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Bedside assessment of myocardial performance in the critically ill

J.N. Shephard[1], S.J. Brecker[2], T.W. Evans[1]

[1] Department of Anaesthesia and Intensive Care, National Heart and Lung Institute, Royal Brompton National Heart and Lung Hospital, London, UK
[2] Department of Cardiology, National Heart and Lung Institute, Royal Brompton National Heart and Lung Hospital, London, UK

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The maintenance of adequate tissue perfusion is one of the primary goals in the management of the critically ill. While pursuing specific targets in terms of oxygen delivery (DO_2) and uptake (VO_2) remains controversial, suitable monitoring is essential [1]. Thus, many factors related to the disease process or that arise as a result of therapeutic interventions can influence both DO_2 and VO_2. The effects of manoeuvres such as intermittent positive pressure ventilation upon the cardiovascular system are well recognised and have been extensively investigated in both patients [2, 3] and animal models [4]. However, the magnitude of these effects cannot be accurately predicted in particular groups of patients or under specific clinical circumstances. Consequently, there is increasing interest in the development of accurate indices of tissue oxygenation. Techniques such as gastric intramucosal pH (pHi) [5] and subcutaneous oxygen tension [6] are potentially more sensitive as indicators of circulatory impairment than conventional measurements of (whole body) DO_2 and VO_2. Whilst they may provide an earlier warning of inadequate tissue perfusion and oxygenation, their place in the intensive care unit (ICU) is not yet fully established.

The factors influencing DO_2 are outlined in Fig. 1. It is arguable that cardiac output is the single variable that can at present be most effectively manipulated therapeutically. The monitoring and manipulation of cardiac performance during circulatory support therefore assumes considerable significance in current therapeutic strategies. The factors which influence cardiac output are summarised in Fig. 2. A number of these can be assessed at the bedside, but while accurate monitoring systems to detect these effects are available, their influence on clinical management and therefore outcome will remain marginal. The ideal characteristics of a monitoring system have been widely discussed and are summarised in

Correspondence to: T.W. Evans, Royal Brompton National Heart and Lung Hospital, Sydney Street, London SW3 6NP, UK

