Twelfth Bethesda Conference

Sponsored by the American College of Cardiology
June 5 and 6, 1981, Heart House, Bethesda, Maryland

Noninvasive Technology in the Assessment of Ventricular Function*

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Introduction

HAROLD T. DODGE, MD, FACC, Chairman • J. WARD KENNEDY, MD, FACC, Co-Chairman

Over the past 35 years invasive techniques of cardiac catheterization and angiography have been highly developed for establishing diagnoses, evaluating the severity of abnormalities and assessing the effects of therapeutic interventions, including surgery. Based on information provided through applications of these invasive techniques, more recently there has been a remarkable development of noninvasive technology for providing diagnostic information in cardiology.

The Twelfth Bethesda Conference on Noninvasive Technology in the Assessment of Left Ventricular Function was held at Heart House, the headquarters of the American College of Cardiology, in Bethesda, Maryland on June 5 and 6, 1981. The idea for the Conference developed from Dr. Borys Surawicz, American College of Cardiology President, whose article, "How to Cope with the New Technology? The Knowledge and the Prudence," had been published on the President's Page of this *Journal*.[1] In that thoughtful discussion, Dr. Surawicz pointed out the need for better understanding and thoughtful integration of the new technology into the general practice of cardiology. He proposed that several state of the art conferences be held in an effort to meet this need. The proceedings of the first of these conferences are the subject of this report.

In developing a plan for the conference, the Chairman, Co-Chairman and some members of the Bethesda Conference Committee decided to limit the scope of the conference to *new technology*. With this definition, it was agreed to include diagnostic ultrasonic techniques of M mode, two dimensional and pulsed Doppler echocardiography and various nuclear cardiology techniques. In addition, it was decided to include discussions of cardiac-computed X-ray tomography and intravenous angiography utilizing digital video subtraction techniques as two methods, currently in the developmental stage, that may soon have clinical application. Older noninvasive methods, including exercise stress testing, systolic time intervals, carotid pulse tracings and phonocardiography, were not considered within the scope of this mini-Bethesda Conference. With the expertise available at the Conference, it seemed appropriate to devote some time to consideration of future developments in echocardiography and nuclear medicine.

It was the overall aim of the Conference to develop a diagnostic strategy that would take full advantage of the new technology and at the same time carefully consider the cost effectiveness of the diagnostic approach to various clinical problems. It was appreciated by all that considerable overlap exists in the information on left ventricular function provided by the various diagnostic methods. It was also understood that, while the Conference was directed toward the evaluation of left ventricular function, in a specific clinical situation the additional anatomic information provided by one method might make the use of that method preferable to another.

New methods are developed or adopted, or both, at different rates in individual institutions and therefore new technology may be unevenly applied from one institution to another. This problem was discussed in the planning of this Conference and it was agreed that expertise in the use of the new technology would be assumed in all of the discussions of the Conference.

It is the purpose of the Bethesda Conference to reach a consensus, when possible, on the problems under discussion. In this Conference we have utilized the evaluation of specific clinical problems in order to focus the discussion and attempt to develop a conclusion. The goal of reaching a consensus was often but not always achieved. It is the hope of the participants at this Twelfth Bethesda Conference that these position papers and case discussions will be helpful to the physician who must integrate the *new* technology into the practice of cardiology.

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PART I: ECHOCARDIOGRAPHY

Introduction: Echocardiographic Evaluation of Ventricular Function: An Overview

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Analysis of ventricular function is fundamental in assessing the significance of certain kinds of heart disease. For example, the degree of left ventricular dysfunction in patients with coronary artery disease is an important determinant of the "natural history" of patients who do not undergo surgery,[1] and it plays a central role in determining operative risk.[2] The presence of left ventricular dysfunction may influence the timing of valve replacement in patients with certain lesions such as aortic or mitral regurgitation.[3,4] Classically, variables of ventricular function have been measured using invasive hemodynamic and angiographic methods.[5] Because it is impractical to subject asymptomatic or minimally symptomatic patients to the risk of these procedures, or to perform invasive measurements repeatedly in a given patient, newer noninvasive techniques have been developed and used to assess ventricular function. One of the major noninvasive techniques currently used to evaluate ventricular function is echocardiography. In a generic sense, echocardiography uses ultrasonic signals reflected from cardiac structures to provide data on cardiac anatomy and dynamics. Several specific adaptations have been developed, including M mode echocardiography, two dimensional echocardiography and Doppler echocardiography. These related techniques have not all developed simultaneously, and they should not be considered equally important in the assessment of ventricular function.

Both M mode and two dimensional echocardiography use pulsed ultrasound to demonstrate the distance between the transducer and ultrasonic targets such as myocardial-blood interfaces. The intensity of echoes reflected from these interfaces is also demonstrated. These techniques can be used to measure ventricular cavity size, shape and wall thickness. M mode and two dimensional echocardiography can be considered proved, clinically accepted methods for assessing ventricular function.

Doppler echocardiography uses the frequency shift of ultrasound reflected (or "backscattered") from moving targets within blood, such as red cells, to evaluate the nature, direction and velocity of blood flow. At present, this should probably be considered an exciting technique that is currently undergoing intensive evaluation but is not yet a clinically proved independent method for assessing ventricular function.

Newer echocardiographic techniques for evaluating ultrasonic energy backscattered from ventricular myocardium have been used to characterize normal, ischemic and myopathic myocardium.[6,7] These techniques hold great promise but need substantial further evaluation.

Clinical Applications

In the clinical setting, the echocardiographic techniques should be viewed as interdependent and used in this fashion. Although more complete discussions of the uses and limitations of each individual technique follow, an initial brief overview seems appropriate.

Among the various echocardiographic techniques, two dimensional echocardiography provides the greatest spatial sampling, and it is thus best used to provide an anatomic "overview," to determine the symmetry or asymmetry of ventricular contraction and to define spatial relations. When regional disorders are present, such as segmental contraction abnormalities or ventricular aneurysm, they are best identified by two dimensional echocardiography. Global ventricular function and the extent of regional dysfunction can be estimated readily, but quantitation is somewhat tedious to perform at present.

M mode echocardiography has passed the test of widespread clinical usage over several years. This technique is well understood, and conventions for recording and measuring data have been accepted. M mode echocardiography offers extremely high temporal resolution and is thus useful for the study of rapidly moving structures such as valve leaflets. Easily quantitated, M mode records provide an excellent appreciation of global cardiac performance when function is uniform. However, when regional abnormalities are present (as demonstrated on a two dimensional echographic study, for example), the extrapolation of M mode data to global ventricular function is hazardous.

Doppler echocardiography allows evaluation of blood flow, and hence offers a method for assessing ventricular performance that is independent of ventricular geometry. This technique also provides additional data on the integrity of valve function, which may be important in a patient in whom ventricular impairment is suspected. Doppler evaluation of flow is best used in conjunction with M mode or two dimensional echocardiographic evaluation of anatomy.

