Comparison of Ultrasound and Cineangiographic Measurements of the Mean Rate of Circumferential Fiber Shortening in Man

By Ronald H. Cooper, M.D., Robert A. O'Rourke, M.D., Joel S. Karliner, M.D., Kirk L. Peterson, M.D., and George R. Leopold, M.D.

SUMMARY
It has been shown that cineangiographic measurement of the mean rate of circumferential fiber shortening (mean V_{CF}) at the minor left ventricular equator is a reliable method for evaluating the mechanics of cardiac performance. Since fiber shortening can be derived from the echocardiogram, we sought to validate the measurement of mean V_{CF} by this noninvasive technic in patients studied by both methods. In 15 patients considered to have normal left ventricular function, the average mean V_{CF} determined by ultrasound was 1.29 ± 0.23 circumferences/sec, while in the 13 patients with reduced left ventricular performance this value was 0.75 ± 0.16 circumferences/sec (P < 0.001). Values of mean V_{CF} by the two technics were similar and separated normal from abnormal ventricular function in 27 of 28 patients. The average mean velocity of posterior wall motion was 4.7 ± 1.1 cm/sec in normal patients and 3.9 ± 1.3 cm/sec in abnormals, but posterior wall velocities did not correlate well with either ultrasound or cineangiographic determinations of mean V_{CF}. Ejection fraction calculated from ultrasound measurements correlated significantly with the ejection fraction calculated by cineangiography (r = 0.83, P < 0.0001). The ejection fraction and mean V_{CF}, as determined by ultrasound in the 28 patients, correlated well (r = 0.92, P < 0.0001), but there were six discordant points.

From these studies we conclude that the ultrasound determination of mean V_{CF} is a valid method for distinguishing normal from abnormal myocardial performance of the left ventricle. These data also support the use of ultrasound in determining ejection fraction. Estimation of posterior wall velocity, although perhaps useful in the serial study of the same patient, seems limited in its ability to assess cardiac performance accurately.

Additional Indexing Words:
Echocardiography Myocardial mechanics Noninvasive technics
Posterior wall velocity

Quantitative hemodynamic and mechanical measurements of left ventricular function in patients with suspected or clinically apparent heart disease have general...

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ly required cardiac catheterization. Since serial studies by invasive technics are difficult to obtain, noninvasive methods, including calculation of systolic time intervals and ultrasound determination of ventricular dimensions, have been proposed as alternative methods for the serial study of left ventricular performance.1-3 Recently it has been shown that under basal conditions the cineangiographically determined mean rate of circumferential fiber shortening (mean $V_{CF}$) provides an accurate measure of cardiac contractility.4 Since mean $V_{CF}$ can be derived from the echocardiogram, we sought to validate this noninvasive measurement of mean $V_{CF}$ by comparing it with the same measure estimated by radiographic technics in patients with and without left ventricular myocardial disease.

Methods

Studies were performed on 28 patients undergoing diagnostic left heart catheterization. Their clinical characteristics together with cineangiographic and ultrasound data are listed in table 1. Patients with major left ventricular dyskinetic areas were excluded from the study. Examination with reflected ultrasound was performed in all patients within 24 hours of cardiac catheterization.

The principles of diagnostic ultrasound previously have been reviewed in detail.5 We employed a commercially available ultrasonoscope (Ekoline 20, Mark II, Smith-Kline) utilizing a 2.25 MHz, 0.75-in transducer with a repetition rate of 1,000 impulses/sec. The echoes received from interfaces between tissues of differing acoustical impedance were displayed on an oscilloscope; for recording the echoes a "time-motion" presentation was used. Photographs of the echo display were taken directly from the face of the oscilloscope with a Polaroid camera. Time-distance markers and a simultaneous electrocardiogram also were displayed on the oscilloscope and incorporated into each photograph. In each patient the ultrasound values reported represent the average measurements obtained from at least three acceptable recordings.

