Echocardiographic Measurement of Cardiac Output
Using the Mitral Valve and Aortic Root Echo

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SUMMARY The current echo method for measuring cardiac output (CO) has various technical limitations and is based on the assumptions that the left ventricle is not dilated and that it contracts uniformly. We have taken a different approach to measuring CO by echo: CO = cross-sectional area of aortic root \times left ventricular ejection time \times mean aortic flow velocity \times heart rate. Using the Fick method, 34 measurements of CO were made in patients with normal aortic and mitral valves, with simultaneous echo recordings from the aortic and mitral valves. The systolic closure slope of the anterior mitral valve leaflet was assumed to represent the mean aortic flow velocity. CO by Fick and the proposed echo method correlated well, both in patients with \((r = 0.94)\) and those without \((r = 0.87)\) asynergy and the overall correlation was strong \((r = 0.90)\). Using the conventional echo and Fick methods, a much weaker association was found between the two measurements in those patients with asynergy \((r = 0.44)\) as opposed to those without asynergy \((r = 0.77)\).

THE ECHOCARDIOGRAPHIC METHOD currently in use for the measurement of left ventricular output is based on the studies of Feigenbaum,1 Popp2 and others.3,4 It relies on measurement of an internal dimension of the left ventricular cavity that approximates its minor axis diameter. The reliability of this method depends on the shape of the left ventricular cavity being a prolate ellipse and on uniformity of contraction of the left ventricular chamber.5 Thus, the presence of nonuniform contraction of the left ventricle, frequently seen in patients with ischemic heart disease, or variations in the relationship between the major and minor axis diameters,6 can produce significant errors in the measurement of cardiac output using this method.

Another drawback of the method currently used is that it requires simultaneous recordings from the interventricular septum and the posterior left ventricular wall, which is often technically difficult or impossible.

The purpose of this study, therefore, was to adopt a different approach to measuring cardiac output by M-mode echocardiography. The principle underlying the method proposed in this study utilizes a basic hydraulic formula pertaining to flow of fluids through a cylinder. The proposed method is based on the measurement of aortic root diameter and left ventricular ejection time from the echocardiogram of the aortic root and valve. The principal assumption made in this method is that mean aortic ejection velocity can be estimated from the systolic closure velocity of the anterior mitral leaflet.

Materials and Methods

Thirty-two patients admitted to the University of Alberta Hospital for diagnostic cardiac catheterization and angiocardiography were studied. Thirty-four determinations of cardiac output were obtained from the 32 patients by the direct Fick method. In one of the patients, two additional recordings were obtained under different hemodynamic conditions induced by the administration of isoproterenol.

Echocardiograms were obtained either during or within five minutes of cardiac output determination by the direct Fick method. Heart rate was calculated from the electrocardiogram recorded during the procedure.

Left ventricular angiograms were obtained in all the patients studied and coronary angiography was performed in all but two cases. The group studied consisted of patients ranging in age from 14 to 64 years (mean age 49.2) and there were 22 male and 10 female subjects. Eighteen patients had significant coronary artery disease (i.e., more than 50% obstruction of one or more of the left main, anterior descending, circumflex or right coronary arteries). Fourteen of these patients had sustained a previous myocardial infarction and 11 of them exhibited one or more areas of hypokinesia or dyskinesis on the left ventricular angiogram. Three other patients exhibited segmental irregularities of contraction and of these two had significant coronary artery disease and one was suspected of having cardiomyopathy. The latter patient had no obvious coronary artery disease but exhibited generalized hypokinesia with a small area of localized dyskinesia. Thus of the entire group studied, 14 patients exhibited irregular ventricular contraction.

Patients with aortic or mitral valve disease, either on clinical grounds or diagnosed at catheterization, were excluded from the study.

Echocardiograms were obtained using a commercially available ultrasonoscope coupled to a strip-chart recorder and a 2.25 MHz transducer, ½ inch in diameter, prefocused at 10 cm and operated at a repetition rate of 1000 impulses per second. Recordings were obtained at paper speeds of either 50 mm or 100 mm per second.