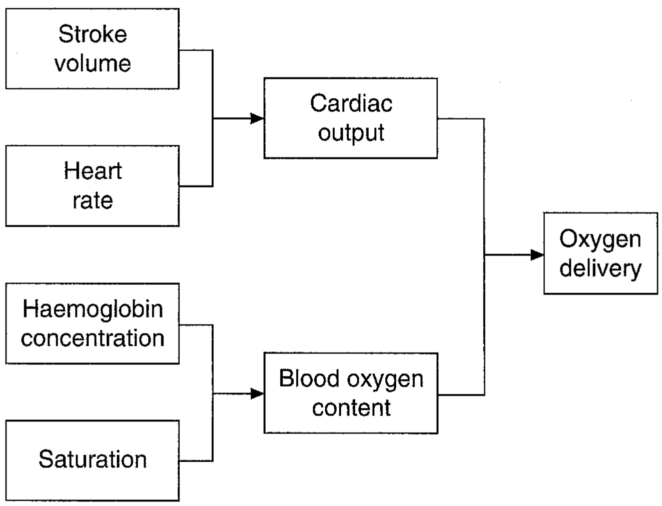

Fig. 1. Factors influencing oxygen delivery

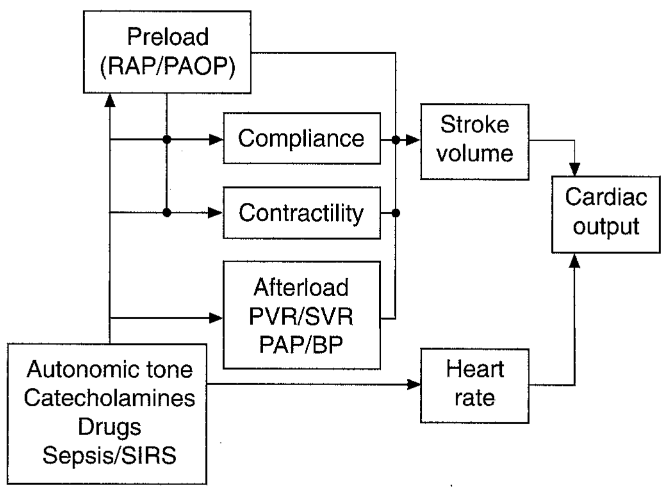

Fig. 2. Factors influencing cardiac output

Table 1. Ideal characteristics for a monitoring technique

Accurate	Results obtained are a true reflection of the actual value
Reproducible results	Results obtained are comparable with those at a different time in individual patients and from different patients
Rapid response	Rapid changes in values can be monitored
Operator independent	Results obtained by different individuals are comparable
Easily applied use	The technique can be used without the need for specialised skills or training
No morbidity	There should be no morbidity or mortality associated with the techniques use
Continuous use	It should be possible to monitor variables continually to distinguish short term and longer term changes
Cheap	Cost effective

Table 1. It is the intention of this review to appraise the currently available options for monitoring myocardial performance at the bed side, together with their advantages and limitations in the light of the clinical problems most frequently encountered in the critically ill.

The clinical problems

Cardiogenic shock

Acute myocardial infarction (AMI) is one of the commonest reasons for admission to an intensive therapy unit. The quoted incidence of cardiogenic shock following AMI varies between 5% and 15% [7]. Currently aggressive and invasive monitoring is advocated in such cases for both diagnostic and therapeutic purposes. Thus a survey from the USA showed an increase in the use of pulmonary artery (PA) catheters in patients admitted with a diagnosis of AMI from 7.2% to 19.9% over the period 1975–1988. However, the benefit of these regimens has been vindicated only through the increase in survival seen in patients with cardiogenic shock. Assessed retrospectively, mortality has fallen from around 80% in 1970 to 50% in 1985 [7]. The intensive monitoring of haemodynamic variables allows the application of appropriate supportive therapy whilst definitive interventions are applied; and for the recovery and inotropic stimulation of stunned myocardium following AMI. Delayed functional recovery of the myocardium following an ischaemic insult has been demonstrated in man and in animal models and improvement of left ventricular (LV) function after successful thrombolysis and reperfusion may occur up to 16 days later [8]. In those patients in which it is possible to increase DO_2, and prevent the development of secondary organ failure the prognosis has been shown to be greatly improved [9].

Monitoring techniques also have an important diagnostic role to play in the aetiology of cardiac dysfunction in the detection of valvular lesions, tamponade and thromboembolic phenomenon.

Post cardiopulmonary bypass (CABG) surgery

Haemodynamic monitoring is an essential component of the post-operative care required following cardiac surgery. Acute reversible myocardial depression following uncomplicated coronary artery bypass grafting is a well-recognised and frequent occurrence [10]. Possible underlying mechanisms include inadequate myocardial protection, the effects of cold cardioplegia, and reperfusion injury. In a recent study following uncomplicated CABG, all patients showed a depression of myocardial performance as assessed by ejection fraction and cardiac output. Inotropic support was required post-operatively by 63% at some time during the first 24 h [10]. In more complex patients with pre-existing myocardial damage the need for accurate monitoring is even greater, if an adequate circulation and tissue oxygenation is to be maintained to prevent secondary organ failure. The quantification of cardiac performance following transplantation is still in its infancy, but the complicating issues of myocardial reperfusion, re-implantation and rejection injuries suggest that a need for effective monitoring is high, deterioration in ventricular function may be the earliest sign of rejection [11].