Choice of technique: Obviously, the various non-invasive (echocardiographic and other) techniques may not all be necessary or even helpful in a particular clinical application. The clinical vignettes that follow the discussion of the various techniques are meant to provide a perspective on when to use these tests. In many instances, the same index of ventricular performance can be measured using several different approaches. For example, M mode and two dimensional echocardiography, first pass and equilibrium gated radionuclide angiography and contrast ventriculography can all measure left ventricular ejection fraction, and the results of one approach generally correlate rather well with those of the other approaches. In order to define which approach is most accurate, these tests would need to be compared with an independent and absolute "reference standard"; unfortunately, in the case of ejection fraction (and most other indexes of function), this cannot be done. Thus, the choice of which test to use often depends on the availability of the tests, the quality of the local laboratory and the ancillary data sought. For example, it might be most sensible to measure left ventricular ejection fraction by contrast angiography in a man with disabling angina (who needs coronary arteriography anyway), by radionuclide angiography in a patient with a suspected intracardiac shunt (which could be defined and quantitated at the same time), and by echocardiography in a pregnant woman with dyspnea and a heart murmur (because chamber and valve function could be assessed without risk to the fetus).

In the final analysis, the physician caring for an individual patient may be able to choose among several "reasonable" approaches to evaluating ventricular function. A more complete understanding of the strengths and limitations of the various techniques available should be helpful in making this choice, and the discussions that follow are directed toward this end.

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M Mode Echocardiographic Assessment of Left Ventricular Function

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Echocardiography in modern usage includes both M mode and two dimensional ultrasonic investigation of the heart. This discussion is confined to M mode echocardiography. The physical principles and techniques of M mode echocardiography can be reviewed in more extensive works on the method[1–3] so these aspects will not be covered in detail here.

From the outset it should be mentioned that M mode echocardiography is most often best performed in conjunction with the two dimensional study. However, this discussion will be focused on M mode applications only, assuming that in many circumstances M mode echocardiography is the only method available. This may provide a basis to view the incremental contribution of two dimensional methods discussed in other papers of this conference and elsewhere.[4]

A specific assumption is that the methods described are performed very well. Obviously application of a technique such as echocardiography may be qualitatively different from laboratory to laboratory, but we will not discuss suboptimal use of the method. We simply add a caution that the people performing these tests must be known for good quality work by the local physician referring his patients to the laboratory.

TABLE I

Echocardiographic Variables of Left Ventricular Function

Variable	Symbol/Formulas
Ventricular dimension	D
Change in dimension	$\Delta D = D_{diastole} - D_{systole}$
Ventricular volume	$V = D^3 \times K$; V = regression equation
Stroke volume	SV = EDV − ESV
Ejection fraction	EF = SV/EDV
Fractional shortening	$\%FS = (\Delta D/Dd) \times 100$
Percent ΔD	$\%\Delta D = (\Delta D/Dd) \times 100$
Circumference	$C = \pi D$
Velocity of circumferential shortening change (mean)	$Vcf = \pi(\Delta D)/et$
Normalized Vcf	$Vcf = \Delta D/(et \times Dd)$
Ventricular mass	$M = [(D + \text{septal thickness} + \text{posterior wall thickness})^3 - V\ \text{diastole}] \times 1.05$; M = regression equation

Dd = diastolic dimension; EDV = end-diastolic volume; ESV = end-systolic volume; et = ejection time; K = constant.

Available Variables and Measurements

The echocardiogram can be used to assess the left ventricle by looking at variables of myocardial function, ventricular function and notation of signs or indexes that have been developed to point toward left heart disease. The signs include left atrial enlargement and subtleties of mitral valve motion, for example. We will not discuss measurements of right ventricular, right atrial and valve disease as specific entities or their assessment as secondary complications of left heart disease because we are mainly interested in discussing left ventricular function.

Directly measured values: Echocardiographic measurements of the left ventricle can be segregated into three categories: (1) directly measured values, (2) calculated or derived values, and (3) indirect indicators of ventricular function (Table I). Direct measurements include (a) the thickness of the interventricular septum, (b) the thickness of the left ventricular posterior wall (at points corresponding to end-diastole or end-systole, or both), and (c) the distance between the endocardial surfaces of the septum and posterior wall that represents the left ventricular internal dimension. In fact these few values (along with time) are the raw data from which most other indexes of function are calculated. Left atrial dimension also is measured directly. A great deal of time and experience has gone into determining methods of standardizing measurement of left ventricular internal dimension and wall thickness.[1,2,5-7] Most people agree where the recordings should be made within the left ventricle. There is one set of recommendations for standardized points of measurement within the cardiac cycle developed by the American Society of Echocardiography that may gain wide acceptance and that seems useful.[7]

Calculated or derived values: The extent of left ventricular myocardial contraction and reduction in cavity size during ejection often are expressed by dividing the change in thickness or cavity dimension by the diastolic value. When this is done for the left ventricular internal dimension, the value is usually multiplied times 100 in order to get a "percent change in diameter" (%ΔD) or "fractional shortening" (%FS). These terms express the same measurement and calculation. It is this type of simple calculation that crosses the border from direct measurements to derived measurements. Other such variables include the change in dimension per unit time (dD/dt) expressed either as a mean or a maximal value. Values of this type during ejection and relaxation have been calculated. One may express the relation of myocardial thickness to cavity size by making a ratio of ventricular wall thickness (h/r) to radius.

Other values commonly derived include extrapolation of the measured ventricular dimension to a left ventricular volume.[8-15] This extrapolation may be made at end-diastole, end-systole or any other point within the cardiac cycle. The calculation assumes that all hearts have a constant shape so there is a fixed relation between the measured dimension and the dimensions of the heart in the directions not measured. In the past, most investigators have assumed a circular cross section for the ventricle, and the measured dimension is assumed to be a diameter of this circle. Also, a roughly ellipsoid ventricular shape is assumed, with the long axis of this ellipsoid ventricle being twice the measured dimension. If these assumptions are made, then the geometry permits us to simply cube the measured dimension to approximate ventricular volume. The difference between the end-diastolic and end-systolic volumes is the stroke volume, and stroke volume divided by end-diastolic volume is the ejection fraction. If the measured dimension represents the diameter of a circular cross section of the ventricle, then the circumference of this ventricle is π times the diameter, and a change in circumference $(\pi)(\Delta D)$ divided by ejection time (et) gives the velocity of circumferential shortening (Vcf) which may be normalized for the end-diastolic circumference ($\Delta D/[et \cdot D\ \text{diastole}] = Vcf$). These derived variables have been used by various investigators and normal values for each of them have been determined (Table II).[16-19] The reader should note that the rate of volume change represents flow and so the mean ejection rate can be determined from these values. Similarly, rate of left ventricular filling may be measured.[19-22] Some investigators choose to observe the time from the onset of systole to peak left ventricular emptying, time to peak left ventricular rate of emptying, or time to peak left ventricular filling in diastole. Here we should mention that each of these variables may be observed serially during interventions with pharmacologic or physiologic maneuvers. Many people object to extrapolation from measured dimensions to volumes, so they prefer to express fractional shortening (%FS) or dimensions alone. It is common to observe the %FS with drug studies or after exercise.