Patients were examined in the supine or partial left lateral decubitus position. The transducer was placed in the fourth or fifth intercostal space along the left sternal border and directed posteriorly until the typical pattern of mitral valve movement was identified. The transducer then was rotated slightly inferolaterally until the mitral valve no longer was in the ultrasound beam. In this plane it was possible to display the endocardial echoes from the intraventricular septum and left ventricular posterior wall by appropriate adjustments of the damp, reject, and gain modalities (fig. 1). Other investigators have characterized the appearance and movement of ultrasound echoes from the left ventricle.2,5 Special care was taken to measure from the endocardial surface of left ventricular posterior wall rather than from discrete echoes from the posterior mitral valve apparatus, which can frequently be recorded anterior to the endocardial echo ("x line," fig. 1). As pointed out by Popp and Harrison, the echoes from the posterior mitral valve apparatus can be recognized by their high intensity, discrete outline, and absence of systolic increase in the distance to the myocardial echoes.6

Left ventricular dimensions were measured between the endocardial surfaces of the left ventricular posterior wall and the left side of the intraventricular septum (fig. 1). The end-diastolic dimension (EDD) was measured on a vertical line drawn through the peak of the QRS complex. The end-systolic dimension (ESD) was defined as the smallest distance separating the septum and left ventricular posterior wall even if points of maximum excursion were not exactly apposed. The difference between the diastolic and systolic dimensions determined the extent of fiber shortening. One normal patient demonstrated paradoxic movement of the septum (i.e., anterior movement during systole) and in this case the amount of fiber shortening was considered to be the sum of the left ventricular posterior wall and septal excursions. The left ventricular ejection time (ET) was defined as the length of time from the peak of the QRS complex to the maximum anterior excursion of the left ventricular posterior wall, less 50 msec for the preejection period when no appreciable fiber shortening takes place.4 The mean rate of circumferential fiber shortening (mean $V_{CF}$) then was calculated from the following equation and the results expressed in circumferences/sec: Mean $V_{CF} = \frac{\text{EDD} - \text{ESD}}{\text{ET}} \times \text{ET}$. Division by the end-diastolic dimension (EDD) allows for comparison of mean $V_{CF}$ among different patients.4

The left ventricular ejection fraction was determined by two methods. The empiric formula of Pombo and associates was used which equates left ventricular stroke volume with the difference in the cubes of the end-diastolic (EDD) and end-systolic (ESD) dimensions.3 The ejection fraction then was equal to stroke volume divided by end-diastolic volume. Also utilized for determining ejection fractions was the regression equation described by Fortuin and co-workers which is reported to give more accurate
Table 1

**Clinical Characteristics and Indices of Left Ventricular Myocardial Performance in 28 Patients**

<table>
<thead>
<tr>
<th>Pt</th>
<th>Age (yr)</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>Mean VcR (circ/sec)</th>
<th>Mean PWV (cm/sec)</th>
<th>Max PWV (cm/sec)</th>
<th>EF</th>
<th>Mean VcR (circ/sec)</th>
<th>EF</th>
</tr>
</thead>
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<td>0.71</td>
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<td>6.3</td>
<td>0.71</td>
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<td>0.81</td>
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<tr>
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<td>45</td>
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<td>CAD</td>
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<td>4.2</td>
<td>5.2</td>
<td>0.58</td>
<td>1.41</td>
<td>0.69</td>
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<tr>
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<td>CAD</td>
<td>1.14</td>
<td>3.3</td>
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<td>0.63</td>
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<tr>
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<td>54</td>
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<td>CAD</td>
<td>1.30</td>
<td>5.4</td>
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<td>0.66</td>
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<td>0.59</td>
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<tr>
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<td>1.23</td>
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<td>4.7</td>
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<tr>
<td>10</td>
<td>32</td>
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<td>0.72</td>
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<td>0.57</td>
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<tr>
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<td>CAD</td>
<td>1.14</td>
<td>5.3</td>
<td>6.4</td>
<td>0.56</td>
<td>1.68</td>
<td>0.57</td>
</tr>
<tr>
<td>14</td>
<td>55</td>
<td>F</td>
<td>CAD</td>
<td>1.39</td>
<td>4.7</td>
<td>4.9</td>
<td>0.77</td>
<td>1.73</td>
<td>0.73</td>
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<td>45</td>
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<td>CAD</td>
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<td>3.6</td>
<td>4.3</td>
<td>0.71</td>
<td>1.92</td>
<td>0.65</td>
</tr>
</tbody>
</table>

