# Intensive Care Echocardiography

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## Introduction

Echocardiography continues to exert an increasing influence in the practice of intensive care medicine. Rapidly and non-invasively obtaining diagnostically accurate pictures of the heart can lead to major management changes when treating critically ill patients. Most intensivists regularly encounter its use, either in receiving a report after the study is performed by someone else, or by personally engaging in the acquisition of the required hemodynamic information. A number of hemodynamic and cardiac function parameters can be measured including cardiac output, pulmonary artery pressure, left atrial pressure, transvalvular pressures, in addition to evaluating the presence of underlying myocardial ischemia. At the very least, an intensivist training today should, from viewing a study, be comfortable in differentiating a well volumed, strongly contracting left ventricle from an underfilled, functionally impaired heart. This chapter is a brief outline of the many applications of echocardiography that are helpful in the intensive care unit.

Comparing the relative value of either the transthoracic (TTE) or transesophageal (TEE) approach is only of use when focusing on the specific patient. Skills in both modalities are essential for the intensivist. Most information is available from the TTE, which fortunately is applied more rapidly. Yet when searching out a left atrial appendage thrombus or infected valve for example, the TEE technique is *par excellence*. Whether a TTE or a TEE is performed, the examination attempted must be a rigorous, full and systematic study. A quick glimpse only of the heart will often turn out to be inadequate and leads to sloppy technique. The TTE study outline should follow the classical 'parasternal-apical-subcostal views' approach (Fig. 1). Gastric, lower/mid/high esophageal views should be performed when performing a TEE.

## Common Hemodynamic Equations in Echocardiography

Theory underlying the application of echo and Doppler needs to be encountered in that certain equations need to be appreciated. One of these equations is the Bernoulli Equation, which states that the pressure drop across any section of a conduit, such as valves or orifices, depends on the convective acceleration, flow acceleration and the viscous friction. However, the flow acceleration and viscous friction can be ignored in most clinical situations. Assuming the proximal velocity is low compared to the distal (peak) velocity, the Bernoulli Equation can be modified to:

