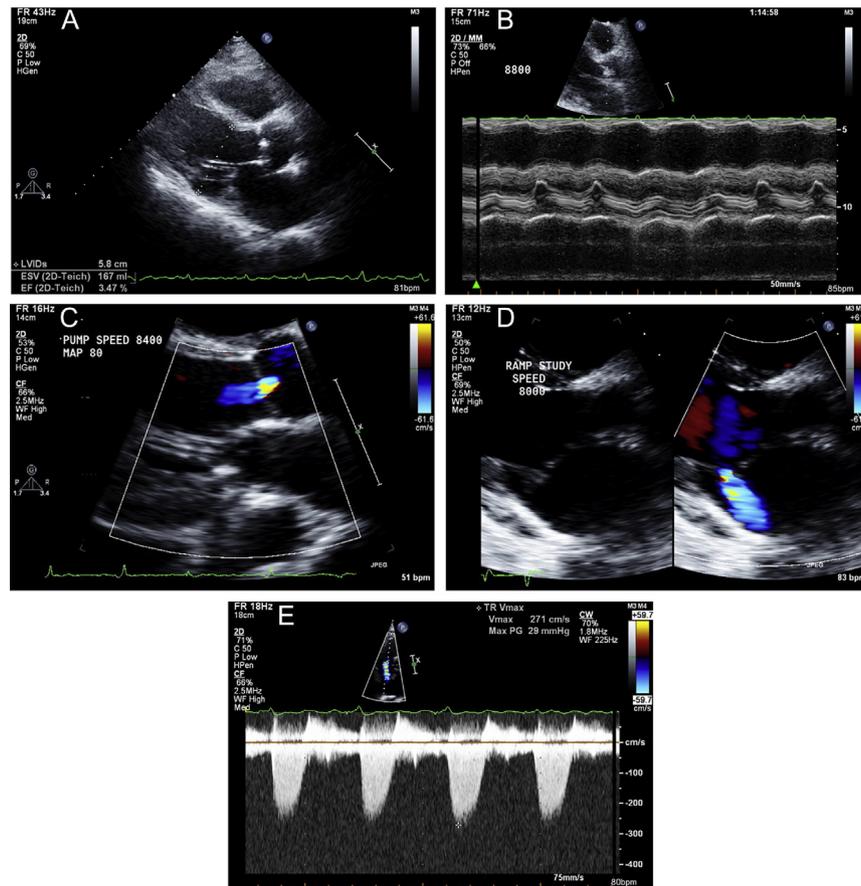


Figure 3 Echocardiographic parameters obtained during the ramp protocol to optimize LVAD settings and assist in the detection of device malfunction. **(A)** LVIDD changes, **(B)** changes in aortic valve opening, **(C)** aortic regurgitation, **(D)** mitral regurgitation, and **(E)** changes in RV systolic pressure with each setting change. Reproduced with permission from Uriel *et al.*¹¹

of LV size, hemodynamics, and valvular function with echocardiography during incremental device speeds. They have been shown in single-center studies to improve speed optimization and assist in the detection of device thrombosis. In this setting, the LVAD backup speed is started at the lowest usable setting (~8,000 rpm) and then increased serially while monitoring LVIDD, LVIDS, aortic valve opening, aortic and mitral regurgitation severity, and RV systolic pressure (Figure 3). Normal results would be gradual reductions in LVIDD as the speed is increased to 12,000 rpm, while flat responses would indicate device malfunction.¹¹ In these protocols, LVIDD is plotted as a function of change in revolutions per minute. An LVIDD slope ≥ -0.16 was diagnostic of flow obstruction from thrombosis or mechanical obstruction in the LVAD tubing.

Echocardiographic guidance has also been used to determine if patients can be weaned from their LVADs. Once the LVIDD decreases to <60 mm and mitral regurgitation is reduced in severity on chronic LVAD therapy, the patient is scheduled for an echocardiographically guided study in which the LVAD is turned off. LVIDD, LVIDS, and RV size and function are then assessed; maintenance of LV function (LVEF $> 50\%$) without the development of worsening RV dilatation during off-pump trials are used as criteria for LVAD removal.¹² A lack of change in LVEF or RV size at end-diastole was also associated with good clinical outcomes after LVAD removal.

