Echocardiographic Evaluation of Left Ventricular Size and Performance During Handgrip and Supine and Upright Bicycle Exercise

MICHAEL H. CRAWFORD, M.D., DAVID H. WHITE, M.D. AND K. WRAY AMON

SUMMARY We used M-mode echocardiography to measure left ventricular dimensions in diastole (Dd) and systole (Ds) and to assess ventricular performance by computing the percent dimensional shortening (%AD) and the normalized rate of dimensional shortening (Vd) during isometric and isotonic exercise in normal subjects. In 27 subjects, isometric handgrip exercise at 50% of maximum grip until fatigue produced a significant increase in Ds (33 ± 3.4 (SD) vs 30.6 ± 3.7 mm, p < 0.001), and a reduction in %AD (34 ± 4 vs 39 ± 5%, p < 0.001) and Vd (1.15 ± 0.15 vs 1.28 ± 0.19 sec⁻¹, p < 0.001). Handgrip exercise at 15% of maximum grip produced similar but less marked changes in the 27 subjects, and acute pressure loading with phenylephrine caused similar but more marked changes in 10 of the subjects. In the 20 subjects who performed at least 12 minutes of supine bicycle exercise, Ds decreased significantly (25.6 ± 4.0 vs 31.7 ± 2.8 mm, p < 0.001) and %AD increased (49 ± 6 vs 36 ± 5%, p < 0.001). We observed similar results in the 12 subjects also studied during upright bicycle exercise. Dd was smaller in the upright position but unchanged during either isometric or isotonic exercise. We conclude that: 1) end-diastolic left ventricular size is maintained during isometric exercise and moderate dynamic exercise, even in the upright position; 2) isometric exercise leads to a mild decrease in left ventricular shortening, whereas dynamic exercise results in marked increases in shortening; this difference may be related to the relatively greater increase in blood pressure than in heart rate during isometric exercise, and 3) M-mode echocardiography can be successfully accomplished in selected subjects during various forms of exercise.

M-MODE ECHOCARDIOGRAPHY is an accurate and reproducible technique for assessing resting left ventricular size and performance in normal-sized hearts without segmental myocardial disease.1-4 The sensitivity of this technique for detecting changes in left ventricular dynamics has been shown in studies evaluating the response to upright tilting,5, 6 the Valsalva maneuver,7, 8 ventricular premature depolarizations,9 normal phasic respiration10 and acute pharmacologic interventions with agents such as amyl nitrite, nitroglycerin, atropine and phenylephrine.11, 12 One advantage of echocardiography is the ability to measure left ventricular diameters intermittently or continuously before, during and after an intervention without risk or discomfort to the subject and without affecting the normal response to the test conditions. Accordingly, we used echocardiography to measure left ventricular size and performance in normal subjects during isometric handgrip exercise and dynamic bicycle exercise in the supine and upright positions.

Methods

The study population consisted of 27 normal subjects who were selected from a group of twice as many because of excellent echocardiograms in the supine position at rest. There were 23 men and four women, ages 19–36 years. Physical fitness varied from subject to subject, but none could be considered a trained athlete. We obtained written informed consent from each subject on a form approved by the Institutional Review Board of the University of Texas Health Science Center at San Antonio. All the exercise studies were performed 6 or more hours after eating.

Handgrip Exercise

All 27 subjects performed isometric handgrip exercise in the supine position using a hand-held, adjustable dynamometer (Stoelting Co.). Maximum isometric grip was determined as the best of three attempts. The subjects then held 15% of their maximum grip until the point of fatigue, at which time blood pressure (cuff sphygmomanometer) and echocardiograms were recorded when the subject indicated that he could exercise for 30 seconds more. After a 15-minute rest, the subjects performed 50% maximum grip to fatigue, then blood pressure and echocardiograms were recorded during the last 30 seconds of exercise.

Acute Pressure Loading

On another day, 10 of the 27 subjects participated in an acute pressure loading study. With the patient in the supine position, we gave 1.5 mg of atropine intravenously, followed by an intravenous drip of phenylephrine (10 mg in 250 ml of normal saline) until systolic blood pressure was approximately 40 mm Hg higher than the basal level. Then, we recorded the echocardiograms and stopped the infusion. The total fluid volume infused was less than 50 ml.