Sepsis and septic shock

Septic shock is the commonest cause of death in intensive care, and the incidence is increasing. The sepsis syndrome carries a mortality of 30–60% and accounted for 100000 deaths pa in the USA in 1989 [12]. Sepsis and the systemic inflammatory response syndrome (SIRS) [13] are associated with many conditions and may occur as a complication of certain therapeutic interventions. SIRS is also seen following major trauma, in conjunction with the adult respiratory distress syndrome (ARDS), and in association with fat embolism or severe medical conditions such as pancreatitis. There are several process involved in the development of this phenomenon including a decrease in peripheral vascular tone leading to a fall in systemic vascular resistance (SVR) and a loss of micro vascular control, thereby altering preload and afterload. Depression of myocardial contractility may develop due to metabolic changes, leading to hypoxia and increased vascular permeability leading to tissue oedema. The direct depression of myocardial contractility by circulating substances in sepsis has been demonstrated both in vitro [14] and in vivo [15]. Several substances which depress myocardial contractility have been identified, including endotoxin, interleukins and tumour necrosis factor (TNF). Global depression of both left and right ventricular function has been demonstrated, although regional abnormalities of the left ventricle have also been described. In survivors, an initial ventricular dilation with an increased left ventricular end diastolic volume (LVEDV), reduced ejection fraction and preserved stroke volume, with a compensatory tachycardia to maintain or increase cardiac output has been described [15].

Abnormal metabolic demands have been demonstrated in septic shock, with pathological supply-dependency of oxygen uptake demonstrated by some workers [16]. Because of the variable nature of the peripheral and central cardiovascular effects of sepsis and their responses to vasoactive drugs [17], any rational treatment regimen requires the direct or indirect monitoring of the blood pressure, cardiac output, circulating volume, myocardial contractility, and vascular tone, to optimise the manipulation of these variables.

Clinical monitoring

The use of basic clinical skills and simple non-invasive monitors such as blood pressure, pulse, urine output and central/peripheral temperature gradients can provide a good deal of information regarding the heart and peripheral circulation and may be sufficient to manage patients with cardiac or circulatory insufficiency who are not critically ill. Studies into the accuracy of bedside estimates of left atrial pressure by clinicians as opposed to invasive measurements of pulmonary artery occlusion pressure (PAOP) have produced levels of agreement as high as 85% following uncomplicated AMI [18]. However, in patients with multisystem failure this level can be as low as 30% [19]. Such a success rate does not imply a level of discrimination that would normally be regarded as acceptable for the guidance of aggressive fluid management or inotropic therapy, and for the majority of critically ill patients more precise methods of monitoring myocardial function are required. While clinical observations and simple monitoring may indicate tissue- and organ-hypoperfusion, they are non-specific and insensitive.

Invasive monitoring

The use of invasive monitoring, and in particular the pulmonary artery (PA) catheter is now considered normal practice in the majority of intensive care units. Central venous pressure (CVP), pulmonary artery pressure (PAP), PAOP, right ventricular ejection fraction [20], cardiac output, and continuous mixed venous oxygen saturation can all be measured using a PA catheter. Although cardiac output is an important prognostic indicator after myocardial infarction [21], in one study patients monitored using PA catheters did less well than those who were not, largely as a result of catheter-associated morbidity [22]. This includes local trauma from the insertion of lines and guide-wires, through infective complications, on to the potential for pulmonary artery rupture. Speculative extrapolations from these figures have suggested that 10000–15000 excess deaths per year in the USA may be attributable to the use of PA catheters [23]. The reported incidence of complications associated with the use of pulmonary artery catheters varies from 1% [24] to 30% [25] though much of this discrepancy is due to classification.