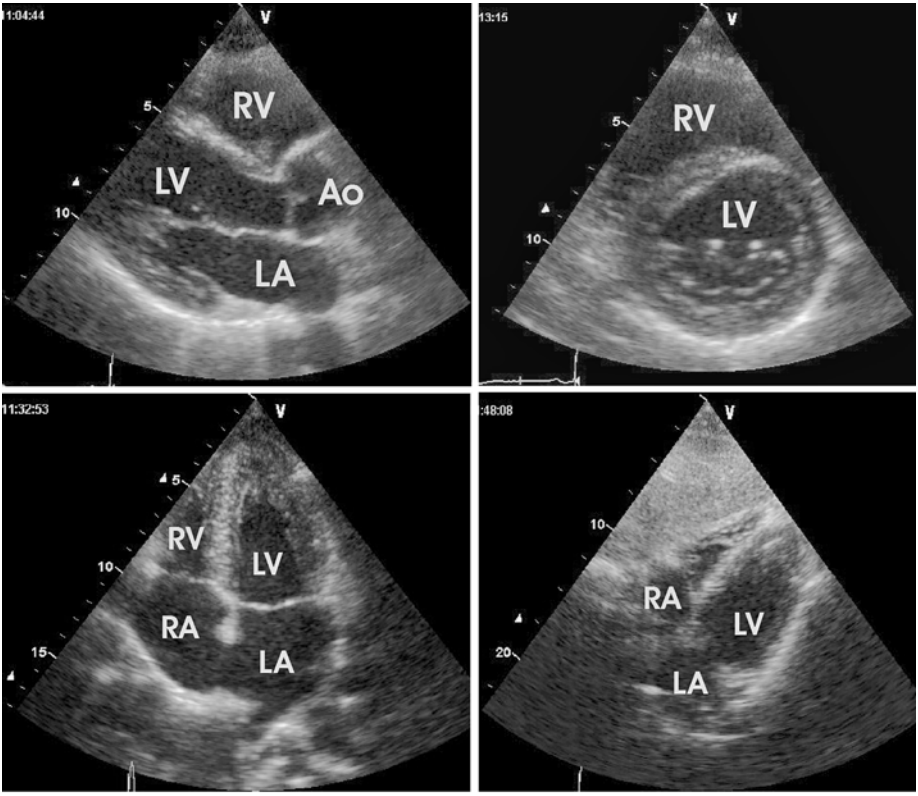


**Fig. 1.** Standard transthoracic echocardiographic views. Upper left, parasternal long axis; upper right, parasternal short axis; lower left, apical four chamber; lower right, subcostal. Ao, aorta; LA, left atrium, LV, left ventricle, RA, right atrium, RV, right ventricle.

$$\Delta P = 4V^2$$

where $\Delta P$ is the pressure gradient and V is the transvalvular (peak) flow velocity. This modified Bernoulli Equation is very versatile in echocardiography. It can be used to estimate chamber pressures in intracardiac shunts, to determine severity of valvular stenosis from the mean or peak pressure gradients, and to estimate pulmonary artery pressures and left atrial pressure [1].

The continuity equation is another important equation in echocardiography and can be used to calculate the area of a stenotic or regurgitant valve [2]. The concept of conservation of flow dictates that the volume of blood entering a valve must be the same as that exiting (i.e., 'what goes in must come out'). Hence, for a stenotic valve

$$A_1 \times VTI_1 = A_2 \times VTI_2$$

where $A_1$ is the cross-sectional area of the location proximal to the stenotic valve, $A_2$ is the valvular area, $VTI_1$ and $VTI_2$ are the velocity time integrals obtained at these two locations, respectively. If $A_1$ and both VTIs are known, the stenotic valve area can be worked out. The application of the continuity equation is not limited to the stenotic or regurgitant valve, it can also be used to estimate the ratio of pulmonary flow to systemic flow (Qp : Qs) in intracardiac shunt.

## Assessment of Left Ventricular Function

### Left Ventricular Systolic Function

The most common use of echocardiography in the critically ill patient is the assessment of left ventricular (LV) contraction. Even though the study may be suboptimal, such as in the person undergoing cardiopulmonary resuscitation, useful information is often obtained [3]. In less critically unstable patients a more objective assessment of LV ejection fraction (LVEF) is possible, with some methods being more useful in the critically ill population. A well-established method using two-dimensional (2D) echocardiography is the biplane method of discs or modified Simpson's rule, which is based on apical 4 and 2 chamber views. Calculation of volume results from the summation of multiple discs or cylinders. Most machines now contain built in quantitative programs to perform the calculations [4, 5]. Combining Doppler measurements with 2D diameter measurements allows volumetric flow to be calculated by LV outflow tract (LVOT) diameter and estimation of flow through the LVOT by pulse wave Doppler. From these data, both stroke volume and cardiac output can be calculated [6]. Although originally practiced with TTE, these same methods have been validated with TEE [7]. Other methods are available in certain patients, such as measuring dP/dt from the mitral regurgitant signal [8]. Although most studies have been performed on a stable population, there have been comparisons of some of the different methods in the critically ill population [9]. Visual estimations of the LVEF are the most frequently used, evidence indicating that in experienced hands this equates with more formal methods of assessment [10, 11]. The presence of underlying ischemic heart disease may be detected such as when segmental wall defects or aneurysm are seen (Fig. 2).