| Abnormal | | | | | | | | |
| 16 | 52 | M | CAD | 0.54 | 3.3 | 4.0 | 0.33 | 0.66 | 0.66 |
| 17 | 41 | M | CAD | 0.64 | 3.0 | 3.3 | 0.40 | 0.72 | 0.29 |
| 18 | 51 | F | PMD | 0.90 | 3.4 | 3.9 | 0.57 | 1.14 | 0.62 |
| 19 | 64 | M | CAD | 0.54 | 1.9 | 3.2 | 0.37 | 0.59 | 0.33 |
| 20 | 58 | F | PMD | 0.58 | 4.1 | 3.8 | 0.30 | 0.81 | 0.27 |
| 21 | 58 | F | PMD | 0.78 | 4.2 | 4.9 | 0.39 | 1.05 | 0.44 |
| 22 | 47 | M | CAD | 1.03 | 6.0 | 5.7 | 0.57 | 1.15 | 0.50 |
| 23 | 52 | M | CAD | 0.84 | 5.4 | 4.6 | 0.49 | 0.97 | 0.27 |
| 24 | 55 | F | PMD | 0.73 | 3.3 | 3.7 | 0.47 | 0.38 | 0.24 |
| 25 | 58 | M | PMD | 0.57 | 2.3 | 2.8 | 0.37 | 0.19 | 0.10 |
| 26 | 43 | M | CAD | 0.95 | 3.1 | 6.9 | 0.54 | 0.79 | 0.50 |
| 27 | 54 | F | PMD | 0.82 | 6.0 | 4.1 | 0.58 | 1.03 | 0.53 |
| 28 | 54 | M | CAD | 0.81 | 4.5 | 6.9 | 0.60 | 0.93 | 0.63 |

| Mean | 0.75* | 3.9† | 4.6† | 0.46* | 0.81* | 0.39* |
| sd | 0.16 | 1.3 | 1.2 | 0.10 | 0.28 | 0.15 |

Abbreviations: ACP = atypical chest pain; VcR = velocity of circumferential fiber shortening; AS = aortic stenosis; circ/sec = circumferences/sec; CAD = coronary artery disease; PWV = posterior wall velocity; PBL = posterior billowing leaflet; EF = ejection fraction; PMD = primary myocardial disease.

*Statistically significant, P < 0.001.
†Not statistically significant.
results, especially in patients with low stroke volume.  

Mean posterior wall velocity (mean PWV) was calculated with ultrasound by dividing the total excursion of the left ventricular posterior wall (in cm) by the ejection time (in sec) (fig. 2). For each patient the maximum value for mean PWV, selected from several recorded beats, was used, rather than the average of mean PWV over several beats since this value correlated better with other indices of cardiac performance. Maximum posterior wall velocity was determined by drawing a tangent to the steepest part of the anterior movement of the posterior wall and measuring the slope, in cm/sec (fig. 2).

Diagnostic cardiac catheterization was performed in the postabsorptive state after administration of sodium pentobarbital, 100 mg i.m. A Cournand needle was placed in the left brachial artery and left heart catheterization was performed by the retrograde arterial technic. Cineangiograms were exposed at 75 frames/sec in the frontal and lateral projections following intravenous injection of 75% diatrizoate sodium (Hypaque) over a 2–3-sec period. A simultaneously recorded electrocardiogram and arterial pressure pulse permitted precise correlation of dimensional changes with electrical and pressure events.