Attempts at derivation of pressure within the left ventricle have been made from measurement of left ventricular wall thickness. This method is based on the assumption that there is a constant and normal value for systolic wall stress in a compensated myocardium.

Left ventricular wall thickness increases as a result of pressure overload of the ventricle in order to normalize wall stress across the myocardial wall.[23] If one knows wall thickness and assumes stress at a constant value, then left ventricular pressure can be determined.[24] Obviously one can measure brachial arterial pressure by cuff manometer in most people. In patients with aortic stenosis, the calculated left ventricular pressure should be higher than the measured brachial arterial pressure by a factor that represents the aortic valve gradient.[25]

TABLE II

Normal Measurement Values

	Range		Reference
Left ventricular dimension (mm)			
Diastole	33–58		3
	35–57	19–32 mm/M²	1
Systole	28–41% (decrease from diastole)		3
Fractional shortening (%)	28–41%		3
	28–44%		1
Interventricular septal thickness (mm)			
Diastole	6–12		3
	6–11		1
Systole	33–65% (increase from diastole)		
Posterior left ventricular wall thickness (mm)			
Diastole	6–12		3
	6–11		1
Systole	30–90% (increase from diastole)		
Normalized mean Vcf (circumferences/s)	1.02–1.50		17
	1.02–1.94		1
	0.91–1.89		[illegible]

Equations for predicting normal echocardiographic measurements from body weight and age:

Measurement	Equation
LV end-diastolic dimension*	$22.4\,(wt)^{0.213} - 0.03\,(age) - 7.2 \pm 12\%$
LV end-systolic dimension*	$14.2\,(wt)^{0.213} - 0.03\,(age) - 4.1 \pm 18\%$
Septal thickness*	$1.88\,(wt)^{0.32} + 0.03\,(age) + 1.5 \pm 18\%$
LV free wall thickness	$1.92\,(wt)^{0.32} + 0.03\,(age) + 1.1 \pm 16\%$

* Measurements made according to standards recommended by the American Society of Echocardiography. In these equations, body weight (Wt) is expressed in kilograms, age in years, dimensions and thickness in millimeters. Plots of range of normal values in **Henry WL, Gardin JM, Ware JH.** Circulation 1980;62:1054–61.

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LV = left ventricular.

Observation of the electrocardiogram and the echocardiographic motion of the aortic valve allows one to measure the preejection period from the onset of the QRS complex to the opening of the aortic valve, as well as left ventricular ejection time from the duration of aortic valve opening. The isovolumic contraction time and isovolumic relaxation time can be observed if the aortic and mitral echoes are observed carefully. The indirect carotid pulse tracing may be used to measure ejection time also, of course.

Indirect indicators of left ventricular function: The indirect indicators include the observations that the mitral valve early diastolic slope may reflect the rate of left ventricular filling and that in patients with reduced global left ventricular function, the mitral valve maximum opening, or E point, is displaced from the interventricular septum.[26,27] This latter sign seems due to a combination of dilation of the ventricle in some patients and possible reduction in transmitral flow in others.[27,28] Very subtle variations in the waveform of the mitral valve during diastole have been correlated with abnormalities of left ventricular function.[29] A very low E point with an accentuated *A* wave has been associated with elevation of the early diastolic pressure in the left ventricle. A shoulder or hesitation on the closure of the mitral valve at end-diastole ("B notch") led to the realization that prolongation of the P-R minus A-C interval was correlated with a large *A* wave elevating left ventricular end-diastolic pressure. Systolic signs of left ventricular function include the area of the aortic valve opening and apparent early closure of the valve during ejection.[1] When the ultrasonic transducer is uniformly swept from the aortic level through the left ventricle, the configuration of the ventricle can be appreciated to some degree.[30] Progressive dilation of the submitral left ventricular dimensions indicates a dilated left ventricle. Multiple combinations of these signs and ratios have been used to accentuate differences between normal and abnormal patients.

In general, the measured raw data are always reported because this is very useful in assessing wall thickness or left ventricular hypertrophy as well as the size and dynamics of the ventricle. Simply calculated variables also are expressed by most laboratories. Timing data may be useful in many situations, but the measurement of rates of change of dimensions often involves obtaining multiple discrete data points during individual cardiac cycles. This is usually done with some sort of "digitizing" tablet and a microprocessor or computer to acquire, process and express these data. All assumptions made for the derived calculations may be less valid as disease states affect the shape and dynamics of the ventricle. In coronary artery disease, the characteristically segmental nature of myocardial involvement in the process may make any assumption of uniformity of contraction invalid. This will be discussed in more detail later. This last point and technical difficulty in recording the ventricular walls have prompted use of the indirect indicators of left ventricular function. These signs have been used most in known abnormal states.

Assessment of Echocardiographic Variables

Many variables have been described, but are they valuable? We still need to ask the questions: How accurate are these measurements, how reproducible are they and how should they be used clinically? These questions are properly put in the context of clinical care, because patients should have had at least a history, physical examination and an electrocardiogram before the echocardiogram is considered. The physical examination, electrocardiogram, chest roentgenogram, echocardiogram, angiocardiogram, flow-directed catheter thermodilution techniques and radionuclide studies may be used to assess left ventricular function.

Correlation with physical and electrocardiographic findings: By palpation of the cardiac apical impulse, Conn and Cole[31] showed that 81 percent of patients (29 of 36) with the left ventricular impulse limited to one intercostal space had normal left ventricular volumes, whereas 79 percent of those (11 of 14) with the left ventricular impulse palpated in two or more intercostal spaces had cardiac enlargement. In these patients a holosystolic left ventricular impulse correctly indicated increased left ventricular mass in 88 percent of patients. Normal left ventricular mass was present in 78 percent of those patients whose apical impulse was confined to early systole. These values for left ventricular hypertrophy and increase in myocardial mass may not be matched by the most well accepted electrocardiographic criteria or even by chest roentgenograms measured in conventional fashion.[32–35]

Correlation with angiographic findings: If one compares echocardiographic measurements of left ventricular size or mass, or both, with angiographically derived values, the reported correlations are good. However, there are problems inherent in each of these measurement procedures and the correlation between two such procedures is never perfect. In studies accumulated over several years,[8–15,36,37] the coefficient of correlation between echocardiographic left ventricular volume and angiographic volume has varied from 0.97 to 0.52. A general value of approximately 0.85 is commonly found. For any one patient the error of the estimate (versus expected angiographic estimate) may be more than 30 ml.[10–15] This may represent a significant uncertainty in the large normal ventricle (175 ml) or mildly diseased ventricle (200 to 250 ml). For this reason the method is considered inaccurate or unacceptable for volume measurement by some physicians.[36] Most use the method while understanding its limitations. The difficulty with comparison of echographic and angiographic work stems from the method of performance of the studies, the type of patients included, the specifics of record measurement, and the facility of the laboratories with echocardiographic versus angiographic techniques. It is interesting to contrast these data with values for left ventricular stroke volume determined by angiography, thermodilution methods and echocardiography. One excellent study examining the problem found internal consistency (reproducibility) was best with thermodilution techniques, but correlations were equal between the two invasive tests or in comparing echocardiography with either angiocardiography or thermodilution techniques.[38] Comparison of values for left ventricular volume between any two of the methods produced correlation coefficients in the range of 0.80 to 0.88. This simply emphasizes the fact that perfect correlation between two indirect measurement systems is seldom to be found and should not be expected.

