TRANSOESOPHAGEAL TWO-DIMENSIONAL ECHOCARDIOGRAPHIC EVALUATION OF ANAESTHETIC EFFECTS ON LEFT VENTRICULAR FUNCTION

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Traditional methods of evaluating anaesthetic effects on left ventricular (LV) function have significant disadvantages. The assessment of pulmonary capillary wedge pressure provides only a limited indication of preload because of the complex relationship of LV diastolic pressure and volume, in addition to which, invasive haemodynamic monitoring is associated with potentially fatal complications. In contrast, two-dimensional transoesophageal echocardiography is potentially safer than invasive techniques and allows direct assessment of LV filling and ejection. It is thus an ideal technology for monitoring the effects of anaesthetics on LV function.

GENERAL THEORY AND TECHNIQUE

Piezoelectric crystals are the transmitters and receivers of the ultrasound waves used in echocardiography. The term “ultrasound” refers to any sound at frequencies above the level detectable by the human ear (> 20000 Hz). Typically, these crystals send intermittent pulses of sound at 2.5–5 MHz and receive the reflected signal. When the ultrasound strikes an interface of different densities—for example that between the epicardium and blood—a portion of the ultrasound is reflected. By using multiple crystals (linear or phased array transducers) or rapidly moving a single crystal (mechanical transducer), multiple “sonar” images of the heart can be collated and displayed by an ultrasonograph as a two-dimensional tomographic image. Most ultrasonographs produce 30 such images per second. Viewed on a monitor, these give the impression of a continuously moving, “real-time,” cross section of the heart.

Modern ultrasonographs can measure the Doppler shift while simultaneously producing two-dimensional echocardiograms. The Doppler shift is the apparent change in frequency of an ultrasound wave when it is reflected from a moving object, for example, blood cells leaving the LV during systole. The change in frequency is proportional to the speed of the object. A point-by-point evaluation of the velocity of blood flow within the heart will quantify stroke volume and valvular function; however, the process is time-consuming. A recent refinement, colour-coded Doppler flow imaging, superimposes real-time colour maps of flow on two-dimensional echocardiographic images. Blood flow away from the transducer may be arbitrarily coded blue, flow toward the transducer may be red, and the differing velocities progressively “hotter” or “colder” shades of these colours. The viewer is presented with an instantaneous, albeit qualitative, image of intracardiac blood flow.

Although the basic principles and processing of transoesophageal and precordial (standard or routine transthoracic) echocardiography are identical, the former technique requires a modified transducer. At the University of California San Francisco, we use a commercially available 3.5-MHz oesophageal transducer system (Diasonic Incorporated, Ultrasound Division, Milpitas, California) consisting of 32 quartz elements mounted on the tip of a gastroscope (fig. 1). The fibreoptics of the gastroscope have been replaced by the wires from the transducer. The transducer is 35 mm long, 15 mm wide and 16 mm thick. Coupled to a commercially available ultrasonograph (Diasonic 3400, CV60, or CV6400), this system provides a 90° sector scan of an area 1–20 cm in front of the transducer.
After induction of anaesthesia and intubation of a patient’s trachea, the transducer is inserted through the mouth and advanced into the oesophagus 35–40 cm from the incisors, providing a view of all cardiac chambers (fig. 2). The transducer is then advanced behind the left atrium, and the gastroscopic controls are used to lift the transducer behind the inferior wall of the LV to provide a short-axis cross-sectional view (fig. 3). Short-axis views can usually be obtained at multiple levels, including mitral valve, mid-papillary, and papillary base level. In approximately 8–10% of patients, the horizontal displacement of the heart by the contents of the abdomen prevents the papillary short-axis view. However, when available, these images can be recorded and analysed with a computer-assisted video system and can yield quantitative estimates of LV filling and ejection that are reproducible to within 10%. Although this analysis is too time-consuming for use in the operating room, it is easily accomplished in the research setting. In most patients, transoesophageal short-axis cross-sectional views are identical to precordial short-axis cross-sectional images. For precordial studies, the patient must be placed in the left lateral position, whereas left lateral or supine position (the usual position of anaesthetized patients) may be used for transoesophageal studies.