The method of estimating mean VCF from cineangiograms has been described previously. Briefly, left ventricular cavity silhouettes were drawn in the lateral projection at end-diastole and end-systole (fig. 3). End-diastole was defined as the peak of the QRS complex; end-systole was defined as the maximum inward wall excursion determined by visual inspection of the cineangiogram. A long axis of the left ventricle was constructed from the midpoint of the mitral valve plane to the cardiac apex. A chord was drawn perpendicular to the long axis at one third (CD) and one half (AB) the distance from the mitral valve plane to the apex. Chord CD then was measured at end-diastole and at end-systole, and the difference constituted the extent of fiber shortening. By statistical analysis it was determined that the mean VCF derived from chord CD correlated best with the mean VCF obtained by ultrasound. Theoretically this chord should give the best correlation since it most nearly approximates the plane of the ultrasound beam. In 11 of 28 patients (eight normal, three abnormal) chord CD impinged on the noncontractile aortic valve ring, and in these patients chord AB was used for calculation of mean VCF. Ejection time was determined by the number of frames exposed between end-diastole and end-systole. As in the echo calculations, 50 msec were subtracted from this time to account for the essentially isovolumetric preejection period. Mean VCF was calculated from the same formula as was used in the ultrasound determination. Biplane volume estimates were made using the area-length method.
Of a total of 52 patients in whom ultrasound estimates of left ventricular performance were attempted, 47 patients had tracings acceptable for analysis, yielding a success rate of 91%. Other investigators have reported a wide range of success in their attempts to record septal and left ventricular posterior wall endocardial movement. Our high success rate is comparable to that reported by Popp and Harrison.6 It is our impression that the time devoted to each study (up to 45 min in some instances) permitted optimal positioning of patient and transducer resulting in a high percentage of acceptable recordings. Twenty-eight patients had cineangiographic studies suitable for analysis (i.e. two consecutive, well-opacified sinus beats). The ventriculograms of 15 other patients exhibited ventricular irritability which precluded determination of mean V CF. In order to study the reproducibility of the method, two patients in the study and an additional four patients had a total of 28 ultrasound determinations of mean V CF (range 2–10). Mean V CF was reproducible within less than 6% in all determinations, a figure which is in good agreement with the reproducibility of mean V CF derived from cineangiographic methods.4 In an additional nine patients, ejection time was derived from both the echocardiogram and from external carotid pulse tracings. The difference in ejection times between each pair of values by the two methods averaged 21 msec (range 10–40 msec). This figure is comparable to the difference between brachial artery pressure tracing and cineangiographic determinations of ejection times previously reported from this laboratory.4

Results

The mean V CF by ultrasound correlated well with the mean V CF measured by angiography (r = 0.81, P < 0.0001). The ultrasound technic was concordant with the angiographic method relative to normal or abnormal values in 27 of 28 (96%) patients (fig. 4A); in one patient mean V CF was diminished by ultrasound, but normal by cineangiography. Mean V CF by ultrasound also correlated well with biplane cine determination of ejection fraction (r = 0.78, P < 0.0001) (fig. 4B). The ejection fraction and mean V CF, both determined by ultrasound, correlated well (r = 0.92, P < 0.0001) but there were six points in which the ejection fraction was normal by echo, but mean V CF was decreased (fig. 4C). The average mean V CF determined by ultrasound in 15 patients considered to have normal left ventricular function by cineangiography was 1.29 ± 0.23 (sd) circ/sec (range 1.06–1.83), while in the 13 patients with reduced left ventricular performance it was 0.75 ± 0.16 circ/sec (range 0.54–1.03, P < 0.001). Since only one patient with a normal mean V CF by cine4 had an echo-determined V CF less than 1.05 circ/sec this value was taken as the lower limit of normal for the ultrasound method (fig. 4A).
Using the empirical formula of Pombo et al., ejection fraction calculated from ultrasound measurements averaged $0.65 \pm 0.08$ in the normal patients and $0.46 \pm 0.10$ in the abnormal patients. These data correlated significantly with the ejection fraction calculated by cineangiography ($r = 0.83, P < 0.0001$).