Correlation with autopsy measurements: In a study of 34 subjects comparing postmortem left ventricular mass with echocardiograms performed just before death and measured using a local convention, it was found that a correlation coefficient of 0.96 occurred with a standard deviation of 29 g over the range of 100 to 500 g of heart weight.[6] Studies of terminally ill heart transplant patients (generally dying from cardiac rejection) with a thick stiff myocardium showed that echocardiographically measured wall thickness was within 1 mm of the autopsy measurements.[39] In vitro studies generally have shown excellent accuracy of echocardiographic data.

Reproducibility of measurements: Reproducibility of echocardiographic measurements is subject to problems in standardization of transducer position and selection of landmarks within the ventricle to guide the operator in consistently measuring the same spot within the ventricle on serial studies.[5] Serial daily measurements of normal subjects show excellent reproducibility from day to day over long periods.[39] In a recent study of the method in patients with cardiomyopathy, weekly outpatient echocardiograms were performed in subjects thought to be in a stable clinical situation. A second group of patients with cardiomyopathy were studied daily when measurement of pressure and flow with indwelling catheters showed them to be in hemodynamically stable condition.[40] In the former group of patients, the mean of the standard deviations for diastolic left ventricular diameter was 4 mm and the 95 percent confidence interval was 8 mm. The mean of the standard deviations for fractional shortening (%FS) was 2.8 percent and the 95 percent confidence interval was 5.6 percent. Comparable results in patients studied daily showed a mean of the standard deviations of 2 mm for left ventricular end-diastolic dimension with 95 percent confidence limits of 4 mm. The %FS showed a mean of the standard deviations of 1.6 percent and 95 percent confidence limit was 3.2 percent. In other studies, the error of echocardiography for measuring either left ventricular end-diastolic volume or %FS was estimated to be 5 percent for acute changes in a given patient.[41,42] The interobserver variability in measurement is rather small and is consistent with the foregoing values.[42,43]

Global ventricular function versus segmental contraction abnormalities: From a qualitative sense, we must separate the accuracy of echocardiography (M mode) in patients with uniformly contracting left ventricles versus those with segmental contraction abnormalities typical of coronary artery disease and some types of cardiomyopathy. In the former, the whole ventricle can be represented by M mode measurements and the estimates of ventricular function are accurate. This may also be true in some patients with coronary artery disease. Echocardiography is highly accurate in measurement of wall thickness and the ventricular dimension that is described by the ultrasound beam. The relation of the length of the ventricle to this dimension and the relation of the third dimension representing the orthogonal or short axis dimension not measured, are the factors that lead to absolute errors in calculating ventricular volume by M mode techniques.[1,2] If one assumes, for example, that the long to short axis ratio of the left ventricle is 2:1, when this ratio may vary anywhere from 2.3:1 to 1.3:1, then variation of the calculated volume from the true volume will be large in either of these extreme cases. These relations do not change a great deal in the same patient with a given intervention. In a single patient, used as his own control, the effect of drugs or other physiologic interventions can be reliably assessed with echocardiography.[39-44] This seems generally true for global left ventricular function, but alterations that are manifest by segmental myocardial changes cannot be well assessed with M mode techniques.

Assessment of pattern of mitral and aortic valve motion: Indirect indexes or signs of left ventricular function, such as changes in patterns of mitral or aortic valve motion, have their genesis in factors that are not completely understood.[26-29,45,46] Since situations that invalidate the observation are not fully understood, the signs have limited applicability. For example, the mitral valve B notch and prolonged P-R A-C interval may occur in patients with acute myocardial infarction, aortic disease or hypertension with myocardial hypertrophy or in extreme degrees of ventricular abnormality. It is not an early sign of deteriorating function but is a good sign of ventricular dysfunction. Some ideas about the cause of this phenomenon have been put forth, but reasons for its general lack of specificity and sensitivity have not been clarified. An increased mitral valve E point-septal separation (greater than 7 mm) seems a relatively good indicator of reduced global left ventricular function manifest by a reduced ejection fraction (less than 50 percent).[27,28] In some patients this sign seems primarily a result of left ventricular dilation; in other patients, with coronary disease or restrictive cardiomyopathy, left ventricular dilation clearly is not necessary for the sign to occur. It might be assumed that reduced transmitral flow reduces the excursion of the mitral valve and yet the mitral valve does not have unrestricted motion dependent solely on mitral flow for the excursion of the valve.[47] Thus, several factors may be interacting to produce a "sign" that is useful, but less useful than it might be if we understood all of the factors involved in its presence.

How is Echocardiography Used and How Should It Be Used?

One can see echocardiography being used in many ways. For example, it is possible, with this noninvasive technique, to screen all patients coming to a physician's office or all people working in an industrial plant or attending school. It is possible for all patients with certain diagnoses such as hypertension, congestive heart failure or valve disease to be "screened" with this method. One could choose to use the method solely for diagnosis of disease, or alternatively use it primarily for follow-up and serial studies of patients with known types of disease. It does not seem cost effective to screen all asymptomatic people or those coming to a physician's office for routine physical examinations with echocardiography. The echocardiogram should not be used as a substitute for the medical history or physical examination. Patients first suspected of or found to have valve disease, hypertension, congestive heart failure (and possible coronary artery disease) may benefit from a single echocardiographic study if the physician has assessed the patient and determined that something available from echocardiography would benefit his formulation of this patient's case. Echocardiography probably is the most accurate way to measure serially small changes in left ventricular size and left ventricular wall thickness. Therefore, serial follow-up studies of patients who have aortic or mitral regurgitation, congestive heart failure or hypertension may be beneficial as a guide to the effectiveness of a given therapy.