The validity of using a single or group of measurements of CO taken over a very short period of time and assuming they are representative and comparing them with a similar set and assuming this reflects accurately the changes over an extended period has also been questioned [26]. Changes in intra-thoracic pressure induced by different modes of mechanical ventilation, changes in thoracic muscle tone and lung compliance, the mal co-ordination of spontaneous respiratory efforts with mechanical breaths, and underlying lung diseases such as COPD, asthma and ARDS can all influence the accuracy of measurements of both CO and LVEDP/PAOP. Additionally, alterations in the filling of the pulmonary circulation, increases in the pulmonary vascular resistance, mitral stenosis and incompetence, aortic incompetence and changes in left ventricular compliance all adversely effect the accuracy of PAOP in reflecting LVEDV and so left ventricular pre-load. The timing of measurements within the ventilatory cycle can have profound effects upon the results. In the past, measurements made at end-expiration or even with the patient transiently disconnected from the ventilator have been regarded as optimal [27]. More recently, investigators have suggested that three or more measurements evenly spaced through the ventilator cycle and averaged are a more accurate reflection of mean cardiac output [28]. Furthermore the precision of measurements of CO made with the PA catheter are at best 4–9% [29] and may be considerably worse.

Measurement of right ventricular ejection fraction (RVEF) is also possible using a suitable PA catheter, clinically this has been applied to monitor the effects of ventilator manipulations, as an indicator of pre-operative ischaemia, and the post-operative dysfunction associated with coronary artery bypass surgery. Work has suggested that the accuracy of these measurements is related to the RV EF and inversely related to heart rate [30].

More recent modifications to the PA catheter have enabled the continuous measurement of CO by thermodilution [31], which is now under widespread evaluation [32]. The clinical value of continuous rather than intermittent data has still to be evaluated but the correlation between the two techniques is close. From a practical point of view the continuous system may be simpler to use and avoids the variations attributable to operator technique. The incorporation of a Doppler probe into the catheter to provide continuous CO measurements has been less successful [33].

A recently-developed alternative technique for the assessment of preload involves the monitoring of intra-thoracic blood volume as an index of circulatory volume, which in ventilated patients may be more valuable than PAOP [34]. However, the technique requires that both a PA and large arterial catheter be inserted and its value remains to be established.

The use of LV conductance catheters allows the real time measurement of LV volume and with a suitable transducer these may be combined with simultaneous pressure measurements. Though still in relatively limited use this technique has been shown to agree closely with angiographic measurements of LV volumes and ejection fraction [35]. There are some practical limitations and the accuracy of the technique in dilated ventricles has been questioned [36]. Secondly, the presence of a catheter in the LV for long periods as a nidus for the formation of emboli is undesirable and limits its application in the ICU setting.

Non-invasive monitoring

Echocardiography

Since its introduction into clinical medicine and cardiology over 20 years ago [37, 38], the use of ultrasound has expanded dramatically. Echocardiography has become a major diagnostic tool, providing detailed information about cardiac anatomy and physiology, and representing a cheap, safe, non-invasive procedure that is particularly suitable for assessing critically ill patients due to the compact and portable nature of ultrasound systems. By definition ultrasound employs a frequency above that perceived by the human ear (20 kHz), and most cardiac applications of the technique utilise frequencies between 2 and 7.5 MHz. Echocardiography has traditionally been performed from the transthoracic approach, and most measurements of ventricular function have been validated using this technique. Commonly a parasternal approach, to obtain short and long axis views of the valves and ventricles, and apical and subcostal approaches to demonstrate all four cardiac chambers. However between 5–10% of ambulant patients have poor transthoracic windows, preventing the derivation of diagnostic and quantitative information. In mechanically ventilated patients, this percentage may rise to 30% or higher, particularly in patients who have undergone cardiothoracic surgery and have sternal wounds and chest drains in situ.

