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Measurement of Left Ventricular Ejection Fraction by Mechanical Cross-Sectional Echocardiography

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SUMMARY Cross-sectional echocardiography is a new noninvasive technique for imaging the heart. We developed a method for using mechanical cross-sectional echocardiograms (sector scans) to determine left ventricular volumes and ejection fraction. Using left ventricular cineangiography as a standard, sector scan ejection fraction correlated better ($r = 0.93$) than M-mode echocardiography by any of three established methods, and the sector scan regression line did not differ from the line of identity ($p > 0.33$). Interobserver variability for sector scan ejection fraction was $2.3 \pm 1.2\%$ (mean $\pm$ SD). Variation between two studies performed within 24 hours and analyzed by the same observer was $1.4 \pm 1.5\%$. However, the sector scans consistently underestimated left ventricular end-diastolic volume. We conclude that sector scan echocardiography is more reliable than conventional M-mode techniques for estimating left ventricular ejection fraction, but estimation of left ventricular end-diastolic volume is unreliable with the methods currently available.

M-MODE ECHOCARDIOGRAPHY is useful for evaluating left ventricular performance and measuring left ventricular volume in patients without regional myocardial dysfunction.$^{1,2}$ However, the presence of regional wall motion disorders has limited the reliability of the single-chord technique for determining ejection fraction.$^{3,4}$ Mechanical cross-sectional echocardiography is a new technique which can image the left ventricle in four planes by using a standard echocardiographic transducer mechanically swept at 60 Hz through an arc of adjustable width.$^{5}$ We applied the techniques of left ventricular angiocraphic analysis to cross-sectional echocardiograms (sector scans) and developed a method for determining left ventricular ejection fraction and end-diastolic volume. In this study we assessed the comparative value of cross-sectional echocardiography and M-mode echocardiography for determining ejection fraction and end-diastolic volume in an unselected group of patients, using left ventricular cineangiography as the reference standard.

Methods

Contrast Angiography

Twenty-four patients who underwent routine cardiac catheterization and left ventriculography were studied.

All cardiac medications (digitalis, diuretics, propranolol and nitrates) were withheld for at least 10 hours, and patients were fasting the morning of catheterization. Biplane left ventriculograms were performed before coronary angiography. Cineangiograms were recorded simultaneously from the $15^\circ$ right anterior oblique and $75^\circ$ left anterior oblique views at 58 to 61 frames/sec. The first well-opacified sinus beat after a sinus beat was selected for analysis. In four patients with atrial fibrillation a supraven-
tricular beat preceded by an RR interval of average duration was selected. The end-diastolic frame was selected at the peak of the simultaneously recorded electrocardiographic R wave, and the end-systolic frame was visually selected as the subsequent frame showing the smallest left ventricular silhouette. Volumes and ejection fraction were calculated by the area-length method of Dodge, which shaves off the papillary muscle silhouettes and compensates for their volume by a regression equation.

M-Mode Echocardiography

Both M-mode and sector scan echocardiograms were taken in the morning. All cardiac medications were withheld in exactly the same manner as before catheterization. Twenty-one patients were studied the day after cardiac catheterization, two within 72 hours and one 10 days after angiography.

M-mode echocardiograms were obtained with the patients in the supine and left lateral decubitus posi-
tion using a Picker 80-C Ultrasonoscope with a 2.25 MHz focused transducer and a Honeywell 1856 optical recorder.\textsuperscript{7,8} The left ventricular internal diastolic dimension (LVID) was measured at the peak of the electrocardiographic R wave,\textsuperscript{3,4} and the end-systolic dimension at the point of maximum apposition of posterior and septal walls.\textsuperscript{5,6,16} Volumes and ejection fraction were calculated by three standard formulas described by Pombo et al.\textsuperscript{9} (volume = LVID$^3$), Fortuin et al.\textsuperscript{4} (EDV = 0.59 × LVID$_d$ - 153, ESV = 0.47 × LVID$_s$ - 120), and Teichholz et al.\textsuperscript{13} ($V = 7.0 \times LVID^3/(2.4 + LVID)$).