Clinical applications: These recommendations must take into account how the technique is used in the community in general and what is usually measured. Most laboratories measure wall thickness, cavity dimensions at end-diastole and end-systole and some variable of change in dimension such as %FS or ejection fraction, and some laboratories have the facilities to measure rate of change of these dimensions. Patients with normal left ventricular function can clearly be separated from those with quite abnormal ventricular function, but this is not the problem in clinical practice. We desire a method of finding *subtle* degrees of left ventricular abnormality and/or means of observing when the left ventricle loses its "myocardial reserve," or both. This is especially pertinent to the timing of interventions for valve surgery or valve replacement. So far, clinical, electrocardiographic, angiographic, hemodynamic and radionuclide studies have not yielded variables that consistently accomplish this purpose. If we use the time-honored clinical observation of progressive dilation of the heart as an indication for surgery, then echocardiography can measure this at least as well as any technique. Recent studies have suggested that patients with aortic regurgitation who have a combination of an extremely dilated heart and reduced %FS do worse after surgery then those with the opposite situation.[48] From these data it has been suggested that patients who are minimally symptomatic or asymptomatic, but whose ventricle exceeds a specified echocardiographic diameter, should be considered for surgery.[49] Similarly, patients who are stressed with increased ventricular afterload or preload normally maintain or increase angiographic ejection fraction whereas a decrease in ejection fraction may indicate loss of myocardial reserve. Such patients have been shown to do badly postoperatively. Echocardiography provides a method to make these observations, but so far tests of this type have not been proved in long-term or large scale clinical trials. Therefore, we still assess each patient individually and do not propose that echocardiographic variables themselves be the indication for sending patients to surgery.

Strengths of M Mode Echocardiography

The most significant strength of M mode echocardiography is our 15 to 25 years of experience with clinical application of the method and the fact that many of the diagnostic criteria developed for M mode echocardiography have stood the test of time in the clinical arena. The relatively low cost of the test (because of the relatively low cost of the equipment) is an attractive feature of M mode echocardiography. More and more laboratories are combining M mode and two dimensional techniques because this often provides increased and better information and because it may be more cost effective than duplication of the tests in a high proportion of patients.[4] The conventional paper strip chart records of cardiac motion are a rather unique way to document cardiac dynamics and allow the observer to assess how well the heart moves. This motion is measured with a very high sampling frequency, approximately 1,000 times/s, giving a high time resolution of motion. As mentioned, echocardiography is a relatively fine tool for measurement of intracardiac structures. Accuracy with echocardiography is in the range of a few millimeters for ventricular dimensions or wall thickness versus a centimeter or so with some other techniques such as radionuclide imaging.

Echocardiography remains a noninvasive method having no radiation hazard and so it is quite good for serial studies. Such serial studies can be used to monitor cardiac function with or without interventions. This technique for left ventricular observation has been standardized using empiric methods of measurement and standards agreed on by a great many laboratories. The method is available throughout the world. Finally, M mode echocardiography provides an excellent time reference in studying cardiac valve motion or measuring dimensions in relation to pressure, flow or occurrence of heart sounds. Simultaneous M mode recordings from two or more areas of the same heart can be used to observe precise timing of motion of various valves or segments of the left ventricle.

Limitations of M Mode Echocardiography

Limited visualization of ventricular walls: Standardized M mode echocardiography is confined by transducer placement in the parasternal and subcostal areas. This means that the yield of technically good to excellent studies is relatively low. Up to 40 percent of patients in the coronary care unit have technically inadequate studies to assess left ventricular function fully. When the parasternal ultrasonic window is small or in an inappropriate place for standardized studies, it is not easy to move the transducer to an alternative position and still understand the M mode measurements. Even in a perfectly standardized study of good quality, one assumes geometry and dynamics for parts of the left ventricle that are out of the field of view of the M mode transducer. Patients having significant coronary artery disease and hypokinetic or dyskinetic segments at the cardiac apex will not have these recognized with most M mode studies. Similarly, apical aneurysms or large akinetic segments generally will be missed with conventional M mode echocardiography. These are important exclusions in most cardiologists' and internists' practices.

Resolution problems: The more "sophisticated" variables derived from M mode studies, such as peak rate of wall thickness change or rate of diameter change, require a method to digitize the record and a microprocessor or computer to process the data as well as graphic displays for optimal appreciation of the dynamics expressed. Such auxiliary devices are expensive. Finally, the physics of ultrasonic recording yield a finite resolution in the axis of the sound beam and a finite resolution in the lateral dimensions.[3,50] Thus, two structures that are very close within the heart, such as chordae tendineae and the left ventricular endocardial surface, may not be resolved as two separate structures and an ambiguity of measurement may thus be introduced. Generally the ability to resolve two structures next to each other is worse than axial resolution. The width of the sound beam at any distance from the chest wall determines the lateral resolution at that depth. Any structures that are displaced laterally from each other by less than the beam width cannot be reliably resolved as separate structures. Again, this creates ambiguities in choosing the echo to be measured and this may result in systematic or sporadic errors.

Requirement for extensive training: Another limitation of the method stems from the extensive training usually required to perform and interpret the studies properly. Several months of intensive training are considered optimal (more than 3 to 6 months) in fellowship programs. Fortunately there is now a sizable group of such well trained people. It is much more difficult for the physician beyond his period of fellowship to obtain optimal, or even minimal, training. This is because he cannot leave his practice for sufficient time periods and because few active laboratories offer such training. There is also a shortage of training programs for technicians (sonographers) when compared with the expressed need for people with these skills. Each echocardiographic laboratory should have an experienced and technically capable physician serving as medical director, even if a well qualified sonographer is there on a daily basis. These matters truly limit the usefulness of the technique because having any test done badly may be worse than not having the test at all. Finally, education of the general medical public of physicians who refer patients for echocardiography is a major task that limits most efficient and effective application of this method for those patients who may benefit most from its use.

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Evaluation of Ventricular Function Using Two Dimensional Echocardiography

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Two dimensional echocardiography potentially offers several advantages over the standard M mode echocardiographic examination for the assessment of ventricular function. The major advantage of the technique is its ability to visualize an entire cross-sectional slice of the ventricle as opposed to a single linear dimension.[1-4] These slice views of the ventricular cavity allow dimensions to be evaluated which are inaccessible by M mode examination. For example, an apical four chamber view allows the motion of the lateral and medial walls of the ventricles to be appreciated, a capability that is not available with M mode echocardiography. Because greater anatomic information is present in two dimensional views of the ventricle, it is also possible to identify and localize myocardial wall segments more accurately. However, these strong points of two dimensional echocardiography have not been fully realized, because the technique requires time-consuming data analysis in order to be quantitative. Instrumentation which either is being developed at present or anticipated in the near future should overcome much of this computational difficulty. The present discussion, therefore, will concentrate on the applications of two dimensional echocardiography to the analysis of ventricular function with use of techniques either currently available or anticipated in the next few years.