All the examinations were carried out with the patient in the supine position with the transducer in the 3rd, 4th or 5th intercostal spaces at the left sternal border. The technique described by Gramiak and Shah9 was used to obtain recordings from the aortic root and leaflets. Mitral valve recordings were obtained exercising the precautions regarding choice of the ideal intercostal space as outlined by Popp et al.9 Recordings were taken from the mitral valve when both the leaflets could be clearly visualized. Recordings from the aortic root and valve were taken when the characteristic parallel echoes from the walls of the root and the typical box-like pattern from the opening and closing movements of its valve leaflets were recognizable. The gain, damp and reject modes were carefully adjusted to record clear echoes.
from the inner aspects of the anterior and posterior walls of the aortic root.

Wherever possible, recordings were also taken from the interventricular septum and the posterior left ventricular wall, as previously described, so that minor axis dimensions during end diastole and end systole could be obtained. These measurements were subsequently used for calculation of stroke volume and cardiac output by the conventional echo method.

In order to validate measurement of left ventricular ejection time by echo, aortic root pressure tracings were recorded simultaneously with echographic recordings of the aortic root in 17 patients.

A separate study was conducted to validate our measurement of aortic root diameter by echocardiography. Echographic recordings of the root were obtained in eight patients prior to open-heart surgery. When satisfactory echographic recordings were obtained, the external diameter of the aortic root was measured. This was taken to be the distance between the outer surfaces of the anterior and posterior wall echoes. At surgery, after adequate exposure of the aortic root had been achieved, the surgeon measured the external circumference of the aortic root by placing a fine sterile ribbon snugly around the exposed aortic root, cutting off the appropriate length of ribbon and measuring its length. Diameter was then derived mathematically from the measured circumference (C), diameter = C/π, and compared with that obtained by echocardiography.

The echocardiographic measurements necessary for calculating stroke volume by the proposed echo method are summarized diagrammatically in figure 1. These included measurement of 1) left ventricular ejection time (LVET) from the points of separation and coaptation of the aortic valve leaflets, 2) aortic root internal diameter (D) between the inner surfaces of the anterior and posterior aortic root wall echoes and 3) the systolic mitral closure slope of the anterior mitral leaflet (SMCS), by joining the points BC occurring during the early part of ventricular systole. In certain cases, point B was not clearly seen and in these cases, slope AC was measured instead.

### Calculations

The theoretical basis for calculation of stroke volume is a simplified hydraulic formula relating to flow of fluids through a cylinder, as depicted in figure 2. Q, the volume of fluid flowing through the cylinder in unit time is given by the product of the mean flow velocity V and the area of cross-section of the cylinder, A. Thus Q = V × A.

Applying this principle to the heart, the aorta can be regarded as a cylindrical conduit, with area of cross section, a (fig. 2). Since flow into the aorta is pulsatile, occurring during left ventricular ejection, the above formula is modified as follows: Q = V × a × LVET, where V is the mean aortic flow velocity during systole, LVET is the left ventricular ejection time, and Q is the stroke volume.

Both aortic diameter and left ventricular ejection time can be measured by echocardiography. Aortic root cross-sectional area can be calculated from the measured diameter, D.

The principal assumption made in this study is that the systolic closure slope of the anterior mitral leaflet is approximately equal to or bears constant relationship to the mean aortic flow velocity during systole.

Echocardiographic calculation of stroke volume was completed in each case before the results from the respective Fick studies were analyzed.

### Results

Representative samples of echocardiograms obtained from the aortic root and valve and from the anterior and posterior leaflets of the mitral valve are shown in figure 3.

Results of the angiographic studies and cardiac output determination by the Fick method and the proposed (Echo) and conventional (Echo) echocardiographic methods are summarized in tables 1 and 2.