Bicycle Exercise

Twelve of the 27 subjects had adequate echocardiograms recorded in the upright position, and these sub-
jects performed upright bicycle exercise on a different day using a Monark Bicycle Ergometer. Bicycle exercise was begun at 150 kilopond-meters (kpm)/min and was increased by 150 kpm/min every 3 minutes. We studied 20 subjects — the 12 who performed upright exercise and eight additional normal subjects (four men and four women) — during supine bicycle exercise on a Quinton Uniwork Ergometer, model 844. Exercise was begun at 200 kpm/min and was increased by 100 kpm/min every 3 minutes. Before exercise in the cycling position (feet upon pedals) and during the last 30 seconds of each 3-minute stage, we recorded blood pressure and echocardiograms. Exercise endurance varied in these untrained subjects. Supine exercise lasted 12–30 minutes (mean 17.5) and upright exercise 9–18 minutes (mean 13.5).

Echocardiography

We obtained echocardiograms using either a Picker Echoview 80-C coupled to an Irex Continutrace 101 recorder or an Electronics for Medicine Echo IV system. Echocardiograms of the left ventricle were taken from the standard intercostal space along the left sternal border with a hand-held transducer (2.25 MHz) and were recorded on a strip-chart recorder at 100 mm/sec paper speed. Using the R wave of the simultaneously recorded ECG as the reference point, we measured end-diastolic dimension (Dd) of the left ventricle at the level of the chordae tendineae. We measured the end-systolic dimension (Ds) as the smallest dimension between the left septal endocardium and the posterior wall endocardium during systole whether or not the two walls were exactly apposed.14 We also recorded simultaneous indirect carotid pulse tracings during isometric exercise and the acute pressure loading studies in order to measure left ventricular ejection time (ET). We calculated the heart rate from the simultaneously recorded ECG. All echocardiograms were performed with the subject in the same position, with the hand-held transducer in the same interspace and when the same anatomic landmarks were present. The echocardiographic measurements were made during expiration and represent the average of at least three heart beats.

Figure 1 shows three echocardiograms for the same subject recorded at rest sitting on the bicycle, after 9 minutes of upright exercise and after 15 minutes of upright exercise. The ECG at the top of each echo indicates the increasing heart rate; the anatomic landmarks are identical in each recording.

From the echocardiographic measurements described above, the percent left ventricular dimension shortening (%ΔD) and the normalized mean rate of left ventricular dimension shortening (Vd) were calculated as follows:

\[
\%\Delta D = \frac{Dd - Ds}{Dd} \times 100\%
\]

\[
Vd = \frac{Dd - Ds}{Dd \times ET}
\]

Statistical Analysis

We compared the subject's resting values and those attained at a certain point during exercise (see below)
using the paired t test; each subject served as his or her own control. Some subjects repeated the exercise studies 1–7 days later at the same time of day, and we compared the measurements at each stage of exercise between the two days using the paired t test.

Results

Handgrip Exercise (fig. 2)

At 15% of maximum grip, a modest but statistically significant increase in heart rate from 65 ± 10 (SD) to 70 ± 10 beats/min (p < 0.001) was observed in the 27 subjects. Systolic blood pressure also increased significantly from 110 ± 11 to 123 ± 12 mm Hg (p < 0.001). Left ventricular Dd was unchanged, but Ds increased significantly from 30.6 ± 3.7 to 31.7 ± 3.5 mm (p < 0.01) and %ΔD decreased significantly from 39 ± 5 to 36 ± 5% (p < 0.01). Vd also decreased from 1.28 ± 0.19 to 1.19 ± 0.16 sec⁻¹ (p < 0.01).

During handgrip exercise at 50% of maximum grip, heart rate was significantly higher than the control (79 ± 10 vs 65 ± 10 beats/min, p < 0.001), as was systolic blood pressure (139 ± 16 vs 110 ± 11 mm Hg, p < 0.001). Dd remained unchanged, but Ds increased (33 ± 3.4 vs 30.6 ± 3.7 mm, p < 0.001) and %ΔD was reduced (34 ± 4 vs 39 ± 5%, p < 0.001). Also, Vd decreased (1.15 ± 0.15 vs 1.28 ± 0.19 sec⁻¹, p < 0.001).

Five subjects repeated the handgrip exercise on another day under similar conditions. Individual values between the two studies varied somewhat, but the overall response to isometric exercise was the same. Mean heart rate, systolic blood pressure, %ΔD, and Vd were not statistically different between the two studies at rest or during 15% and 50% maximal grip (table 1).