Instrumentation

Digital scan converters: The major instrumentation advance that allows a more quantitative assessment of ventricular function from two dimensional echocardiography is the incorporation of digital scan converters in current two dimensional equipment. The digital scan converter changes the sector scan image into a series of very small picture elements, known as "pixels" that, when displayed in video format on a standard rectangular television screen, recreate the two dimensional echocardiographic image. Because the precise location of each pixel is known, it is possible to identify specific points and to trace boundaries directly from the two dimensional image. Once specific points and boundaries have been identified by the user, the computer is able to determine distances and to compute volumes using standard area-length methods.

Analyzing two dimensional images: Two options are available for analyzing two dimensional images. One method involves performing the data analysis while the echocardiographic study is in progress. For example, the two dimensional transducer can be placed directly on the patient's chest and the resulting two dimensional images viewed on the instrument's video display in real time. From direct examination of the real time images, it is possible to determine whether wall motion abnormalities are present and to assess qualitatively the extent of any wall motion abnormalities that exist. At present, this method of direct visualization of the ventricular chamber in real time precludes a precise quantitative analysis of ventricular size or volume. This limitation can be partly overcome by using an electrocardiographic-triggered method to freeze one frame of the two dimensional echocardiographic image on the video display of the instrument. If the electrocardiographic trigger is set at the onset of the QRS complex, the frozen frame would represent end-diastole. Ventricular volume could be estimated from this frame using either a manual method (that is, tracing the image onto a transparent overlay) or an electronic method (using a light pen or joy stick to trace the boundary of the ventricle). By resetting the electrocardiographic trigger to a specified time after the onset of the QRS complex, it is also possible to freeze a frame near end-systole and estimate the end-systolic volume of the ventricular cavity.

This method has many shortcomings, including the fact that it usually requires the sequential analysis of diastolic and systolic frames that are not from the same cardiac cycle. Because of the time delay between freezing the diastolic and systolic frames, it is possible that the operator will have moved the transducer slightly causing a different two dimensional slice to be recorded. Moreover, the method requires that the computations occur while the patient is being imaged, thus requiring a longer time to perform the study. As a consequence, this method is discouraged.

The alternative method for evaluating ventricular function from two dimensional images is to record the data initially onto videotape for subsequent playback and analysis. If this method is to be fully utilized, the videotape recorder should have several features. These features include the ability to run the tape recorder in slow motion and to freeze a full frame or a field of video during playback. An additional and desirable feature is the ability to run the recorder in slow motion in a reverse direction. This feature is not found on current recorders. If a tape recorder is available which provides both slow motion and freeze-frame capabilities, it is possible to record the two dimensional studies on videotape so that the videotape can be played back at a later time either through the same instrument or through a separate analysis instrument.

One advantage of this approach is that sequential frames can be analyzed from the same heartbeat. Another advantage is that the analysis can be done either with the same two dimensional instrument when it is not in patient use or with a separate analysis instrument, thereby allowing a more efficient utilization of equipment and minimizing patient examination time.

Video disc: An additional device that further simplifies the outlining of the ventricular cavity is the video disc. This device allows several seconds of two dimensional data to be recorded. These data can then be played back at various speeds in both the forward and reverse directions. In addition, stop-frame images from video discs are of excellent quality. Advances in the near future should allow longer recording times and random access to selected frames. This latter feature should be a particularly attractive operational feature.

Unique Measurements From Two Dimensional Echocardiograms

All dimensional measurements that can be obtained from M mode echocardiograms can also be derived from two dimensional echocardiograms, including left ventricular internal dimensions and myocardial wall thicknesses. Because two dimensional echocardiograms allow linear measurements to be made in directions oblique to the ultrasonic beam, it is possible to measure dimensions not available from M mode echocardiograms. It is also possible to measure the area of structures seen in the cross-sectional images. This ability to measure the area of the slices of cardiac structures is a unique feature of two dimensional echocardiography. Area measurement may have useful clinical applications such as the noninvasive measurement of mitral orifice area in patients with mitral stenosis.[5] In regard to the evaluation of ventricular function, the ability to measure the area of a slice of the ventricular cavity may allow estimation of ventricular volume. Likewise, the ability to measure the area of a specific region of a myocardial wall might allow an estimation of the extent of myocardial damage or, more importantly, of the amount of remaining viable myocardium. The ability to obtain these additional measurements that cannot be obtained from M mode echocardiograms makes two dimensional echocardiography a particularly powerful tool for assessing global and segmental ventricular function.

Evaluation of Global Ventricular Function

Left ventricular volumes and ejection fraction: Global function of the left ventricle can be evaluated by placing a wide angle transducer in either the parasternal or apical position with the scan plane oriented parallel to the long axis of the left ventricle.[6-11] With this approach, it is possible to visualize a cross-sectional slice of the long axis of the ventricle. If an 80 to 90° scan angle is used, the resulting images will extend from near the cardiac apex to the aortic root. If one then assumes that the ventricular cavity is circular in all cross sections perpendicular to the long axis, it is possible to estimate left ventricular volume at end-diastole and at end-systole and, thereby, estimate left ventricular ejection fraction. This approach of assessing global left ventricular function has significant advantages over the M mode technique particularly in diseases that produce irregular shapes of the left ventricle, such as hypertrophic cardiomyopathy[12,13] or coronary artery disease.[6,8,10]

Qualitative evaluation: Although quantitative assessment of ventricular function is desirable, it is also possible to use two dimensional echocardiography to obtain a qualitative evaluation. Thus, the large and diffusely hypokinetic ventricle seen in patients with a dilated cardiomyopathy can be easily identified and distinguished from the ventricle seen in normal subjects or in patients with diseases in which ventricular systolic function is usually normal, such as aortic stenosis or systemic hypertension. Qualitative assessment is most useful in identifying gross abnormalities. However, identification of more subtle dysfunction requires a more quantitative approach.

Shortcomings: Like M mode echocardiography, two dimensional echocardiography has shortcomings. For example, it is necessary to have the scan plane parallel to the long axis of the left ventricle and to transect the left ventricle through the center of the left ventricular cavity. If the long axis plane used to estimate volume either is not parallel to the long axis of the left ventricle or does not pass through the center of the ventricular cavity, one will underestimate the volume of the left ventricle. In addition, the endocardial surfaces of the left ventricle must be clearly visualized in order for an accurate volume to be estimated.