Measurement of aortic root diameter (external) by echocardiography and from direct measurements made at surgery, were 3.64 ± 0.51 cm and 3.55 ± 0.49 cm, respectively, which correlated strongly (r = 0.97, N = 8). Similarly, left ventricular ejection time measured by echo (mean 304.9 ± 45.2 msec) and from the pressure tracings (mean 306.5 ± 46.7 msec) correlated well (r = 0.94, N = 17). The regression equation for each is shown below:

\[
D_{Echo} = 0.06 + 1.01 D_{Surgery}
\]

\[
LVET_{Echo} = 25.6 + 0.89 LVET_{Pressure \ Trace}
\]

The above results confirmed the validity of using echocardiography for measuring aortic root diameter and ejection time, and supported the reported findings of others.

The results obtained for mitral valve slope ranged from 13.7 cm sec\(^{-1}\) to 49.9 cm sec\(^{-1}\) with a mean of 27.4 ± 8.1 cm sec\(^{-1}\) in our patients. These figures fall well within the range for the BC or AC slope of the mitral leaflet echo reported by Buynkozturk et al. Yoshitoshi and his group used
Doppler ultrasound to derive mitral closing velocity and the range they reported in their group of normal subjects was 20 to 40 cm sec\(^{-1}\) with a mean of 27 cm sec\(^{-1}\).

Comparison of cardiac output measurements by the Fick and proposed Echo methods is shown in figure 4. Close correlation was found between the two methods \((r = 0.90)\).

We were only able to measure cardiac output by the conventional method \((\text{Echo}_2)\) in 21 of 32 patients. Results obtained by this method correlated weakly with those obtained by the Fick method \((r = 0.58)\) (fig. 5).

We also analyzed the results from patients with and without asynergy separately and compared the results obtained from these subgroups by the proposed and the conventional Echo methods with those obtained by the Fick.
method. Using the proposed method, strong correlations were found with the Fick method: patients with asynergy (N = 16), r = 0.94; patients without asynergy (N = 18), r = 0.87. Results obtained from patients with and without irregularities of ventricular contraction by the conventional Echo method correlated much more poorly with those obtained by the Fick method: patients with asynergy (N = 8), r = 0.44; patients without asynergy (N = 13), r = 0.77.

In order to be certain that the differences in strength of correlation did not arise from the different populations used in the proposed and conventional Echo methods, we took the results obtained by the proposed Echo method only from the 21 patients from whom conventional Echo measurements had also been obtained and compared these with the results obtained by the Fick method. No change was found in the strong correlation exhibited by the entire group or by the subgroups with and without segmental contraction abnormalities.

Discussion

Various groups of investigators have successfully shown that left ventricular volumes and cardiac output can be measured by echocardiography. The methods proposed by these investigators are all based on the measurement of the distance between the endocardial surface of the posterior left ventricular wall and the left side of the interventricular septum. The cube of this dimension at end diastole and end systole is assumed to represent end-diastolic and end-systolic volumes, respectively, and stroke volume is then derived from the differences between these two values.

The assumptions on which this method is based pertain to the shape (prolate ellipse), size and uniformity of contraction of the left ventricular chamber. Unfortunately, the geometric assumptions made are not applicable to all cases and constitute potential sources of error in the measurement of ventricular volumes and output. Thus, for example, errors can arise from applying this method to patients with cardiac enlargement as has been indicated by Fortuin and his colleagues. These errors have been attributed to alterations in the shape of the ventricular cavity from the usual ellipsoidal to a more or less spherical configuration. This causes a disruption of the major:minor axis relationship assumed in these calculations and thus invalidates the approximation volume = cube of minor axis diameter. Similarly, in the small ventricle with a long and narrow cavity, the major:minor axis ratio may be as high as 3:1, leading to an underestimation of the true volumes and hence the stroke volume. Teichholz and his associates recently showed that the major:minor axis ratio between end systole and end diastole varied considerably from the assumed 2:1 figure.