M-mode echocardiography. M-mode echocardiography, the original application of transthoracic cardiac ultrasound, remains the imaging modality of choice for analysing the timing of wall motion abnormalities, and no other technique has such a high sampling frequency. M-mode echocardiography produces a recording of motion along a thin slice through the heart, and is derived from a single beam of ultrasound of high frequency. The sampling rate of 1000 pulses per second represents one of the highest degrees of temporal resolution available for clinical measurement, and provides a large amount of information from a localised segment of the heart. M-mode echocardiograms were first used to measure LV dimensions in the early 1970s [39] and estimations of the LV minor axis have been widely used in the assessment of ventricular function. Cavity dimensions, shortening fraction (degree of systolic reduction in the minor axis expressed as a percentage of end-diastolic dimension) and velocity of circumferential fibre shortening (an index of systolic rate of dimension change) can all be used as indicators of systolic ventricular disease [40] and are commonly used to assess post operative cardiac function. M-mode echocardiography of the left ventricle can also be used to assess diastolic function, and due to the high sampling frequency, has advantages over all other imaging modalities in this respect [41, 42]. Isovolumic relaxation time may be conveniently measured from aortic closure on the phonocardiogram, to the initial separation of mitral cusps on the mitral echogram. Shape changes during isovolumic relaxation are a particularly sensitive marker of incoordinate relaxation commonly found in ischaemic heart disease and an important influence on diastolic function. More recently, M-mode measurements have been made of longitudinal motion of the atrioventricular rings, reflecting longitudinal myocardial, and indeed atrial function [43–45]. Computer analysis of short axis M-mode traces by digitisation, provides further information such as peak rate of cavity dimension increase, and rate of posterior wall thinning, which are physiologically useful measures of left ventricular diastolic function. Clear continuous echoes from the septum, the posterior wall endocardium and epicardium are necessary in order to digitise the M-mode trace [46, 47]. When combined with high fidelity pressure measurements, the stress-strain relation of a region of the posterior wall can be derived [47]. However the time required for digitisation well as cost and availability of the hardware limits its current clinical use.

With the advent of two-dimensional echocardiography came the introduction of additional methods of evaluation. However, although now widely used in the non-invasive assessment of ventricular function, limitations to the technique must be addressed. By forming a cross-sectional image, a compromise must occur between spatial and temporal resolution. Thus images with high spatial resolution can only be formed at low frame rates. Nevertheless, global left ventricular function can be assessed visually, to evaluate overall and regional wall motion, ventricular dimensions and areas of hypokinesis. Regional hypo- or dyskinesis are typical in myocardial infarction and chronic ischaemic disease [48].

Transoesophageal echocardiography (TOE). Over the past few years, the technique of TOE has developed and grown [49–51], finding a particular niche in the peri-operative assessment of ventricular function in patients undergoing surgery and in ventilated patients in intensive care. One or two 5 MHz transducers are mounted on the tip of a standard gastroscope, and the probe is inserted into the oesophagus either blindly or under direct vision. From a practical point of view, the important view to assess ventricular function is the horizontal plane transgastric short axis view of the left ventricle, just above the papillary muscles, although longitudinal plane images from biplane systems may provide additional information. From the short axis view, the entire circumference of the left ventricular wall can be seen, and segmental wall motion abnormalities can be assessed. Acoustic quantification of a high quality image together with on-line analysis can provide quantitative measurements such as fractional area change and d Area/dt. The methods of analysis of M-mode recordings already discussed with respect to transthoracic echocardiography apply equally to transoesophageal echocardiography, although validation of normal ranges is incomplete at this time. Simultaneously acquired data of left ventricular dimension, together with high fidelity intraventricular pressure recordings, can be combined to obtain a pressure-dimension loop. This allows the measurement of end systolic and end diastolic area-pressure relationships which may be considered the best available reflection of myocardial properties and provide a technique for assessing the Frank-Starling mechanism in the clinical situation. Such analysis may reveal subtle abnormalities of function not detected by other techniques, though at present remains a research tool. Two-dimensional images from either the transthoracic or transoesophageal approach may reveal extrinsic causes for a compromised circulation such as pericardial fluid, with compression or collapse of the right atrium or ventricle [52, 53]. The transoesophageal approach is superior in identifying localised thrombus with focal right atrial tamponade [54], and this should be considered in post cardiac surgery patients with a falling cardiac output despite rising right atrial pressures. TOE has a high diagnostic sensitivity and specificity, though it's precision as a quantitative monitor is very much more limited. In common with other echo techniques TOE is also highly operator and observer dependent [55]. This is an expensive technology which is unlikely to be universally available and is not suitable for continuous real time use.