Comparison with contrast ventriculography: The ability of two dimensional echocardiography to assess left ventricular volume accurately and evaluate global left ventricular function has been studied by comparing the ventricular volumes and ejection fraction derived from two dimensional images with those derived from standard contrast angiograms.[7-11] Studies thus far indicate that although there is a reasonably close correlation between the two techniques, the two dimensional echocardiographic volumes are generally smaller than those estimated from the contrast angiographic studies. Whether this discrepancy is due to methodologic errors inherent in the two dimensional technique or is related to inaccuracies in the determination of ventricular volume from contrast angiography cannot be clearly determined at present. However, a good correlation has been found between left ventricular ejection fraction estimated from two dimensional echocardiographic images and that determined from contrast angiograms.[7-11]

Studies during exercise: Radionuclide angiographic studies have clearly demonstrated that it is useful to assess global left ventricular function during exercise.[14] This is particularly true in the assessment of patients with suspected or known coronary artery disease. As a result, investigators have begun studying the feasibility of performing two dimensional echocardiographic studies before and immediately after treadmill or handgrip exercise to determine if the technique can be used to estimate ventricular ejection fraction before and after stress.[15-23] Preliminary studies indicate that it is feasible to estimate left ventricular systolic function both at rest and immediately after exercise. It has not been possible to analyze ventricular function at peak exercise because the rapid and deep breathing that accompanies maximal exercise prevents reliable ventricular visualization. However, studies performed with breathholding immediately after exercise appear technically feasible and may be clinically useful.

Clinical applications: The ability to image the left ventricle and assess its global function has important clinical applications. For example, it is very useful in routine patient management to determine whether left ventricular systolic function is normal or reduced. It is also important in those patients with reduced systolic function to distinguish the patient who has a dilated, diffusely hypokinetic ventricle from the patient with normal systolic function at the base of the heart but overall global dysfunction because of an aneurysm or a dyskinetic myocardial wall. The ability to distinguish patients with normal systolic function from those with decreased systolic function has important therapeutic implications in that patients with congestive heart failure who have a diffusely hypokinetic ventricle are best treated with an inotropic drug such as digitalis, whereas patients with congestive heart failure due to decreased ventricular compliance are more appropriately treated with diuretic therapy.

Evaluation of Segmental Ventricular Function

Imaging in multiple planes: One of the unique features of two dimensional echocardiography is its ability to visualize virtually any segment of the ventricular walls. For example, the left ventricle can be imaged from multiple areas on the chest including the parasternal, apical and subcostal regions and can be imaged in three orthogonal planes. The left ventricle can be imaged from the parasternal region in either a short or long axis plane. From the apical region the ventricle can be imaged in either a long axis or a four chamber plane, whereas from the subcostal region it can be imaged in either the four chamber or short axis plane. Moreover, by rotating the transducer around its long axis, it is possible to image the ventricle from planes intermediate between these three general imaging planes. This ability to image the ventricle in multiple planes from several different regions on the chest, coupled with the ability to visualize intracardiac anatomy and thereby localize wall segments more precisely, allows two dimensional echocardiography to be a powerful tool in assessing segmental left ventricular function.

Identification of wall segments and wall motion abnormalities: To facilitate the evaluation of segmental wall motion abnormalities, the American Society of Echocardiography recently adopted image orientation standards as well as standard nomenclature for identifying ventricular wall segments.[24,25] The nomenclature for ventricular wall segments is based on identifying intracardiac structures, such as papillary muscles, and using them to subdivide the ventricle into approximately 15 segments. Recent studies[6,8-10] of patients with coronary artery disease demonstrated that lesions in specific coronary arteries produce wall motion abnormalities in specific myocardial segments. For example, a myocardial infarct caused by a lesion in the left anterior descending coronary artery usually produces wall motion abnormalities in the anterior segments of both the ventricular septum and left ventricular free wall.[6,10] These clinical observations are supported by studies in experimental animals demonstrating that sudden occlusion of a coronary artery will produce an immediate cessation of contraction and, consequently, the development of a wall motion abnormality in the corresponding myocardial segment supplied by that coronary artery. This ability of two dimensional echocardiography to identify myocardial segments precisely should prove very useful in the evaluation and assessment of patients with both acute and chronic coronary artery disease.

Measuring wall thickness: In addition to being able to assess wall motion abnormalities, two dimensional echocardiography also allows the thickness of various myocardial wall segments to be measured. This ability to measure wall thickness should prove useful in evaluating patients to determine whether dyskinetic myocardial walls are thin and therefore presumably consist of fibrous tissue, or are of normal thickness and presumably still contain viable myocardium. This distinction could have important therapeutic implications because surgical resection of wall segments seems to be most successful when the wall being resected consists primarily of fibrous tissue. In addition, the visual appearance of the myocardium may provide useful information for identifying either the presence of abnormal tissue, such as fibrous tissue or disorganized myocardial cells, or abnormal substances, such as amyloid or iron.[12,26] It remains to be determined whether the visual appearance of the myocardium or a more quantitative assessment of the interaction between the myocardium and ultrasonic energy will allow tissue characterization to be performed noninvasively.[illegible]

Identifying abnormal cavity masses: An additional clinical advantage of two dimensional imaging of the left ventricle is its ability to identify abnormal masses inside the left ventricular cavity. Recent studies have suggested that the incidence of intracardiac thrombi in the setting of an acute myocardial infarction is much greater than previously suspected. Although the therapeutic implication of detecting these clots is unclear, studies are now underway to determine whether these clots are associated with an increased number of embolic events or are a relatively benign accompaniment of an acute myocardial infarction.

Evaluation of Ventricular Function in Conjunction With M Mode Echocardiography

Because two dimensional echocardiography allows a clearer visualization of intracardiac structures, it is possible to use the two dimensional images to locate more precisely the region of the heart from which M mode echocardiographic tracings are being obtained. In the past, the T scan method has been used with M mode echocardiography in an attempt to assure that the ultrasonic beam was passing through the center of the left ventricular cavity.[31] The use of two dimensional echocardiography to locate the ultrasonic beam provides direct visual confirmation of the location of the M mode beam and thereby allows greater measurement reliability and reproducibility.

In addition, two dimensional imaging allows patients with wall motion abnormalities to be identified and distinguished from those with either a normal or diffusely hypokinetic ventricle. Thus, a study that combines two dimensional and M mode echocardiography allows a more precise evaluation of ventricular function than a study using only the standard M mode echocardiographic technique. For example, if two dimensional images identify major wall motion abnormalities, then any assessment of ventricular function from M mode echocardiography should be viewed with considerable skepticism. In contrast, if two dimensional echocardiographic imaging demonstrates that a focal major wall motion abnormality is not present, then the M mode echocardiographic assessment of left ventricular function should be a reliable assessment of the systolic performance of the entire left ventricle. Moreover, two dimensional echocardiography can be used to ensure that the M mode beam is being reflected from the center of the left ventricular cavity below the tips of the mitral valve and above the papillary muscles. Therefore, M mode echocardiographic studies obtained in conjunction with two dimensional imaging should provide a reproducible and computationally simple method for evaluating the systolic and diastolic functions of the left ventricle.