A major shortcoming of the conventional method, however, is its inapplicability in the presence of segmental abnormalities of contraction, as has been shown in this study. Spuriously high or low readings of cardiac output may be obtained as a result of ultrasonic recordings from localized areas of compensatory hyperkinesis or akinesis.

Alternative approaches to obtaining echographic estimations of cardiac output have been proposed by other investigators. Feigenbaum's group has shown that there is close correlation between the degree and duration of separation of the anterior and posterior mitral leaflets during the diastolic filling period and the stroke volume. On the other hand, Yeh et al. have looked at the separation of the aortic valve leaflets during ventricular ejection and have derived an index of cardiac output from this structure. Neither of these methods, however, involves estimation of the velocity of flow of blood and hence, actual values of flow per unit time are not obtained.

Under these circumstances, therefore, an echocardiographic method that is independent of geometric assumptions pertaining to the shape of the ventricle and does not need to rely on the assumption that the entire ventricle contracts uniformly, should offer a superior approach to the conventional and presently available methods, particularly in the presence of asynergistically contracting segments. The method proposed in this study fulfills the above criteria. Results obtained from the cardiac output study show that while there was good correlation between results obtained by the Fick method and by the conventional echo method in patients without asynergy, this correlation was not as close in the entire group taken as a whole. In contrast, there was little difference in the correlations between the results obtained by the Fick and proposed echo methods both in the presence and absence of asynergy, showing that the results obtained by the new echo method are quite unaffected by the presence of asymmetric ventricular contraction.

In the method proposed in this study, the major assumption made was that the closure slope of the echogram of the
TABLE 2. Results of Echocardiographic Measurements for the Calculation of Cardiac Output and Results of Cardiac Output Measurement by the Fick Method

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<th>Patient</th>
<th>SMCS (cm/sec)</th>
<th>AoD (cm)</th>
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<th>EDD (cm)</th>
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Abbreviations: CO = Cardiac output; SMCS = Systolic mitral closure slope; AoD = Aortic diameter; LVET = left ventricular ejection time; EDD = End-diastolic diameter; ESD = End-systolic diameter; Fick = Fick method; Echo = Proposed echo method utilizing mitral and aortic echocardiograms; Echo = Conventional echo method utilizing internal dimensions of the left ventricular cavity.

Figure 4. Comparison of cardiac output obtained by the direct Fick method and the proposed echocardiographic method (34 subjects). 

Figure 5. Comparison of cardiac output obtained by the direct Fick method and the conventional echocardiographic method (21 subjects).
the ejection phase of contraction. In addition, it has been recently elucidated that the velocity imparted to the blood entering the aorta, which is a function of ventricular systole, is related to the stroke volume generated by that ventricle. The role of ventricular systole in mitral valve closure in patients in sinus rhythm has recently begun to become somewhat clearer. In view of these considerations, it would therefore seem logical to suggest that in the continuum of systolic events commencing with the build-up of left ventricular wall tension and pressure and culminating in the expulsion of blood into the aorta, quantitative relationships exist between the various events that occur during this period, e.g., mitral valve closure, aortic valve opening and aortic ejection.

The principal advantages of the method we have proposed are that it circumvents the assumptions pertaining to the ellipsoidal geometry of the ventricular cavity and the results obtained are largely unaffected by nonuniformity of contraction of parts of the left ventricle. In addition, it is our experience that it is a technically easier method to use.

There are, however, shortcomings to the method proposed; the more important are that the method might not be accurate in patients with mitral or aortic valve disease and that the method does not measure actual ventricular dimensions. In addition, in patients with atrial flutter or fibrillation, the closure velocity of the mitral valve and its relationship to mean aortic velocity have not been ascertained.

Nevertheless, the method proposed in this study is technically easier and more accurate than the currently available echographic methods for measurement of cardiac output, particularly in the presence of segmental nonuniformity of contraction.

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