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REVIEW ARTICLE

Transoesophageal echocardiography in the critically ill

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Summary
Echocardiography offers real-time bedside diagnosis and monitoring of a variety of structural and functional abnormalities of the heart. Transoesophageal echocardiography, in particular, provides information on cardiac contractility, filling status and output, valvular morphology and function and on the structure of the ascending and descending aorta in the critically ill patient. The full range of modalities of echocardiography, including M-mode, 2-D-mode, colour Doppler and spectral Doppler, is at the disposal of the intensive care specialist. In this review, the indications for and the clinical impact of transoesophageal echocardiography and Doppler are discussed.

Keywords *Measurement techniques*; transoesophageal echocardiography.

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Since its introduction into the critical care setting, echocardiography has become an invaluable technique in the diagnosis of cardiac pathology. Both transthoracic and transoesophageal echocardiography provide real-time bedside information about a variety of structural and functional abnormalities of the heart. Although transthoracic echocardiography remains the approach of choice, transoesophageal echocardiography (TOE) has been shown to be of additional value due to its ability to provide excellent visualisation of cardiac structures [1–3], providing important information about contractility, filling status, cardiac output and valvular morphological and functional abnormalities in critically ill patients. This review aims to summarise the current knowledge about the value of TOE in the management of the critically ill adult.

Technical aspects

Echocardiography uses the physical principle that sound is reflected from tissue interfaces, allowing a two-dimensional image of cardiac structures to be constructed. Ultrasound uses piezo-electrical crystals to transmit and receive acoustic signals as an imaging modality after conversion of the electrical energy of a sinusoidal wave to mechanical energy and vice versa.

The M-mode was the first technique used by echocardiographers. This technology uses a single ultrasound beam to scan cardiac structures. This application is an essential element in the assessment of myocardial contractility and valvular function. Later on, two-dimensional visualisation of the various cardiac structures (B-mode) with enhanced imaging quality became possible. The first transoesophageal echo probes available scanned only in the transverse plane [1, 2], permitting the evaluation of cardiac structures in well-defined standard planes: the short axis view of the ventricles at the level of the midpapillary muscles at ≈ 40 cm depth, the long axis four-chamber view from the midoesophageal position and the view of the superior mediastinum visualised at about 25 cm. During the past decade, the number of imaging planes has been extended from the transverse plane described above [1, 2] to a biplane [3] and a multiplane approach [4]. For this reason, the transducer is shifted electronically with incremental steps anticlockwise from the transverse plane to a longitudinal and to a 180° plane. The standard biplane views conform to conventions used in transthoracic two-dimensional echocardiography, using both flexion and rotation of the TOE probe. The transgastric view in the longitudinal plane shows the apex of the left ventricle and the basal structures

(left atrium, mitral valve and chordae tendineae). At the midoesophageal level, a long axis view, similar to the image described above, can be obtained by rotating the TOE probe to the left. Rotation of the TOE probe to the right provides short axis imaging of the right heart (right atrium, tricuspid valve, right ventricular outflow tract and pulmonary valve). At the level of the superior mediastinum, four standard images can be obtained by rotation of the probe: the two-chamber view (left heart), the right ventricular outflow long axis view, ascending aorta in conjunction with atrial septum view and caval, right atrial and atrial septum view.

When an ultrasound beam strikes a moving object, e.g. a moving blood cell, the frequency of the reflected sound is altered. This phenomenon is known as the Doppler principle or shift, first described by Christian Johann Doppler, an Austrian mathematician and physicist, in 1842. An impressive example is that of a moving train. As it approaches towards a listener, the wavelengths of its whistle are compressed and the pitch is perceived as being increased. When the train moves away, the wavelengths of the whistle are elongated and the frequency of the waves is perceived as being decreased. The shift in frequency is directly related to the velocity of the moving object and to the cosine of the angle of insonation, as stated in the Doppler equation. Modern echocardiographic devices calculate velocity from frequency shift, while simultaneously acquiring two-dimensional B-mode images. Doppler echocardiography shows the acquired data as a spectral display. Movements of blood cells towards the probe appear positive; movements away from the probe appear negative. On the echo screen, the graphical display of Doppler recordings is arranged beside a miniaturised two-dimensional B-mode image which serves to guide the Doppler beam. The Doppler screen displays the instantaneous blood flow velocities in $cm.s^{-1}$ (ordinate) plotted over time. The instantaneous blood flow velocities throughout one cardiac cycle at a certain point in the heart or in the great vessels form a characteristic waveform. Variations from normal flow patterns may suggest an underlying pathophysiological process. The velocity of blood flow can be expressed as peak or mean velocity throughout the cardiac cycle. The integration of instantaneous blood flows over one cardiac cycle produces a value called the time velocity integral. The time velocity integral indicates the distance covered by one red blood cell during one single beat of the heart.

