Dynamic Exercise Echocardiography

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SUMMARY To evaluate left ventricular (LV) reserve, we developed a method of dynamic exercise echocardiography (DEE). Forty-six healthy persons and 47 cardiac patients performed bicycle ergometer exercise in the supine position. A special table was used on which the subjects could be firmly attached at shoulder level to prevent bodily movements which might disturb the recordings. In 83% of the subjects in whom a clear echocardiogram was obtained at rest, a clear echocardiogram was also obtained during dynamic exercise. During exercise, cardiac output estimated from the echocardiogram and that from the dye-dilution method showed an excellent correlation. The changes of the mean velocity of LV circumferential shortening during exercise permitted discrimination between older and younger healthy men, and also between healthy subjects and those with either mild or severe LV dysfunction. We conclude that DEE is useful for evaluating LV reserve.

IN EVALUATING cardiac patients, it is important to be able to estimate left ventricular reserve. This can be done by measuring various parameters of cardiac mechanics during exercise. However, reliable and easily available methods have been lacking. For example, left ventricular catheterization cannot be easily performed during exercise. Radionuclide imaging shows great promise, but problems of image resolution remain. Recently, echocardiography has been used to obtain indices of left ventricular performance at rest. Stefadouros et al. applied echocardiography to static exercise. However, there are important differences between static and dynamic exercise. Reports of the application of echocardiography to studies of dynamic exercise are scarce. Krauz and Kennedy and Smithen et al. attempted to use echocardiography for this purpose, but they analyzed only left ventricular posterior wall movement (presumably epicardial) and not the transverse diameter of the left ventricle. Redwood et al. made recordings of cardiac movements by echocardiography with subjects in an upright position, but it required very complicated apparatus.

We have developed a method of dynamic exercise echocardiography (DEE) that is performed with the patient in the supine position. It enables us to obtain the same parameters of left ventricular performance as at rest. This method has been applied to healthy men and to cardiac patients.

Methods

Ninety-three subjects were separated into three groups. Group 1 included 46 healthy subjects in whom physical and laboratory examinations revealed no abnormal findings. This group included 16 young people (age 20–30 years, mean 25.2 ± 2.0 years), 18 middle-aged (31–49 years, mean 40.7 ± 10.0 years) and 12 older people (age 50–71 years, mean 56.8 ± 2.0 years). There were equal numbers of males and females in the study and in the age subgroups.

Group 2 consisted of 35 patients with a variety of diseases affecting the left ventricle. This group included 15 patients with hypertension, six with mitral valvular disease, five with aortic valvular disease, five with idiopathic cardiomyopathy, and four who had various other conditions. Diagnoses were based on physical and laboratory examination, including chest x-ray films, ECG, phonocardiography, echocardiography, and cardiac catheterization. Group 2 contained 21 patients younger than 50 years (young-middle-aged subgroup) and 14 patients 50 years and older (older subgroup). Patients were chosen whose left ventricular disease was not so advanced that it prevented the performance of a degree of ergometer exercise sufficient to raise the heart rate to 100 beats/min (method described below) with no subjective complaints. Thus, severe cases were excluded from this study, since their state of malfunctions was obvious and they did not require the discriminatory separation that we hoped to achieve by the exercise test.

The patients in group 2 were divided into two subgroups. Group 2A patients had mild left ventricular disease, and group 2B patients had moderately severe left ventricular disease. An estimate of severity was determined by a scoring system using the following criteria: 1) a history of congestive heart failure (present — 1, absent — 0); 2) New York Heart Association functional classification (class I — 1, class II — 2, class III — 3); 3) objective symptoms of congestive heart failure (present — 1, absent — 0); 4) cardiothoracic ratio on the chest x-ray film (> 50% — 1, < 50% — 0); and 5) left ventricular hypertrophy by ECG (present — 1, absent — 0).

Group 3 included 12 subjects with exertional angina pectoris. All subjects in this group were older than 50 years. The diagnosis was based on the history of anginal attacks on exertion and laboratory examination, including ECG, stress ECG and coronary arteriograms.

The subjects performed ergometer exercise in a supine position on a special table (fig. 1) that we developed for this method. The surface of the table is firm, so the subject does not sink during exercise. The subject is fixed at shoulder level by attachments that extend from the tip of the shoulders to the neck (figs. 2...
and 3). These prevent shaking movements that would have disturbed the echocardiogram. The shoulder attachments were movable to any position on the long axis of the table by means of a screw. This permitted a tight fit of the apparatus regardless of the subject's height. The head of the table could be raised as required for comfort.