Echocardiography requires no ionizing radiation, and ultrasound has never adversely affected humans. At the University of California San Francisco, we have monitored more than 1000 patients using transoesophageal echocardiography, without complication, and we estimate that more than 5000 patients have undergone the procedure.
procedure at other institutions. One published report describes two patients who suffered temporary unilateral vocal cord paralysis after transoesophageal echocardiography was used during "sitting" craniotomies [4]. Both patients were positioned with nearly full neck flexion, and the recurrent laryngeal nerve was probably injured when the larynx, tracheal tube, and shaft of the gastroscope were compressed between the chin and vertebral column. These investigators now use a 5-mm gastroscope for patients positioned with extreme flexion of the neck, and have reported no further complications. Unless urgently required, we do not use transoesophageal echocardiography in patients who have a history of swallowing complaints, oesophageal disease or mediastinal radiation.

GLOBAL INDICES OF LV FUNCTION

Preload

LV preload is the stretch applied to the left ventricle as the blood distends it at end-diastole. If all other conditions remain unchanged, LV end-diastolic volume (LVEDV) correlates directly with stroke volume (the Frank-Starling effect) and can provide a reasonable assessment of preload. However, during anaesthesia, LVEDV is difficult to measure directly and thus preload is often derived indirectly by monitoring LV end-diastolic pressure (LVEDP) or pulmonary artery occlusion pressure (PAOP). Unfortunately, the relationship between LVEDV and LVEDP is not linear [8]. Moreover, in the presence of mitral valve dysfunction or changes in LV compliance, that relationship is unpredictable, and PAOP may not correlate with LVEDV. Transoesophageal echocardiography offers a practical solution to intraoperative preload assessment because, as with precordial echocardiography, it directly images the LV. Early studies demonstrated that two-dimensional echocardiography produces reliable estimates of LVEDV if an accurate geometric model of the LV is used and a sufficient number of different echocardiographic cross sections are evaluated [6, 20]. Typically, the heart is assumed to be shaped like a prolate ellipsoid. At end-diastole, LV length (L) is estimated from a long-axis cross section and LV area (Ae) from the short-axis cross section. LV volume (V) then equals $2/3(L)(Ae)$ [37]. More complex models are sometimes used, resulting in somewhat more accurate estimates of LVEDV, when they incorporate many cross sections. However, echocardiographic estimates of LVEDV are consistently lower than angiographic estimates, probably because the former calculation excludes the volume of blood within the LV trabeculations.

Compared with precordial echocardiographic assessment of LVEDV, transoesophageal echocardiographic assessment is limited in one important way: LV length (L) cannot be estimated directly because the oesophageal transducer cannot be angled sufficiently to produce a true long-axis image. However, previous studies have shown that changes in Ae, rather than L, more directly reflect changes in LVEDV. Ae and LVEDV have been shown to have a linear relationship over a wide range of LVEDV [30]. Consequently, changes in Ae will consistently indicate changes in LVEDV, although an individual estimate of LVEDV derived from Ae may be greater or less than the actual LVEDV. Therefore, we recommend using transoesophageal echocardiography to estimate change in Ae as a direct indicator of change in LVEDV, but not as a method to derive absolute LVEDV.

When subsequent measurements of LVEDV are to be compared, an identical cross section must be viewed, and the relative function of the imaged and non-imaged areas of the heart must be constant. In a normal ventricle, Ae at the mitral level is greater than that at the papillary levels. We measure Ae at the tips of papillary muscles because Ae is near maximum at this point and septal contraction is still present. Above this level, the septum becomes membranous and does not contract.