Strengths of Two Dimensional Echocardiography

Two dimensional echocardiography allows a cross section of the ventricle to be imaged rather than a single chord. This has several potential advantages. One advantage is that a larger portion of the ventricle is imaged so that it is easier to identify the myocardial segment being visualized. Also, the greater field of view allows abnormalities of ventricular configuration to be visualized. In addition, quantitative assessment is performed by measuring changes in an area of the myocardial cavity or wall rather than changes in a chord or the perimeter of the cavity. At least one study suggests that measurement of changes in the area of the ventricle can be made more reliably than changes in a perimeter or chord.[9]

Because two dimensional echocardiography allows an improved visualization of the spatial relations of various myocardial walls, one can measure distances between myocardial walls in directions other than those parallel to a single ultrasonic beam. This allows chamber dimensions to be measured from many more regions on the chest and in directions not feasible with M mode echocardiography.

Compared with other noninvasive techniques, two dimensional echocardiography allows ventricular function to be assessed in an unlimited number of cardiac cycles and without the use of contrast agents, such as iodinated dye or radioactive tracers. Moreover, the method allows excellent spatial resolution and precise quantitative evaluation of segmental myocardial function.

Limitations of Two Dimensional Echocardiography

Although two dimensional echocardiography allows visualization of a cross-sectional slice of the ventricle rather than a single chord, it still cannot be used to assess global ventricular function unless certain assumptions are made or multiple views and complex computations are performed. Moreover, the same attention to technique required for M mode quantitation must be followed when recording two dimensional images of the heart so that oblique cross sections do not result in quantitative inaccuracies. Thus, the slice visualization of the heart makes two dimensional echocardiography an ideal method for assessing segmental function but it is less satisfactory for global function.

A second limitation of two dimensional imaging is that quantitative analysis of ventricular function requires a trained observer to outline the boundaries of the ventricular cavity and left ventricular walls. This requires considerable observer training and is time-consuming. Although it may be possible to automate this process, such methods are not yet available.

Another limitation of the two dimensional technique is that it is difficult to image the heart when the lungs are overinflated, as occurs in patients during exercise or in patients with obstructive lung disease. Recent studies have indicated that it may be possible to visualize the heart immediately after exercise, particularly if the apical transducer position is used.[16,18,23] However, it remains to be determined whether this technique can be performed reliably in a large percentage of patients and in a large number of echocardiographic laboratories.

Compared with M mode echocardiography, the two dimensional approach has not yielded a large body of quantitative measurements. For example, the effect of body size and age on M mode measurements has been well described in a large group of normal subjects and regression equations have been developed to allow prediction of M mode echocardiographic measurements in a subject of known age and body weight.[32] Such data allow subtle changes in cardiac dimensions to be identified. Similar data have not yet been developed from two dimensional echocardiograms. Until they are, this relative lack of normal quantitative data will be a limitation of the two dimensional echocardiographic technique.

Summary

Two dimensional echocardiography is potentially a more accurate and reliable method for assessing ventricular function than the standard M mode echocardiographic technique. More widespread clinical application of this technique for the quantitative assessment of left ventricular systolic function has been limited by the fact that quantitation was very time-consuming. Recent advances in two dimensional instrumentation allow quantitation to be performed with less difficulty and in a shorter time period. As a result, two dimensional echocardiography should find widespread clinical use in the evaluation of global and segmental ventricular function.

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Evaluation of Ventricular Function Using Doppler Echocardiography

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In comparison with other techniques that utilize reflected ultrasound to assess ventricular function, Doppler echocardiography should probably be assigned secondary importance. Doppler techniques cannot evaluate ventricular geometry or dynamics directly; two dimensional and M mode echocardiography are better suited to such applications. However, the Doppler approach provides a novel method for assessing ventricular function, because (unlike two dimensional and M mode echocardiography) it does not depend on specification of, or assumptions about, ventricular geometry. Moreover, the Doppler investigation does provide data not always apparent from the anatomic findings, and this is a useful adjunct to conventional echographic studies. A Doppler examination should be done at the same time as an M mode or two dimensional examination (or both); when done in this fashion, the Doppler study requires about 15 minutes extra time and it entails no known risk or discomfort. Although costs for all procedures vary from hospital to hospital and city to city, a Doppler study invariably costs less than an M mode echocardiogram, so that it is relatively inexpensive. Indeed, M mode, two dimensional and Doppler echocardiography should probably be viewed as related but different diagnostic applications of reflected ultrasound[1]; depending on the cardiac disease in question, one or another of these techniques may be more or less useful. For evaluating ventricular performance, Doppler echocardiography should at present be viewed in a supporting role.

When compared with noninvasive techniques that use energy modalities other than ultrasound to examine the heart, Doppler echocardiography shares the advantages and limitations of the other ultrasonic techniques. Doppler echocardiography does not use ionizing radiation; it is painless, thought to be harmless and provides data on a beat to beat basis. However, it is subject to the same limitations governing ultrasonic penetration as are other ultrasonic methods; when penetration is poor (due to air-filled lung, fat or excessive tissue depth interposed between the transducer and the region of interest), the technical quality of recordings is limited.

Some of the technical problems peculiar to pulsed and continuous wave Doppler echocardiography will be discussed here; many are well recognized, and solutions are being actively pursued. It appears that in the future, Doppler echocardiographic methods will be less restricted by technologic limitations and more amenable to quantitation of intracardiac blood flow. Doppler echocardiography is thus likely to play an increasingly important role in the assessment of ventricular function.

Doppler Techniques

Flow velocity and volume flow: The Doppler principle can be used to detect blood flow within the heart and great vessels. When an ultrasonic beam traverses blood, backscattering of ultrasonic energy from particles (primarily red cells) in the blood occurs.[2] If a component of blood flow is oriented parallel to the ultrasonic axis, the frequency of ultrasound backscattered from moving red cells is altered so that it differs from that of the original incident beam. This frequency alteration is called a "Doppler shift." Under ideal conditions, one could compute actual flow velocity from the Doppler frequency shift if one could quantitate the Doppler shift accurately, and if one knew the angle between the ultrasonic beam and the axis of blood flow. One could also calculate volume flow through a cardiac chamber or great vessel by measuring the mean velocity of flow through, and the cross-sectional area of, that chamber or vessel. In practice, however, quantitation of the preceding variables requires a number of assumptions and approximations. It appears premature to consider Doppler echocardiography an accepted technique for measuring volume flow.

Detection of turbulence: Doppler echocardiography also can be used in a qualitative fashion as a turbulence detector.[3] Normal blood flow is organized, and red cells move in an orderly, relatively parallel fashion. Adjacent red cells flow with similar velocities at any instant in the cycle, although flow velocities obviously change with time over the cardiac cycle. Accordingly, uniform Doppler frequency shifts will be recorded from red blood cells as they flow through a localized area of sampling. However, disorganization of flow occurs when blood traverses a stenotic orifice; under some circumstances, regurgitant flow is also disorganized. Under these conditions, adjacent red cells move with differing velocities and in different directions, so that the corresponding Doppler shifts show a broad spectrum of frequencies. Using current Doppler instrumentation, one can evaluate intracardiac flow *patterns* to determine if they are normal or if they indicate disorganization ("turbulence").[4] Although this approach does not measure ventricular function directly, it is of use in