Echocardiographic left ventricular masses in distance runners and weight lifters

JOHN C. LONGHURST, ALLAN R. KELLY, WILLIAM J. GONYEA, AND JERE H. MITCHELL

Harry S. Moss Heart Center and Pauline and Adolph Weinberger Laboratory for Cardiopulmonary Research, Department of Internal Medicine, University of Texas Health Science Center at Dallas, Texas 75235

LONGHURST, JOHN C., ALLAN R. KELLY, WILLIAM J. GONYEA, AND JERE H. MITCHELL. Echocardiographic left ventricular masses in distance runners and weight lifters. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 48(1): 154-162, 1980.—Sixty individuals including 17 competitive weight lifters (CWL), 12 competitive long-distance runners (LDR), 7 amateur (noncompetitive) weight lifters (AWL), 14 heavy controls (HC), and 10 light controls (LC) were studied at supine rest with echocardiographic determination of the left ventricular mass (LVM) by the Penn convention. Lean body mass (LBM) was estimated by the Wilmore-Rehnke method. The absolute LVM (mean ± SE) was increased in the two competitive athlete groups compared to controls (LDR: 195 ± 12; CWL: 190 ± 10 vs. LC: 122 ± 10; HC: 151 ± 9 g). The AWL had a mass (174 ± 20 g) intermediate between the LDR-CWL and the HC-LC groups. A significant (P = 0.033) correlation of LVM was found with LBM although the correlation coefficient was low (r = 0.276). Normalizing LVM by LBM revealed a significantly higher mass for LDR compared to all other groups but equalized CWL and HC (LDR: 3.2 ± 0.2; CWL: 2.5 ± 0.1; AWL: 2.5 ± 0.2; HC: 2.3 ± 0.2; LC: 2.0 ± 0.2 g). These data suggest that training for competitive long-distance running (dynamic training) elevates LVM compared to nonathletic controls and CWL. On the other hand, training for weight lifting (static training) increases absolute LVM but only to the extent that LBM is increased.

Several studies have demonstrated that the mass of the left ventricle is increased in athletes (1, 5, 8, 17, 21, 24, 30). In this regard, hearts of athletes who perform dynamic exercise such as marathon running and swimming have been shown to be larger than hearts of nonathletic populations (5, 8, 17, 21, 24, 30). On the other hand, there are fewer studies of athletes who mainly perform static exercise such as rowing, weight lifting, or shot putting. The studies that are available on these individuals suggest that their hearts are enlarged and that this increase in mass is independent of the generalized increase in body mass that occurs with this form of exercise (21). There is, however, disagreement on this latter point and others believe that cardiac mass, especially left ventricular mass, is intimately related to body mass (12). Therefore, one might expect that the cardiac hypertrophy occurring with dynamic training is real and out of proportion to any increase in body mass, whereas the cardiac hypertrophy associated with static training is more related to the increased body mass, especially that part due to skeletal muscle hypertrophy.

To determine the relationships of different forms of exercise training to left ventricular mass and to determine the interrelationships with body mass, a study was conducted in which controls matched for age, body weight, and body surface area were compared to groups of competitive long-distance runners (dynamic training), competitive weight lifters (static training), and amateur (noncompetitive) weight lifters. In each group, left ventricular mass was determined echocardiographically then related to body weight, body surface area, and lean body mass.