Doppler echocardiography. Doppler echocardiography has now become an integral part of any cardiac ultrasonic examination, particularly with respect to functional assessment [56, 57]. Apart from the assessment of valvular stenotic and regurgitant lesions, which will not be discussed further, Doppler characteristics of the flow into the ventricles have been widely and rapidly adopted as markers of diastolic function [58–60]. The ease of measurement, and convenience of deriving a ratio of early diastolic/atrial filling velocities (the E/A ratio), perhaps explains the popularity. However, it is now recognised that age, heart rate, left atrial pressure and peripheral vascular resistance may all influence the transmitral Doppler E/A ratio quite independently of intrinsic diastolic properties of the ventricle [61–63]. In ischaemia and hypertrophy, the nature and duration of isovolumic relaxation are the strongest determinants of the E/A ratio, and it appears that they act as a final common pathway through which all other influences operate [64]. Nevertheless, when used with other information such as end-diastolic pressure, such indices may provide useful information. Doppler flow velocity traces of aortic flow have proved useful in assessing systolic function, and cardiac output may be calculated from this technique. Finally, Doppler recordings of tricuspid regurgitation can provide a useful non-invasive measure of pulmonary artery pressure [65–67]. The peak tricuspid regurgitant velocity is directly related to the right ventricular – right atrial pressure drop, and peak pulmonary artery systolic pressure can be estimated from this. Even if the peak velocity is not recorded, the time interval from pulmonary closure to the end of the tricuspid regurgitant signal may be used as a measure of peak systolic pressure [68].

Doppler flow probes. Simple oesophageal Doppler probes without an imaging facility can also be used for monitoring indices of cardiac output by measuring flow velocity in the descending aorta. Since the technique was first used in 1971 [69] there has been considerable development. In use the operation of such devices is relatively simple and atraumatic with the probe positioned blind and manipulated until a good signal is received. Though selection of a suitable ultrasound frequency (5.1 MHz) limits the depth of view so that only blood flow in the aorta is monitored without interference from other mediastinal vessels.

The signal from the probe is fed into a spectral analyser which produces a velocity/time curve for blood flow in the aorta. From the analysis of the area under the curve cardiac output and stroke volume can be calculated. By analysis of the shape of the curve changes in inotropic state, volume status and vascular resistance can be recognised [70]. This technique has been used with some success in both ICU and the peri-operative period. The reproducibility of indices of cardiac output comparing favourably with thermodilution methods [71], though a relative rather than absolute value is obtained as measurements are made in the descending aorta excluding blood flow to the subclavians and carotids. This compensated for using a correction coefficient assuming that the relative distribution of blood flow remains constant. Additionally in common with other Doppler techniques the accuracy relies on several assumptions, that the cross-sectional area of the aorta is constant throughout the cardiac cycle, that the angle of the probe to the direction of blood flow is constant and that there is laminar flow of blood within the aorta [72].

Radio nuclide techniques

The use of radioisotopes to study cardiac performance began with simple measurements of circulation time in 1927 [73] and developed with the development of quantitative techniques in the early 1960s. All techniques rely upon the labelling of the circulation with a radioactive tracer which will remain in the circulation for a time appropriate for the investigation performed. In the case of first pass studies, that is a study which records the passage of a single bolus of activity through the heart, this may simply be an injection of a suitable salt. For studies of a longer duration the blood may be labelled with a protein such as albumin which remains in the circulation, or the red blood cells can be labelled. The changing volume of blood in the heart is then imaged or measured to provide the data on cardiac function.