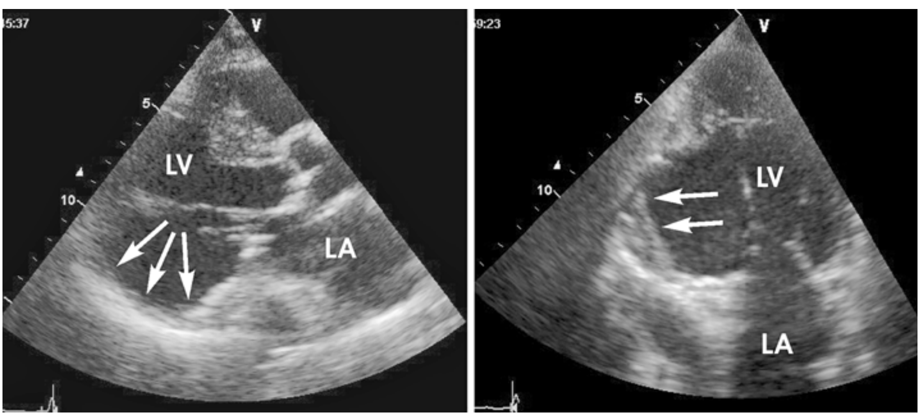


**Fig. 2.** Left ventricular inferior wall aneurysm in a patient with cardiogenic shock. Left: long axis view; right: apical 2 chamber view. Note the large aneurysm at the basal inferior wall (arrows). LA, left atrium, LV, left ventricle

### Left Ventricular Diastolic Function

Diastolic dysfunction of the left ventricle is an area of intrigue where as clinicians we are aware of its importance, yet measuring it has proved difficult. Its importance in the critically ill is unknown but must be significant when it is estimated that 30–40% of ambulant patients with symptoms and signs of congestive cardiac have normal LV systolic function and their condition is considered to be a result of diastolic dysfunction [12, 13]. The ratio of early to late diastolic velocity (E/A), deceleration time of mitral inflow, isovolumic relaxation time (IVRT) and pulmonary wave form analysis have been useful, but far from adequate, tools for evaluating diastolic function for many years [14]. Fortunately the advent of Doppler tissue imaging (DTI) has provided more accurate and easily applied tools to assess diastolic dysfunction, as can be seen with measuring mitral valve annulus motion [15, 16].

## Assessment of Right Ventricular Function

The crescentic-shaped right ventricle and its position in the chest (beneath the sternum) render the assessment of right ventricular (RV) function a challenge in echocardiography. Many of the quantitative evaluations for the left ventricle are not directly applicable to the right ventricle. For example, the estimation of RV ejection fraction (RVEF) is virtually impossible, and segmental wall motion analysis has no direct bearing on the RV assessment. To date, the function of the right ventricle is most commonly inferred from RV size and thickness – a qualitative approach. RV dilation is normally associated with volume or pressure overloading (Fig. 3). RV hypertrophy (wall thickness $>0.5$ cm) is regarded as abnormal and is suggestive of long-standing pressure overload (e.g., cor pulmonale), although it may also be associated with infiltrative or hypertrophic cardiomyopathies.

Quantitative evaluations of RV function are limited. The lateral tricuspid annular displacement (TAD) appears to be the easiest and most consistent method to quantify RV systolic function [17]. Briefly, the lateral peak-to-peak TAD is obtained

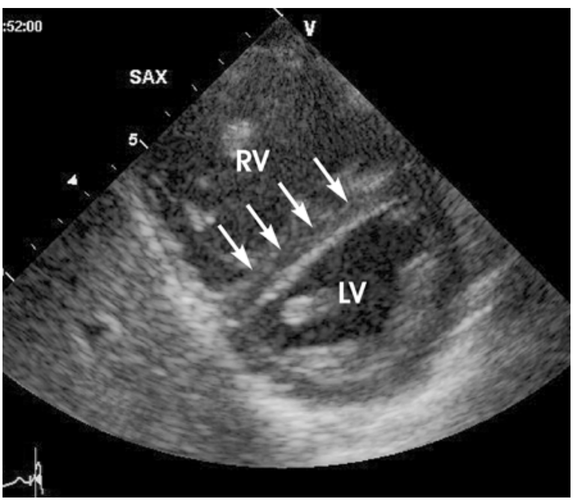


**Fig. 3.** Parasternal short axis view demonstrating volume overloading in an ICU patient. Note the dilated right ventricle (RV) and flattening of septum towards the left ventricle (D-shaped) during diastole.