METHODS

Subject selection and group characteristics. Sixty white male subjects were studied including 24 untrained controls, 12 long-distance runners (LDR), 17 competitive weight lifters (CWL), and 7 amateur (noncompetitive) weight lifters (AWL). Based on body weight (BW) and body surface area (BSA) the untrained controls were further divided into two groups including 10 light controls (LC) and 14 heavy controls (HC) for comparison with the runners and weight lifters. The criteria for selection of the untrained controls required that these individuals had not trained for any athletic activity for at least 6 mo prior to the study. Likewise, individuals who performed any type of regular recreational sports activity were excluded from the study. The long-distance runners were all actively training and competitive marathon runners were averaging 79 ± 6.7 mi/wk (range 50-115 mi/wk). These athletes had been running for a mean of 6.4 ± 1.2 yr (range 2-16 yr). The competitive weight-lifter group was also actively training and was composed of eight Olympic weight lifters and nine power lifters. Olympic weight lifters were defined as those individuals who trained with squats, the snatch lift, and the clean and jerk lift. Power lifters (AAU) were defined as those individuals who trained with squats, the dead lift, and the bench lift. In the Olympic weight-lifting group for their weight classification, one had placed ninth in the Olympics, one had won the Pan American Games, two had placed in the National Championships (1 second and 1 fifth), and two had placed in the State Championships (1 first for 8 yr in a row and one second). In the power-
lifter group, for their weight classification, three placed in the National Championships (1 first for 2 yr in a row, 1 fifth, and 1 in the top 10), one placed first in the US Regional Championships, and three placed in the State Championships (1 third, 1 fourth and fifth for 2 yr, and 1 in the top 10). The Olympic weight lifters had competed for 8.9 ± 2.5 yr (range, 1.5-21 yr). The power lifters had competed for 5.8 ± 0.86 yr (range, 3-10 yr). The amateur weight lifters were composed of individuals who were interested primarily in body building, but often combined this activity with running for short distances (1-4 mi), and had not participated in any competitive weight lifting or professional body building. Compared to the competitive weight lifters, who maximized the weight lifted, the amateur lifters attempted to maximize the number of repetitions of weight lifting and therefore did not achieve the same absolute amount of weight lifted for each repetition.

**Anthropometric studies.** All individuals were weighed to the nearest kilogram (BW) and their height was measured to the nearest centimeter. Body surface area was estimated from the DuBois nomogram (7). Subsequently the thigh skinfold (TSF), bi-iliac diameter (BID), neck girth (NG), and abdominal girth (AG) were obtained for estimation of the lean body mass (LBM) by the Wilmore-Behnke method (31)

\[
LBM = 10.14 + 0.926(BW) - 0.188(TSF) + 0.637(BID) + 0.489(NG) - 0.595(AG) \tag{1}
\]

In addition, measurements of the chest skinfold (CSF), scapular skinfold (SSF), and biacromial diameter (BAD) were made and then lean body mass was calculated according to the Pollock formula (22)

\[
LBM = BW[1 - (4.95/1.13 - 0.006(CSF) - 0.00072(SSF) - 0.0008(TSF) + 0.00144(HAD) - 0.0005(HT))] - 4.5] \tag{2}
\]

and the Sloan formula (27)

\[
LBM = BW[1 - (4.95/1.10 - 0.00133(TSF) - 0.00131(SSF))] - 4.5] \tag{3}
\]

Because there were no significant differences between these three methods (average values for all 60 subjects—Wilmore-Behnke: 67.7 ± 1.18 kg; Pollock: 69.5 ± 1.26 kg; Sloan: 69.0 ± 1.18 kg) when compared by an analysis of variance, only values obtained from the Wilmore-Behnke regression equation were used for calculations.

**Cardiovascular studies.** Each individual's systolic and diastolic (= Korotkoff's IV sound or abrupt muffling of the Korotkoff's sounds) arterial blood pressure was recorded by standard sphygmomanometric methods after a period of 10-15 min of supine rest. For the larger individuals, appropriately larger arm cuffs were utilized to prevent overestimation of the blood pressure. At this same time, resting heart rate was recorded by a modified chest lead electrocardiogram (ECG) and averaged over a 15-s period. A modified orthogonal (Frank) lead ECG was also obtained at rest (3) with a MFE four-channel recorder (model M24-CGAHA) and scalar Rx, Ry, and Rz voltage was measured and compared between each group of controls and athletes. From the scalar voltages, by triangulation, maximal spatial QRS voltages for the frontal, horizontal, and right sagittal planes were determined.