On this table, the echocardiogram was recorded by standard methods, using an Aloka SSD 110 ultrasonoscope with a 3.5-MHz, 13-mm diameter transducer focused at 7.5 cm. The transducer was placed in the third or fourth left intercostal space at the left sternal edge, where the characteristic echo from the anterior cusp of the mitral valve could be identified. Then the transducer was angled to demonstrate the interventricular septum and the left ventricular posterior wall just below the tip of the mitral leaflets at the level of the chordae tendineae. Reject and attenuation controls were manipulated to achieve optimal echoes. The transducer was held at the same point on the chest wall throughout the examination.

To obtain the true minor dimension of the left ventricular cavity, and to standardize the technique between patients, as well as in the same patient at rest and during exercise, the left ventricle was scanned along its major axis during both rest and exercise, until a satisfactory echocardiogram was obtained. Recordings were made mainly during the expiratory phase. Echocardiograms were photographed on Polaroid film or on light-sensitive paper (Kodak Linagraph, 1895) at a paper speed of 50 mm/sec, using a Honeywell 1856 strip chart recorder. An electrocardiographic lead was recorded on the echocardiogram to facilitate timing of the cardiac cycle. A carotid pulse tracing, obtained through a funnel held manually over the carotid artery, was also recorded on the echocardiogram.

Left ventricular minor diameters were measured as the distance between the echo of the left side of the interventricular septum and the endocardial echo of the left ventricular posterior wall. Measurements of end-diastolic left ventricular diameter (Dd) were made at
FIGURE 3. Drawing of the attachments on the table. A) Side view; B) horizontal view.

The time of the R wave of the ECG, and measurements of end-systolic diameter (Ds) were made at the time of least separation of the two echoes. Distances were measured using a centimeter scale superimposed on all records. Left ventricular end-diastolic and end-systolic volumes (LVEDV and LVESV) were calculated using the equation of Gibson, and stroke volume was calculated as end-diastolic volume minus end-systolic volume. Cardiac output was calculated as stroke volume times heart rate. Ejection fraction (EF, percent) was calculated as stroke volume \( \times \) 100/LVEDV. Left ventricular ejection time (LVET) was measured from the carotid pulse tracing. The mean velocity of circumferential fiber shortening (mean Vcf, circ/sec) was calculated as

\[
\frac{(D_d - D_s)}{D_d \times LVET}.
\]

The total excursion of the posterior wall endocardium during systole (PWE, cm) and the total excursion of the interventricular septum during systole (IVSE, cm) were measured, and by dividing these by Dd and by LVET, the normalized mean posterior wall velocity \( V_{pww} \text{, sec}^{-1} \), and the interventricular wall velocity \( V_{wva} \text{, sec}^{-1} \) were calculated by the method of Quinones et al. These can be considered as the parameters of local myocardial contractility of the left ventricular posterior wall and of the interventricular septum.

The measurements at rest were performed with the subject's legs already attached to the bicycle ergometer (Monark). Then, ergometer exercise was performed at 40 cycles/min in a supine position with ECG monitored by oscilloscope, until the heart rate rose to 97–109 beats/min (abbreviated to 100 beats/min), when the measurements were again recorded. Exercise was begun at a level of 0.5 kg; if the heart rate did not rise to 100 beats/min by 1 minute, the level was increased by 0.5 kg every 2 minutes until heart rate did rise to 100 beats/min. Mean exercise level was 1 kg and average exercise periods lasted 2 minutes. In some cases, exercise was continued until the heart rate rose to 120–130 beats/min. In group 3, the exercise was also interrupted at the appearance of typical anginal pain, ST-segment depression 2 mm, or life-threatening dysrhythmias on ECG.

In 12 subjects, cardiac output was measured by the dye-dilution method simultaneously with echocardiography, both at rest and during exercise. A 19-gauge polyvinyl catheter 60 cm long was inserted into the antecubital vein. Five milligrams of indocyanine green dye in 1 ml distilled water was flushed into the vein with 10 ml saline. A dye-dilution curve was recorded by densitograph (Nihon-kohden Company), using an earpiece, and cardiac output was calculated. (The validity of measuring cardiac output using an ear-oximeter has been validated by correlating this method with dye-dilution curves obtained by arterial blood withdrawal.) The cardiac output measurements by the two methods were performed in the steady state at rest and during exercise at heart rate of 100 beats/min, except one case in which the heart rate rose to 144 beats/min after 9 minutes of exercise.

