Two-dimensional Echocardiographic Assessment of Left Ventricular Volumes and Ejection Fraction in Children

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with the technical assistance of Barbara Sternlight, R.D.M.S.

SUMMARY The ability of two-dimensional echocardiography to measure left ventricular volumes and ejection fraction was evaluated in 25 children with congenital heart disease. Dimensions and planimetered areas were obtained in the short-axis view at the mitral valve and high and low papillary muscle levels and in the apical two- and four-chamber views. Eight algorithms using five geometric models were assessed. Left ventricular end-diastolic volume, end-systolic volume and ejection fraction were compared with data from biplane cineangiograms. The correlation varied with the algorithm used. Algorithms using short-axis views appeared superior to those using only apical long-axis views. Four algorithms estimated left ventricular volumes with equal accuracy (Simpson's rule, assuming the ventricle to be a truncated cone; Simpson's rule, assuming the ventricle to be a truncated ellipse; hemisphere cylinder; and ellipsoid bpline). The single algorithm that best estimated left ventricular ejection fraction was the ellipsoid bpline formula using the short-axis view at the papillary muscle level (r = 0.91, slope = 0.94, SEE = 6.7%). Thus, two-dimensional echocardiography can accurately assess left ventricular volumes and ejection fraction in children with congenital heart disease.

NONINVASIVE estimation of left ventricular performance is important in the initial and prospective evaluation of children with congenital and acquired heart disease. M-mode echocardiography has been used to estimate left ventricular volumes and ejection fraction, but its value is compromised by segmental wall motion abnormalities and ventricular overload. Except for abnormalities of septal motion, segmental wall motion abnormalities are unusual in children. In children with left ventricular overload, angiographic and echocardiographic left ventricular end-diastolic diameters correlate poorly. Moreover, various indirect methods for measuring left ventricular performance using mitral valve motion, aortic valve motion, or both have been proved inferior to direct assessment of changes of left ventricular dimensions and volumes. Preliminary reports of electrocardiographically triggered B-mode echocardiographic scanning indicate that two-dimensional echocardiography is better than M-mode echocardiography for calculating left ventricular ejection fraction.

Several investigators have reported the accuracy of two-dimensional echocardiography in assessing left ventricular volumes and ejection fraction in experi-

mental animals and in adult patients with valvular or coronary artery disease. The heart with a congenital defect, however, is subjected to different loading conditions.

The use of two-dimensional echocardiography in apical views to estimate left ventricular volumes in children has also been reported. However, all possible models and views for estimating left ventricular volumes were not examined. We further evaluated the optimal two-dimensional views and the geometric assumptions to be made with these views for estimating left ventricular volumes and ejection fraction noninvasively in children with congenital heart disease.

Materials and Methods

Twenty-five patients scheduled for diagnostic or preoperative cardiac catheterization and two-dimensional echocardiography were included in the study. The patients were 6 weeks to 20 years old (mean 6.5 years). The clinical diagnoses are summarized in table 1.

Cineangiocardograms

After routine catheterization premedication, bplane left ventricular cineangiograms were obtained in the anteroposterior and lateral views at 50 frames/sec. In all patients, angiographic studies were free of extrasystoles and were of adequate technical quality for calculating angiographic volumes. A grid was filmed at the position of the heart and used to correct for linear magnification. Well-opacified, arrhythmia-free beats were used to measure end-diastolic and end-systolic left ventricular volumes. Volumes and ejection fraction were calculated by the area-length method. The computed volumes were then corrected according to previously derived regression equations.

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Supported by grants from the Foundation de l'Industrie Pharmaceutique pour la Recherche, Direction Générale de la Recherche Scientifique (France); by USPHS grants HL-25476 and HL-24148, NHLBI; and by grant 5061G7 from the American Heart Association, Greater Los Angeles Affiliate.

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Received April 10, 1981; revision accepted August 3, 1981.