**Exercise testing.** To compare the state of aerobic conditioning between groups, maximal exercise testing was performed utilizing a commercially available bicycle ergometer (Monark). The maximal oxygen consumption \( (VO_{2\max}) \) was estimated by the duration of the exercise by a modified method of Sanne (26).

**Echocardiographic methods.** Echocardiographic measurements were made in the 20° upright or 30° left lateral decubitus position using an M-mode echograph equipped with a 2.25-MHz 4-7-cm focused transducer (Unirad Series C). This transducer was placed in the third to fifth left intercostal space, adjacent to the sternum and directly posteriorly. All records were made on light-sensitive rapid-developing paper at a speed of 50 mm/s. A simultaneous electrocardiogram was superimposed on the echocardiogram. Diastolic dimension measurements were taken at the peak of the R wave. Careful attention was given to recording left ventricular dimensions in a constant position for all subjects either at the mitral valve leaflets or just below the tips of the leaflets in the region of the chordae tendineae. The position that afforded the clearest simultaneous endocardial septal and free wall echo reproductions and the widest internal cavity dimension was chosen. In 12 subjects measurements of the left ventricular internal dimension, wall thickness, and calculated left ventricular mass were compared from both positions. There were no significant differences in the measurements at these two sites so that measurements taken at either location were grouped together.

The diastolic interventricular septal thickness (IVSd), left ventricular internal diameter (LVIDd), and left ventricular posterior wall thickness (LPWd) were taken from only high-quality unambiguous echograms (Fig. 1) by both standard (29) and Penn conventions (6). Careful attention was given to ensure correct identification of the right and left septal endocardial surfaces for septal thickness estimation (2). Therefore, the right septal endocard-
dial echo was identified as the most intense right border-
forming echo associated with a series of parallel-moving
echoes. The left septal echo was identified as the most
intense left border-forming echo with a prominent notch
in end systole. The left ventricular free wall thickness in
all cases was determined as the distance between the
endocardial and the epicardial surfaces. The epicardial
surface was identified by its position against the pericar-
dium, the strongest remaining echo when all the echoes
were attenuated (Fig. 1). Measurement of each cardiac
dimension was recorded as the average from three card-
iac cycles by two independent observers (JCL and
ARK) and recorded to the nearest 0.5 mm. Both individu-
als were unaware of the subjects’ activity status. Dis-
crepancies in the two sets of measurements by more than
5% (generally 0.5–1 mm) were carefully reevaluated by
both individuals.

Left ventricular mass (LVM) was determined by both
standard (29) and Penn conventions (6) by the following
regression equations

\[
\text{standard mass (LVM}_d) = 1.05(4\pi/3)[(LVIDd/2) + IVSd + LPWd] - ((LVIDd/2)^2 (LVIDd))
\]

\[
\text{Penn mass (LVM}_p) = 1.04 [(LVIDp) + LPWd]^2 - (IVSdp)^3 - (LVIDdp)^3 - 13.6g
\]

Mean muscle thickness was determined by the formula

\[
\text{IVSd} + \text{LPWd}/2
\]

Left ventricular end diastolic volume (LVVd) was cal-
culated by the cube method (28)

\[
\text{LVVd} = 1.047(LVIDd)^3
\]

Total left ventricular volume was subsequently calcu-
lated by adding the left ventricular cavity volume to the
left ventricular muscle volume. To convert the left ven-
tricular muscle mass (Penn) to left ventricular muscle
volume, the specific gravity of cardiac muscle was as-
sumed to be 1.05. Previous studies have related left ven-
tricular mass to left ventricular volume to determine if
the hypertrophy is appropriate to the increase in vol-
ume (10). Others have related cardiac mass to wall ten-
sion through the application of Laplace’s law (13). There-
fore, the left ventricular mass (Penn)-to-volume ratio
and the left ventricular radius-to-posterior wall thickness
(Penn) ratios were determined for each subject.