In six subjects, DEE was performed twice with an interval of about 15 minutes, and the values were compared to investigate the reproducibility of the method.

Statistical comparisons were made with the \( t \) test.

**Results**

Figure 4 shows a resting and a dynamic exercise echocardiogram in a 36-year-old female. The endocardial echo of the left ventricular posterior wall and left side of the interventricular septum can be seen clearly, even during exercise. Echoes of chordae tendineae indicate that these echocardiograms are from the same part of the left ventricle, both at rest and during exercise. Among subjects in whom a clear echocardiogram could be obtained at rest, a clear exercise echocardiogram was also obtained in 83%.

Figure 5 shows a comparison of cardiac output determined by echocardiography and by the dye-dilution method at rest and during exercise. Almost identical values were obtained by the two methods. The correlation coefficient was highly significant \((r = 0.96, p < 0.01)\).

Figure 6 is a comparison of Dd, LVEDV, stroke volume and mean Vcf between the first and second dynamic exercise echocardiograms in six subjects.

Table 1 shows the hemodynamic parameters obtained by DEE in males and females. Their age distribution was not statistically different. Dd, LVEDV
Figure 4. Echocardiogram of a 36-year-old female at rest (A) and during dynamic exercise (B). Paper speed is 50 mm/sec. CAR = carotid wave; IVS = interventricular septum; LVPW = left ventricular posterior wall; PCG = phonocardiogram; HR = heart rate. The arrow points to the end-expiratory cycle that we used to make the measurements.

Figure 5. Comparison of the cardiac output determined by echocardiography and by the dye-dilution method. The asterisk indicates cardiac output at a maximum heart rate of 144 beats/min.

and cardiac output were greater in males, but their values corrected for body surface area showed no significant differences between the sexes. The other parameters showed no significant differences between the sexes. Cardiac index and mean Vcf showed significant increases with exercise in both sexes, but there was no difference in the extent of the increase, as shown in table 2.

Table 3 shows the hemodynamic parameters obtained by DDE in young, middle-aged and older subjects. Each subgroup included an equal number of both male and female subjects. Dd and LVEDV, which were significantly greater in the older subjects at rest, showed no significant change during exercise. Cardiac output increased with exercise in all of the age categories to the same degree (table 4). During exercise, mean Vcf increased to the same degree in the young and middle-aged subjects (table 4), but in the older persons, it showed no significant change and became even smaller than the values for the young and middle-aged subjects at rest. EF did not differ among the age categories, and did not change during exercise in all ages studied.

Figure 7 shows the changes in mean Vcf during exercise, as an average in young-middle-aged and older individuals in group 1, and in each case of group 2A and 2B. (As the exercise response of young healthy men and middle-aged healthy men showed no difference, young and middle-aged subjects were combined and contrasted to older subjects.) The heart rate at rest was: in the young-middle-aged, group 1 — 66.6 ± 2.0 beats/min; group 2A — 71.4 ± 2.8 beats/min; and in the older patients, group 1 — 68.9 ± 2.5 beats/min; group 2A — 68.1 ± 4.3 beats/min. There were no significant differences among the groups. Mean Vcf at rest showed no significant
Table 1. Hemodynamic Parameters Obtained by Dynamic Exercise Echocardiography in Male and Female

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>HR (beats/min)</th>
<th>Dd (cm)</th>
<th>Ddi (cm/hr)</th>
<th>LVEDVI (ml)</th>
<th>LVEDV (ml)</th>
<th>SV (ml)</th>
<th>CO (l/min)</th>
<th>CL (l/min/m²)</th>
<th>Mean Vcf (cm/sec)</th>
<th>EF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male (n = 23)</td>
<td>40.3 ± 3.1</td>
<td>66.6 ± 2.4</td>
<td>5.2 ± 0.1</td>
<td>3.1 ± 0.1</td>
<td>159 ± 7</td>
<td>31 ± 1</td>
<td>152 ± 6</td>
<td>86 ± 4</td>
<td>6.80 ± 0.38</td>
<td>4.05 ± 0.23</td>
</tr>
<tr>
<td>Female (n = 23)</td>
<td>41.3 ± 2.9</td>
<td>66.9 ± 2.1</td>
<td>4.7 ± 0.1</td>
<td>3.1 ± 0.1</td>
<td>123 ± 6</td>
<td>31 ± 1</td>
<td>126 ± 5</td>
<td>86 ± 4</td>
<td>5.80 ± 0.26</td>
<td>3.94 ± 0.22</td>
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<tr>
<td>Exercise</td>
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</table>