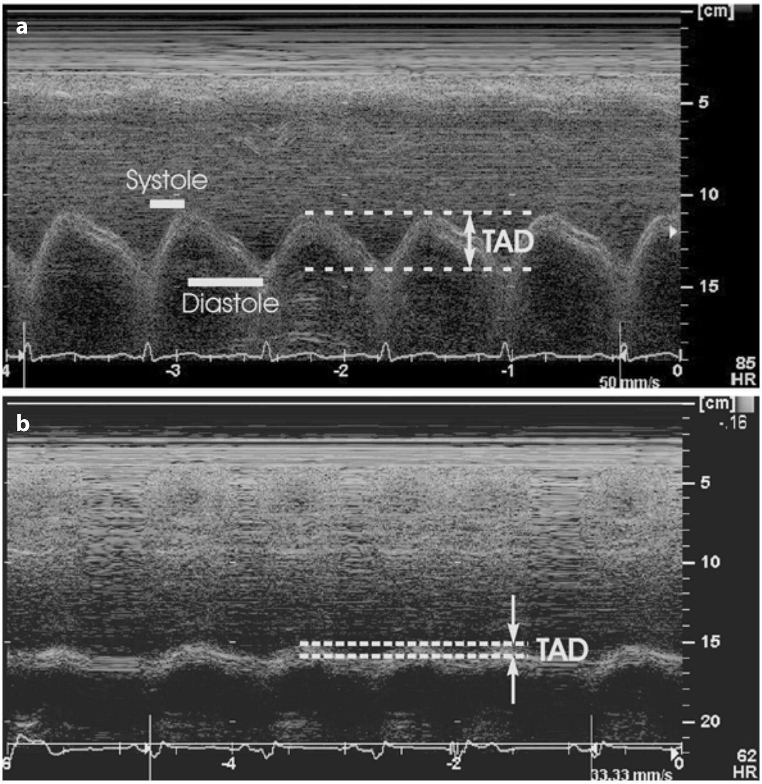


**Fig. 4.** Lateral tricuspid annular displacement (TAD) in a normal patient (a) and in a patient with right heart failure (b).

from the M-mode in the apical view (Fig. 4). A value of < 2.0 cm suggests impairment in systolic function. The tricuspid annular tissue Doppler velocity has also been demonstrated to correlate with RVEF [18]. Global myocardial function can be assessed by the myocardial performance (or Tei) index – calculated from the measurement of Doppler-derived time intervals (Fig. 5) [19]. The index is a measure of the ratio of isovolumic time intervals and ejection time. While the isovolumic contraction time increases and ejection time decreases in systolic dysfunction, the IVRT is prolonged in diastolic dysfunction. Prolongation of the Tei index is, therefore, associated with RV dysfunction. It should be noted, however, that although this index has been well validated in some categories of right heart dysfunction, the validity is nullified by the presence of heart block and arrhythmias.

## Preload Assessment

In clinical practice the term 'preload' is used to represent the filling volume and pressures of both the right and left ventricles. A number of tools are utilized for this purpose in the ICU, including the invasive indices of central venous pressure (CVP), pulmonary artery occlusion pressure (PAOP), intrathoracic blood volume

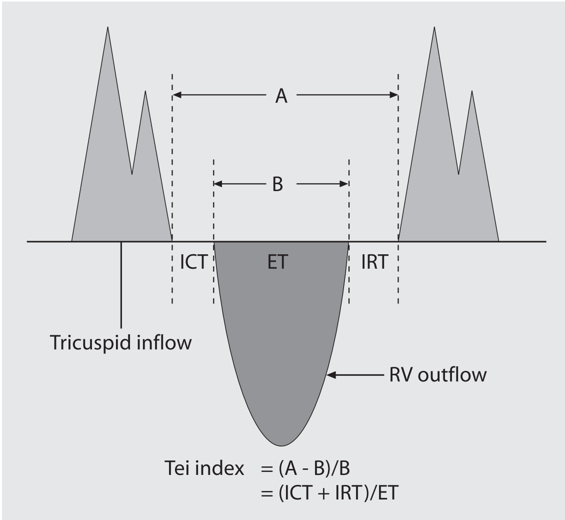


**Fig. 5.** Schematic diagram demonstrating the calculation of the Tei index for the right ventricle. The Tei index is calculated by measuring the time intervals A and B, and is a measure of the ratio of isovolumic time intervals and ejection time. ICT: isovolumic contraction time; IRT: isovolumic relaxation time; ET: ejection time.