Despite these limitations, LV preload is better estimated by transoesophageal echocardiography than by measurement of PAOP. In the study of 32 patients undergoing cardiovascular surgery, we found that the estimates of stroke volume (compared with thermodilution estimates) obtained from the short-axis echocardiographic cross section were consistent in 91% of patients, indicating the validity of the measurements [1]. In contrast, end-diastolic Ae correlated with PAOP in only 23% of patients. Because marked changes in LV compliance occur during cardiovascular surgery, PAOP becomes an inadequate guide to LV preload. In a research setting transoesophageal echocardiography provides a practical alternative.
**Afterload**

In the isolated or intact heart, the velocity and extent of ejection are inversely related to afterload, the force required to eject blood from the LV into the aorta. This force per unit area of myocardium is the systolic wall stress and is determined by the Laplace relationship: wall stress is related directly to the product of systolic arterial pressure and the radius of the LV, and inversely related to LV muscle mass or thickness. The traditional indices of LV afterload, systolic arterial pressure (SAP) and systemic vascular resistance (SVR), are unreliable measures of afterload because they fail to account for the influence of LV radius and wall thickness. For example, the hypertensive patient who has normal LV function usually has normal afterload systolic wall stress or force per unit of myocardium) because of compensatory LV hypertrophy. Echocardiography can provide reliable estimates of LV radius and thickness [6, 17, 38] which will yield valid estimates of systolic wall stress. For instance, Reichek and his colleagues [17] found that systolic wall stress estimates calculated using precordial M-mode measurements and arterial pressure determined by cuff correlated closely (r = 0.97) with estimates made from angiographic parameters and LV pressures. St John Sutton’s group [19] have published a two-dimensional correlate of this formula which can be applied to short-axis echocardiograms to allow calculation of meridional systolic wall stress (SWS$_m$):

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SWS_m = (1.3)(SAP)(A_e)/(A_t - A_e)
\]

where $A_e$ is the cross-sectional area of the LV cavity and $A_t$ is the total area of LV enclosed by epicardium and the right side of the septum. The denominator of the equation, $(A_t - A_e)$, is the cross-sectional area of the LV myocardium (fig. 3). This equation is valid if the cross section of the LV is approximately round and all segments contract equally.

Afterload, like preload, heart rate and contractility, is a primary determinant of myocardial oxygen consumption. Failure to assess afterload adequately may handicap the accurate interpretation of cardiovascular studies. In a study of 38 patients monitored by transoesophageal echocardiography during carotid endarterectomy, we randomly assigned phenylephrine or “light anaesthesia” to augment arterial pressure [23]. Patients given phenylephrine had significantly higher systolic wall stress values ($172 \pm 57$ (SD) $v$. $100 \pm 44$ dyn cm$^{-2}$ $10^3$) and a higher incidence of myocardial ischaemia. The values in both groups for SAP, heart rate and carotid back (“stump”) pressure were similar. Thus the most likely causes of a higher incidence of ischaemia were phenylephrine administration, different depth of anaesthesia or a significant difference in afterload. Had afterload been evaluated by SAP alone, the third, and perhaps most important, of these causes would have been overlooked.

**Contractility**

Anaesthetics may depress LV contractility directly, or indirectly by decreasing endogenous concentrations of catecholamines. However, assessing contractility is difficult because the readily available indicators are confounded by the changes anaesthetics induce in LV loading conditions. Echocardiography offers a number of approaches to this problem. First, it reliably estimates LV ejection fraction [6, 28, 33] and velocity of LV contraction [15, 16], while simultaneously producing the information necessary to assess preload and afterload, the factors which alter the direct relationship between these indices and contractility. Echocardiography can therefore provide fairly direct information about anaesthetic effects on contractility. In a study of 24 ASA I or II patients undergoing elective surgery, echocardiographic evaluation revealed that increasing concentrations of halothane, enflurane or isoflurane consistently decreased the velocity of LV contraction simultaneously with no change or a decrease (isoflurane) in systolic wall stress and no change in preload or heart rate [2]. Thus all three anaesthetic agents could be seen to depress LV contractility.