Table 2. Changes in Cardiac Output and Mean Velocity of Circumferential Fiber Shortening During Dynamic Exercise Echocardiography

<table>
<thead>
<tr>
<th></th>
<th>ΔCO (%)</th>
<th>Δmean Vcf (%)</th>
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</thead>
<tbody>
<tr>
<td>Male</td>
<td>50.3 ± 5.2</td>
<td>8.2 ± 4.4</td>
</tr>
<tr>
<td>Female</td>
<td>44.2 ± 4.6</td>
<td>6.8 ± 2.1</td>
</tr>
<tr>
<td>p</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Abbreviations: ΔCO = change in cardiac output; Δmean Vcf = change in mean velocity of circumferential fiber shortening.
Table 3. Hemodynamic Parameters Obtained by Dynamic Exercise Echocardiography in Young, Middle-aged and Older Subjects

<table>
<thead>
<tr>
<th></th>
<th>HR (beats/min)</th>
<th>BP (mm Hg)</th>
<th>Dd (cm)</th>
<th>Ds (cm)</th>
<th>LVET (sec)</th>
<th>LVEDV (ml)</th>
<th>CO (l/min)</th>
<th>EF (%)</th>
<th>Mean Vcf (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young (n = 16)</td>
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<tr>
<td>Rest</td>
<td>66.6 ± 2.8</td>
<td>133 ± 3</td>
<td>73 ± 3</td>
<td>5.0 ± 1</td>
<td>3.3 ± 0.1</td>
<td>0.288 ± 0.005</td>
<td>141 ± 9</td>
<td>6.11 ± 0.48</td>
<td>67 ± 2</td>
</tr>
<tr>
<td>Exercise</td>
<td>129 ± 5</td>
<td>85 ± 3</td>
<td>4.9 ± 1</td>
<td>3.2 ± 1</td>
<td>0.267 ± 0.007</td>
<td>139 ± 9</td>
<td>9.01 ± 0.48</td>
<td>68 ± 1</td>
<td>1.31 ± 0.05</td>
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<tr>
<td>p</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.02</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
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<tr>
<td>Middle-aged (n = 18)</td>
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</tr>
<tr>
<td>Rest</td>
<td>66.5 ± 2.3</td>
<td>119 ± 2</td>
<td>77 ± 2</td>
<td>4.8 ± 1</td>
<td>3.1 ± 0.1</td>
<td>0.298 ± 0.006</td>
<td>133 ± 5</td>
<td>6.10 ± 0.21</td>
<td>70 ± 1</td>
</tr>
<tr>
<td>Exercise</td>
<td>146 ± 4</td>
<td>94 ± 2</td>
<td>4.8 ± 1</td>
<td>3.0 ± 1</td>
<td>0.286 ± 0.006</td>
<td>132 ± 6</td>
<td>9.00 ± 0.29</td>
<td>71 ± 1</td>
<td>1.30 ± 0.03</td>
</tr>
<tr>
<td>p</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
</tr>
<tr>
<td>Older (n = 12)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>68.9 ± 2.5</td>
<td>124 ± 4</td>
<td>86 ± 2</td>
<td>5.2 ± 0.2</td>
<td>3.4 ± 0.1</td>
<td>0.316 ± 0.006</td>
<td>159 ± 13</td>
<td>6.87 ± 0.57</td>
<td>68 ± 2</td>
</tr>
<tr>
<td>Exercise</td>
<td>142 ± 2</td>
<td>92 ± 2</td>
<td>5.2 ± 0.2</td>
<td>3.4 ± 0.1</td>
<td>0.303 ± 0.006</td>
<td>160 ± 11</td>
<td>9.53 ± 0.58</td>
<td>68 ± 2</td>
<td>1.13 ± 0.05</td>
</tr>
<tr>
<td>p</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
</tr>
</tbody>
</table>

*p between the groups at rest

Between young and middle
Between middle and older
Between young and older

NS = not significant

Abbreviations: HR = heart rate; BP = blood pressure; Dd = left ventricular end-diastolic diameter; Ds = left ventricular end-systolic diameter; LVET = left ventricular ejection time; LVEDV = left ventricular end-diastolic volume; CO = cardiac output; EF = ejection fraction; Mean Vcf = mean velocity of circumferential fiber shortening.