**Sector Scan Echocardiography**

Sector scan echocardiograms were obtained immediately after M-mode scan using a Picker 80-C Cardiac Imager with a 2.25 or 3.5 MHz transducer mechanically swept through a 20° to 60° arc at 60 sweeps per second. Studies were recorded on a Sanyo VTC 7100 video-recorder and tape-copied to a Sanyo VTC 8400 video-recorder for single-frame stop-motion analysis. Four views were obtained. The long-axis view (figs. 1 and 2) was obtained from the third, fourth or fifth intercostal space along the left sternal border, with the sector plane parallel to the long axis of the left ventricle. The initial image recorded included the aortic valve, mitral valve and most of the left ventricular cavity. The transducer was then moved down one interspace so that a view including the mitral valve and apex was obtained.

The short-axis view (figs. 3 and 4) was obtained from the same position as the long-axis view by

**Figure 3.** Mechanical sector scanner position for obtaining the short-axis view. At upper right is the view obtained with the ultrasonic fan intersecting the mitral valve. At lower left is the view obtained with the transducer directed inferiorly to transect the body of the left ventricle. RV = right ventricle; ALMV = anterior leaflet mitral valve; LV = left ventricle, PM = papillary muscle.

**Figure 4.** Photographs of the short-axis view of the left ventricle in systole and diastole. The mitral valve leaflets are seen in the open position in late diastole and in the closed position in late systole. The crescent of the right ventricle appears in the left superior aspect of the image.
rotating the transducer 90° so that the sector plane was perpendicular to the long axis and the left ventricular cavity appeared circular.

The axial view (figs. 5 and 6) was obtained with the transducer at the apex of the left ventricle and the sector plane directed to transect the true anterior and posterior walls of the left ventricle and the left atrium. The hemiaxial view (figs. 7 and 8) was obtained from the same position by rotating the transducer 90°. In this view the posterolateral and septal walls of the left ventricle could be imaged, as well as all four cardiac chambers.

We replayed the video tape on a Sanyo VTC 8400 and made a subjective decision as to which of two orthogonal views (long axis/axial, hemiaxial/short axis, axial/hemiaxial or axial/short axis) dem-

**Figure 5.** Mechanical sector scanner position for obtaining the axial view. LA = left atrium; LV = left ventricle.

**Figure 6.** A) Axial view of the left ventricle above and the left atrium below, separated by the mitral valve at end-systole. The posterior papillary muscle is usually seen in the right aspect of the image and the true anterior left ventricular wall on the left side of the video image. B) The outline of the left ventricular silhouette was drawn from frame-by-frame and slow-motion viewing.
HEMIAXIAL

HEMIAXIAL

FIGURE 7. Mechanical sector scanner position for obtaining the hemiaxial view. A narrow sector arc was used to improve resolution of the left ventricular walls. LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle.

HEMIAXIAL

HEMIAXIAL

DIASTOLIC

DIASTOLIC

FIGURE 8. A) Left ventricular image at end-diastole in the hemiaxial view. The left ventricular apex is at the top and mitral valve and left atrium below. The interventricular septum and portions of the right ventricle and right atrium are on the left. A single video frame contains only half of the available video lines, and the advantage of motion in defining the endocardium is lost. B) shows the outline of the left ventricular silhouette defined using stop-frame and slow-motion viewing.
was visible on each frame, except in the long-axis view. In the long-axis view the apex and aortic valve were usually not seen in the same frame due to the limitations of the 60° arc of the mechanical sector scan. Therefore, the section of left ventricular cavity from apex to mitral valve was imaged separately (fig. 9A) from the section containing both the mitral and aortic valves (fig. 9C) and the two images were then superimposed using the anterior mitral leaflet as a reference point (fig. 9E). The endocardial outline of each view was drawn exactly as it appeared. The papillary muscle images were not separated from the myocardium.