Critical Care Monitoring

Although echocardiography plays an invaluable role in assessing the cause of hemodynamic compromise in critically ill patients, its role

for monitoring patients with respiratory failure, sepsis, or unexplained arrest has not been elucidated. In these settings, there are several parameters that could be followed that would be unique to echocardiography over other monitoring tools, such as PA catheters or oxygen saturation monitors (Table 4), but to date, no clinical studies comparing the techniques have been performed. There are advantages and disadvantages with either technique. Although serial echocardiography has the advantage of providing anatomic information regarding changes in systolic and diastolic function, PA catheters are more useful when many serial interventions that may affect CO and LV filling pressures are being performed rapidly at the bedside in an acute setting. In the setting of septic shock, goal-directed therapy has been shown to improve patient outcome.⁴³ Although this study used central venous pressure, mean arterial pressure, and central venous oxygen saturation to guide fluid, blood, and vasopressor management, echocardiographic parameters might be substituted for most parameters. IVC collapse could be used to assess central venous pressures and LVOT stroke distance to monitor CO. These noninvasive assessments could be combined with blood pressure monitoring to guide therapy in this setting. In small numbers of critically ill patients, an increase in LVOT VTI of $>12.5\%$ during passive leg raising predicted increases in SV in response to intravenous fluids with 77% sensitivity and 100% specificity.⁴⁴ The change in LVOT VTI with passive leg raising was more accurate than changes in LV dimensions or mitral inflow patterns in predicting fluid responsiveness.

Table 4 Methods by which critical monitoring parameters are assessed with a PA catheter versus serial echocardiographic measurements

Monitoring technique	PA catheter	Echocardiography	Advantage*
Filling pressures	RAP, PCWP directly measured	RAP, PCWP indirectly measured	PA catheter
Cardiac output	Thermodilution	Doppler derived	Equal
Valve assessment	Not possible	Anatomic/Doppler	Echocardiography
Systolic/diastolic function	Estimated from PCWP/CO	Table 1 parameters	Echocardiography
Risks	Invasive technique	Noninvasive	Echocardiography
Speed of assessment	Immediate changes detected	Operator dependent	PA catheter

PCWP, Pulmonary capillary wedge pressure.

*Advantage refers to which monitoring parameter the writing group considered better suited for the particular application.

Pericardial Tamponade Monitoring

Echocardiographic guidance has played a critical role in decision making for patients presenting with significant pericardial effusion and guiding pericardiocentesis and postpericardiocentesis management. Echocardiographic monitoring plays a vital role in patients presenting with pericardial effusion when the rate of accumulation is unknown and the patients have nonspecific symptoms. Approximately 33% of large idiopathic pericardial effusions may suddenly develop tamponade physiology.⁴⁵ Along with monitoring for increase in pericardial effusion size, monitoring for the development of right atrial collapse (lasting for greater than one-third of the cardiac cycle), early RV diastolic collapse, and IVC plethora have been used for determining when pericardiocentesis may be indicated.⁴⁵

For pericardiocentesis, echocardiographic monitoring has replaced fluoroscopy at many centers because of its ability to detect and guide needle and catheter placement for loculated effusions.⁴⁶⁻⁴⁸ Using echocardiographic guidance has resulted in more apical, rather than subxiphoid, approaches to pericardiocentesis, mainly because the distance to effusion from the skin surface is smallest in this location. The use of saline contrast administered through the pericardiocentesis needle confirms pericardial entry (Figure 4, Video 1; available at www.onlinejase.com). After this confirmation, echocardiography can be used to confirm both guidewire and pigtail catheter placement into the pericardial space.⁴⁸ Drainage then proceeds until there is near disappearance of pericardial effusion on echocardiography (Video 1). The ultrasound transducer can be either sterilized by placing a gel-filled sterile sleeve over the transducer or placed in an imaging area that is outside the sterile field. This echocardiographically guided procedure has a >95% success rate, with a large single-site study demonstrating minimal complications.⁴⁶ After drainage of the effusion, repeat echocardiography within 24 hours is indicated to examine for reaccumulation. At this point, IVC collapse can be reevaluated to see if RAPs have decreased or if RAPs remain elevated, as may occur in effusive constrictive pericarditis.⁴⁵

Pulmonary Embolism Therapy Monitoring

Despite the widespread use of echocardiography in assisting in the diagnosis and initial management of pulmonary embolism, there are very few published data on the usefulness of monitoring RV systolic function or PA pressures in this setting. Nonetheless, echocardiography plays a significant role in making therapeutic decisions in patients with pulmonary embolism and can facilitate a change in management by identifying those at high risk who might otherwise be treated with less aggressive therapies.⁴⁹⁻⁵¹ In addition, it can help

assess whether thrombus within the main PA is present, which may warrant surgical embolectomy. Most important, it is useful to monitor RV function and PA systolic pressure when thrombolysis is administered.⁵²