Echocardiography offers three different applications of the Doppler principle. The first one is pulsed wave Doppler. This modality uses a one-beam technology. The single beam is used successively to transmit and receive ultrasound signals. In pulsed wave Doppler mode, blood flow velocities are obtained in only a small area termed the 'sample volume'. Guided by the B-mode image, the sample volume is placed along the Doppler beam in a region of interest. Blood flow measurements are obtained from this small region at a specific depth. Pulsed wave Doppler ignores reflected ultrasound from other flows that pass by the beam on its way to the sampling site, allowing assessment of flows at precisely the desired location. Moreover, pulsed Doppler has a better signal-to-noise ratio than continuous Doppler mode, resulting in a more accurate recording of weak signals. For example, when investigating transmitral or pulmonary vein flow patterns, spectral analysis by pulsed wave Doppler is used, allowing easier recording of maximum velocities and reduction or avoidance of underestimation of weak high-frequency Doppler signals. The main drawback of pulsed wave Doppler is the limitation of this approach in measuring high-frequency shifts and hence high velocities. When the Doppler frequency shift exceeds half the sampling frequency (the Nyquist limit), aliasing occurs, i.e. the pulsed wave Doppler signal becomes ambiguous. Hence, continuous wave Doppler is better when high blood flow velocities occur, e.g. as a result of the formation of jets.

A second application of the Doppler principle is continuous wave Doppler. This modality uses a two-beam technology: a transmit beam and a receive beam. In this way it is possible to overcome the Nyquist limit and to allow the measurement of high blood flow velocities. This is important in the measurement of flow across obstructions and of jets, e.g. in severe valvular stenosis. Continuous wave Doppler detects all the flows along the path of the Doppler beam. Hence, using this technique it is possible to detect the highest blood flow velocity more easily and to estimate the angle between the flow and the Doppler measurement. However, the disadvantage is the fact that all blood flows intersecting the Doppler beam are processed to a final signal that is graphically displayed on the monitor. Hence, it is difficult to isolate from where along the beam the signal is originating, restricting its application to the computation of high velocities.

The third application of the Doppler principle is colour Doppler. In contrast to the Doppler modes mentioned above, whose recordings are presented as a separate graphical display in addition to the B-mode image, colour Doppler information is superimposed upon the original two-dimensional image of cardiac structures. Colour Doppler can be considered to be a combination of pulsed wave Doppler and B-mode echocardiography. Different from pulsed wave Doppler with its small, well-defined sample volume, the colour Doppler mode uses multiple sample volumes along the Doppler beam, thus indicating the flows in an area. This mode shows the anatomy and the

blood flow within cardiac and vascular structures both simultaneously and continuously. The blood flow information is encoded as a moving blue or red colour-stream overlain over the 2-D image: blue indicates blood cells moving away from the probe, red represents blood cells travelling towards the probe. In addition to this, information about flow velocity is provided. The brighter the blue and red colours appear on the screen, the higher the velocity of the blood flow. A scale at the edge of the screen correlates the shades of blue and red with numerical velocity data.

Pulsed and continuous wave Doppler allow not only the determination of velocities and the direction of transvalvular flows but also the calculation of transvalvular pressure gradients by means of a modified Bernoulli equation. This provides pressure gradients through measured velocities across an interrogated plane:

$$\text{pressure gradient} = 4 \times (\text{peak velocity})^2.$$

In this way the severity of valvular disease and intracardiac flow restrictions can be evaluated. The pressure gradient is calculated from the difference between distal and proximal peak velocities occurring in the interrogated plane. Moreover, using the complete velocity profile instead of the peak velocity in cases of a regurgitant jet through the mitral or the tricuspid valve, by transforming it to a pressure gradient profile, instantaneous dP/dt is given as the first derivative of the pressure gradient profile.

In summary, several techniques are used in modern echocardiography: 2-D mode, M-mode, colour Doppler, pulsed Doppler and continuous wave Doppler. In the future, three-dimensional reconstructions will add further important information to the noninvasive diagnosis of cardiac disease.

Patient preparation

Before starting a TOE examination, some preventive and safety criteria should be fulfilled. These standards can be divided into device-related, patient-related and investigator-related measures.

Preparation of the echocardiograph and TOE probe

After each investigation, the TOE probe should be cleaned and immersed in a glutaraldehyde bath. As a result of the inconvenience of this kind of preparation (unpleasant smell and airway toxicity), most centres use latex covers filled with ultrasound contact gel, allowing rapid evaluation of consecutive patients during anaesthesia and in the intensive care unit (ICU). In order to introduce the probe safely, a bite ring must be used in awake or lightly sedated patients to prevent damage to the probe.

Preparation of the patient

The awake and nonintubated patient should be informed about the importance of the TOE investigation and how the investigator will perform the examination. When possible, the awake patient should be positioned in the left lateral position. Patients should fast for at least 3 h. Sedation may be provided under continuous ECG and oxygen saturation monitoring. Topical lignocaine (10%) is used to provide local anaesthesia of the tongue, pharynx and the larynx of the patient.

In mechanically ventilated critically ill patients, midazolam in small doses can be administered intravenously [5]. The investigator usually stands at the patient's side, guiding the probe into the patient's mouth with the index finger. Rarely, a laryngoscope is needed in intubated patients to displace the base of the tongue and allow insertion of the probe. Difficulties in introducing the probe are encountered in $\approx$1.4% of patients [6].

The safety of TOE has been extensively examined. At the power levels of ultrasonic energy used in clinical echocardiography, there is no known risk to the patient or the investigator. Daniel *et al.* reported a procedural mortality of 0.0098% in a multicentre study of 10 419 TOE examinations [6]. Cardiac, pulmonary or bleeding complications necessitating interruption of the TOE investigation were described in 0.18% of the cases. However, bleeding problems and rhythm disturbances are more common in ICU patients and therefore firm indications for the investigation must exist when these problems occur.

