Measurement of Ventricular Volume in Man

SINCE THE INITIAL observations of William Harvey and the physiologic studies of Ernest Starling, the importance of changes in volume in the ventricles of the heart has been recognized. In physiologic and clinical studies of the heart, measurements of chamber pressure and cardiac output have been more easily obtained than volume, and only in recent years have methods been developed for the estimation of ventricular volume in man. The measurement of ventricular volume not only can be related to other physiologic events in the cardiac cycle but also permits comparison of cardiac function in various pathologic conditions of the heart. In this manner information on ventricular volume and the derived parameters of cardiac function have contributed to the understanding of clinical heart disease.

The two basic clinical methods for the estimation of left ventricular volume in man include the angiographic technique and the indicator washout technique. In the quantitative angiographic method, cardiac catheterization is performed and contrast material injected into the left ventricle or left side of the circulation with rapid biplane filming and simultaneous recording of the electrocardiogram and pressure. Filming of the opacified left ventricle at a rate determined by the radiographic equipment utilized is generally carried out over a period of 4–6 sec. Large film changers can produce 6–12 films per sec, while cinefluorographic units have capabilities of 30–60 frames per sec. The angiographic technique necessitates corrections for: (1) the magnification resulting from nonparallel X-ray beams due to the close proximity of the X-ray tube to the heart; and (2) the volume of structures such as papillary muscles which project into the cavity. The calibration, as well as the accuracy of the radiographic technique, has been tested by injecting known amounts of contrast material into the left ventricle of human postmortem hearts and employing the angiographic technique to estimate chamber volume. In addition, clinical corroboration has been derived from stroke volume determined by the conventional Fick or indicator dilution techniques compared to the angiographic stroke volume obtained as the difference between end-diastolic and end-systolic volume. The biplane angiographic technique has been modified to estimate ventricular chamber size from single-plane cineangiographic studies.

Similarly, the indicator dilution technique requires catheterization with the injection of dye or a cold solution into the ventricular chamber which is detected by a special catheter at the root of the aorta or in the pulmonary artery. The signal from the sensor describes a washout curve, and calculations provide an estimate of end-diastolic volume. Stroke volume must then be obtained from conventional measurement of cardiac output, and the difference between end-diastolic volume and stroke volume is end-systolic volume.

Limitations and inaccuracies still exist in the available clinical techniques for the measurement of ventricular volume. The angiographic method is limited at present to measurement of the left ventricle, but the indicator dilution technique can be performed in the right as well as the left ventricle. The biplane angiocardiographic method requires cardiac catheterization, special radiographic equipment, and measurement of biplane film pairs. When large films are taken at the rate of 6–12 per sec, the individual estimations of ventricular volume are usually related to the onset of the QRS complex, and measurements over several sequential cardiac cycles are related to construct a composite ventricular volume curve. Naturally, cardiac stability is a basic requirement for the technique at slower filming rates, and irritability resulting from
the injection of contrast material remains a persistent problem in obtaining chamber measurements in all studies. Although biplane and single-plane cineangio
graphy allow many observations to be made in individual cardiac cycles, contrast and detail in individual frames are sacrificed. An additional technical problem in the use of cineangio
graphy is encountered in patients with moderately enlarged left ventricular chambers since the entire chamber silhouette may not fit within the film frame. An essential requirement for the angiographic technique is that the entire ventricular silhouette be contained within the film margins. A large amount of the tedium in the volume calculations from individual frames has been eliminated by the development of computer programs, which significantly facilitate the calculations.11 Although the indicator dilution technique does not require specialized radiographic equipment, the cardiac output must be measured independently in order to derive end-systolic volume from the estimated end-diastolic volume. In clinical heart disease the presence of mitral incompetence introduces a significant error in the estimation of left ventricular volume with the indicator dilution technique, since not all of the indicator is ejected directly into the aorta.