Patients with suspected pulmonary embolism often present with signs and symptoms that are nonspecific, which can make it difficult to distinguish the diagnosis from other life-threatening disorders. Although not diagnostic of pulmonary embolism, initial TTE can help in identifying when pulmonary embolism may be the cause by detecting RV dilation (RVIDD/LVIDD ratio > 0.9) and assist with ruling out other causes, such as pericardial effusion or myocardial infarction.^{50,51} Once the diagnosis of pulmonary embolism is established, these patients can be risk-stratified according to the effects of elevated RV afterload: hypotensive patients and those with elevated cardiac biomarkers or echocardiographic indices of RV strain are at an increased risk, and thrombolysis is considered a class II indication.⁵² Patients with massive pulmonary embolism can have serial assessments of RV size and FAC (Figure 5), assessments of RV systolic pressure, and IVC assessments using ASE RV guidelines for normal ranges.³¹ The writing group recommends that considerable attention be given to maintaining the same identical imaging plane of the right ventricle when serially examining RV size and FAC, as slight deviations in the imaging plane may alter these values.

Prosthetic Valve Thrombosis Monitoring

Both TTE and TEE have been used to detect prosthetic valve thrombosis and monitor therapy effectiveness.⁵³⁻⁵⁶ Fibrinolytic therapy is recommended if left-sided prosthetic valve thrombus area (planimetered on a 2D image) is <0.8 cm², with serial Doppler echocardiographic monitoring of mean gradients across the valve to assess effectiveness of either fibrinolytic or unfractionated heparin treatment.⁵⁵ A significant reduction in the transvalvular gradient at 24 hours is indicative of effective therapy. TEE and TTE are complementary in these settings, with serial TEE giving better visualization of residual thrombus burden, but both are equally effective at monitoring for reductions in transvalvular gradients.

Echocardiographic Monitoring in Trauma

TTE and TEE have been proposed as methods to monitor volume status and regional and global systolic function in a wide variety of traumatic settings. Although they have proved useful in the immediate assessment of LV and RV systolic function, volume status, and detection of significant pericardial or aortic pathology, their role in