(ITBV) as determined by PiCCO – all requiring invasive monitoring. Echocardiography is very useful in the critically ill patient because it is readily applied, non-invasive, and often provides additional information relevant to improving organ perfusion. If, and when, selected parameters need to be continuously monitored, the decision to proceed with invasive monitoring can be made. The fact that numerous echocardiographic techniques are available, attests either to the imprecision of some of the techniques in certain scenarios (i.e., in the patient with atrial fibrillation) or the obvious level of skill required.

Subjective review of chamber sizes, although a crude guide to preload status, can be helpful especially where marked hypovolemia is suspected [20]. Decreased size of the cardiac chambers can be a quick guide to inadequate filling, especially when resuscitating the patient. Fixed bowing of the interatrial septum, from left to right, during the cardiac cycle, indicates a PAOP greater than 18 mmHg [21]. In the operating room, the use of LV end-diastolic area (LVEDA) as a guide to volume status is well established. In the critical care setting, this parameter is not always so helpful in that it is not influenced by fluid challenge, nor predictive of increasing stroke volume with a fluid challenge [22, 23]. Pulsed wave Doppler echocardiography has been validated in non-critically ill subjects [24]. Analysis by Doppler of the mitral inflow and pulmonary vein waveforms in addition to utilizing DTI have demonstrated good correlation to invasive measurements and are helpful in the clinical setting where experienced echocardiographers perform the procedure.

DTI of the mitral valve annulus velocities can also assist in assessing left atrial pressure. Combining mitral inflow E velocity measurements with the mitral annulus Em DTI measurement, Ommen and colleagues described an accurate method of measuring LV filling pressures in 100 consecutive patients undergoing cardiac catheterization [25]. An E/Em $<8$ indicated normal mean LV diastolic pressures and an E/Em $>15$ indicated an elevated mean LV diastolic pressure. Although useful in the normal and very high ranges, additional Doppler data was required to determine those in the range between 8–15 mmHg. This method has been validated in critically ill ventilated patients [26].

For many years now right atrial pressure has been accurately estimated using inferior vena cava (IVC) and hepatic vein diameters and their alterations with inspiration [27]. The collapse of the IVC by >50% during inspiration indicates a right atrial pressure of <10 mmHg. A useful extension in measurements of the major venous veins has come from work by Vieillard-Baron and colleagues [28]. The variation of the superior vena cava (SVC) diameter in mechanically ventilated patients, the SVC being extrathoracic in location, serves as a guide to preload dependence (as opposed to measuring preload itself) in that it predicts the hemodynamic response to intravascular filling. The same authors have demonstrated that respiratory variation in the aortic or pulmonary outflow Doppler signal also serves as a guide to preload dependence, but when combined with the IVC variation with mechanical ventilation, is a very useful predictor of fluid loading response [29].

## Miscellaneous Diagnoses and Applications of Echocardiography

Some cardiovascular pathologies are only readily obtainable by echocardiography, particularly when speed to diagnosis is important. Infectious endocarditis, thoracic aorta dissection, pericardial tamponade, left atrial appendage thrombi, intracardiac shunts, severe valvular dysfunction – if identified can lead to a dramatic change in management (Fig. 6). Alternatively ruling these pathologies out can reduce the number of investigations that require transfer of the patient outside the ICU or emergency department. Tables 1 to 3 provide quick guides to echocardiography in selected clinical scenarios.

Although echocardiography cannot fulfill a minute-to-minute monitoring purpose, it can nevertheless be used as a guide for treatment monitoring over a period of hours or days such as in fluid resuscitation, reversible myocardial depression and acute heart failure [30].