Acute Pressure Loading (fig. 3)

Ten of the 27 subjects who performed handgrip exercise were also given atropine and phenylephrine at another time for comparative purposes. This pharmacologic combination increased heart rate from 65 ± 7 to 91 ± 18 beats/min (p < 0.01) and augmented systolic blood pressure from 109 ± 5 to 157 ± 9 mm Hg (p < 0.001). Dd was unchanged, but Ds increased significantly from 31.1 ± 2.4 to 35.4 ± 3.4 mm (p < 0.001) and %ΔD decreased significantly from 38 ± 4 to 31 ± 5% (p < 0.001). Vd also fell significantly from 1.26 ± 0.16 to 1.07 ± 0.24 sec⁻¹ (p < 0.01).

Supine Bicycle Exercise (fig. 4)

The 20 subjects who performed supine bicycle exercise pedaled for at least 12 minutes. During each exercise load, heart rate and systolic blood pressure increased progressively, but for statistical purposes the control state was compared with 12 minutes of exer-

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**Figure 2.** Effect of handgrip exercise at 15 and 50% of maximum voluntary contraction to the point of fatigue on heart rate (HR), systolic blood pressure (SBP), percent left ventricular minor dimension shortening (%ΔD) and mean normalized rate of dimensional shortening (Vd) in 27 normal subjects.
exercise, so that all the subjects could be included in the analysis.

During the twelfth minute of exercise, heart rate had increased from 66 ± 9 to 124 ± 13 beats/min (p < 0.001), and systolic blood pressure had risen from 108 ± 4 to 153 ± 13 mm Hg (p < 0.001). Dd was not changed (49.8 ± 4.0 vs 50.3 ± 4.5 mm, p > 0.05). Ds decreased significantly from 31.7 ± 2.7 to 25.6 ± 4.0 mm (p < 0.001) and %ΔD increased from 36 ± 4 to 49 ± 4% (p < 0.001).

Eleven of these 20 subjects repeated supine bicycle exercise on another day under similar conditions. All 11 subjects again completed at least 12 minutes of exercise; four increased their exercise duration by one stage (3 minutes); one subject's tolerance decreased by one stage; and the remaining six completed the same amount of exercise. The heart rate, systolic blood pressure, Dd, Ds, and %ΔD at rest and at 3, 6, 9, and 12 minutes of supine exercise were not statistically different between the two exercise studies. The comparative data for Dd, Ds and %ΔD are shown in figure 5.

Upright Bicycle Exercise (fig. 6)

The 12 subjects completed at least 9 minutes of upright pedaling. Therefore, the values during the ninth minute of exercise were selected for group statistical analysis. In general, the results were quite comparable to those obtained during supine exercise except that the resting values were different in the upright position.

During the ninth minute of exercise, heart rate had increased from 72 ± 14 to 126 ± 21 beats/min (p < 0.001) and systolic blood pressure had risen from 106 ± 10 to 141 ± 11 mm Hg (p < 0.001). A small

| TABLE 1. Repeat Handgrip Exercise Studies in Five Subjects |
|----------------------------------|----------------------------------|
|                                  | HR beats/min                      | SBP mm Hg                        |
|                                  | B 15% 50%                         | B 15% 50%                        |
| Study 1                         | 57 ± 9 62 ± 13 75 ± 9             | 109 ± 11 119 ± 11 135 ± 20       |
| Study 2                         | 66 ± 11 69 ± 11 77 ± 9            | 104 ± 4 120 ± 7 135 ± 7          |
| Study 1                         | 38 ± 4 34 ± 7 34 ± 4              | 1.21 ± 0.22 1.09 ± 0.22 1.11 ± 0.18 |
| Study 2                         | 38 ± 4 34 ± 7 33 ± 4              | 1.28 ± 0.20 1.13 ± 0.18 1.15 ± 0.25 |

Abbreviations: HR = heart rate; SBP = systolic blood pressure; %ΔD = percent left ventricular minor dimension shortening; Vd = normalized mean rate of left ventricular dimension shortening; B = baseline.