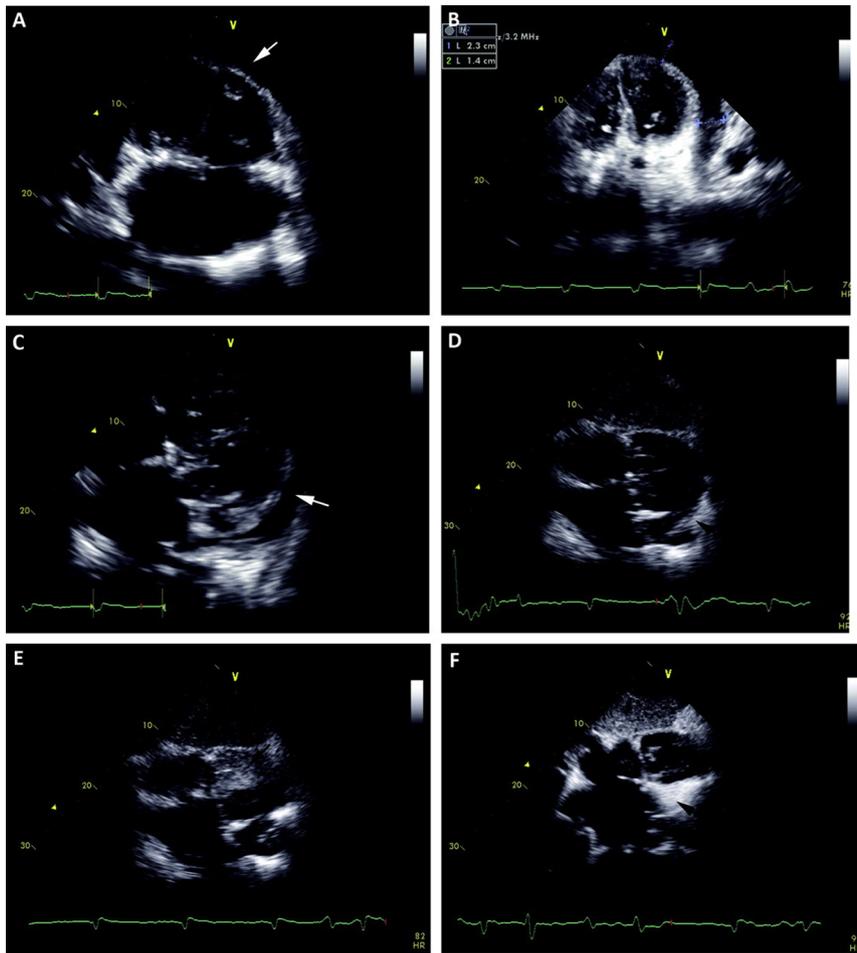


Figure 4 Demonstration of an echocardiographically guided apical approach to pericardiocentesis. Once needle entry into a fluid filled space was confirmed, agitated saline contrast was administered (**C–F**) to confirm that the needle was in the pericardial space. Reproduced from Ainsworth and Salehian.⁴⁸

monitoring specific parameters has not been validated sufficiently, even in single-center, unblinded studies. Therefore, no recommendations can be given regarding the use of transesophageal or transthoracic echocardiographic monitoring at this time.

IV. PERIOPERATIVE MEDICINE

The American Society of Anesthesiologists endorses the use of TEE when surgery or the patient's cardiovascular pathology may result in severe hemodynamic, pulmonary, or neurologic compromise.¹ Although the basic perioperative transesophageal echocardiographic examination consensus statement outlines the specific views required to obtain these measurements,⁸ the use of echocardiography as a monitoring tool in this setting requires quantitative transesophageal echocardiographic monitoring of specific Doppler hemodynamics (transmitral E and e', tissue Doppler s' measurements in the right ventricle) and RV and LV size and systolic function in the immediate preoperative, perioperative, and postoperative setting. **Figure 6** depicts the changes in transmitral E/A ratio and E/e' ratio that occurred with echocardiographic monitoring in the operating room that guided fluid management in a patient with underlying diastolic dysfunction.

The specific surgical settings that would benefit from transesophageal guidance are discussed below.

Echocardiographic Monitoring During Liver, Kidney, and Lung Transplantation

Perioperative management of liver transplantation patients presents unique challenges in a population at risk for volume overload or tissue hypoperfusion. Underlying cardiac dysfunction from cirrhotic cardiomyopathy and abnormal SVR make fluid and drug management of these patients difficult.⁵⁷ TEE diagnosis of intracardiac thrombus, pulmonary embolism, myocardial ischemia, cardiac tamponade, acute right heart failure, and systolic anterior motion of the anterior MV have all been described during liver transplantation in situations in which other hemodynamic monitoring tools failed to detect these phenomena.^{58–62} TEE guidance in detecting and managing these problems during liver transplantation has led to its use by >85% of transplantation anesthesiologists surveyed at 30 transplantation programs in the United States.⁶³ Doppler echocardiography can play a role in the ongoing assessment of cardiac filling status using transmitral E and e', LVOT VTI, and assessment of pulmonary pressures. Doppler-derived SVR and LV end-systolic dimensions may be