Investigator-related precautions

A TOE examination will only provide full information when the investigator is well trained and skilled: the greatest danger to the patient is the incorrect interpretation of the images and signals [7]. Recently, guidelines for education and practice at different levels of training in TOE in the peri-operative setting were approved by a Task Force of the American Society of Anesthesiologists and Society of Cardiovascular Anesthesiologists [8]. Structured courses conducted in collaboration with cardiologists should also be initiated in Europe. Moreover, both technical skills and a thorough knowledge and understanding of cardiovascular physiology and pathophysiology should be acquired before conducting TOE examinations.

The echocardiographer should perform bedside TOE examinations when an accurate assessment of the haemodynamic status of the critically ill patient is required. Transoesophageal echocardiography should also be available for patients who have suffered major trauma [9].

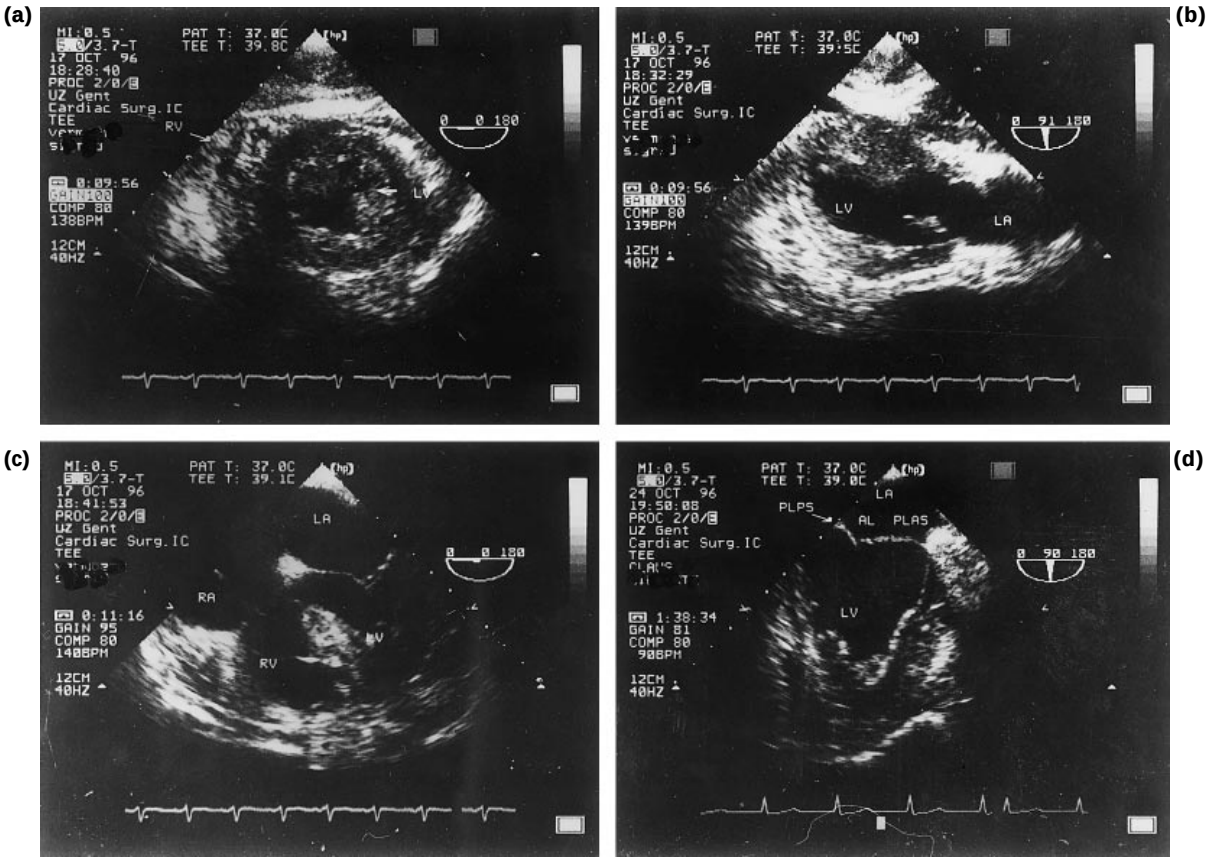

Figure 1 (a) Short axis view of the left ventricle (transverse plane) with anterolateral and posteromedial papillary muscles. The anterior wall of the left ventricle is shown at the bottom, the posterior wall is closest to the TOE probe, i.e. at the top. The lateral-inferior wall is shown on the right. LV: left ventricle. (b) Longitudinal plane at the same level as (a), showing the apex of the left ventricle. Closest to the TOE probe is the postero-inferior wall of the left ventricle. The anterior wall is at the bottom of the image. LA: left atrium. (c) Four-chamber view showing the four chambers (RA: right atrium, RV: right ventricle) and the mitral valve (anterior and smaller posterior leaflet medial scallop). (d) Longitudinal view at the same level as (c) with the anterior leaflet of the mitral valve (AL), the anterior scallop (PLAS) and the posterior scallop (PLPS) of the posterior leaflet.

Routine transoesophageal echocardiography in the critically ill: anatomical correlations

A basic investigation should comprise a sequence of views, always obtained in the same order (Figs 1 and 2). Here we propose such a sequence, starting from the transgastric short axis view, which is one of the most important monitoring images for anaesthetists and intensive care specialists.