Figure 3. Effect of intravenous atropine and phenylephrine (A + P) on heart rate (HR), systolic blood pressure (SBP), percent left ventricular minor dimension shortening (%ΔD) and mean normalized rate of dimensional shortening (Vd) in 10 normal subjects.
rise in Dd was not statistically significant (46.5 ± 3.6 vs 48.9 ± 5.7 mm, p > 0.05). Ds decreased significantly from 29.1 ± 3.8 to 24.2 ± 4.4 mm (p < 0.001) and %ΔD increased from 38 ± 6 to 51 ± 6 (p < 0.001).

Five of the 12 subjects repeated upright bicycle ex-
Exercise on another day and their exercise duration was unchanged (one 12 minutes, four 15 minutes). Individual values at each stage between the two studies varied somewhat, but the overall response to exercise was the same. Mean heart rate, systolic blood pressure, Dd, Ds and %ΔD were not statistically different between the two studies at rest, nor at 3, 6, 9, and 12 minutes of exercise (table 2).

**Discussion**

The circulatory response to handgrip exercise is complex and partly dependent on the severity of the handgrip stress. The general response to isometric exercise is similar to that of any type of exercise and consists of an increase in heart rate, blood pressure and cardiac output. However, in contrast to other forms of exercise, at 50% or greater of maximum voluntary contraction, stroke volume has been noted to decrease. Our results, using echocardiography to measure the left ventricular internal dimensions, are in agreement with these findings. We saw a diminution in %ΔD and Vd during handgrip exercise, which was most marked at 50% of maximal voluntary contraction.

There are few previous data concerning changes in end-diastolic volume during handgrip exercise. In five normal persons studied with a plain radiographic technique, the cardiac silhouette decreased during 15% maximum voluntary grip. A recent cineangiographic study evaluated six normal persons during a 30% maximum voluntary grip and showed a decrease in end-diastolic volume. An earlier echocardiographic study using the Polaroid technique showed no change in Dd during 50% of maximal grip in 20 normal subjects. Our results showed no significant change in Dd at the point of fatigue at either 15% or 50% of maximum grip. Therefore, the results of the

**Table 2. Repeat Upright Exercise Studies in Five Subjects**

<table>
<thead>
<tr>
<th>Study</th>
<th>Dd (mm)</th>
<th>Ds (mm)</th>
<th>%ΔD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>6 min</td>
<td>12 min</td>
</tr>
<tr>
<td>1</td>
<td>46.2 ± 3.9</td>
<td>49.8 ± 3.3</td>
<td>48.6 ± 4.0</td>
</tr>
<tr>
<td>2</td>
<td>47.7 ± 2.4</td>
<td>49.9 ± 2.2</td>
<td>49.3 ± 3.0</td>
</tr>
</tbody>
</table>

Abbreviations: Dd = left ventricular end-diastolic dimension; Ds = left ventricular end-systolic dimension; %ΔD = percent left ventricular minor dimension shortening.
radiographic and echocardiographic studies differ. There are certain methodological problems with the radiographic studies. The plain radiographic technique does not accurately distinguish the left ventricle from the rest of the cardiac silhouette. Also, cineangiographic contrast material injected for the control angiographic study may affect left ventricular size and performance and modify the subsequent response to isometric exercise. However, the response to handgrip exercise is complex and the smaller number of subjects in the two radiographic studies (11 total) than in the echocardiographic studies (47 total) may be a more important factor in explaining the differences than methodological problems.

Studies in animals21 and man12 have shown that acute pharmacologic pressure loading results in a decrease in Vd. Our results with handgrip exercise at 50% maximal grip show a reduction in left ventricular performance which was similar to that produced by intravenous atropine and phenylephrine in 10 of the subjects. These findings support the theory that isometric exercise represents an afterload stress to the left ventricle. Acute pharmacologic afterloading has been used in a variety of studies to assess left ventricular reserve in disease states22, 23 and after therapeutic agents.24, 25 Strenuous handgrip exercise seems to accomplish the same result, is simple to perform in cooperative patients, and may represent a more "physiologic" approach to the evaluation of left ventricular functional reserve.

In animals, studies using endocardial echo crystals inserted surgically across the left ventricular chamber for the continuous measurement of diameter have shown a progressive decrease in Ds during dynamic exercise which corresponds to an increase in stroke volume.26-28 Human studies using surgically placed epicardial lead markers fluoroscopically visualized during bicycle exercise have also demonstrated a decrease in the distance between the clips at end-systole with progressive exercise.29 Also, studies using left ventricular contrast angiography30 and radionuclide angiography31 have shown a decrease in end-systolic volume at maximum bicycle exercise. Our results are in agreement with these findings and support the concept that increases in stroke volume are an important part of the normal response to isotonic exercise.