Suga and Sagawa [29] have introduced a second approach, an analysis of the pressure–volume ratio of the LV during systole which yields estimates of contractility that are independent of LV loading conditions. Because this ratio is most sensitive to changes in contractility during late systole, end-systolic pressure and volume are usually evaluated. Varying preload or afterload provides multiple points for the plot of pressure $v.$ volume, which results in a linear relationship having a slope believed to be the best available in vivo index of LV contractility. Echocardiography is ideal for this application because it provides consistent estimates of LV volume. Moreover, the substitution of SWS$_m$ for LV pressure in the pressure–volume analysis is both
valid and advantageous [18]. First, $SWS_m$ is the force per unit of myocardium, and produces estimates of contractility that are independent of the size of the heart or mass of myocardium. Second, compared with SAP, smaller changes in preload or afterload are required to produce significant changes in $SWS_m$. The application of the pressure–volume ratio to precordial echo-cardiographic evaluation of contractility in man has been successful [30]. Studies using this method with transoesophageal echocardiography to evaluate anaesthetic effects are in progress.

It should be noted that the quantitative parameters discussed for contractility, afterload and preload are valid only if their underlying assumptions remain valid. For example, estimates of LV volume are critically dependent on echocardiographic imaging of the appropriate cross section. Estimates of systolic wall stress will be invalid in the presence of abnormal segmental contraction. Normal function of the cardiac valves also may be important. During aortic stenosis, for example, systolic wall stress estimates derived non-invasively will be lower than the actual wall stress values. Similarly, ejection fraction measurement will overestimate contractile function during mitral regurgitation. Our preliminary work with colour-coded Doppler flow imaging suggests that this new modality will provide a sensitive technique for detecting mitral or aortic valve dysfunction. In the meantime, quantitative Doppler techniques are highly reliable, albeit somewhat time consuming, in detecting valvar function [3, 9–11, 26, 35, 39], and we have succeeded in assessing intraoperative mitral regurgitation using transoesophageal Doppler echocardiography [22].

Echocardiography thus provides the means to evaluate LV preload, afterload, contractility and valvular function quantitatively. The methods developed for precordial echocardiography are applicable to transoesophageal techniques. However, precordial echocardiographic data can be obtained before induction of anaesthesia, but most investigators do not initiate transoesophageal echocardiography studies until after induction. The short-axis cross sections obtained with both types of transducer are usually comparable. The fundamental advantage of echocardiography over traditional techniques is the ability to image LV structure and function directly.

EVALUATION OF REGIONAL LV FUNCTION

Segmental wall motion

Tennant and Wiggers [32] first described the association of segmental wall motion abnormalities and myocardial ischaemia in 1935. Ischaemic segments of myocardium exhibit abnormal inward wall motion or thickening during systole [7, 21]. Although focal myocarditis and certain rare infiltrative disorders and myocardial tumours also may produce segmental wall motion abnormalities, ischaemic heart disease is the most common cause. The presence of an akinetic (non-contracting) or dyskinetic (paradoxically moving) LV segment will usually indicate a previous infarction or a scar [36], while the development of new segmental wall motion abnormalities, for example, during a stress test, will almost certainly reflect myocardial ischaemia [14]. Because twodimensional echocardiography reliably detects segmental wall motion abnormalities, it plays a vital role in the evaluation of patients who have ischaemic heart disease [12–14, 36].