1 The transgastric short axis view in a transverse plane at the level of the posteromedial and anterolateral papillary muscles (Fig. 1a) is reached at ≈ 40 cm from the incisors. In order to obtain this image, the TOE probe should be placed in the gastric fundus with anterior flexion of the tip, withdrawing the probe until good contact is achieved. The left ventricle in the transverse plane is shown with the anterior wall at the lower side of the image and the posterior wall closest to the oesophagus. The lateral and inferior walls are shown on the right and the interventricular septum is shown on the left. Instantaneously, three major haemodynamic features can be assessed: global left ventricular and right ventricular contractility, a rough impression of the filling status and identification of segmental wall motion abnormalities. Hence, the short axis view is the most important image for haemodynamic monitoring of a patient.

At this level, an additional longitudinal view (Fig. 1b) should be obtained to exclude the presence of thrombi in the apex of the left ventricle. Moreover, it is possible to observe the movement of the global postero-inferior (upper segments), apical and anterior (lower segments) walls in this view.

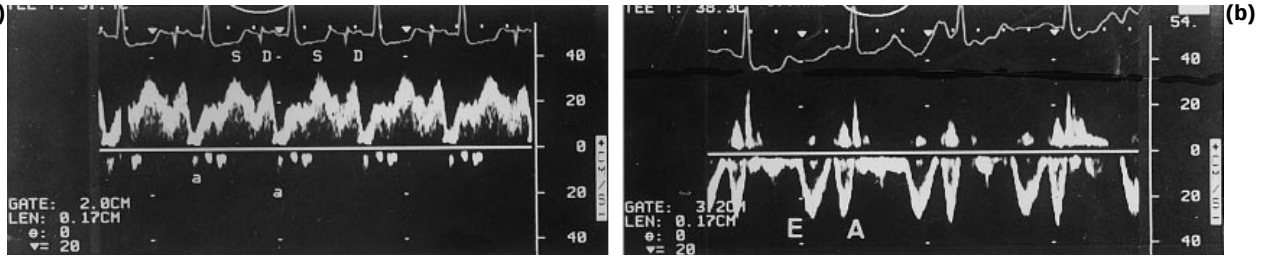

Figure 2 (a) Normal pulmonary vein flow pattern with a small atrial reverse flow wave (a), larger anterograde (often biphasic) systolic flow wave (S) and diastolic flow wave (D). (b) Normal transmitral flow pattern with early filling (E) and atrial flow wave (A).

2 Pulling back the TOE probe a few centimetres while staying in the stomach provides a first image of the mitral valve at a level just above the short axis. In this image, the closing of the mitral leaflets can be clearly seen.

3 Pulling back the TOE probe further into the distal oesophagus allows the four-chamber view to be seen (Fig. 1c). This view allows visualisation of both mitral and tricuspid valvular apparatuses, the interventricular septum, both atria, the inferolateral left ventricular wall and the free wall of the right ventricle. This image, in conjunction with its longitudinal counterpart (Fig. 1d), offers the best opportunity to evaluate mitral valve morphology (leaflet and annular morphology and coaptation of the leaflets, i.e. the closing capacity of the mitral valve leaflets in systole) and mitral valve function. This is due both to the position of the transducer just behind the left atrium and the small intercept angle between the Doppler beam and blood flow through the valve.

Both morphological and functional assessment of the mitral valve can be performed:

• Morphological evaluation consisting of a multiplane scanning approach: rotation of the transducer from the transverse to the longitudinal plane provides a global view of the different parts of the anterior and posterior leaflets, including visualisation of the three scallops of the posterior leaflet (Fig. 1d).

• Functional assessment comprises colour and pulsed wave Doppler:

—Colour Doppler in appropriate planes, in order to determine potential mitral insufficiency, characterised by a red turbulent flow towards the TOE probe in systole.

—Pulsed wave Doppler at the level of the mitral valvular anulus or at the tips of the mitral leaflets (sampling always at the same position, to allow later comparisons between diastolic Doppler flow patterns). This pattern consists of two flow waves: the E and A waves (Fig. 2). The E wave represents the early filling of the left ventricle and is characterised by velocity (amplitude), flow time, deceleration time and time velocity integral (Fig. 2b). Also, velocity, flow time and time velocity integral of the atrial contraction (*A*) wave can be obtained. Finally, a ratio of early to late filling velocities (*E*/*A*) can be calculated. All these parameters offer additional information about the left ventricular diastolic function and the filling status of the left ventricle.

—The transmitral Doppler pattern should always be interpreted in conjunction with pulsed wave Doppler of the pulmonary vein flow (Fig. 2a). Depending on the direction of the mitral regurgitant jet, a right or left pulsed wave Doppler pulmonary vein tracing should be obtained. Both systolic and diastolic flow waves are characterised by velocity, flow time and time velocity integral.

4 Pulling back the TOE probe a few centimetres further allows the five-chamber view to appear in the transverse plane (Fig. 3a). In addition to the four cardiac chambers, the left ventricular outflow tract can be imaged. The function of the aortic valve can be assessed in the same plane. Placing the sample volume between the two valves allows the investigator to find a point where the outflow from the left ventricle and the inflow into the left ventricle can be traced simultaneously, allowing Doppler measurement of the isovolumetric relaxation time. In the same view, colour M-mode through the left ventricular outflow tract provides information about aortic valve function, allowing aortic regurgitation to be excluded. Rotating the transducer to the longitudinal plane images the left ventricle outflow tract, the aortic valve and the first 4–5 cm of the ascending aorta (Fig. 3b).