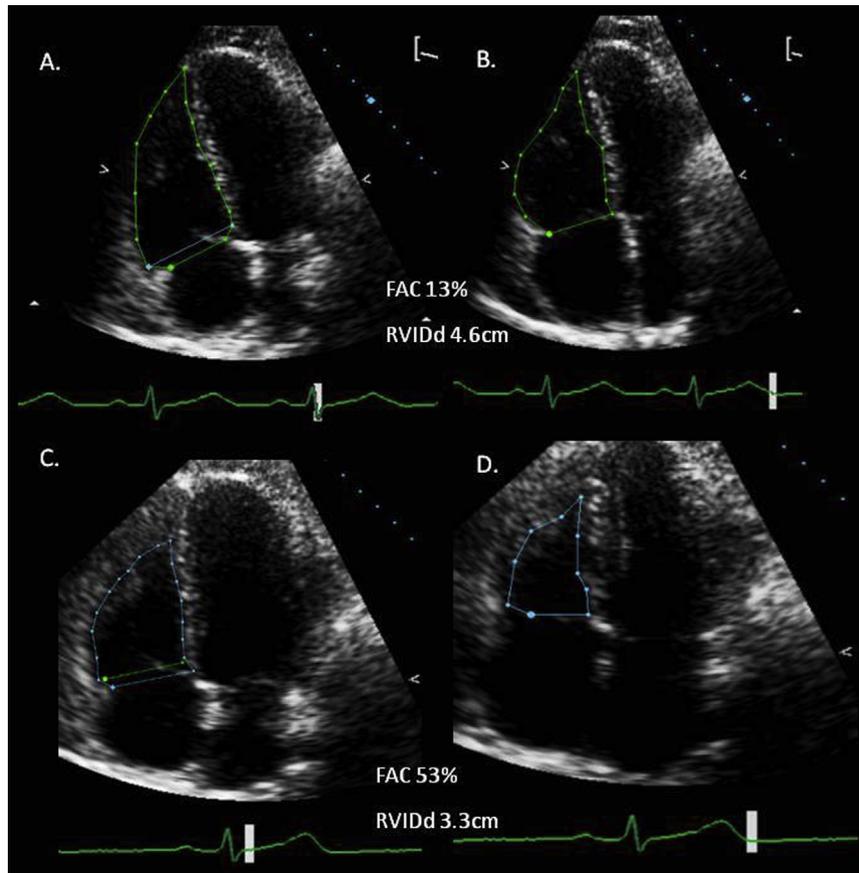


Figure 5 Serial echocardiograms in a patient with a pulmonary embolus treated with fibrinolytic therapy. FAC improved significantly after fibrinolytic therapy, and RVIDD decreased. RV systolic pressure decreased by >50 mm Hg.

used to monitor dynamic changes in vasodilated states. Detection of intracardiac thrombus, ventricular function, pericardial effusion, and monitoring for systolic anterior motion of the mitral valve can all be detected with serial 2D TEE monitoring in this population (Figure 7, Video 2; available at www.onlinejase.com), in which changes in hemodynamic and prothrombotic conditions occur rapidly.⁶⁴⁻⁶⁷ As long as a patient is not receiving positive pressure ventilation, IVC collapsibility and size can be used to predict fluid responsiveness for postoperative fluid management along with ongoing 2D and Doppler hemodynamic and function assessment. Before considering TEE as a monitoring tool during liver transplantation, it is important to note that esophageal varices may be present and that this is considered a relative contraindication to performing TEE.³⁹ Therefore, the writing group recommends lubrication and careful probe insertion to minimize esophageal variceal bleeding.

Large systematic evaluations of the role of TEE monitoring in kidney transplantation are lacking, and there are only limited data to demonstrate that it can add to central venous pressure monitoring in volume assessment and management of ischemia reperfusion injury.⁶⁸ The writing group recommends that the use of TEE as a monitoring tool of LV and RV systolic and diastolic function be considered only if coexisting cardiovascular disease is present.

With regard to echocardiographic monitoring during lung transplantation, there is a consensus that TEE is essential to monitoring RV systolic function during and after transplantation.⁶⁹ Changes in

RV contractility must be identified early, so that inotropic support or inhaled PA vasodilators can be initiated before overt hemodynamic compromise occurs. TEE is also used to monitor the pulmonary veins for any stenoses that may develop from thrombosis at the anastomotic sites.⁷⁰

Major Vascular Surgery

Direct clamping of major vessels causes a sudden significant increase in cardiac loading conditions, which may lead to hemodynamic instability from ventricular failure, myocardial ischemia, and end-organ hypoperfusion. Echocardiography indices can be used to monitor effects of cross-clamping of the aorta or the vena cava on both diastolic and systolic function.⁷¹⁻⁷⁵ Previous studies have shown TEE to be more sensitive than PA catheters in the detection of alterations in systolic and diastolic function during cross-clamping of the thoracic and thoracoabdominal aorta.^{73,74} Echocardiographic indices that are recommended to detect these dynamic changes include changes in CO, LV ejection fraction, LV end-diastolic dimensions, regional wall motion in the transgastric SAX view, and transmitral Doppler flow patterns.

Complete occlusion of the vena cava can also cause significant changes in preload and afterload. Intraoperative assessment of ventricular filling, wall motion, and both diastolic and systolic function may be used to guide medical intraoperative therapy during vena cava cross-clamping.