Using the regression equation recently described by Fortuin and associates, ejection fraction averaged $0.67 \pm 0.08$ in the normal patients, $0.50 \pm 0.07$ in the abnormal patients, and yielded a poorer but still significant correlation between the echo and cine measurements ($r = 0.61, P < 0.0005$).

**Figure 4**

Mean $V_{CF}$ by ultrasound plotted against: (A) mean $V_{CF}$ determined by cineangiography; (B) ejection fraction determined by cine; and (C) ejection fraction determined by ultrasound. The crossed lines represent the lower limits of normal for each measurement (1.05 circ/sec for mean $V_{CF}$ by echo, 1.20 circ/sec for mean $V_{CF}$ by cine, and 0.52 for ejection fraction).
In the 16 normal patients, mean posterior wall velocity (PWV) by ultrasound averaged 4.7 ± 1.1 cm/sec while in those patients with impaired left ventricular performance the corresponding value was 3.9 ± 1.3 cm/sec, a difference which was not significant (P > 0.1). Average maximum PWV in the normal and abnormal groups was 5.5 ± 1.0 cm/sec and 4.6 ± 1.2 cm/sec, respectively, again with no statistically significant difference (P > 0.1). Mean PWV correlated poorly with ultrasound-determined mean VCF (r = 0.56); with cineangiographic determination of mean VCF (r = 0.46); and with ejection fraction (r = 0.40), (fig. 5A, B, and C). Substituting maximum PWV for mean PWV...
sightly improved the correlation with cine-ejection fraction \( r = 0.51 \) but decreased the correlation with echo \( r = 0.54 \) and mean \( V_{CF} \) determined by cine \( r = 0.40 \).

Discussion

Much recent attention has been focused on the assessment of left ventricular performance in man. It would be desirable to have an accurate and reproducible noninvasive technic for estimating alterations in left ventricular performance which occur as the consequence of disease, specific drug therapy, or surgical interventions. Under basal conditions, both the ejection fraction\(^4\, 10\) and mean \( V_{CF} \) determined angiographically have been reported to provide estimates of the contractile state of the human left ventricle. However, under conditions of reduced impedance to ventricular emptying, such as occur in mitral regurgitation, measurement of contraction velocity may be more accurate than ejection fraction in assessing myocardial performance.\(^11\)

Although it has been suggested that calculation of mean \( V_{CF} \) by ultrasound is a useful method for the detection of impaired myocardial contractility,\(^12\) there has not been a comparison of this noninvasive method with standard cineangiographic technics for determining \( V_{CF} \).\(^4\) The highly significant correlation found in the present study between angiographic and ultrasound determinations of mean \( V_{CF} \) serves to validate the use of echocardiography in the calculation of internal shortening velocities in man.

In the normal subjects of this study the average mean \( V_{CF} \) determined by ultrasound was 1.29 circ/sec, a figure somewhat lower than the value of 1.45 circ/sec recently reported by Paraskos and his associates.\(^12\) In the latter study, mean \( V_{CF} \) was normalized by dividing by the average internal circumference \([(\text{end-diastolic} + \text{end-systolic circumference})/2] \) while in our study, normalization was achieved by dividing by end-diastolic circumference alone. In any given calculation, use of the former method will yield a higher value for mean \( V_{CF} \). Ejection times, although calculated differently in the two studies, should be approximately equivalent since no appreciable anterior movement of the left ventricular posterior wall occurs during the preejection period.