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TABLE 1. Detail

<table>
<thead>
<tr>
<th>Sex</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age range</td>
<td>6 wee mean 6.5 yea</td>
<td>&lt; 2 years</td>
</tr>
<tr>
<td></td>
<td>2-10 years</td>
<td>10-15 years</td>
</tr>
<tr>
<td></td>
<td>15-20 years</td>
<td>Diagnosis</td>
</tr>
<tr>
<td></td>
<td>Aortic stenosis</td>
<td>Aortic insuffici</td>
</tr>
<tr>
<td></td>
<td>MV prolapse</td>
<td>ASD</td>
</tr>
<tr>
<td></td>
<td>VSD and pulm</td>
<td>VSD</td>
</tr>
<tr>
<td></td>
<td>Pulmonary ste</td>
<td>Congestive car</td>
</tr>
<tr>
<td></td>
<td>PDA</td>
<td>Normal</td>
</tr>
</tbody>
</table>

*Postoperative
†Associated w Abbreviations defect; VSD = v arteriosus.
TABLE 1. Details of the Patient Population (25 Patients)

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic stenosis (subaortic stenosis)</td>
<td>6 (2*)</td>
</tr>
<tr>
<td>Aortic insufficiency</td>
<td>2 (1†)</td>
</tr>
<tr>
<td>MV prolapse and insufficiency</td>
<td>1</td>
</tr>
<tr>
<td>ASD</td>
<td>1</td>
</tr>
<tr>
<td>VSD and pulmonary hypertension</td>
<td>2</td>
</tr>
<tr>
<td>VSD</td>
<td>3</td>
</tr>
<tr>
<td>Pulmonary stenosis</td>
<td>4 (1*)</td>
</tr>
<tr>
<td>Congenital cardiomyopathy</td>
<td>1</td>
</tr>
<tr>
<td>PDA</td>
<td>2</td>
</tr>
<tr>
<td>Repaired tetralogy of Fallot</td>
<td>2</td>
</tr>
<tr>
<td>Normal</td>
<td>1</td>
</tr>
</tbody>
</table>

*Post surgical evaluation.
†Associated with aortic stenosis.

Abbreviations: MV = mitral valve; ASD = atrial septal defect; VSD = ventricular septal defect; PDA = patent ductus arteriosus.

Echocardiograms

Echocardiographic studies were performed immediately after angiography. Real-time two-dimensional echocardiographic studies were obtained with a phased-array sector scanner (Toshiba, model SSH-10A). The transducer consisted of 32 2.4-MHz piezoelectric crystals; the ultrasonic beam was focused dynamically and steered electronically through a 78° sector arc. The focal point was adjusted to 4, 5 or 7.5 cm, depending on the size of the patient. Lateral and axial resolution were determined with a 100-mm test object phantom box. Axial resolution was 1 mm at any depth, and lateral resolution was 1.5–2 mm at and before the focal point. Lateral resolution was 2.5 mm at 2 cm from the focal point, and 3 mm at 5 cm from the focal point. The images were displayed in real-time and recorded on 3/4-inch videotape cassette at 30 frames/sec (Nipon Electric Company). The videotape could be played back in real time; at one-ninth, one-eighth, one-thirtieth and one-seventy-second of real-time, and in stop-frame, frame-by-frame, forward and reverse modes, which allowed isolation of beats for area and dimensional measurements.

Left parasternal short-axis and apical long-axis views were used routinely. The parasternal short-axis views were obtained in the usual fashion. The patient was examined in the left lateral decubitus position. The transducer was placed in the third or fourth left intercostal space with the plane of the sector perpendicular to the left ventricular long axis. The views were obtained at the level of the mitral valve, at the tips of

**SHORT AXIS VIEWS**

**ED**

**ES**

**PM₂**  **PM₁**  **MV**

**Figure 1. Two dimensional short-axis views used for echocardiographic estimation of left ventricular volumes. ED = end-diastole; ES = end-systole; MV = mitral valve level; PM₁ = tips of the papillary muscles; PM₂ = base of the papillary muscles.**
the papillary muscles, and at the base of the papillary muscles (fig. 1). The apical four-chamber view was obtained as previously described.\textsuperscript{29} The transducer was rotated 90° counterclockwise to record the apical two-chamber view. To avoid foreshortening in this view, the aortic valve, aortic root and the apex were imaged (fig. 2).