Statistical analysis. The directly determined echocar-
diographic measurements as well as the derived masses,
volumes, and ratios were all analyzed by an analysis of
variance with an appropriate multiple comparison’s test
(Fischer’s significant difference test or by the Duncan’s
rank sum test) to assess for nonrandom variation. In
addition, simple linear and nonlinear regression analyses
were applied to determine the relationship between the
two methods of left ventricular mass calculation and the
estimated maximal oxygen consumption or the anthro-
pometric measurements. Differences were considered
statistically significant at \( P \leq 0.05 \).

RESULTS

Characteristics of study population. Average ages of
the athletes and their respective controls were in the mid
to late twenties (Table 1). Heights of the five groups
studied were also comparable. On the other hand, the
weights and body surface areas of the competitive and
amateur weight lifters and the heavy controls were sig-
ificantly higher than the runners and the light controls.
Lean body mass of the competitive weight lifters was sig-
ificantly greater than the other groups, except for
amateur weight lifters who had masses intermediate be-
tween the competitive lifters and all the other groups.

Marathon runners displayed resting heart rates that
were much lower than the other groups including the
weight lifters (Table 2). There were slight but significant
variations in resting systolic and diastolic blood pressures
between groups although no group was within the hyper-
tensive range. The two heaviest groups, competitive
weight lifters and heavy controls, had highest blood
pressures and highest resting heart rates.

Estimated maximal oxygen consumption of the run-
ers was significantly greater than all other groups when
it was normalized for body weight or lean body mass
(Fig. 2). Unadjusted estimated maximal oxygen con-
sumption of the weight lifters was just below that of the
runners. When the oxygen consumption was normalized
for body weight or lean body mass, the ranking of com-
petitive weight lifters decreased significantly, to a value
comparable to the control groups. At the time of fatigue
maximum heart rates were significantly less in the run-
ners (175 ± 8.9 beats/min) than the other groups, which
ranged from 181 to 193 beats/min. Correlation of maxi-
mum oxygen consumption with body weight, body sur-
face area, and lean body mass revealed a significant
correlation only with the latter parameter (\( \text{VO}_2 \text{max} = 0.022 \text{LBM} + 1.09, r = 0.430, P < 0.001 \)).

Left ventricular mass. In 12 individuals comparisons
of the left ventricular internal diameter, the interventric-
lar septal thickness, the posterior wall thickness, and

<table>
<thead>
<tr>
<th>Table 1. Physical characteristics</th>
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<tbody>
<tr>
<td>Age, yr</td>
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<tr>
<td>---------</td>
</tr>
<tr>
<td>Age, yr</td>
</tr>
<tr>
<td>Height, cm</td>
</tr>
<tr>
<td>Weight, kg</td>
</tr>
<tr>
<td>Body surface area, m²</td>
</tr>
<tr>
<td>Lean body mass, kg</td>
</tr>
</tbody>
</table>

Values are means ± SE. Values outside each set of brackets are significantly different at \( P \leq 0.05 \) from values in brackets.
TABLE 2. Resting blood pressure and heart rate

<table>
<thead>
<tr>
<th></th>
<th>Heavy Controls</th>
<th>Competitive Weight Lifters</th>
<th>Long-Distance Runners</th>
<th>Amateur Weight Lifters</th>
<th>Light Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic blood pressure, Torr</td>
<td>129 ± 3.1</td>
<td>126 ± 3.3</td>
<td>120 ± 2.5</td>
<td>122 ± 3.6</td>
<td>116 ± 2.2</td>
</tr>
<tr>
<td>Diastolic Blood Pressure, Torr</td>
<td>81 ± 1.2</td>
<td>82 ± 2.7</td>
<td>78 ± 2.7</td>
<td>78 ± 2.0</td>
<td>70 ± 2.4</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>73 ± 2.9</td>
<td>71 ± 2.5</td>
<td>68 ± 3.3</td>
<td>63 ± 2.7</td>
<td>53 ± 2.9</td>
</tr>
</tbody>
</table>

Values are means ± SE. Values outside each set of brackets are significantly different at \( P \leq 0.05 \) from values in brackets.