Calculation of mean \( V_{CF} \) by ultrasound clearly differentiated normal from abnormal left ventricular performance. Only one patient in our study demonstrated a normal mean \( V_{CF} \) by cineangiography and a reduced mean \( V_{CF} \) by ultrasound (fig. 4A). An isolated wall motion disorder did not appear to account for this discordant observation. Since calculation of mean \( V_{CF} \) separates normal from reduced cardiac performance, it appears unnecessary to determine instantaneous \( V_{CF} \) throughout systole either by ultrasound\(^15\) or by cineangiography.\(^13\)

The correlation between cineangiographic and ultrasound determinations of ejection fraction was also highly significant, confirming previous work by other investigators.\(^8\, 6\) A recent report suggests that a regression equation\(^7\) rather than a cube function\(^8\) is more accurate for the determination of ejection fraction by ultrasound. We employed both methods for this calculation and found the cube method to correlate better \( r = 0.83 \) vs \( r = 0.61 \) with biplane cine-determined ejection fraction. The ultrasound calculation of ejection fraction (cube method) also correlated well with the ultrasound determination of mean \( V_{CF} \) \( r = 0.93, P < 0.0001 \). Nevertheless the results were discordant in six patients who had reduced left ventricular mechanical performance \( \text{mean} \ V_{CF} < 1.05 \text{ circ/sec} \) in the face of a normal ejection fraction \( \text{EF} > 0.52 \). These data are consistent with cineangiographic observations made in our laboratory in which diminished shortening velocities have been noted in the presence of normal ejection fractions.

It has been suggested that motion of the posterior left ventricular wall reflects the velocity of circumferential fiber shortening.\(^8\) Posterior wall velocities (PWV) are reported to be sensitive to changes in cardiac performance produced by physiologic\(^8\) and pharmacologic interventions,\(^14\) as well as to alterations
induced by acute myocardial infarction. In this study we calculated both a maximum PWV and mean PWV (fig. 2). Neither measurement provided an accurate, reproducible index of cardiac performance when compared with other indices of proven value (fig. 5A, B, and C). Mean PWV was found to yield poor but significant correlation with the cineangiographically determined mean $V_{WF}$ ($r = 0.46, P < 0.005$) and ejection fraction ($r = 0.39, P < 0.05$). The correlation with ultrasound-determined mean $V_{WF}$ was also significant but poor ($r = 0.56, P < 0.005$). Substituting maximum PWV for mean PWV decreased two of these three correlations. The most likely explanation for this is found in the methods of determining the maximum slope of left ventricular posterior wall motion which we found to be a highly subjective, poorly reproducible procedure. Mean PWV correlated only moderately well with maximum PWV ($r = 0.65, P < 0.001$) (fig. 6). On the basis of these observations we feel that measurements of posterior wall velocities, while potentially useful in serial studies of the same patient, are limited by their inability to distinguish consistently normal from abnormal cardiac function.

Since ultrasound calculation of mean $V_{WF}$ and ejection fraction requires visualization of the interventricular septum and that portion of the left ventricular posterior wall adjacent to the mitral valve, anterior and apical dyskinesis will not be detected. Thus, some patients with these wall motion abnormalities might be expected to demonstrate a falsely normal ejection fraction by ultrasound, while in patients with marked posterior or septal wall dyskinesis ejection fraction could be falsely low. Similarly, the accuracy of the ultrasound-determined mean $V_{WF}$ is dependent on visualizing an area of myocardium which, in patients with abnormal wall motion, may not necessarily be representative of the entire left ventricle. In an analogous situation, comparison of mean $V_{WF}$ derived from frontal and lateral cineangiographic projections has revealed differences in mean $V_{WF}$ due to dyskinetic areas. It is noteworthy, however, that only one patient in 29 was excluded from the study because of wall motion disorder of such magnitude and location as to yield grossly discordant results between the two technics of calculating mean $V_{WF}$. Thus, it would seem that the echocardiographic method of determining mean $V_{WF}$ is applicable in the majority of patients without large dyskinetic areas.

The possibility of adequate echocardiographic recordings in most patients, the reproducibility of the method, and its validation by comparison with cineangiography, would seem to establish the use of ultrasound determinations of mean $V_{WF}$ as an important technic in the serial noninvasive assessment of left ventricular performance in man.

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