Images and a calibration factor were traced with a grease pen on transparent plastic sheets affixed to a 12-inch playback monitor (Setchell-Carlson, Inc.). Calibration was validated with a fluid-filled phantom box. End-diastole was defined as the frame at which the reference ECG reached the peak of the R wave. End-systole was defined as the frame at which the reference ECG reached the end of the T wave or the smallest left ventricular silhouette. Mitral valve motion did not define end-systole and end-diastole accurately. The papillary muscles were excluded from the outline tracings. The images were then retraced with a graphic image analyzer (Neumonics, Inc.) connected to a mini-computer (Wang, Inc.), which allowed analysis of the end-systolic and end-diastolic areas. The short-axis dimension of the left ventricle was measured at the level of the mitral valve and the tips of the papillary muscles by constructing a line from the midpoint of the septum to the posterolateral wall. An axis perpendicular to this short-axis dimension was also constructed in these same views to measure orthogonal short-axis diameters. The long axis was measured in the apical four-chamber view from the mid-mitral valve to the apex of the heart. The apical four-chamber view was selected because the length was greatest in this view. Dimensions and areas were measured at end-systole and end-diastole.

End-diastolic and end-systolic left ventricular volumes were assessed prospectively using eight algorithms based on five geometric models (fig. 3).

Simpson's Rule

Simpson's rule, which uses multiple short-axis views, was applied to two geometric models. In one model, the volume of the left ventricle was considered as the sum of a volume of a cylinder (from the base to the mitral valve), of a truncated cone (from mitral valve to mid-papillary muscle), and of a cone (from mid-papillary muscle to apex). The left ventricle was, therefore, transacted by three short-axis sections that divided the ventricle into four parts:

$$\text{Volume} = (Amv + \frac{Amp_1 + Amp_2}{2}) + \frac{Amp_1 + Amp_2}{2}$$

$$+ \frac{Amp_2}{3} \left( \frac{L}{4} \right)$$

In the second model, left ventricular volume was also calculated assuming the volume of the ventricle to be the sum of small cylinders and a truncated ellipse:

$$\frac{L}{3} \left( Amv + Amp_1 \right) + \frac{Amp_2}{2}$$

$$\frac{L}{3} + \frac{\pi}{6} \left( \frac{L}{3} \right)^3$$

where \( L \) = the longest length measured from the apical four-chamber view, \( Amv \) = the area of the short axis at the mitral valve level, \( Amp_1 \) = the area of the short axis at the tips of the papillary muscles, and \( Amp_2 \) = the area of the short axis at the base of the papillary muscles.

Hemicylinder-Hemioellipsoid Model

The left ventricle was divided equally. The volume of a cylinder was added to the volume of a half ellipse...
2-D ECHO ASSESSMENT OF LV PERFORMANCE/Mercier et al.

ALGORITHM

FORMULA

GEOMETRIC MODEL

SIMPSON'S RULE I

\[ V = \frac{1}{6} \left( A_0 + 2A_1 + A_2 \right) \]

SIMPSON'S RULE II

\[ V = \frac{1}{3} \left( A_0 + 2A_1 + A_2 \right) \]

HEMISPHERE CYLINDER (RVI)

\[ V = \frac{5}{3} \pi R^2 \]

HEMISPHERE CYLINDER (PMI)

\[ V = \frac{5}{3} \pi R^2 \]

ELLIPSOID SINGLE PLANE

FOUR CHAMBER VIEW

\[ V = 0.25 \pi a^2 L \]

ELLIPSOID SINGLE PLANE

TWO CHAMBER VIEW

\[ V = 0.25 \pi a^2 L \]

ELLIPSOID BIPLANE (RVI)

\[ V = \frac{\pi}{6} L D_1 D_2 \]

ELLIPSOID BIPLANE (PMI)

\[ V = \frac{\pi}{6} L D_1 D_2 \]

(volume = \( \frac{5}{6} A L \)). Short-axis areas (A) at the level of the mitral valve and high papillary muscles were separately applied to this formula. The length (L) of the ventricle was measured from the apical four-chamber view.