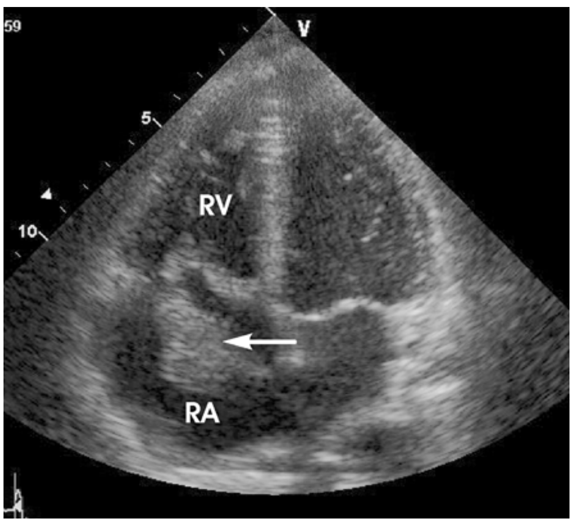


**Fig. 6.** Detection of endocarditis in an ICU patient. Apical four chamber view showing vegetation on the tricuspid valve leaflet (arrow).

**Table 1.** Guide to echocardiography: Hypotensive Patient

| Consider | Review |
|---|---|
| 1. Hypovolemia | ▮ chamber sizes<br>– end-systolic ventricular cavity<br>– left atrial size<br>– hyperdynamic small ventricles<br>▮ E/Em<br>▮ SVC variation |
| 2. Pump failure | ▮ left ventricular contraction<br>– ? Pre-existing reduced LV contraction<br>– ? RWMD – ischemic/non-ischemic<br>– ? Acute myocardial infarction<br>▮ right ventricular contraction |
| 3. Valvular | ▮ visualize valve opening:<br>– ? stenosis<br>– ? subvalvular obstruction<br>▮ color Doppler to identify significant regurgitation<br>▮ presence of vegetations |
| 4. Obstructive | ▮ pericardial tamponade<br>▮ valvular stenosis<br>▮ pulmonary embolus – RA/RV size/contraction<br>– PAP by TR method |
| 5. Miscellaneous | ▮ consider less common pathology<br>– intracardiac shunts<br>– LV diastolic dysfunction |

E/Em: mitral inflow/mitral annulus Doppler tissue velocity; PAP: pulmonary artery pressures; RA: right atrial; RV: right ventricular; RWMD: regional wall motion dysfunction; SVC: superior vena cava; TR: tricuspid regurgitation.

## Training and Accreditation

Who performs echocardiography in the ICU is dictated by local institutional factors. If the ICU is within an institution with large and active cardiology or radiology departments which provide a quick efficient echocardiographic service 24 hours a day/7 days a week, then intensivists do not need to replicate the service. In smaller hospitals where limited number of intensivists work this is also desirable. Many hospitals are now in the position of having large and busy cardiology departments where immediate echocardiography availability is compromised because of competing work interests. Even where an urgent study can be performed, experienced specialist interpretation is often delayed. Yet the presence of a trained and experienced doctor during performance of the study greatly assists decision making, especially when speed is of the essence. It is on this background that many intensivists have personally taken up the challenge of performing echocardiography. The challenge for the intensivist echo trainee is twofold. The first is defining what is an acceptable level of training (and how to gain and grant accreditation). The second is how to obtain this training. The objective should be full and comprehen-

**Table 2.** Guide to echocardiography: Septic patient

| Consider | Review |
|---|---|
| 1. Intravascular volume status | chamber sizes<br>hepatic vein diameter<br>left atrial pressure<br>E/Em<br>SVC variation |
| 2. Myocardial contractility | LV contraction overall<br>LV segmental wall defects<br>RV contraction |
| 3. Endocarditis | valvular: native/prosthetic<br>rarely: pacing wire, Eustachian valve |
| 4. Cardiac output | Simpson's method<br>LVOT continuity equation |

E/Em: mitral inflow/mitral annulus Doppler tissue velocity; SVC: superior vena cava; RV: right ventricular; LVOT: left ventricular outflow tract

**Table 3.** Guide to echocardiography: Dyspneic patient

| Consider | Review |
|---|---|
| 1. Left ventricular failure | contractility<br>diastolic function |
| 2. Left heart valve disease | mitral<br>aortic |
| 3. Right heart failure | contractility<br>ventricular wall thickness<br>chamber sizes |
| 4. Pulmonary hypertension | right heart chamber sizes<br>PAP by TR method |
| 5. Pericardial effusion | impairment of chamber filling<br>RA diastolic indentation |
| 6. Pleural effusions | |