5 At the level of the left atrium, the left atrial appendage can be examined as well as the interatrial septum, allowing detection of atrial thrombi and septal defects.

6 Pulling the TOE probe back further, the superior mediastinum is visualised in the transverse plane: a short axis view of the ascending aorta, superior vena cava and the main trunk of the pulmonary artery (Fig. 3c). In the longitudinal plane, the right branch of the pulmonary artery can be imaged in conjunction with the aortic valve and the first few centimetres of the ascending aorta (Fig. 3d).

7 Turning the probe through 180° provides an image of

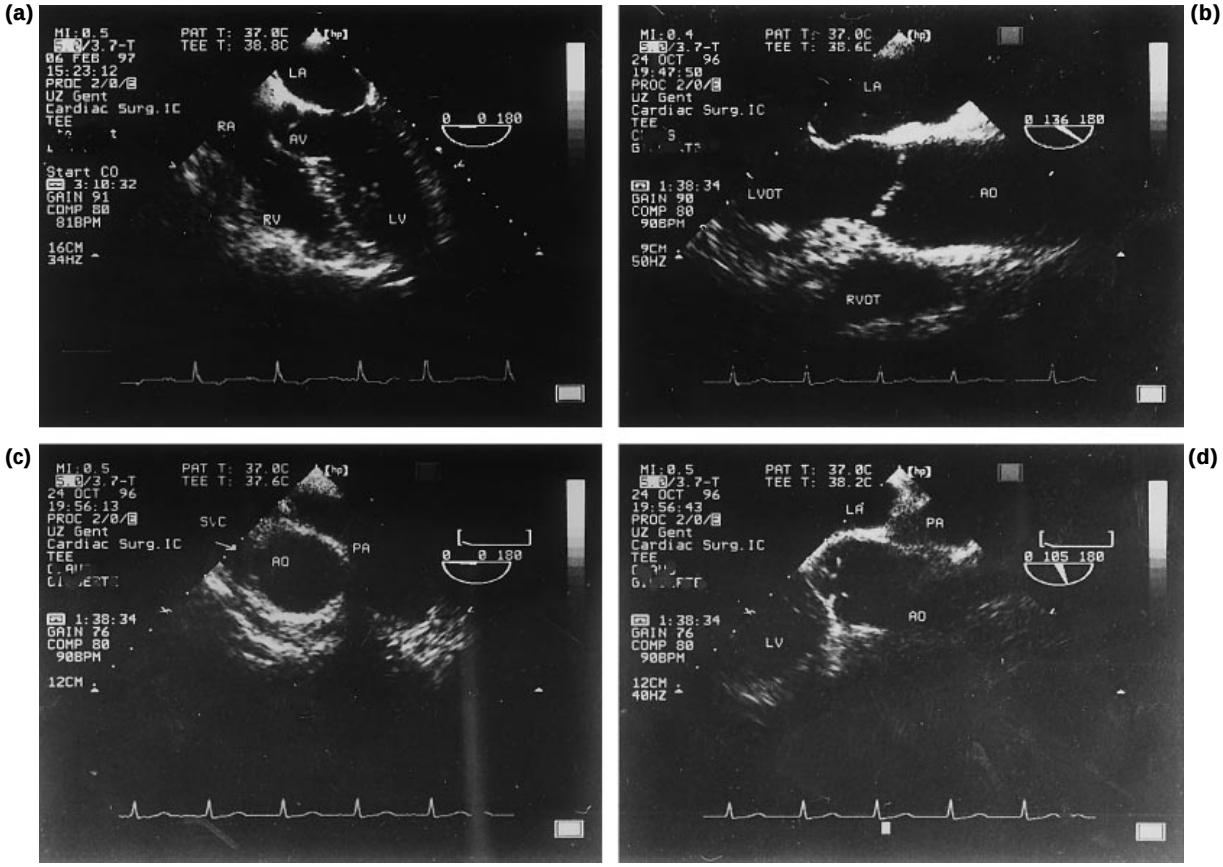

Figure 3 (a) Five-chamber view (transverse plane). AV: aortic valve. (b) Longitudinal view at the same level as (a) showing the left ventricular outflow tract (LVOT), ascending aorta (AO) and right ventricular outflow tract (RVOT). (c) Short axis of the superior mediastinum. SVC: superior vena cava, PA: pulmonary artery. (d) Longitudinal plane at the same level as (c) showing the right branch of the pulmonary artery (PA).

the descending aorta, starting at the second half of the aortic arch. The whole course of the aorta can be followed in both transverse and longitudinal planes. Atherosclerotic plaques, dissection of the descending aorta and the correct placement of the tip of an intra-aortic balloon catheter can be seen.

8 Finally, scanning from the roof of the left atrium while moving from a transverse scanning plane towards a longitudinal (90°) and then to a transverse plane (180°), an overview of the different cardiac structures can be obtained without probe displacement (Fig. 4).