Controversy exists concerning left ventricular end-diastolic volume during dynamic exercise. Animal studies using implanted subendocardial echo crystals showed no change in end-diastolic diameter during mild-to-moderate exercise, but an increase during severe exercise.26-28 Also, in a recent study using radionuclide angiography during submaximal upright bicycle exercise (85% of maximum predicted heart rate), two-thirds of the subjects exhibited a modest increase in end-diastolic volume and the mean difference was statistically different (p < 0.02).31 However, the resting data were done 10-30 minutes after the exercise study. By contrast, human studies using angiography and epicardial clips have demonstrated a 5-10% decrease in Dd during moderate supine exercise.29, 30 Our results showed no significant change in Dd during moderate supine or upright bicycle exercise. The inability of echocardiography to detect consistent changes in Dd during exercise may represent a technical sensitivity problem or could be related to the submaximal amount of exercise performed by most of our subjects. Four of our subjects achieved what could be considered severe isotonic exercise (heart rate ≥ 170 beats/min), but there was no consistent difference in Dd.

The sensitivity of the external echocardiographic technique for assessing change in left ventricular size is demonstrated by comparing the resting Dd supine and upright (on the bicycle) in the 12 subjects who performed both types of exercise. Resting Dd supine was 50.9 ± 4.2, significantly larger than the Dd upright of

![Figure 7. Percent change in heart rate (HR), systolic blood pressure (SBP), and percent left ventricular minor dimension shortening (%ΔD) from rest to handgrip exercise at 50% of maximum grip (HG) and to 9 minutes of supine (SUP) and upright (UP) graded bicycle exercise.](Image)
47.0 ± 3.3 (p < 0.01). This difference persisted during exercise but was less marked. Six of these 12 subjects had more than a 2-mm change in Dd between the upright resting recording and the 3 minutes of exercise recording and in all six the change was an increase in Dd (+ 2.7 to 6.8 mm). These findings support the concept that the activation of the leg muscles at the onset of upright cycling initially augments left ventricular end-diastolic volume. Such changes during the first 3 minutes of exercise were not seen in the supine position; presumably, venous return is near maximum at rest.

There are potential problems with external echocardiography during exercise. Even though we very carefully recorded the resting tracings in the position in which the exercise was to be performed, used the same transducer position for each recording, recorded only when the same anatomic landmarks were present, and analyzed only the beats recorded during the same phase of respiration as the resting tracing, changes in heart position during exercise could have occurred and influenced our results. We noted small changes in left ventricular size and performance in some of the subjects who repeated the exercise studies which may have been due to spontaneous alterations in sympathetic tone, a training effect, etc., but the directional changes in Dd, Ds and %ΔD with each form of exercise were always the same.

A comparison of the hemodynamic response to isometric and dynamic exercise may partly explain their opposite effect on left ventricular performance. Figure 7 shows the percent change in heart rate, systolic blood pressure and %ΔD during isometric handgrip exercise at 50% of maximum grip and 9 minutes of supine and upright bicycle exercise. Heart rate increases much more during dynamic exercise than during isometric exercise, yet the increases in blood pressure are similar. Therefore, isometric exercise produces a relatively greater increase in blood pressure than in heart rate that may result in sufficient afterload stress to account for the decrease in left ventricular performance.

This study shows that M-mode echocardiograms of the left ventricle can be successfully recorded in selected subjects during various types of exercise. These results in normal subjects form a basis for evaluating differences in the response of the left ventricle to exercise in disease states and under the influence of cardioactive drugs. For example, if a patient has compensated cardiac function at rest, left ventricular size and performance indices could be normal, but during the stress of exercise an abnormal response may be detected. Preliminary data suggest that twodimensional echocardiographic studies can also be performed during exercise, which should be of more value in patients with segmental myocardial disease.

Acknowledgment

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References

17. Payne RM, Horwitz L, Mullins CB: Comparison of isometric exercise and angiotensin infusion as stress test for evaluation of left ventricular function. Am J Cardiol 31: 428, 1973
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 ($r > 0.93$). 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. However, the presence of regional wall motion disorders has limited the reliability of the single-chord technique for determining ejection fraction. 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. We applied the techniques of left ventricular angiographic 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° right anterior oblique and 75° 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-
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