The grease pencil outlines and the calibration grid were traced from the video monitor onto paper. Ventricular volumes were calculated by applying the area-length method of Dodge et al. to the silhouettes. The image with the longest apparent long axis was used to measure the long axis, L1. In the axial and hemiaxial views the long axis was measured from apex to mitral valve, since the aortic valve is not usually imaged in these views. One short axis (L2) of the assumed ellipse was calculated from the same view that contained L1 using the planimetered area (A) from the formula for the elliptical area L2 = 4A/π. The orthogonal view was used to calculate the other short axis, L3, by the same method. Correction factors were calculated from a wedge-shaped calibration grid. Ventricular volume was then calculated using the elliptical assumption V = πL1 L2 L3/6. Ejection fraction was calculated from the formula EF = (end-diastolic volume-end systolic volume)/end-diastolic volume.

Reproducibility and Interobserver Variability

Seven patients were studied twice with cross-sectional echocardiography within a 24-hour period. Reproducibility was tested by comparing the calculated ejection fraction of the two studies analyzed by the same observer. Interobserver variability was tested by comparing ejection fraction from the first study measured independently by two observers.

Results

Twenty-two of the 24 sector scan echocardiograms were of acceptable quality; two studies were inadequate due to poor endocardial definition. These 22 patients were used for the subsequent analysis. Mean heart rate during angiography (75.0 ± 13.4 beats/min, mean ± SD), cross-sectional echocardiography (74.0 ± 11.8 beats/min) and M-mode echocardiography (75.5 ± 16.8 beats/min) were not different. Clinical data are presented in table 1.

Left Ventricular Angiography

Fourteen biplane angiograms were used to calculate ventricular volumes and ejection fraction (tables 1 and 2). In the other eight patients only the right anterior oblique views were used. Six patients had regional wall motion disorders consisting of akinesis or hypokinesis.

![Figure 9](http://circ.ahajournals.org/)

**Figure 9.** A) Long-axis left ventricular image from apex to mitral valve (as in fig. 2). B) shows the outline derived from that image. Although the anterior leaflet of the mitral valve is not easily discernible from the photograph, it is easily seen in the sector scan image and is shown in the outlines as a bold black line. Figures 9C and D show the long-axis view of the mitral valve with the aortic root and the outline of the image. The anterior mitral valve leaflet was used as a reference point and outlines as shown in 9C and D were superimposed to form an entire left ventricular outline, as in figure 9E.
### Table 1. Ejection Fraction for Each Patient by Method Listed

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<th>Patient</th>
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*Technically inadequate study.
†Atrial fibrillation.
‡Regional wall motion disorder.
Abbreviation: CAD = coronary artery disease.

### Sector Scan Echocardiograms

Results of ejection fraction calculations for the patients are shown in table 1. The correlation between sector scan and angiographic ejection fraction was $r = 0.93$. The line of identity was within one standard error of the line of regression at all points (EF-SECTOR = 0.89 EF-ANGIO + 4.8%; fig. 10). When the four patients with atrial fibrillation were excluded the correlation was $r = 0.92$, and the regression line

### Table 2. End-diastolic Volume Indices for Each Patient by the Method Listed

<table>
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<th>Patient</th>
<th>Angiography</th>
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*Technically inadequate study.
was essentially unchanged. In the six patients with left ventricular asynergy, the sector scan ejection fraction was 2.0 ± 3.3% (mean ± SEM, range −12 to +11%) different from the angiographic ejection fraction.

The correlation between sector scan and angiographic end-diastolic volume index (EDVI) was good ($r = 0.93$), but the sector scan underestimated left ventricular volume (EDVI-SECTOR = 0.59 EDVI-ANGIO + 10 ml, fig. 11). When the patient with the largest EDVI (patient 20) was excluded, the range of volumes was greatly reduced so that the scatter of the data relative to the standard error was greatly increased. Thus, the correlation without the data of patient 20 was poor ($r = 0.46$).
M-Mode Echocardiograms

Three methods of calculating ejection fraction and end-diastolic volume index from M-mode echocardiograms were used. The formula of Teichholz et al.13 yielded the best M-mode correlation (r = 0.81) for ejection fraction, but the slope of the regression line differed from the line of identity (p < 0.01) (EF-TEICHHOLZ = 0.65 EF-ANGIO + 25%; fig. 12).