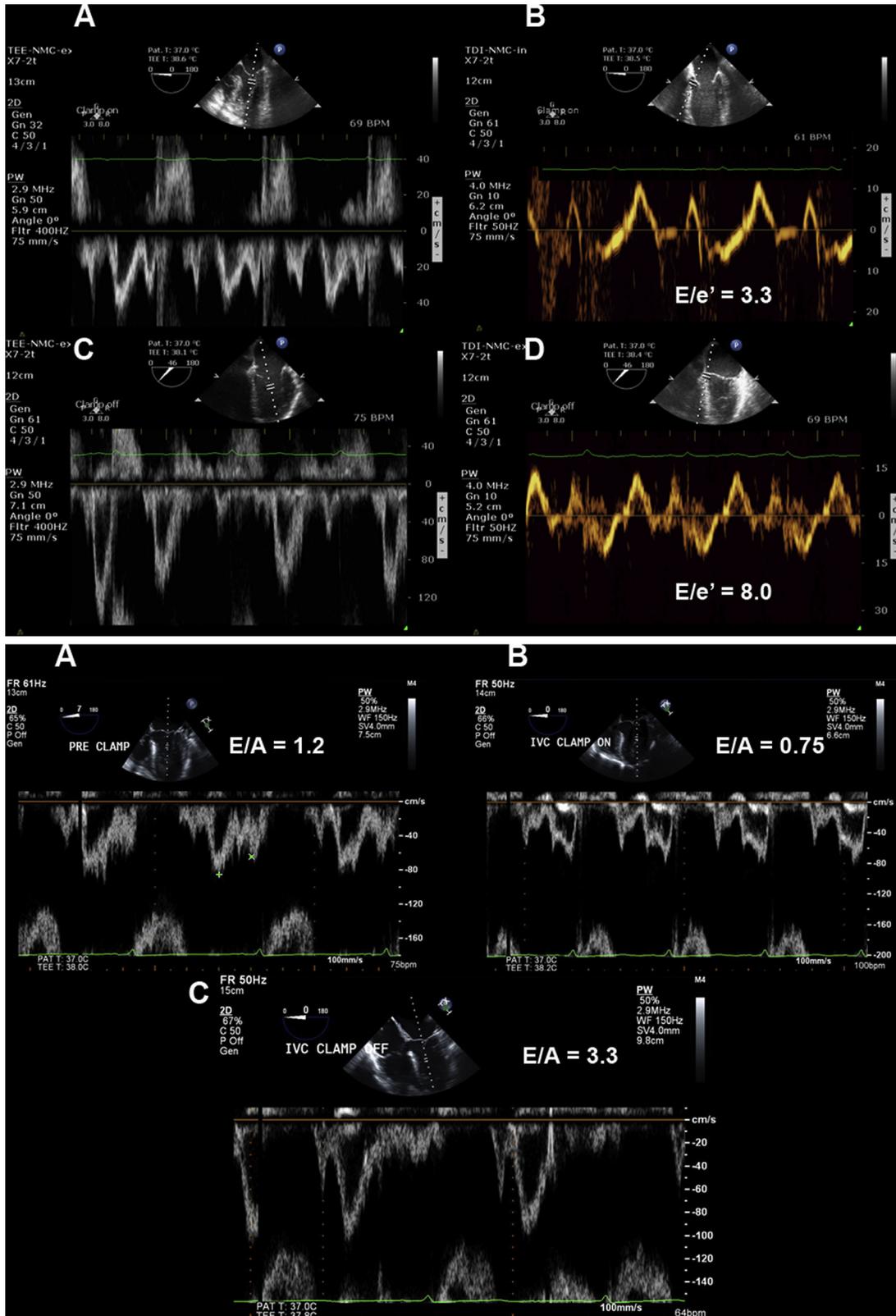


Figure 6 Intraoperative transesophageal echocardiographic monitoring in two different liver transplantation cases. In the *top panel*, one sees a normal relatively low E/e' ratio before liver transplantation, followed by an increase to 8 (**C,D**) after IVC clamp removal. This led to a cessation of intravenous fluid administration. In the *bottom panels*, one sees a decrease in the E/A ratio during IVC clamping during liver transplantation (**B, bottom panel**) but a dramatic increase in the E/A ratio after clamp removal (**C, bottom panel**). This led to an immediate reduction in fluid administration.