Ellipsoid Single-plane Model

The left ventricle was assumed to be ellipsoid. Volumes were calculated by planimetrying the area (A) of the left ventricle from either the apical four-chamber or two-chamber views and measuring the longest length (L). Volume = \( 0.85 \frac{A^2}{L} \).

Ellipsoid Biplane Model

Volumes were calculated by measuring the longest length (L) from the apical four-chamber view and the orthogonal minor-axis diameters (D₁, D₂) from the short-axis view at the mitral valve or papillary muscle level. Volume = \( \frac{\pi}{6} L D_1 D_2 \).

Teichholz Formula

Volume = \( (7.0/2.4 + D) D^3 \), where D = the internal dimension measured from M-mode tracings.

Statistics

Left ventricular end-diastolic and end-systolic volume and ejection fraction obtained by each method were compared with volumes and ejection fraction obtained from biplane cineangiography. Linear regression analysis was performed using the least-squares method, and the standard error of the estimate was calculated as:

\[ SD \times \sqrt{\left(1 - r^2\right)} \]

\[ \sqrt{\frac{(n - 1)}{(n - 2)}} \]

where \( r \) = correlation coefficient and \( n \) = number of cases.

Results

Left Ventricular Volumes

There was no significant difference in heart rates at catheterization and echocardiographic study (106 ± 24 vs 96 ± 24 beats/min, respectively). The echocardiographically estimated volumes and injection fraction are shown with the angiographically determined values in table 2. End-diastolic volume calculated from cineangiograms ranged from 25–242 ml. End-systolic volume ranged from 4.8–144 ml. The correlation of volumes estimated with two-dimensional echocardiography and those determined with angiography varied with the algorithm used. All echocardiographically determined volumes underestimated angiographically determined volumes. Algorithms using multiple short-axis views (Simpson's rule) produced a good correlation regardless of
Table 2. Comparison of Echocardiographically Estimated Left Ventricular Volumes and Ejection Fraction with Angiographically Determined Values

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>End-diastolic volume</th>
<th>End-systolic volume</th>
<th>Ejection fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>Slope</td>
<td>SEE (ml)</td>
</tr>
<tr>
<td>Simpson's Rule</td>
<td>1*</td>
<td>0.98</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>11*</td>
<td>0.98</td>
<td>0.78</td>
</tr>
<tr>
<td>Hemisphere-cylinder (MV)</td>
<td>0.98</td>
<td>0.85</td>
<td>10.9</td>
</tr>
<tr>
<td>(PM)*</td>
<td>0.96</td>
<td>0.69</td>
<td>11.7</td>
</tr>
<tr>
<td>Ellipsoid single-plane</td>
<td>4C</td>
<td>0.93</td>
<td>0.56</td>
</tr>
<tr>
<td>2C</td>
<td>0.73</td>
<td>0.38</td>
<td>20.0</td>
</tr>
<tr>
<td>Ellipsoid biplane</td>
<td>(MV)</td>
<td>0.97</td>
<td>0.69</td>
</tr>
<tr>
<td>(PM)*</td>
<td>0.97</td>
<td>0.64</td>
<td>8.4</td>
</tr>
<tr>
<td>Teichholz formula</td>
<td>0.79</td>
<td>0.89</td>
<td>30.1</td>
</tr>
</tbody>
</table>

*Algorithms considered most optimal.