PAP: pulmonary artery pressure; RA: right atrial

sive training. Echocardiographic studies (apart from TEE) are usually more difficult in the critically ill subject and hence prior adequate experience with the ambulant, relative agile subject (for better positioning during the study) is very important. Also, unlike the elective study, many critically ill patients are 'blind studies' in that the underlying diagnosis is not known prior to the commencement of the procedure. The existence of structured training courses for intensivists varies from country to country, but there are few worldwide. Critical care echocardiography is different to that necessary for the cardiac patient and as such specific training requirements are necessary, yet paradoxically less training is available. In our institution in Australia the standards match those of cardiology training (300 TTE and 100 TEE routine studies) enhanced by a one year Fellowship based in Critical Care Echocardiography.

Perhaps intensivists should be creating an international diploma in critical care echocardiography. This would surmount many of the national politics encountered by many of our colleagues facing other craft groups whose actions are dictated by a perceived 'loss of turf'. This attractive proposition, however, faces the obvious challenges of which body takes on this responsibility, what is an acceptable training program, and how accreditation should be undertaken.

## Conclusion

The interplay between cardiac function and general systemic disturbances is at the core of intensive care practice. Echocardiography is becoming 'mainstream', in that many ICUs now have their own machine and the objective is to utilize it during, as well as outside, regular working hours. Clinical urgency demands application at any time. Echocardiography frequently yields important diagnostic information, non-invasively, usually rapidly, and it can be readily reapplied as the situation demands. It has evolved from being a useful adjunct in the past to what is now an indispensable tool in the management of the critically ill patient.

### References

1. Seppelt I, McLean A, Ting I (2000) Tricuspid regurgitant jet measured by transthoracic echocardiography accurately estimates pulmonary artery pressures in the critically ill. Anaesth Intensive Care 29:193 (abst)
2. Skjaerpe T, Hegrenaes L, Hatle L (1985) Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two-dimensional echocardiography. Circulation 72:810–818
3. McLean AS (1999) The value of echocardiography during Cardiopulmonary Resuscitation. Asia Pacific Heart J 8:106–109
4. Schiller NB (1991) Two-dimensional determination of left ventricular volume, systolic function, and mass. Circulation 84 (Suppl I):I280–I287
5. Erbel R, Schweizer P, Lambertz H, et al (1983) Echoventriculography – a simultaneous analysis of two-dimensional echocardiography and cineventriculography. Circulation 67:205–215
6. Nishimura RA, Callahan MJ, Schaff HV, Ilstrup DM, Miller FA, Tajik AJ (1984) Noninvasive measurement of cardiac output by continuous-wave Doppler echocardiography: initial experience and review of the literature. Mayo Clin Proc 59:484–489
7. Izzat MB, Regragui IA, Wilde P, Angelini GD, Bryan AJ (1994) Transoesophageal echocardiography measurements of cardiac output in cardiac surgical patients. Ann Thor Surg 58:1486–1489
8. Chung N, Nishimura RA, Holmes DR Jr, Tajik AJ (1992) Measurement of left ventricular dP/dt by simultaneous Doppler echocardiography and cardiac catheterization. J Am Soc Echocardiogr 5:147–152
9. McLean AS, Needham A, Stewart D, Parkin R (1997) Estimation of cardiac output by non-invasive echocardiographic techniques in the critically ill subject. Anaesth Intensive Care 25:250–254
10. Mueller X, Stauffer JC, Jaussi A, Goy JJ, Kappenberger L (1991) Subjective visual echocardiographic estimate of left ventricular ejection fraction as an alternative to conventional echocardiographic methods: Comparison with contrast angiography. Clin Cardiol 14:898–902