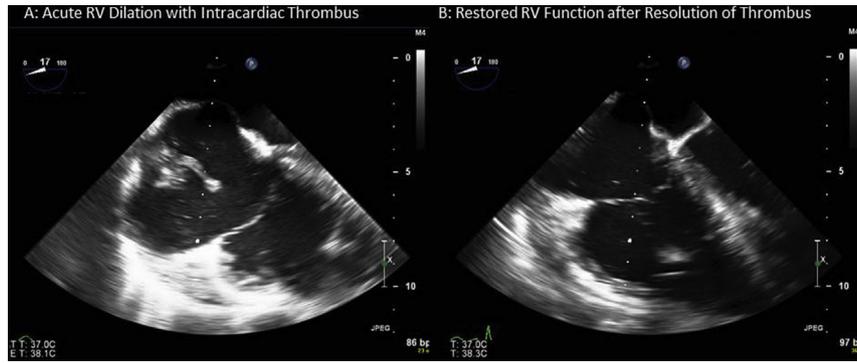


Figure 7 Transesophageal echocardiographic images during liver transplantation demonstrating acute RV dilation due to embolization of debris during the initial dissection (*left*). After the procedure was aborted and anticoagulation given, there was dissolution of debris, and RV size decreased (*right*). See [Video 2](#) (available at www.onlinejase.com).

Orthopedic and Spinal Surgery

Intraoperative TEE is used in this setting primarily as a rescue procedure. Hip arthroplasty, spinal surgery, and knee arthroplasty are all associated with significant risk for intraoperative cement and fat emboli. Hypotension, ventilation-perfusion mismatch, hypoxemia, pulmonary embolism, and cardiac collapse can all occur during intramedullary reaming and release of microparticulate matter.⁷⁶ Intraoperative rescue TEE can be used to monitor microemboli and detect intracardiac shunting using color-flow Doppler through a patent foramen ovale.⁷⁷ Both TEE and TTE have been reported to be useful hemodynamic monitors for lengthy orthopedic and spinal surgery.⁷⁸⁻⁸¹ However, it should be noted that the majority of spinal surgery is done in the prone position, and TEE is not used. Changes in RV function due to increases in acute pulmonary vascular resistance can be detected using TAPSE, pulmonic valve VTI, and peak tricuspid regurgitant jet velocity measurements. Fat emboli can be visualized with TEE during hip arthroplasty; its identification has been associated with neurologic dysfunction and a subsequent higher American Society of Anesthesiologists physical status (\geq III).⁸¹ Despite its limited use, TEE has detected thromboembolic events during cervical spine surgery.⁸²

Neurosurgery

The vast majority of all neurosurgery (other than spinal) in the United States is done in the supine position, and TEE monitoring is used primarily in a rescue setting. The potential for venous air embolism during neurosurgery has led to the “equivocal” endorsement of the use of intraoperative TEE as category B by the American Society of Anesthesiologists during such procedures.¹ Evaluation of the interatrial septum by color-flow Doppler and agitated saline contrast to assess the risk for paradoxical emboli associated with a patent foramen ovale can be performed during intraoperative monitoring. Doppler assessment of right-sided pulmonary pressures and 2D assessment of RV function can detect changes secondary to venous air embolic load, especially in procedures done in the sitting position.^{83,84} TEE has been used to guide the placement of right atrial aspiration catheters to an optimal location at the junction of the superior vena cava and right atrium.^{85,86} Ongoing intraoperative assessment for air entrapment into right-sided cardiac chambers is recommended when the risk for paradoxical emboli is high. Identification of these complications early, along with careful qualitative and quantitative assessments of RV systolic function, may assist significantly in preventing hemodynamic deterioration and permit

earlier pharmacologic or surgical interventions. Although TEE monitoring is useful for neurosurgery in the sitting position, it should be noted that TEE monitoring in the sitting position has been associated with posterior tongue edema and even necrosis.⁸⁷ Further controlled studies are needed to define the beneficial role of transesophageal monitoring in this setting.

V. WHEN HAS A MEANINGFUL CHANGE IN A MONITORING PARAMETER OCCURRED?

On the basis of available evidence, the use of echocardiography for monitoring purposes is justified when categorical changes have occurred, such as an increase in LAP from normal to abnormal (an increase in E/e' ratio from <8 to >13 in the setting of normal systolic function). It can be used for continuous monitoring in settings in which LVIDD, RV FAC, or PA systolic pressure are being reevaluated in ramp or weaning protocols. In both of these settings, it is important to note what degree of change must occur before one can say the given change is beyond the interobserver variability of the measurement ([Table 5⁸⁸⁻⁹³](#)). Although only small numbers of patients are included in these studies of variability measurements, they do provide assistance in determining what cutoffs to use when deciding whether a change in a parameter is beyond what would be expected on the basis of interobserver variability or coefficients of variation. In the specific areas of IVC collapsibility index, E/e' , E/A , and PA systolic pressure changes, we have added categorical changes (on the basis of guidelines) that should be used when guiding management. These categorical changes are well within the published data regarding coefficient of variation and interobserver variability of the monitoring parameter.