FIG. 2. Estimated maximal oxygen consumption in three groups of athletes and two control groups. Values are expressed in absolute terms and in relation to body weight and lean body weight. Bars are means and vertical brackets the SE. Values outside each set of horizontal brackets indicate values significantly different at \( P < 0.05 \) from values in brackets.

FIG. 3. Comparison of left ventricular mass determined by Penn to left ventricular mass determined by standard method (see text). Linear regression equation, correlation coefficient, and significance of correlation are listed. Individual groups are distinguished by different symbols as indicated.

The calculated left ventricular mass (Penn) were made with the transducer directed toward the mitral valve tip (MV) and toward the chordae tendineae (CT). Changing from one position to the other resulted in no significant change in the left ventricular internal diameter (MV: 5.36 ± 0.14 to CT: 5.47 ± 0.19 cm), the septal thickness (MV: 0.93 ± 0.03 to CT: 0.94 ± 0.04 cm), the posterior wall thickness (MV: 0.89 ± 0.04 to CT: 0.86 ± 0.03 cm) or the left ventricular mass (MV: 183 ± 12 to CT: 193 ± 14 g).

Left ventricular mass measured by standard method correlated closely with the left ventricular mass determined by Penn (Fig. 3). However, up to approximately 200 g LVM<sub>s</sub>, overestimated LVM<sub>p</sub>.

The individual components of the left ventricular mass equation including diastolic interventricular septal thickness, the left ventricular diastolic internal diameter, the diastolic posterior wall thickness, and the average of the septal and posterior wall thicknesses, the mean muscle thickness, for all groups are shown in Fig. 4. Septal thickness tended to be greater in the three athletic groups although the values were not statistically greater than in the control groups. End-diastolic diameter was signifi-
However, although the runners' total ventricular volume was greater than that of the light controls, there was not a significant difference between the levels for the competitive lifters and heavy controls. Runners had a signifi-
Left ventricular mass-to-volume ratio was greater in the competitive weight lifters than heavy controls but was not significantly different in all other groups (Fig. 7). There was no difference in the wall thickness-to-radius ratio between all groups.

**ECG data.** R-wave voltage in Frank lead X, sum of R-wave voltages in leads X and Z, and the frontal (X, Y), transverse (X, Z), and right sagittal (Y, Z) mean spatial QRS vectors were greater in runners than the light control group (Table 3). There was no significant difference between weight lifters and heavy control group using any of the electrocardiographic parameters.

**DISCUSSION**

This study was composed of five groups of subjects including three groups of athletes and two control groups. Several investigators have demonstrated that left ventricular mass increases with increasing age and increasing body surface area (9, 15). Therefore, one aim in selecting the control groups was to match them with the athletes with respect to age, body weight, and body surface area. The criteria used for athlete selection was to obtain groups of athletes that performed markedly different types of exercise training. On one end of the spectrum individuals who trained with predominantly static exercise (i.e., weight lifters) were selected. On the other end of the spectrum individuals who trained with mostly dynamic exercise (i.e., running) were selected. For both groups, competitive athletes were chosen because it was felt that these individuals would have trained more seriously than noncompetitive athletes. To help verify this latter contention, a group of noncompetitive (amateur) body builders who trained primarily with repetitive weight lifting and some running were studied.

In addition to the history of training, characterization of each athlete was accomplished by measurement of resting hemodynamic parameters (heart rate and blood pressure) and estimation of the maximal oxygen consumption. No individual had a resting blood pressure that could be considered hypertensive although, in general, the largest individuals, the weight lifters and the heavy controls, had the highest blood pressure. The estimated maximal oxygen consumption was low, especially for the endurance-trained athletes. However, this determination served adequately to separate the groups. The runners had the lowest resting heart rates and the highest estimated maximal oxygen consumptions, findings that served to separate the aerobic capacity of this group from all other groups. The oxygen consumption when normalized for body weight and lean body mass particularly separated the runners from the weight lifters and the runners from the control groups but tended to equalize the weight lifters and the control groups. The maximal oxygen consumption was most appropriately normalized by the lean body mass as they were significantly related. These findings are consistent with observations from other investigators who have noted that the maximal oxygen consumption is closely related to lean body mass (4). The estimated maximal oxygen consumption of the amateur weight lifters was higher than the competitive weight lifters and the heavy controls but lower than the runners likely because of the small amount of endurance training that these individuals tended to perform.