The variables measured are commonly ejection fraction (EF), ejection and filling rates and times, from which relative cardiac output may be calculated, and when using imaging techniques, regional contraction phase and amplitude information. When interpreting the data from these studies it is important to appreciate the clinical significance of the data. Ejection fraction is primarily dependant upon myocardial contractility and afterload and to a lesser extent preload, it has been shown to be an important prognostic indicator post myocardial infarction and has also been used as a predictor of cardiovascular risk prior to cardiac and major vascular surgery. However, its place as a bed side index of myocardial performance has not been established. Regional wall motion abnormalities correlate well with areas of infarction and ischaemia.

Imaging techniques. Multiple Gated Acquisition (MUGA) scans, first introduced in the early 1970s, and radionuclide ventriculography (RNV) now have a recognised place in cardiology. The labelled blood pool is imaged within the heart using a gamma camera. The images obtained are recorded by gated acquisition using an ECG signal so that accurate systolic and diastolic images can be built up. The reproducibility of the measurement of EF using different analysis techniques is of the order of 10% [74, 75]. The technique has been refined and validated against other techniques such as angiographic ventriculography. MUGA scans can be performed using a portable gamma camera and therefore within the ICU environment, but the system does have shortcomings for routine bedside use. The equipment required is cumbersome and the time required for accurate measurements to be made is long in comparison with other techniques such as thermodilution cardiac output. Once acquired, images require processing to provide quantitative data. There is also only a limited period during which scans can be made after the initial blood pool is radiolabelled as the half-life of the most widely used isotope (Technetium $^{99}Tc^{m}$) is 6 h. The rate of image acquisition, which depends upon the number of counts measured for the fidelity of the image produced, therefore increases. The development of new technology such as multi-wire cameras and the use of new isotopes such as tantalum may provide a more portable systems with rapid image acquisition and processing and a greatly reduced radiation dose facilitating repeated studies. Preliminary results suggest that this system will provide a level of precision similar to conventional cameras [76]. However, these will never be on-line techniques and require a skilled dedicated operator to perform the study and analyse the images.

Non-imaging techniques. Some of the drawbacks outlined above have been obviated by the new generation of non-imaging detection systems, which trade the spatial resolution of the conventional gamma camera for very much higher temporal resolution by viewing the left ventricle as a single pixel and monitoring changes in activity within this field, gated against an ECG signal to provide a measurement of changing left ventricular volume. These devices have the additional advantage of being physically smaller and some provide near realtime monitoring of left ventricular function. The first device available which could be used at the bed side, the "Nuclear Stethoscope" was developed in 1976 [77] and has been considerably refined since. More recent refinements mean that ejection fraction, ejection time, peak ejection rate, peak filling time, time to peak filling rate, first one third filling fraction, relative stroke volume, end systolic volume, and end diastolic volume can all be measured. A relative cardiac output is derived from these values. Such devices measure indices of diastolic function, such as peak filling rate and time-to-peak filling in addition to indices of systolic function in the form of ejection fraction and peak ejection rate. The importance of changes in diastolic function has been demonstrated in both ischaemic heart disease and sepsis [15]. Measurement of ejection fraction using these techniques has been validated in a number of clinical settings; for diagnostic use in ischaemic heart disease [78, 79], for continuous ambulatory monitoring of left ventricular function, in the monitoring of vasodilator therapy [80, 81], pre-, post- and during angioplasty [82], and pre- and post-cardiac surgery [83]. The principal disadvantages of these techniques are the necessity of labelling the red blood cells with radioisotope (99m-technetium), the limited duration of the labelling allowing typically 8 h of monitoring after each labelling. Their use may also be excluded for practical reasons, such as an ability to position the probe on the chest wall or anatomical abnormalities which mean that a straightforward view of the LV from the chest wall is not possible.