Transoesophageal echocardiography and haemodynamics

Transoesophageal echocardiography has proved to be of particular value in the assessment of left ventricular systolic function [10, 11] and filling [11]. In critical care management, TOE was first introduced in cardiovascular anaesthesia. Even during the initial learning phase, TOE was shown to be very useful, providing supplementary information that can guide management in the immediate postbypass period and in the postoperative setting after cardiovascular surgery [12, 13]. Transoesophageal echocardiography provides detailed information that can help determine the cause of hypotension that is refractory to inotropic or vasopressor infusions [8–10], as shown by Reichert *et al.* [12]. The causes revealed in this study were left ventricular failure (27%), hypovolaemia (23%), right ventricular failure (18%) and biventricular failure (13%). In 9% of the cases, however, TOE was not helpful in determining the cause of hypotension [12]. In another study [10], the combination of fractional area contraction as a quantitative parameter of left ventricular function and the regional wall motion analysis score (estimated qualitatively) were predictive for survival. Fractional area

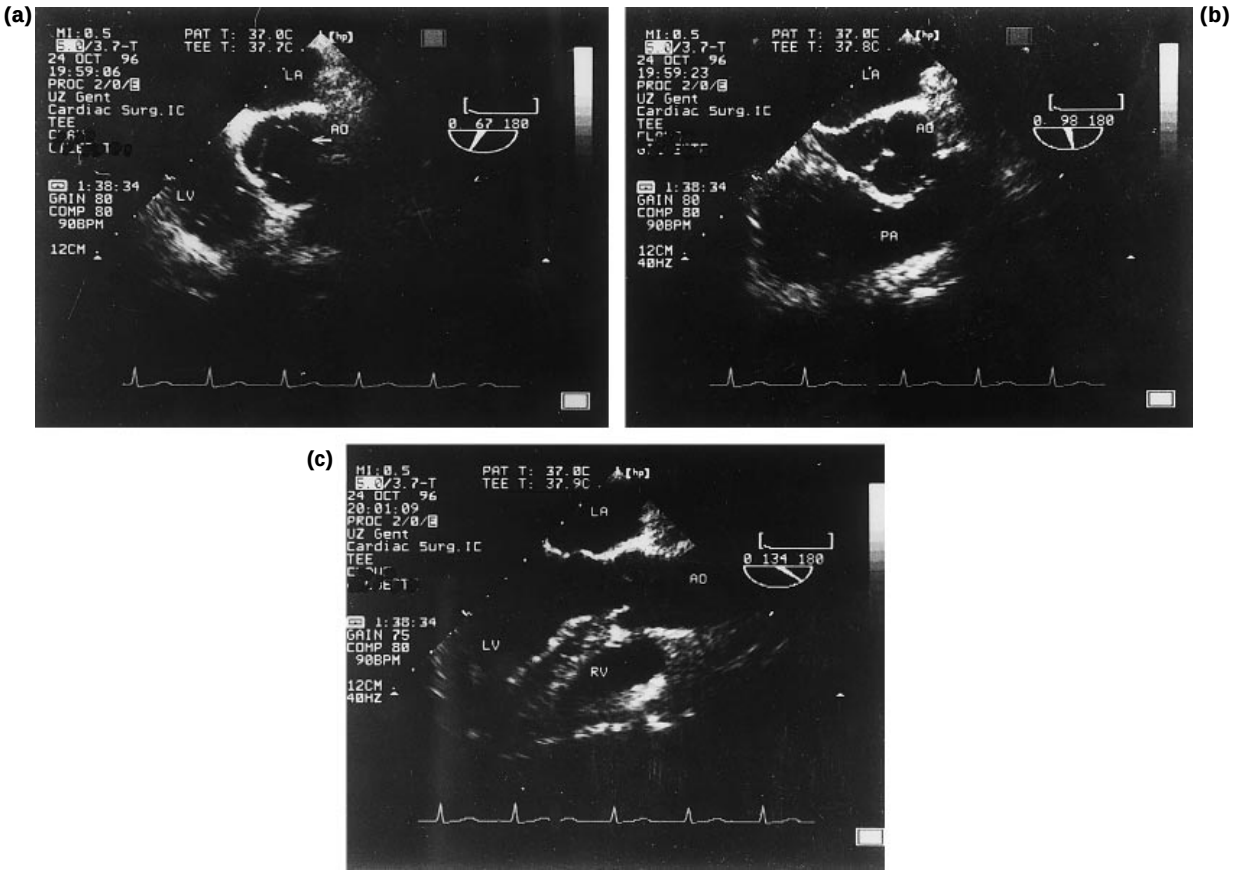

Figure 4 The transducer is located at the level of the roof of the left atrium, scanning from transverse (0°) to longitudinal and again to transverse plane (180°). (a) Aortic valve, allowing assessment of the tricuspid valve. (b) Outflow tract of the right ventricle and the pulmonary artery. (c) Left ventricular outflow tract (LV), ascending aorta (AO) and right ventricular outflow tract (RV).

contraction is a surrogate for ejection fraction, calculated from the difference between the end-diastolic and end-systolic area of the left ventricular image.

Analysis of regional wall motion includes a numerical scoring system in order to describe the movement of the different regions of the left and right ventricle (0 = normokinesia, 1 = mild hypokinesia, 2 = severe hypokinesia, 3 = akinesia and 4 = dyskinesia). Visualised from the short axis view of the left ventricle, a complete overview of myocardial areas perfused by the three major coronary arteries can be obtained. The anterior part of the septum and the anterior wall of the left ventricle, imaged at the left and the lower side of the 2-D image, are perfused by the left anterior descending artery. The circumflex artery supplies the lateral wall on the right side of the image. The postero-inferior wall and the posterior part of the interventricular septum are perfused by the right coronary artery in 90% of the patients. Ischaemic events can be diagnosed, depending on the coronary perfusion pressure, as normokinesia (no defects), mild hypokinesia (mild decrease in systolic inward motion), severe hypokinesia (severe decrease in systolic inward motion), akinesia (no movement of the myocardial segment with contraction) and dyskinesia (outward movement of the myocardial segment with systole). The regional wall motion analysis score therefore consists of a summation of all myocardial segments and provides a good descriptive estimate of segmental wall motion abnormalities.