Abbreviations: 4C = four-chamber view; 2C = two-chamber view; MV = mitral valve; PM = papillary muscle.

The geometric model (figs. 4 and 5). The biplane ellipsoid algorithm using the longest length from the apical four-chamber view and two minor-axis diameters from the short axis was equally accurate estimating left ventricular volumes (figs. 4 and 5). The hemisphere-cylinder method using the planimetered area from the short axis (mitral valve or papillary muscle level) was only slightly less optimal. The single-plane apical methods and the Teichholz formula (M-mode) were least optimal.

Left Ventricular Ejection Fraction

Two-dimensional echocardiographic estimation of ejection fraction by the Simpson's rule algorithm correlated well with angiographically determined values regardless of the geometric model used, as did the hemisphere-cylinder and ellipsoid biplane methods using the short-axis view at the papillary muscle level (fig. 6). The M-mode Teichholz formula and other two-dimensional methods were inferior and correlated poorly with angiographically determined ejection fraction (table 2).

Discussion

The noninvasive evaluation of left ventricular volumes by two-dimensional echocardiography may provide new insights into left ventricular performance in children with congenital heart disease. Two-dimensional M-mode imaging may increase the diagnostic accuracy of echocardiography in cases of multiple images of the left ventricle.

FIGURE 4. (left) Correlation of left ventricular end-diastolic volume (LVEDV) estimated by echocardiography (echo) with LVEDV calculated by angiography (angio). Echocardiographic estimates by Simpson's rule using multiple short-axis views assumed the ventricle to be a truncated cone. (right) Ellipsoid biplane method using the short axis at the papillary muscle level (PM) as one of the sector planes. The correlation of left ventricular end-diastolic volume estimated by echocardiography with LVEDV calculated by angiography is shown.
The determined left ventricular end-systolic volume (LVESV) estimated by echocardiography (echo) with LVESV calculated by angiography (angio). Echocardiographic estimates by Simpson's rule using multiple short-axis views assumed the ventricle to be a truncated cone. (right) Ellipsoid biplane method using the short axis at the papillary muscle level (PM) as one of the sector planes. The correlation of LVESV estimated by echocardiography with LVESV calculated by angiography is shown.

The unique ability of two-dimensional echocardiography to image the heart in an infinite number of planes has produced many methods for estimating left ventricular volumes and ejection fraction. In patients with coronary artery and valvular disease, Carr and associates calculated left ventricular volumes from short-axis and apical views by the formula \( \frac{\pi}{6} LD_1 D_2 \). Using the same paired biplane echocardiographic views, Schiller et al. produced similar results in an identical patient population despite the application of a modified Simpson's rule method. In the present study, we used the method of Carr et al. and our data in children with congenital heart disease are in agreement with their results.

Folland et al. compared the value of different mathematical algorithms in determining left ventricular volumes. These studies show that algorithms...
using multiple short-axis views combined with the longest length from the apical four-chamber view are superior to algorithms using either single-plane or biplane apical views, regardless of geometric assumptions. This concept was further supported by studies in which echocardiography was used to measure left ventricular mass and volumes in dogs.24 This approach is particularly useful when left ventricular dyssynergy is present.26 The hemispheric-cylinder algorithm can also accurately estimate left ventricular mass. Our data support these findings.

In an initial study in children with congenital heart defects, Silverman et al.18 used single-plane and biplane biplane apical views to determine left ventricular volumes. They used a single-plane and biplane area-length method and a Simpson's rule method.24 The biplane area-length method uses both apical views best estimated left ventricular volumes and ejection fraction. Our data do not confirm this finding. These investigators, however, used a light-pen microprocessor system that avoided parallax distortion, which occurs when the ventricles are outlined on clear plastic. This may explain the discrepancy, because parallax distortion could not be avoided with our equipment. Because parallax distortion is minimal in the center of the video monitor screen, algorithms using short-axis views, which occupy primarily the center of the monitor screen, are superior to algorithms using only apical views, which occupy a greater portion of the video screen. We found optimal visualization of the anterolateral wall difficult to achieve in the apical two-chamber view.