Discussion

Echocardiographic Evaluation of Left Ventricular Performance

Although the measurement of angiographic left ventricular volume and other parameters derived from it have valuable information about left ventricular performance, cardiac catheterization and hemodynamic evaluation provide more detailed information. Additionally, echocardiography allows for non-invasive assessment of cardiac function under dynamic conditions, which is particularly relevant for exercise settings.

In figure 9A, both the velocities changed in the same direction during exercise, but in figure 9B, they changed in the opposite directions. Figure 7 demonstrates changes of mean velocity of circumferential fiber shortening rate during exercise. When the heart rate increased to 100 beats/min, in group 1, it is shown on average about young-middle-aged subgroup and older subgroup. In group 2A and 2B, it is shown about each case of group 3 (fig. 9B). In figure 7, it is shown about mean Vcf changes in the opposite directions. Figure 9B shows increase in mean velocity of circumferential fiber shortening, mean Vcf = mean velocity of circumferential fiber shortening.
angiocardiology are not without risk and cannot be performed repeatedly to assess the progression of myocardial dysfunction. Recently, echocardiography has been used to study left ventricular performance. Measurements of cavity dimensions can be used to estimate left ventricular volumes from which one can derive stroke volume, cardiac output and EF. A second index of ventricular performance, the mean Vcf, has been derived from simultaneous measurements of cavity size and LVET, and shown to correlate with other indices of contraction.

The reliability of these parameters of left ventricular performance is controversial, especially left ventricular volume obtained by echocardiography. However, it is widely believed that the parameters directly obtained from the measurements of transverse diameter, such as Dd and Ds, are reliable when they are recorded just below the tip of the anterior mitral leaflet and when the endocardial surface of the left ventricular posterior wall echo and the septal echo are clearly recorded. Left ventricular volume can be calculated from assumptions about ventricular geometry, except in special cases, such as ischemic heart diseases with asynergy.

### Technique of Dynamic Exercise Echocardiography

Only a few reports concerning echocardiography during dynamic exercise are available. Kraunz et al. recorded echocardiograms after exercise. Their observations and those of Smithen et al. showed only left ventricular posterior wall movement. From the figures in their papers one has difficulty identifying the endocardial surface of the left ventricular posterior wall. In order to obtain our hemodynamic estimates we measured the transverse left ventricular diameter, which provides an estimate of the diastolic volumes of the ventricle, a parameter of left ventricular preload. Observations of the transverse diameter just below the tip of anterior mitral leaflet can be a valuable marker to insure reproducibility in repeating the measurements during exercise. We did not find it necessary to use a device to hold the transducer in an upright position as was done by Redwood, and felt that this addition would be too cumbersome.

There may be two principal problems in DEE: whether clear echocardiograms can be obtained during exercise, and whether the values obtained from them should be considered an index of left ventricular performance.

To solve the first problem, we have taken the following steps: 1) Ergometer exercise was performed in a supine position. Redwood et al. carried out echocardiography during exercise with the patient in the standing position, but found this method difficult. With the patient in the supine position, the transducer can be held in an optimal position during dynamic exercise and at rest. 2) We designed a special table for

### Table 5. Statistical Comparisons of the Percent Change in Mean Velocity of Circumferential Fiber Shortening

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2A</th>
<th>Group 2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young-middle-aged</td>
<td>+12.1 ± 1.2</td>
<td>+7.1 ± 1.0</td>
<td>-15.5 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>p &lt;0.02</td>
<td>p &lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Older</td>
<td>+2.8 ± 2.7</td>
<td>-7.6 ± 0.5</td>
<td>-11.2 ± 2.7</td>
</tr>
<tr>
<td></td>
<td>p &lt;0.05</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p &lt;0.01</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>p &lt;0.001</td>
<td>p &lt;0.001</td>
<td>NS</td>
</tr>
</tbody>
</table>