The superiority of TOE in the bedside determination of the type and cause of haemodynamic derangement has been demonstrated by various authors with immediate consequences for patient management and cost containment [12–15]. More invasive monitoring including pulmonary artery catheterisation should only be initiated when the apparent cause of haemodynamic instability has been demonstrated by echocardiography to be of cardiac origin. In other cases, less invasive haemodynamic monitoring can be used.

Table 1 Situations in which transoesophageal echocardiography offers substantial advantages over transthoracic echocardiography.

- Ventilated patients, especially prone ventilation
- Cardiac tamponade
- Diagnosis of vegetations, endocarditis
- Exclusion of a cardiac source of embolism
- Assessment of prosthetic valve function
- Diagnosis of ascending or descending thoracic aortic dissection
- Structural and functional evaluation of native valves, including postoperative assessment of mitral valve repair
- 'Minimally invasive' cardiac surgery
- Acute peri-operative haemodynamic derangements

Comparison of transthoracic and transoesophageal echocardiography

The easiest and least invasive way to image cardiac structures is echocardiography by the transthoracic approach. In several clinical settings, however, TOE offers important advantages with respect to its diagnostic power in comparison to the transthoracic approach (Table 1). The diagnosis of pericardial tamponade by transthoracic echocardiography is sometimes difficult due to similarities in the appearance of haematoma and surrounding tissue because of acoustic interference and far-field images. Transoesophageal echocardiography provides better images for the diagnosis of tamponade and is therefore preferable. The TOE probe is physically closer to the structures of interest and the 2-D images are therefore less disturbed by ventilation. Furthermore, TOE is far more sensitive in the detection of thrombi in the left atrium and the left atrial appendage [16]. Meta-analysis of nine studies demonstrated the high failure rate of transthoracic echocardiography compared to TOE: in only two cases could thrombi be visualised by the transthoracic approach whereas TOE detected thrombi in 183 patients [16]. In addition, TOE can be used to guide the placement of an intra-aortic balloon pump catheter and provides bedside qualitative assessment of both left and right ventricular performance and recovery of ventricular function in patients who are being treated with intra-aortic balloon pumps [17, 18]. These studies clearly demonstrate substantial advantages of the transoesophageal approach, mainly due to its superior image clarity.

Indirect measures such as fractional area contraction offer important data on systolic function. A low flow state, i.e. the presence of a low cardiac output, is shown as a spontaneously occurring increase in blood density and is an ominous sign of increased thrombogenicity. In this context, TOE is far more sensitive in demonstrating swirling 'spontaneous contrast' [19] which in itself is an indication for anticoagulation.

Assessment of mitral valve morphology and function

Accurate assessment of mitral valve morphology and function is a principal advantage of TOE [20, 21], particularly after mitral valve repair. The combined use of multiplane two-dimensional echocardiography and Doppler permits complete screening of the mitral valve apparatus. Evaluation of the mitral valve comprises assessment of the morphology of the valvular leaflets (degree of coaptation, prevalence of prolapse or the existence of flail leaflet with (partial) rupture of the chordae tendineae), as illustrated by Fig. 5(a).

Functional assessment of the mitral valve consists of colour flow screening, Doppler assessment at the level of the mitral valve and at the level of the pulmonary veins. The occurrence of reversed flow in the pulmonary veins during systole (Fig. 5b) is a highly sensitive and specific indicator of severe mitral regurgitation [22].

Estimation of filling status

Determination of preload is another important issue in the peri-operative management of critically ill patients. The presence of a small left ventricular end-diastolic area is characteristic of a low filling state [11]; but the combination of short axis 2-D imaging and Doppler at the level of the mitral valve and a pulmonary vein offers additional information about the preload of a critically ill patient [23–25]. A decrease in preload causes a significant reduction in the E wave (early filling flow wave) velocity in conjunction with a decrease of the S wave (systolic flow wave) velocity in a pulmonary vein. Consequent filling results in an increase of the time velocity integral of both E and S waves and of cardiac output. In clinical practice, the ratio of the early filling wave velocity to the atrial contraction wave velocity (E/A) is easy to assess; the normal value of this ratio is more than 1 (Fig. 2b). In conjunction with normal contractility of the left ventricle, a low E/A is a characteristic sign of inadequate preload. However, both transmitral and pulmonary vein Doppler patterns are strongly dependent on intrinsic and external factors and are not purely affected by the loading conditions of the left ventricle. A description of the various influences is beyond the scope of this review [26]. Besides the filling status, ventricular contractility and afterload have an important impact on both flow patterns: decreased left ventricular function will decrease both E and S wave velocities [22]. Interpretation of these parameters should therefore only be done in conjunction with a global analysis of cardiac function obtained by TOE. Table 2 illustrates how echocardiography can be used in the differential diagnosis of various shock states. Only the combination of 2-D imaging and interpretation of Doppler patterns allows a rapid diagnosis.