As with any study the results are largely dependent on the accuracy of the methods or techniques used to obtain the results. The echocardiographic technique was used to obtain the left ventricular dimensions and thereby the left ventricular mass. Angiographic methods were originally used as the standard for the echocardiographic ventricular dimensions (15, 20, 29). From these studies regression equations were developed for estimation of ventricular volumes and ventricular mass assuming the left ventricle to be an ellipsoid of rotation (29). Although some investigators have taken measurements at both the mitral valve tips and in the chordae tendineae, others

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### TABLE 3. ECG data

<table>
<thead>
<tr>
<th></th>
<th>Long-Distance Runners</th>
<th>Amateur Weight Lifters</th>
<th>Competitive Weight Lifters</th>
<th>Light Controls</th>
<th>Heavy Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_x$</td>
<td>1.77 ± 0.16</td>
<td>1.49 ± 0.12</td>
<td>1.11 ± 0.06</td>
<td>1.12 ± 0.11</td>
<td>1.04 ± 0.07</td>
</tr>
<tr>
<td>$R_y$</td>
<td>1.34 ± 0.18</td>
<td>0.86 ± 0.11</td>
<td>0.84 ± 0.08</td>
<td>0.97 ± 0.11</td>
<td>0.96 ± 0.04</td>
</tr>
<tr>
<td>$R_z$</td>
<td>1.00 ± 0.11</td>
<td>1.05 ± 0.09</td>
<td>0.90 ± 0.07</td>
<td>0.93 ± 0.11</td>
<td>0.93 ± 0.08</td>
</tr>
<tr>
<td>$R_x + R_y$</td>
<td>2.77 ± 0.15</td>
<td>2.54 ± 0.17</td>
<td>2.01 ± 0.11</td>
<td>2.05 ± 0.11</td>
<td>1.96 ± 0.10</td>
</tr>
<tr>
<td>$QRS_{XY}$</td>
<td>2.98 ± 0.19</td>
<td>1.73 ± 0.15</td>
<td>1.49 ± 0.08</td>
<td>1.57 ± 0.11</td>
<td>1.57 ± 0.10</td>
</tr>
<tr>
<td>$QRS_{XZ}$</td>
<td>2.09 ± 0.13</td>
<td>1.84 ± 0.19</td>
<td>1.45 ± 0.08</td>
<td>1.51 ± 0.09</td>
<td>1.42 ± 0.07</td>
</tr>
<tr>
<td>$QRS_{YZ}$</td>
<td>1.71 ± 0.18</td>
<td>1.39 ± 0.08</td>
<td>1.25 ± 0.10</td>
<td>1.45 ± 0.08</td>
<td>1.91 ± 0.08</td>
</tr>
</tbody>
</table>

Values are means ± SE, given in mV. Values outside each set of brackets are significantly different at $P \leq 0.05$ from values in brackets.
have noted that as the left ventricle enlarges and becomes more spherical, the minor axis is displaced downward away from the mitral valve leaflets (19). The effect of moving the transducer from the mitral valve tips down into the region of the chordae tendineae in this study demonstrated negligible differences in left ventricular septal, posterior wall, and internal dimension. Thus, left ventricular mass was felt to be equally estimated by the Penn convention from both positions. Recently, the accuracy of the Penn convention has been verified through direct anatomic correlation (6). These investigators demonstrated that the standard method (29) yielded a greater variation and a systematic overestimation of the anatomic left ventricular mass. These findings were collaborated in the present study showing that up to a ventricular mass of 200 g, the standard method overestimated the Penn LVM.