Whereas the indicator dilution technique provides directly an estimate only of end-diastolic volume, the angiographic technique can be employed to describe a ventricular volume curve throughout the cardiac cycle. Therefore, measurements of end-diastolic volume, end-systolic volume, total left ventricular stroke volume, and the ratio of left ventricular stroke volume to end-diastolic volume, or the ejection fraction, can be obtained. In the absence of valvular regurgitation, similar measurements can be derived from the indicator dilution technique. The angiographic method frequently permits the measurement of the free left ventricular wall thickness, which can be added to the chamber dimensions, and an estimate of the left ventricular mass can be obtained.12 Left ventricular chamber pressure can be related to the volume curve, and the pressure-volume rela-
tionship throughout the cardiac cycle can be described. The pressure-volume loop or dia
gram provides information, not only on the periods of systolic ejection and diastolic filling, but also on isovolumic contraction and isovolu-
mic relaxation.9,13 Measurements of the area within the pressure-volume loop, as well as the area beneath the loop, provide estimates of the mechanical work done by the left ventricle in systole as well as the work done on the left ventricle during the diastolic filling phase. In addition, rates of systolic ejection and diastolic filling can be derived from the slopes of the ventricular volume curves. Correlation of the diastolic volume and pressure relationships permits an analysis of ventricular compliance or distensibility. Estimation of forces within the ventricular wall can be derived from chamber dimensions, pressure, and wall thickness of the left ventricle.14 Finally, the force-velocity relationship of cardiac muscle and the contractile state of the left ventricle can be described from these measurements during the systolic phase of the cardiac cycle.15–17

The information provided by the various techniques for the quantitation of ventricular volume in man has made significant contributions toward the understanding of the altered physiology in clinical heart disease. The measurements of left ventricular volume and pressure describe the mechanical performance of the left ventricle. Since the angiographic estimation of left ventricular volume supplies total stroke volume, the measurement of regurgitant volume per beat across the aortic or mitral valve can be obtained by subtracting forward stroke volume by the Fick or dye technique from the angiographic left ventricu-
lar stroke volume.18 Angiographic estimation of ventricular mass in clinical heart disease has proved to be more sensitive than any other available clinical technique when compared to pathologic weights. The percent ejected end-diastolic volume or ejection fraction provides an overall estimate of left ventricular performance. The pressure-volume work of the left ventricle in various cardiac disorders can be related to the extent of dilatation and hypertrophy in order to understand and assess...
the compensatory cardiac mechanisms in chronic heart disease.\textsuperscript{19, 20} Furthermore, the valvular and myocardial components of cardiac performance can be identified by the accurate estimation of regurgitant volumes as well as relating the extent of dilatation and hypertrophy to the pressure-volume work of the ventricle. In various chronic cardiac disorders, discrepancies have been shown between the left ventricular end-diastolic pressure and the volume and mass of the ventricle.\textsuperscript{21, 22} Since preload is the force that distends the relaxed myocardial fiber, and afterload is the force that resists shortening, these determinants of cardiac performance can be estimated at end-diastole and the time of aortic valve opening from ventricular wall stress, which is calculated from chamber pressure, volume, and wall thickness. In coronary artery disease, akinetic and dyskinetic areas of the ventricle can be accurately identified on biplane angiograms, and in certain circumstances the size of the aneurysm can be measured and the amount of wasted or ineffective work estimated.\textsuperscript{23} The relationship between diastolic volume and pressure in various cardiac disorders can be analyzed in an effort to understand the alterations in distensibility or compliance that accompany cardiac abnormalities.

Several noninvasive techniques have been developed to estimate ventricular volume and derived expressions of cardiac function. A relationship between systolic time intervals and ejection fraction has been shown in chronic heart disease.\textsuperscript{24} Movements of the apical impulse as recorded by apexcardiography have demonstrated a relationship to ventricular performance in various forms of valvular heart disease. A technique with radioisotope injection and continuous recording by the Anger scintillation camera has provided values for ventricular volume.\textsuperscript{26} More recently ultrasound has been employed to estimate changes in cardiac dimensions and volume.\textsuperscript{27} All these noninvasive techniques offer the exciting prospect of providing information on cardiac dimensions in various forms of heart disease without the need for catheterization.

In summary, the immediate and future applications of methods for the measurement of ventricular volume include: (1) quantitation of the mechanical and myocardial components of altered cardiac function in valvular heart disease; (2) assessment of the relationship between left ventricular dilatation and hypertrophy in the course of various forms of chronic heart disease; (3) measurement of left ventricular function in coronary artery disease and the assessment of dilatation, hypertrophy, mitral regurgitation, and localized defects in wall motion; (4) quantitation of the response of left ventricular function to surgical intervention in valvular and coronary artery disease; and (5) calibration of noninvasive techniques for estimating cardiac function such as systolic time intervals, apexcardiography, kinetocardiography, ultrasound, and precordial scanning techniques.

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