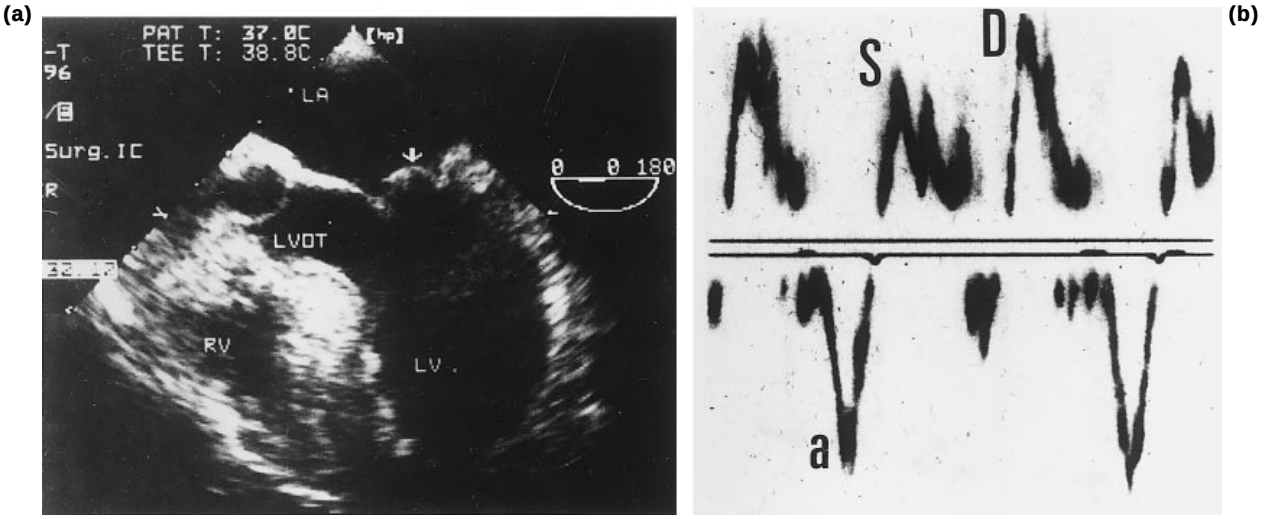

Figure 5 Left: visualisation of the mitral valve in transverse plane with a prolapse of the posterior leaflet of the mitral valve (arrow). Right: characteristic pulmonary vein Doppler pattern with a large negative flow wave (a: atrial contraction wave), a small systolic flow wave (S), a small negative flow wave (systolic reverse flow) and a larger positive flow wave (D).

Table 2 Transoesophageal echocardiographic determination of the underlying nature of hypotension or low cardiac output [21–24].

Diagnosis	LVFAC	RV	*E/A*	*S/D*
Hyperdynamic shock	+	Small	>/<1	>1
Cardiogenic shock	–	Dilated	<1	>1
Haemorrhagic shock	+	Small	<1	<1
Pulmonary embolism	–	Dilated	<1	>1
Cardiac tamponade	–	Small	<1	>1

LVFAC, left ventricular fractional area contraction. RV, right ventricle. *E/A*, ratio of the early filling flow wave velocity to the atrial contraction flow wave velocity. *S/D*, ratio of the systolic pulmonary venous flow wave velocity to the diastolic pulmonary venous flow wave velocity. +, increase; –, decrease.

The use of transoesophageal echocardiography in determining cardiac output

Since the introduction of TOE into the care of critically ill patients, its use in determining stroke volume and cardiac output from various echocardiographic or Doppler parameters has been evaluated. The following formula describes the relationship between time velocity integral, cross sectional area (*CSA*) and heart rate (*HR*):

$$\text{cardiac output (ml.min}^{-1}\text{)} = \text{time velocity integral (cm)} \times CSA\ (\text{cm}^2) \times HR\ (\text{beats.min}^{-1}).$$

Time velocity integral, the integral of instantaneous blood flow velocities during one cardiac cycle, can be theoretically derived from Doppler sampling at the level of the pulmonary artery, mitral valve or left ventricular outflow tract (Fig. 6). Cross-sectional area passed by the related blood flow can be obtained either by measurement of the diameter, assuming a circular surface, or by directly tracing the interrogated surface.

Savino *et al.* and Muhuideen *et al.* determined cardiac output from pulmonary artery spectral Doppler measurements [27, 28]. Although a correlation coefficient of 0.87 has been shown between pulmonary artery Doppler derived cardiac output and cardiac output measured by thermodilution [27], the anatomical relationship between the pulmonary artery, the oesophagus and the left main bronchus did not allow interpretable spectral Doppler signals in 24% of patients. Therefore, other techniques were evaluated to improve the results.

Promising results have been obtained from time velocity integral measurement at the level of the left ventricular outflow tract [29]. The major difficulty in assessing cardiac output by the Doppler method is the measurement of the effective surface of the aortic valve. Some authors approached this problem through measurement of the diameter of the left ventricular outflow tract [30, 31]. Correlations of 0.90 between cardiac output obtained by thermodilution and pulsed wave Doppler techniques were described using measurements of subaortic diameter in a longitudinal plane [32]. In this investigation, the mean (SD) difference in cardiac output was 0.1 (0.6) l.min^{-1}. In some echocardiography machines, time velocity integral can be measured on-line, providing an automated cardiac output if the diameter of the aortic valve or the cross-sectional area of the left ventricle outflow tract is