In absolute terms, the left ventricular mass was greatest in the runners and slightly but not significantly less in the weight lifters. However, compared to control groups, both groups of competitive athletes had greater ventricular masses than their appropriately matched controls. Normalizing the left ventricular mass by any expression of body size separated the long-distance runners from all other groups including the weight lifters. Further, normalizing the ventricular mass by lean body mass, the only parameter with which it was significantly correlated, equalized the values for both groups of weight lifters and the heavy controls. These data strongly suggest, therefore, that dynamic exercise training promotes a true increase in left ventricular mass. On the other hand, static exercise training increases left ventricular muscle mass in absolute terms but not in relation to skeletal muscle mass. The amateur weight lifters had an absolute left ventricular mass that was intermediate between the competitive athletes and the control groups. Relatively, the normalized ventricular mass in these non-competitive athletes was very similar to the competitive weight lifters yet not significantly different from control groups.

The finding that dynamic exercise training increases left ventricular mass is indirectly supported by the results of several groups of investigators who have studied the heart size of athletes radiologically (16, 17, 24), and more directly by echocardiographic methods of determining left ventricular mass (1, 24, 30). Further, several groups have shown that longitudinal studies that dynamic exercise training of nonathletes significantly increases left ventricular mass (5, 8) and that detraining of similar types of athletes decreases left ventricular mass (8). Other longitudinal studies have shown that bed rest decreases the roentgenographic cardiac size while it is increased by training (29).

There are no studies in the literature that examine the left ventricular mass of athletes who perform exclusively static exercise training. However, there are a few studies of athletes (including wrestlers, shot putters, and oarsmen) who trained with high-resistance exercise (17, 21). These studies suggest that the left ventricular masses or the heart volume of these types of athletes is elevated. Neither study determined the lean body mass of the subjects studied. In one study (21), the authors stated that the left ventricular mass of wrestlers and shot putters remained increased relative to the control subjects when the mass was related to the body surface area. However, in that study the actual statistics were not provided and in one group (the shot putters) the mean body surface area and the age appeared to be significantly greater than control groups (2.5 vs. 1.9 m² and 26 vs. 20 yr, respectively). In the other study (17), the radiological cardiac volume and the echocardiographic posterior wall thickness were significantly greater in the oarsmen than the control subjects although the body weights of the oarsmen were greater than the control subjects (82 vs. 66 kg). Thus, the finding that competitive athletes who train with predominantly static exercise have an increased absolute left ventricular mass but relatively the same left ventricular mass as a control population matched for age and body weight is a new finding that extends the observations of previous studies.

Roentgenographic total heart volume was not determined although the total left ventricular volume was estimated by adding the end-diastolic left ventricular cavity volume to the left ventricular muscle volume. The total left ventricular volume measurement demonstrated that runners had larger volumes than the light controls but that weight lifters had volumes similar to the heavy controls. These data are quantitatively similar to those of left ventricular mass normalized by lean body mass and confirm that dynamic training increases total heart volume whereas static training does not. The former conclusion has been amply verified by several other roentgenographic studies (16, 24). Concerning the latter conclusion, Howald et al. (17) confirmed that radiological heart volume was only minimally (11.9 ± 8 ml/kg) increased in oarsmen compared to normals (10.6 ± 0.9 ml/kg).

The mass-to-volume ratio of the left ventricle of the competitive weight lifters was significantly greater than the heavy controls, whereas the amateur weight lifters and the runners had ratios similar to the appropriate control groups. These data suggest, therefore, that competitive weight lifters develop an "inappropriate" hypertrophy, i.e., a greater increase in muscle mass than the increase in ventricular volume (11). This conclusion is reinforced by the observation that the free wall of the left ventricle in the competitive weight lifters was greater than the control group but the left ventricular diameter was similar in both groups. On the other hand, the runners and amateur weight lifters developed "appropriate" hypertrophy, i.e., a proportional increase in ventricular volume and muscle mass. The mechanism(s) that caused an increased diastolic volume in the runners cannot be determined in this study but, in part, may be due to the relative bradycardia rather than a structural alteration. Although there were significant variations in the mass-to-volume ratios between the groups in the present study, the means did not exceed the normal limits of 1-1.3 g/ml (18).