Echocardiographic interpretation of segmental wall motion abnormalities is critically dependent on the reviewer’s ability to distinguish between segmental motion of the endocardium resulting from contraction of underlying myocardium, and motion generated by the translational and rotational movement of the heart. The reviewer must be able to evaluate the abnormalities in a moving frame of reference which translates and rotates in perfect synchrony with the heart. Unfortunately, no available automated wall motion analysis system can adequately compensate for these two types of movement in transoesophageal echocardiographic cross sections, and we must continue to rely on qualitative analysis by experienced observers. However, when we compared the outcome of monitoring by echocardiography with monitoring by electrocardiography (ECG), we found the echocardiographic method far superior in detecting myocardial ischaemia. We studied 50 patients at high risk for myocardial ischaemia during coronary artery or major vascular surgery, and 10 low-risk patients [24]. At predetermined intervals, we recorded echocardiograms and multi-lead ECG, both of which were evaluated by "blinded" observers. We diagnosed the onset of myocardial ischaemia if the ST segment changed more than 1 mm in any ECG lead or if segmental LV systolic function worsened by more than 1 class according to the following scale: 1 = normal,
2 = mild hypokinesis, 3 = severe hypokinesis, 4 = akinesis, and 5 = dyskinesis. Our echocardiographic analysis system was a modification of that of Van Reet [34]. Using a floating reference system guided by the papillary muscles, we divided the cross-sectional image into four segments (fig. 4). A segment was judged to contract normally if its imaginary radius to the centre of the LV shortened by more than 30% and the segment wall thickened considerably. Mild hypokinesis was determined by shortening of the radius by 10–30% and slightly reduced wall thickening, and marked hypokinesis by less than 10% shortening of the radius and minimal wall thickening. Akinesis was defined by no shortening of the radius and no wall thickening, and dyskinesis by outward segment movement and thinning during systole. These analyses were visual estimates of endocardial motion and myocardial thickening. Two observers independently analysed the ECG and echocardiogram without knowledge of either the patient’s identity or clinical course. Of the high-risk patients, six had intraoperative ST-segment changes diagnostic of ischaemia, whereas 24 revealed new segmental wall motion abnormalities indicating ischaemia. No high-risk patient experienced an ST-segment change before or in the absence of a corresponding segmental wall motion abnormality. Three of the 50 patients suffered intraoperative myocardial infarction during operation and all three had an abnormality develop and persist in the corresponding area of myocardium. Only one of the three had any intraoperative ST-segment change. For 21 of 50 patients, coronary anatomy was known, and segmental wall motion abnormality never developed in areas of the heart served by insignificant lesions. Among the 10 healthy patients, there were no motion abnormalities or ST-segment changes indicative of ischaemia, and no myocardial infarctions. The detection of intraoperative myocardial ischaemia is thus more reliable with two-dimensional transoesophageal echocardiography than with multi-lead ECG.

**Segmental myocardial perfusion**

Anaesthesia and the stress of surgery may alter the distribution of myocardial blood flow. Echocardiography provides a unique method for tracking the distribution of myocardial blood flow without interrupting clinical care. Newly developed echocardiographic contrast agents make it possible [5]. Sonicated (producing 4-µm air bubbles) Renografin-76 was injected to the root of the aorta or left atrium in patients undergoing cardiovascular surgery, and produced a flow of 4-µm air bubbles [25]. The distribution of the microbubbles embedded in the myocardium was recorded with transoesophageal echocardiography and evaluated quantitatively. The microbubbles consistently produced contrast enhancement of the myocardium and caused no adverse effects. Because the microbubbles collapse within minutes, the study can be repeated. Other preliminary studies in man suggest that this method assesses accurately the distribution of myocardial blood flow [27]. Newer contrast agents are expected and, unlike previous ones, will be structured to survive transit through the pulmonary circulation. With these newer agents, peripheral injection of the contrast should produce echocardiographically detectable “maps” of myocardial perfusion.

**CONCLUSIONS**

Recent results of intraoperative studies using two-dimensional transoesophageal echocardiography indicate that the technique offers monitoring capabilities that are superior to those of traditional monitors of LV preload, afterload, contractility, valvular function and segmental myocardial contraction. Both clinical care and research efforts are likely to benefit from the application of this new technique. Unlike previous techniques, two-dimensional transoesophageal echocardiography...
TRANSOESOPHAGEAL 2-D ECHOCARDIOGRAPHY

provides direct images of LV structure and function; using these images, anaesthetists should attain a clearer more precise knowledge of the effects of anaesthetics on LV function.

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REFERENCES