The correlation coefficient between left ventricular angiography and ejection fraction calculated by the method of Pombo et al.3 was r = 0.80, and by the method of Fortuin et al.4 was r = 0.68. The regression lines were further from the line of identity than the regression line by the method of Teichholz. In five of the six patients with left ventricular asnergy who had interpretable studies, M-mode echocardiography (using the Pombo formula) uniformly overestimated ejection fraction by 22.6 ± 5.1% (mean ± SEM, range 6–38%, table 1).

Reproducibility and Interobserver Variability (table 3)

The mean absolute value of the difference of sector scan ejection fractions calculated from two studies done 24 hours apart was 1.4 ± 1.5% (mean ± sd, range 0–4%). The mean heart rates did not differ. The mean absolute error between sector scan ejection fractions analyzed independently by two different observers was 2.3 ± 1.2% (range 0–4%).

Discussion

Ejection Fraction

Our data indicate that cross-sectional echocardiography using a mechanical sector scan device can reliably estimate ejection fraction in unselected patients with and without regional wall motion abnormalities. The results indicate that cross-sectional echocardiography has important advantages in accuracy over M-mode echocardiography for estimating ejection fraction. The correlation coefficient was best for cross-sectional echocardiography, and the regression line was not significantly different from the line of identity.

While M-mode echocardiography is a good method for assessing ejection fraction in patients without regional wall motion abnormalities, cross-sectional echocardiography appears to be superior because abnormal wall motion does not invalidate the results. In the six patients with left ventricular asnergy the M-mode echocardiogram uniformly overestimated ejection fraction by 22.6 ± 5.1% (mean ± SEM). In the
same patients the sector scan ejection fraction was not different from the angiographic ejection fraction \((p > 0.33)\). A disadvantage of the sector scan method is that the time involved in quantitating ejection fraction is considerably longer than by M-mode techniques. As much as 40 minutes of physician time was involved in each sector scan analysis for the replaying of all views and drawing the endocardial silhouettes.

The small variance between observers and between studies performed within 24 hours demonstrates that this method is both reliable and reproducible.

End-Diastolic Volume

The sector scan method we used to estimate EDVI correlated poorly and underestimated angiographic EDVI. There are several explanations for this non-systematic underestimation of EDVI. First, angiography images a shadow of the left ventricle which results in a maximal area for that projection, while the sector scan images a slice which may not cut across the maximum area possible in that view. Second, no correction was made for excluding the papillary muscle from the endocardial outline of the ventricular cavity. Third, angiography images the left ventricular cavity including volume between trabeculae, while cross-sectional echocardiography images the endocardium at the innermost trabeculae because they are the first to reflect ultrasound. Lack of echo beam focus at the endocardial surface may lead to resolution uncertainty, which causes the cavity to appear smaller than it actually is. Fourth, the long axes in the axial and hemi-axial views were measured from apex to mitral valve, while the long axes were measured from apex to aortic valve in the angiogram. The apex-to-mitral valve distance is usually shorter than the apex-to-aortic valve distance. This shorter distance measured in the sector scan apical views leads to an underestimation of left ventricular volume. However, these errors in volume determination, which may not be systematic errors between patients, will affect systolic and diastolic cross-sectional areas in the same view to the same degree in an individual patient, and therefore do not alter the calculated ejection fraction.

Previous Studies

A preliminary report has demonstrated small intraobserver, interobserver and beat-to-beat variation in measurements of cross-sectional left ventricular area made from phased-array sector scan images in dogs and patients.\(^a\) To our knowledge, reproducibility has not been previously demonstrated with mechanical cross-sectional echocardiography. These workers also showed reliability of left ventricular volume and mass measurements of dog hearts using a variety of formulas and a phased-array sector scanner.\(^b\) Three other groups\(^b\) (Schiller NB: personal communication) have shown that ejection fractions calculated from phased array sector scan images correlated well with angiographically derived ejection fractions. EDVI was generally underestimated, as in our study. There are no prior studies demonstrating reliability of ejection fraction calculations from mechanical sector scanner images.