All methods used in the present study underestimated end-diastolic volume, end-systolic volume and ejection fraction. The degree of underestimation depended on the algorithm; paired apical and short-axis views provided the best determinations of end-diastolic and end-systolic volume. Because echocardiography underestimated end-diastolic and end-systolic volumes to the same degree, ejection fraction correlated well with angiographic data. The best ejection fraction data were provided by the ellipsoid biplane model using the short-axis plane at the papillary muscle level and the apical four-chamber view.

Ease of data acquisition must be considered in the clinical practice of medicine. Because four of five methods produced similar results, the simplest would be the best. Our Simpson's rule and hemispheric-cylinder algorithms require planimeting one or more short-axis views. Other echocardiographic methods applied to left ventricular volume determination in children with congenital heart disease use a planimetered area.24, 26 These methods are time-consuming and tedious. The ellipsoid biplane model, however, requires only the measurement of two perpendicular minor-axis diameters from a short-axis view and the longest length from the apical four-chamber view. This is the least difficult approach and is therefore the most practical for clinical use.

We and others agree that two-dimensional echocardiography is superior to M-mode echocardiography in calculating left ventricular volumes and ejection fraction. Of the two-dimensional approaches evaluated in children with congenital heart disease, paired biplane methods are superior to single-plane methods. In addition, at least one plane should be a short-axis view along the left parasternal border for both algorithms using sections through this plane are the most accurate, regardless of geometric assumption.

Acknowledgment

The authors thank Cathy Heteniak for editing and typing this manuscript.

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Pulmonary Regurgitation Studied with the Ultrasonic Pulsed Doppler Technique

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YUNG-DAE PARK, M.D., HIROSHI SAKAKIBARA, M.D., AND YASUHARU NIMURA, M.D.

SUMMARY Sixty patients with pulmonary regurgitation were studied by the pulsed Doppler technique combined with two-dimensional and M-mode echocardiography. Patients with pulmonary regurgitation had abnormal Doppler signals just below the pulmonic valve in the right ventricular outflow tract in diastole on the two-dimensional image. These signals were considered to indicate the regurgitant flow.

There are two patterns of pulmonary regurgitant Doppler signals. In pulmonary hypertension, the maximal component of instantaneous flow velocity is sustained at about the same signal strength throughout diastole, but when the pulmonary arterial pressure is normal, the velocity slows down gradually from early diastole to end-diastole.

Pulmonary regurgitation was detected by phonocardiography in about half the patients. In the remaining half, pulmonary regurgitant murmur could not be differentiated from aortic regurgitant murmur or was masked by coexistent aortic regurgitation or patent ductus arteriosus, whereas the Doppler technique indicated pulmonary regurgitation.

THE ULTRASONIC pulsed Doppler technique is useful in the noninvasive assessment of intracardiac blood flow. Blood flow from the right heart can be measured from the precordial approach because the right heart is located near the anterior chest wall and the flow direction is nearly parallel to the direction of the ultrasound beam for the Doppler technique. We investigated pulmonary regurgitation using a range-gated, pulsed Doppler technique combined with two-dimensional echocardiography and compared its sensitivity for diagnosis of pulmonary regurgitation with phonocardiography.

Methods
We examined 1200 patients by the pulsed Doppler method from January 1979 to August 1980. In 60 of these patients, abnormal diastolic Doppler signals were detected in the subpulmonic area and the right ventricular outflow tract. These 60 patients were the
Two-dimensional echocardiographic assessment of left ventricular volumes and ejection fraction in children.
J C Mercier, T G DiSessa, J M Jarmakani, T Nakanishi, S Hiraishi, J Isabel-Jones and W F Friedman

Circulation. 1982;65:962-969
doi: 10.1161/01.CIR.65.5.962
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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