Theoretically, the use of these devices is attractive as they provide a continuous on-line monitor of both systolic and diastolic function and avoid the morbidity associated with the more invasive techniques. Current work suggest that the data that they provide on myocardial contractility in terms of EF and ejection rates, and compliance in terms of filling rates and changes in diastolic volume are reproducible and at least as precise as other currently available non-invasive techniques. Before their place in intensive care can be established further work in needed.

Impedance cardiography

Impedance cardiography is an attractive technique to use at the bedside, providing an estimation of EF and stroke volume, from which end diastolic volume is calculated. It is non-invasive, requiring only surface electrodes, involves no radiation exposure, provides real-time data and does not require a dedicated, skilled operator. A significant correlation between this technique and RNV [84] has been reported, but recent work and analysis of the original data using more appropriate statistical techniques [85] suggest that the limits of agreement between the two techniques are too wide to be clinically acceptable.

Summary

No measurement of myocardial performance currently available in the ICU can be regarded is ideal. Table 2 summarises the main features of the major monitoring techniques. As many of the indices of myocardial performance are interdependent, quantifying the contribution of each component to overall cardiac function is not possible currently, and the clinical utility of monitoring each individually is not therefore established. Bedside measurements of LV dimensions, volumes and ejection fraction, and the other indices of systolic and diastolic function can now be made, but the case for their routine use in influencing clinical practice remains unproven. Transoesophageal echocardiography has an important and established diagnostic role and has been used successfully for continuous monitoring during surgery, but practical considerations seriously limit its potential for routine use. Radionuclide techniques allow the measurement of many of the same parameters and have the potential for continuous use, but practical problems and the additional risk of radiation exposure may limit this application in the critical care environment. Doppler techniques are non-invasive, provide continuous data and are simple to operate,

Table 2. Summary of properties of the major monitoring techniques

Technique	Dedicated operator	Continuous data	Diagnostic utility	Monitoring utility	Parameters monitored	Precision and reproducibility	Complications
Transthoracic/ transoesophageal echocardiography	Yes	No	High (52–54)	Under evaluation	Anatomy, valvular function, qualitative wall motion. Quantitative, systolic and diastolic function with suitable analysis. Estimations of CO and pressures with Doppler	Operator dependant [55]	Rare [87]
Oesophageal Doppler flow probes	No	Yes	Low	Under evaluation	CO. Qualitative data on contractility, vascular resistance and volume status with wave form display [70]	Coefficient of variation 4% [71]	Rare
Pulmonary artery catheter	No	Yes-pressure No-CO	Low	High	RAP, PAP, PAOP, CO. SvO_2 with fiberoptic catheter	4%–9% (measurement of cardiac output under ideal circumstances) [29]	≈3.5% (1% [24]–30% [25])
Continuous cardiac output PA catheter	No	Yes	Low	High	RAP, PAP, PAOP, CO	Comparable with above, eliminates variation in technique	Assumed to be as above.
Radionuclide ventriculography	Yes	No	High	No	EF, pFr, pEjr, regional wall motion information	5–10% [74] Reproducibility 3 EF units [75]	Radiation exposure (1 in 2000)†
Non-imaging nuclear probes	Yes	Yes	Low	Not established	EF, pFr, pEjr, relative CO	5–10%	Radiation exposure (1 in 2000)†

Key: CO, cardiac output. RAP, right atrial pressure, PAP, pulmonary artery pressure. PAOP, pulmonary artery occlusion pressure. EF, ejection fraction. pFr, peak filling rate. pEjr, peak ejection rate. †: Following dose of 740 Mbq $^{99}Tc^{m}$ 1 in 2000 lifetime risk of fatal malignancy

but the data provided has important limitations. Although the pulmonary artery catheter has been in use for over twenty years, questions regarding the information is provides concerning myocardial function remain and the extent to which it should influence therapeutic decisions is still controversial. However with the development of additional facilities, particularly the continuous measurement of cardiac output the pulmonary artery catheter seems likely to remain the mainstay of bedside monitoring of myocardial performance in the critically ill in the immediate future.

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