11. Amico AF, Lichtenberg GS, Reisner SA, Stone CK, Schwartz RG, Meltzer RS (1989) Superiority of visual versus computerized echocardiography estimation radionuclide left ventricular ejection fraction. Am Heart J 118:1259–1265
12. Soufer R, Wohlgelernter D, Vita NA, et al (1985) Intact systolic left ventricular function in clinical congestive heart failure. Am J Cardiol 55:1032–1036
13. Dougherty AH, Naccarelli GV, Gray EL, Hicks CH, Goldstein RA (1984) Congestive heart failure with normal systolic function. Am J Cardiol 54:778–782
14. Nishimura RA, Housmans PR, Hatle LK, Tajik AJ (1989) Assessment of diastolic function of the heart: background and current applications of Doppler echocardiography. Part I. Physiologic and pathophysiologic features. Mayo Clin Proc 64:71–81
15. Rodriguez L, Garcia M, Ares M, Griffin BP, Nakatani S, Thomas JD (1996) Assessment of mitral annular dynamics during diastole by Doppler tissue imaging: comparison with mitral Doppler inflow in subjects without heart disease and in patients with left ventricular hypertrophy. Am Heart J 131:982–987
16. Sohn DW, Song JM, Zo JH, et al (1999) Mitral annulus velocity in the evaluation of left ventricular diastolic function in atrial fibrillation. J Am Soc Echocardiogr 12:927–931
17. Hammarstrom E, Wranne B, Pinto FJ, Puryear J, Popp RL (1991) Tricuspid annular motion. J Am Soc Echocardiogr 4:131–139
18. Meluzin J, Spinarova L, Bakala J et al (2001) Pulsed Doppler tissue imaging of the velocity of tricuspid annular systolic motion. Eur Heart J 22:340–348
19. Tei C, Dujardin KS, Hodge DO, et al (1996) Doppler echocardiographic index for assessment of global right ventricular function. J Am Soc Echocardiogr 9:838–847
20. Leung JM, Levine EH (1984) Left ventricular end-systolic cavity obliteration as an estimate of intraoperative hypovolaemia. Anesthesiology 81:1102–1109
21. Royse CF, Royse AG, Soeding PF, Blake DW (2001) Shape and movement of the interatrial septum predicts change in pulmonary capillary wedge pressure. Ann Thorac Cardiovasc Surg 7:79–83
22. Cheung AT, Savino JS, Weiss SJ, Aukburg SJ, Berlin JA (1994) Echocardiographic and hemodynamic indexes of left ventricular preload in patients with normal and abnormal ventricular function. Anesthesiology 81:376–387
23. Axler O, Tousignant C, Thompson CR, et al (1996) Comparison of transesophageal echocardiographic, Fick, and thermodilution cardiac output in critically ill patients. J Crit Care 11:109–116
24. Pozzoli M, Traversi E, Roelandt JR (2002) Non-invasive estimation of left ventricular filling pressures by Doppler echocardiography. Eur J Echocardiogr 3:75–79
25. Ommen SR, Nishimura RA, Appleton CP, et al (2000) Clinical utility of doppler echocardiography and tissue Doppler imaging in the estimation of left ventricular filling pressures. Circulation 102:1788–1794
26. Combes A, Arnoult F, Trouillet JL (2004) Tissue Doppler imaging estimation of pulmonary artery occlusion pressure in ICU patients. Intensive Care Med 30:75–81
27. Kircher BJ, Himelman RB, Schiller NB (1990) Noninvasive estimation of right atrial pressure from the inspiratory collapse of the inferior vena cava. Am J Cardiol 66:493–496
28. Vieillard-Baron A, Augarde R, Prin S, Page B, Beauchet A, Jardin F (2001) Influence of superior vena cava zone condition on cyclic changes in right ventricular outflow tract during respiratory support. Anaesthesiology 95:1083–1088
29. Vieillard-Baron A, Prin S, Chergui K, Dubourg O, Jardin F (2003) Hemodynamic instability in sepsis: bedside assessment by Doppler echocardiography. Am J Respir Crit Care Med 168:1270–1276
30. McLean AS, Huang SJ, Nalos M, Ting I (2005) Duration of the beneficial effects of levosimendan in decompensated heart failure as measured by echocardiographic indices and B-type natriuretic peptide. J Cardiovasc Pharmacol 46:830–835