### Table 6. Statistical Comparisons of Changes in Cardiac Output during Exercise

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2A</th>
<th>Group 2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young-middle-aged</td>
<td>+51.0 ± 3.9</td>
<td>+43.5 ± 6.8</td>
<td>+26.0 ± 5.8</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p &lt;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Older</td>
<td>+37.8 ± 4.3</td>
<td>+22.4 ± 3.6</td>
<td>+22.4 ± 5.8</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p &lt;0.05</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
this examination, as shown in figures 1, 2 and 3. The surface of the table is firm, so the subject does not sink during exercise. The attachments fix the subject to the table and prevent him or her from shaking, thus significantly increasing the proportion of subjects in whom tracings of good quality can be obtained. The shoulder attachments can be adjusted to suit the subject's height. 3) The recordings of the echocardiogram were performed mainly during the expiratory phase. 4) The transducer was placed at the same point on the thorax at rest and during exercise, but was not fixed in a certain direction. During each recording period, both at rest and during exercise, the left ventricle was scanned with the transducer along its major axis, until a satisfactory left ventricular echocardiogram, just below the tip of the anterior mitral leaflet, could be obtained. Scanning during exercise is not difficult. By using these four precautions in subjects in whom a clear echocardiogram was obtained at rest, we could obtain acceptable recordings during exercise in 83% of our patients.

The second problem has been investigated as follows: 1) To standardize the part of the left ventricle measured, the recording was always performed just below the tip of the anterior mitral leaflet. 2) The cardiac output obtained by the echocardiogram showed almost the same value as that obtained by the dye-dilution method both at rest and during exercise. (The left ventricular volumes and mean Vcf could not be compared with other methods, because they could be confirmed only by angiography.) 3) The values of hemodynamic parameters were reproducible in repeat examinations. If the echocardiogram can be obtained during exercise from the same part of the left ventricle as at rest, it can be used to obtain hemodynamic indices comparable to those obtained at rest. There may be a small difference in the part of the left ventricular echograms examined between at rest and during exercise; but we avoided this problem in many cases by trying to obtain similar echocardiographic patterns by scanning the left ventricle at each recording.

**Figure 8.** Changes of mean velocity of circumferential fiber shortening during exercise in each case of group 3.

**Figure 9.** Changes in mean posterior wall velocity \( V_{pw} \) and mean interventricular velocity \( V_{iv} \) during exercise A) in 12 cases who were sampled from groups 1 and 2 by a random sampling method, and B) in all cases in group 3.

**Technique of Dynamic Exercise**

Bicycle ergometer exercise in this study was performed at a level that increased heart rate to 100 beats/min in a supine position. The reasons this method was chosen are:

1) Heart rate is a parameter that can be used to assess exercise stress. There is a good correlation between the heart rate and oxygen consumption up to near-maximal levels of exercise; thus, heart rate can be used to predict oxygen consumption.\(^{16}\)

2) Exercise that elevates heart rate up to 100 beats/min is considered safe even for older persons,
because this exercise level is frequently experienced in daily life even by patients with ischemic heart disease. As shown in this study, even these mild levels of exercise induced significant changes in hemodynamic parameters.

3) Severe exercise often induces extreme expansion of the lungs that interferes with the echocardiogram. Exercise associated with heart rates of up to 100 beats/min did not disturb the recordings in most subjects.

Left Ventricular Reserve

Cardiac output is usually regulated by heart rate and stroke volume. Stroke volume is affected by preload, myocardial contractility and afterload. Left ventricular reserve is defined by the maximal left ventricular performance, and is primarily determined by myocardial contractility. Many cardiomechanical parameters, including mean Vcf, have been studied in an effort to define myocardial contractility. In the present study, we tried to express left ventricular reserve, especially the reserve of myocardial contractility, by the response of mean Vcf to exercise. The ideal expression of reserve is the response to maximal exercise, but when the response to even mild exercise can discriminate groups with different levels of severity of left ventricular disease, maximal exercise is not necessary. Thus, maximal exercise, which is not always safe in cardiac patients, can be avoided.