VI. CONCLUSIONS REGARDING TRAINING AND USE OF ECHOCARDIOGRAPHY AS A MONITORING TOOL

The writing committee emphasizes that a minimum of level II training experience⁹⁴ is required to use echocardiography as a quantitative monitoring tool, regardless of the clinical scenario for which it is being applied. Although level II Core Cardiology Training Symposium training experience in TTE is sufficient to monitor LV dimensions and IVC collapsibility, additional level III Core Cardiology Training Symposium training experience with both TTE and TEE is required

Table 5 Interobserver variability and coefficients of variation for specific echocardiographic monitoring parameters, with recommended meaningful changes that must occur in a clinical scenario (monitoring setting)

Echocardiographic monitoring parameter	IOV/CV	Monitoring setting	Meaningful changes from baseline in a monitoring setting
IVC collapsibility index	Not demonstrated	CHF, trauma, perioperative	>10% ³² Change from <50% to >50% ³¹
E/A ratio Depressed LV systolic function	6% CV ⁸⁸	CHF, perioperative	Change from <1 to 1–2 to 2
E/e' Normal LV systolic function	8% CV	CHF, perioperative	>8% ⁸⁹ Change from <8 to 9–14 to ≥15 ¹⁵
LVOT VTI LVOT area	6% IOV 4 % IOV	CHF, perioperative setting	>6% change in VTI or SV ⁹⁰
PASP	3% IOV	Pulmonary embolus, perioperative, CHF	>3% ⁹¹ Change from <40 to 40–60 to >60 mm Hg ³¹
LVIDD, LVIDS	8% IOV	Perioperative, CHF ramp/weaning	>8% ⁹²
RV FAC, S', and TAPSE	RV FAC:10% (IOV) RV s': 1.6 mm/sec (IOV) TAPSE: 1.9 mm (IOV)	Pulmonary embolus Perioperative Pulmonary hypertension CHF LVAD	RV FAC > 10% ⁹³ RV s' > 1.6 mm/sec ⁹³ TAPSE > 1.9 mm ⁹³

CV, Coefficient of variation; IOV, interobserver variability; PASP, PA systolic pressure.

to ensure accurate Doppler and advanced hemodynamic pressure measurements in intensive care units, emergency departments, and surgical suites. Because echocardiographic monitoring is currently used in a wide range of clinical settings, it is imperative that the person using quantitative echocardiography to guide therapeutic decision making (whether an anesthesiologist, a cardiologist, or an emergency room physician with level II or level III experience) understand the interobserver variability of each of the quantitative measurements (as displayed and referenced in Table 5) and have the technical expertise required to ensure the serial measurements are obtained accurately. Although high-quality images can be obtained by those with lesser experience, as outlined in the basic perioperative transesophageal echocardiography consensus statement and focused cardiac ultrasound recommendations,^{8,13} the interpretation and use of the quantitative parameters to guide therapeutic decision making outlined in this document should be done only by level II and III trained personnel. For example, is there a significant global wall motion abnormality in the left or right ventricle that has developed during the intraoperative monitoring? Such detection would be required for basic perioperative or critical care monitoring, but does not require a quantitative assessment of LVIDD or LVIDS or the IVC to guide fluid resuscitation and does not require a measurement of RV FAC in the setting of monitoring or guiding interventions in pulmonary embolus or intraoperative embolism after the release of IVC cross-clamping. Quantitative measurements, when used to guide therapeutic decision making, require a minimum of level II training.

In conclusion, a sufficient body of literature exists, originating from critical care, anesthesiology, and emergency medicine, demonstrating the potential role of echocardiographic monitoring. Clinical studies have demonstrated the role of echocardiographic monitoring in guiding management of pulmonary emboli, pericardial effusions, thrombosed prosthetic valves, and acute heart failure management. However, large-scale clinical trials documenting the effectiveness of echocardiography as a monitoring tool are lacking in all of these areas,

and basic clinical trials are lacking on the use of echocardiography in guiding trauma management or other critical care and surgical applications. Although a sufficient amount of data have been published using interventional echocardiography to guide percutaneous cardiac interventions,⁹⁵ it is a strong consensus recommendation from the writing group that additional clinical trials be performed that document the utility of both TTE and TEE as dynamic monitoring modalities to aid in the treatment of several acute medical and surgical conditions.

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SUPPLEMENTARY DATA

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.echo.2014.09.009>.

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