Methodology

We selected the best set of orthogonal views subjectively. The main criteria we used were 1) visualization of the entire left ventricle in the view, and 2) endocardial resolution. Flexibility in choice of views allowed maximum use of the information; in 22 of 24 patients ejection fraction and ventricular volume could be calculated.

Conclusions

We have established the reliability and reproducibility of cross-sectional echocardiography in the determination of left ventricular ejection fraction by applying the methods developed by Dodge et al.\(^b\) to sector scan images using left ventricular angiography as the standard. The regression correlation was excellent and the regression line was not statistically different from the line of identity. Comparison of cross-sectional echocardiography with M-mode echocardiography demonstrated a distinct advantage of the former in determining ejection fraction. The estimation of end-diastolic volume by cross-sectional echocardiography was poor using this method.

Acknowledgment

The authors thank Valmik Bhargava, Ph.D. and Joel S. Karliner, M.D. for their expert assistance, and Ana M. Gil for her secretarial assistance.

References

Idiopathic Hypertrophic Subaortic Stenosis Viewed by Wide-Angle, Phased-Array Echocardiography

RANDOLPH P. MARTIN, M.D., HARRY RAKOWSKI, M.D., JAMES FRENCH, M.D.
AND RICHARD L. POPP, M.D.

SUMMARY A wide-angle, phased array ultrasonic sector scanner was used to view the heart in 18 patients with idiopathic hypertrophic subaortic stenosis (IHSS). The rapid systolic anterior motion (SAM) of the mitral apparatus appeared quite separate from movement of either the left ventricular posterior wall or prominent papillary muscles. The SAM always occurred in a location judged to be the chordal end of the mitral leaflets. The SAM involved the whole mitral apparatus more extensively in patients with high outflow tract gradients at rest (>60 mm Hg), and in all patients during Valsalva maneuver or amyl nitrite inhalation. The mitral apparatus, including the papillary muscles, was anteriorly displaced in short-axis images of these patients' hearts. True end-systolic cavity obliteration was not seen at rest in any patient, since a small space persisted posteriorly between the papillary muscles in short-axis images. We believe these data support some and negate other previously proposed mechanisms for the mitral valve SAM and abnormal left ventricular dynamic geometry in patients with IHSS.

Localized subaortic thick septal myocardium was seen in each case. Additionally, we noted an unusual echo pattern within the myocardium and especially in portions of the thick septum. This pattern was present among 20-100% (mean 50%) of the septal length, and 16-40% (mean 25%) of the left ventricular circumference, and in the posterobasal myocardium in two patients. We speculate that this echo pattern within the thick septal myocardium may be related to abnormal myocardial structure or myocardial fibrosis noted previously by histologic methods.

IN THE 20 YEARS since the original anatomic1 and functional2 description of idiopathic hypertrophic subaortic stenosis (IHSS), few diseases have sparked so much interest and controversy.3-14 Since the late 1960s, single-dimensional echocardiography has been proposed and used as a sensitive, convenient, noninvasive tool for the diagnosis and therapeutic assessment of IHSS.15-19 Although single-dimensional echocardiography is useful for the detection of IHSS, it is limited by its narrow field of view and lack of spatial orientation.

Two-dimensional echocardiography has proven to be an exciting technique, presenting dynamic images of the heart in multiple cross-sectional planes. Some work has been published using various two-dimensional echocardiographic systems to study IHSS.20-23

We used a prototype two-dimensional, real-time, phased-array 80° sector scanner24 to study the echocardiographically displaced anatomy and dynamic pathology of patients with IHSS.

Methods

Patient Selection

Eighteen patients referred for evaluation of cardiac murmurs, chest pain, or abnormal electrocardio-
Measurement of left ventricular ejection fraction by mechanical cross-sectional echocardiography.
K W Carr, R L Engler, J R Forsythe, A D Johnson and B Gosink

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