Laplace's law states that the ventricular wall tension is proportional to both pressure and radius of curvature. Therefore, to keep systolic tension constant per cross-sectional area of muscle the ventricular wall thickness must increase as the radius of curvature increases. This
relationship is described by the wall thickness-to-radius ratio (w/r) and for normal ventricles ranges between 0.32 to 0.36 (13, 14). An increase in the left ventricular wall thickness with a concomitant increase in left ventricular radius, or no change in w/r, has been termed eccentric hypertrophy. An increase in left ventricular wall thickness without a change in radius, i.e., an increase in w/r, has been called concentric hypertrophy (13). The weight lifters in this study tended to have higher w/r than the runners and the control groups. However, the differences between all groups were statistically insignificant and the ratios were within normal limits.

Electrocardiographic measurements demonstrated by both scalar and spatial methods, that long-distance runners have more voltage than the controls. The weight lifters' ECG measurements, on the other hand, were not significantly different from the control group's despite the fact that their absolute left ventricular masses were increased. The differences between the two groups of athletes may be the larger absolute ventricular masses, the larger cavity volumes, or perhaps the thinner chest walls (as demonstrated by the lower lean body weight) and shorter heart-electrode distances in the runners as compared to the weight lifters (23).

Many groups have demonstrated increased precordial scalar ECG voltage in endurance athletes (5, 21, 23, 24). The ECG data on the weight lifters is also consistent with that from Morgan-roth and co-workers (21) who noted that only 25% of the wrestlers and shot putters had increased precordial voltage compared to 67% of the runners who manifested increased voltage. There is only one vectorcardiographic study of athletes in the literature (23). Long-distance skiers in this study were found to have an increased magnitude of all instantaneous vectors that may be the result of an increased dipole current measurement. There is currently no data available on the vectorcardiographic changes from static exercise training other than that presented in this study.

In summary, the absolute left ventricular masses of long-distance runners and competitive weight lifters were increased compared to nonathletic controls matched for age, body weight, and body surface area. Of the components in the mass equation, the internal diameter was increased in runners compared to lean controls, and the posterior wall thickness was increased in weight lifters compared to heavy controls, but the septal thickness and mean muscle thickness were similar for all groups. The left ventricular mass for all individuals studied was significantly related to lean body mass although the correlation was poor. Intragroup comparisons revealed that the endurance athletes have a greater relative left ventricular mass than all other athletes and controls when the mass was normalized by body weight, body surface area, and lean body mass. Also, when electrocardiographic voltage was assessed, the runners demonstrated larger QRS voltages compared to the light controls.

When the ventricular mass of competitive weight lifters was normalized by lean body mass, the value did not significantly differ from the heavy control group. For the amateur weight lifters, the absolute left ventricular mass was intermediate between other athletes and controls, but when normalized by any of the indices of body size, the mass was similar to the control groups. The mass-to-volume ratio was inappropriately increased only for the competitive weight lifters, not for the runners.

The authors thank Ms. Arvella Peters and Ms. Linda Spradlin for their technical help in obtaining the echocardiograms and performing the stress testing, respectively, and Ms. Jan Wright for secretarial and editorial assistance. Dr. Gunnar Blomqvist is thanked for his critical appraisal and helpful suggestions in preparing this manuscript. J. C. Longhurst is supported by National Institutes of Health Young Investigator Award HL-22669. This study was supported in part by a National Institutes of Health Program Project Grant HL-06296, National Aeronautics and Space Administration Grant NSG 9026, and the Lawson and Rogers Lacy Research Fund in Cardiovascular Disease.

A. Kelly is currently a medical student at the University of Texas, Southwestern Medical School, Dallas.

Received 27 April 1979; accepted in final form 9 August 1979.

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