In our study, mean Vcf at rest was not different among the age categories. This observation confirmed the findings of Gerstenbilith et al.17 Moreover, our study revealed that in young and middle-aged men mean Vcf increased during exercise, but this did not occur in older men. This suggests that in older men left ventricular reserve is decreased. The increase of cardiac output with exercise showed no difference among young, middle-aged or older healthy men, as shown in table 4, which is comparable to the study of Dominick et al.18 However, mean Vcf was different among them. As shown in figure 7 and table 5, the responses of mean Vcf to exercise were significantly different depending on the age and the severity of heart disease, although the resting values of mean Vcf were not different. This indicates differences in left ventricular reserve due to these factors. Mean Vcf is a useful parameter for detecting left ventricular reserve, because it is more sensitive than cardiac output as an index of contractility (tables 5 and 6).

In patients with exertional angina pectoris, we calculated mean Vcf as we did for normal subjects or other cardiac patients. It decreased during exercise in four cases. During exercise, Vpw and Vvw, which are the parameters of local myocardial contractile velocity of left ventricle, changed in the opposite directions in the patients of exertional angina pectoris, but changed in the same direction in the other subjects (figs. 9A and 9B). Thus, in ischemic heart disease, the changes of Vpw and Vvw might be more sensitive parameters of myocardial reserve than the change of mean Vcf.

Bruce et al.19 calculated the percent deviation from observed values for maximal pressure-rate product and maximal heart rate in healthy subjects of various age groups and emphasized the importance of distinguishing between the response to maximal exercise caused by cardiovascular diseases and that caused by aging. Our study is in accord with these observations, with data derived from ventricular mechanics.

Characteristics in Dynamic Exercise Echocardiography

DEE is useful because 1) it gives information about the reserve of left ventricular performance, including left ventricular dimension, which can not easily be measured by other methods; 2) it discriminates the difference in left ventricular reserve among normals and mild and moderately severe left ventricular disease; 3) it is noninvasive and can be performed repeatedly; 4) the movement of the chambers of the heart can be observed directly; and 5) the left ventricular performance of each beat can be observed.

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Acute Hemodynamic Effects of Cigarette Smoking in Man Assessed by Systolic Time Intervals and Echocardiography

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SUMMARY Sixteen healthy subjects, ages 18-35 years, were studied in the supine position by means of systolic time intervals and echocardiography before and after smoking a high-nicotine cigarette (2.5 mg nicotine) and a tobacco cigarette of very low nicotine content (< 0.02 mg nicotine) to assess and compare the immediate effects upon left ventricular function.

Smokers (n = 12) and nonsmokers (n = 4) behaved alike. High- and low-nicotine cigarettes both caused significant increases in heart rate, systolic and diastolic blood pressure and the triple product (systolic blood pressure × left ventricular ejection (LVET) × heart rate), prolonged LVETc and decreased the prejection period (PEP) and PEP/LVET. In addition, smoking a nicotine reference cigarette increased the echocardiographically derived LV end-diastolic volume by 7.5%, augmented ejection fraction by 4%, while significantly enhancing mean normalized circumferential fiber shortening by 12.5% and mean normalized posterior wall velocity by 9%. Smoking a tobacco cigarette of ultra-low nicotine content resulted in comparable increases in ejection fraction and mean circumferential fiber shortening, albeit on the basis of a significant decrease in end-systolic volume without alteration in end-diastolic volume.

These data suggest that in the supine position smoking a high-nicotine cigarette acutely increases venous return and augments the principal determinants of myocardial oxygen consumption—the heart rate, contractility, preload and afterload—and that cigarette smoke may contain inotropic and chronotropic substances other than nicotine.

CIGARETTE SMOKING has been linked epidemiologically as a risk factor in the development of myocardial infarction and has been associated with an increase in sudden death among chronic cigarette consumers.1,2 The cause of this increased morbidity and mortality has not been established; among the factors under consideration are hypoxemia,3 enhanced coronary atherogenesis,4 increased platelet adhesiveness,5,6 and defective fibrinolysis.7,8 Although it has long been known that cigarette smoking has acute effects upon the circulation, including increases in both heart rate and blood pressure, the implied cardiovascular stress produced in healthy subjects has not been assessed quantitatively nor its pathogenesis elucidated adequately.

Thus, the present study was designed to define non-invasively the hemodynamic effects of smoking a high-nicotine content tobacco cigarette vs an ultra-low nicotine content tobacco cigarette.

Materials and Methods

Study Design

Experiment 1

Comparison between a high-nicotine cigarette and a
Dynamic exercise echocardiography.
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