Mechanical Properties of Rat Cardiac Muscle during Experimental Hypertrophy

By Oscar H. L. Bing, Satoru Matsushita, Barry L. Fanburg and Herbert J. Levine

ABSTRACT

The mechanical properties of trabecular muscles from the hearts of 77 rats subjected to aortic arch constriction were compared with those from 77 unoperated and sham-operated control animals at 1, 3, 7, 14, and 28 days after operation. Significant hypertrophy, as evidenced by an increase in left ventricle to body weight ratio, was first seen at three days (P<0.02), reached a maximum of 30 to 40% by seven days (P < 0.001), and remained relatively constant throughout the remainder of the experiment. Depression of isotonic shortening velocity and maximum isometric force of trabecular muscles from hypertrophied hearts was first seen at seven days. These changes persisted at 14 and 28 days. When alterations in muscle mechanics due to changes in muscle thickness were taken into consideration, muscles from hypertrophied hearts demonstrated a depressed maximum velocity of shortening (P< 0.001), while development of isometric tension was unaltered. The latter appeared to be maintained at least in part by a prolonged contraction time, as reflected by increases in the time to peak isometric tension (P < 0.05) and the time to peak "unloaded" isotonic shortening (P < 0.001). Resting tension was increased in trabecular muscles from hypertrophied hearts. Tissue hydroxyproline concentration was elevated with hypertrophy. The observed depression in muscle shortening velocity at light loads may be explained by altered contractile state or by increased stiffness of the parallel elastic element.

KEY WORDS

aortic constriction  isolated muscle studies  force-velocity relationships  hydroxyproline  lactic dehydrogenase
RAT CARDIAC MUSCLE IN EXPERIMENTAL HYPERTROPHY

Methods

Inbred Charles River CD rats, weighing 180 to 220 g, were used in the present experiments. Seventy-seven animals were subjected to constriction of the aortic arch, while 77 animals served as unoperated or sham-operated controls. Operations were carried out as previously described (4) except that animals were anesthetized with 60 to 70 mg of chloral hydrate given intraperitoneally. Animals were decapitated at 1, 3, 7, 14, and 28 days after operation. The chest was opened, and the heart was removed rapidly and placed in oxygenated Krebs-Henseleit solution (5).

MUSCLE PREPARATION AND MECHANICAL MEASUREMENTS

The columnar carnean muscle of the left ventricle was dissected free, mounted between two spring clips, and placed in a chamber containing Krebs-Henseleit solution with 100 mg glucose per 100 ml. The solution was gassed with 95% O₂ and 5% CO₂ (pH = 7.4) and maintained at a temperature of 25°C. The lower spring clip was attached to a 0.0017-inch tungsten wire which passed through a mercury seal at the bottom of the chamber to a Statham model G7B-0.75-350 force transducer. The upper spring clip was connected to a thin gold chain which was attached to an isotonic lever arm above which was placed a micrometer stop for adjustment of muscle tension. At voltages which were 10% greater than the maximum muscle shortening velocity (Max V), the lever arm ratio of 8:1. A displacement transducer (Sanborn DC DT-050) was mounted above the top of the chamber to a Statham model G7B-0.75-350 force transducer. The upper spring clip was connected to a thin gold chain which was attached to an isotonic lever arm above which was placed a micrometer stop for adjustment of muscle tension. The lever arm was made from magnesium with a ball-bearing fulcrum and a gravity of 1.000. All values were normalized for muscle length and cross-sectional area. Each experiment was carried out with four muscles contracting simultaneously in four chambers with common temperature regulation and oxygenation. The experiment was designed so that each set of four muscles included those from an unoperated animal, a sham-operated animal, and two animals with aortic constriction. When there was no significant difference between measurements from sham-operated and unoperated animals, they will be referred to interchangeably as controls or combined to increase the sample size.

DETERMINATIONS OF HEART WEIGHTS, PROTEIN CONTENT, HYDROXYPROLINE CONTENT, LACTATE DEHYDROGENASE ACTIVITY, AND ISOENZYME PATTERNS

After removal of the trabecular muscles, the remainder of the heart was blotted and weighed. A portion of the heart was also weighed after overnight drying to a constant weight in an oven. Protein determinations were carried out by the Folin method (6) on columnar carnean muscles. The free wall of the left ventricle was divided into endomyocardial and epimyocardial slices, and hydroxyproline was measured on samples of approximately 20 mg of tissue (dry weight) according to the method of Prockop and Udenfriend (7). The assay for lactate dehydrogenase was based on the photometric changes with oxidation of DPNH at 340 nm, which is a direct measure of the reduction of pyruvate to lactate (8). The LDH isoenzymes were separated by electrophoresis at 1.5 ma for one hour with cellulose acetate strips at a buffer pH of 8.9 (9).

Results

CHANGES IN HEART SIZE AND EVALUATION FOR WATER RETENTION

At three days after aortic constriction, there was a 17.5% increase in the left ventricular weight, a 22.5% increase in the left ventricular/body weight ratio (LV/BW), and a 20% increase in the trabecular muscle cross-sectional area (Fig. 1). By seven days after operation, these values had reached their maximum of 30 to 40% above controls and remained relatively constant during the remaining 21 days of the study. All the increases were significant at and after seven days with P values <0.001.

We found little if any macroscopic evidence of pulmonary edema or hepatic congestion on.
FIGURE 1
Effects of aortic constriction on left ventricular weight, left ventricular to body weight ratio, and trabecular muscle cross-sectional area.

careful examination of tissues of animals with aortic constriction. The water content of hearts and lungs from these animals did not differ significantly from controls (Fig. 2). The elevated dry/wet weight ratio for lungs from unoperated animals at 14 days after operation could not be explained and appeared to be a spurious value. Trabecular muscles were individually too small to measure the dry weights accurately, but the determination of the protein content indicated that no significant water retention had taken place in these muscles. These data suggest that the group of animals with aortic constriction had left ventricular hypertrophy without congestive heart failure.

FIGURE 2
Assessment of combined left and right ventricles and of lungs for water content and of trabecular muscles for protein content. Values were obtained from animals used for Table 1. Brackets indicate ± one standard error.
operation. However, at one week after operation, Max V and maximum isometric tension were depressed when compared with controls. No further changes were seen at two and four weeks after operation.

The cross-sectional areas of trabecular muscles from hypertrophied hearts were greater than those from controls (Fig. 1). To determine whether this change was responsi-
TABLE 1

Data for All Animals Studied*

<table>
<thead>
<tr>
<th></th>
<th>1 Day</th>
<th>2 Days</th>
<th>3 Days</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trabecular muscle cross-sectional area (mm²)</td>
<td>Const 0.85 ± 0.05</td>
<td>ns</td>
<td>0.71 ± 0.07</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LV wt (mg)/100 g body wt</td>
<td>Const 227 ± 3</td>
<td>203 ± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max V (muscle lengths/sec)</td>
<td>Const 234 ± 6</td>
<td>ns</td>
<td>236 ± 9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resting tension (g/mm²)</td>
<td>Const 3.11 ± 0.05</td>
<td>ns</td>
<td>3.01 ± 0.10</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Developed tension (g/mm²)</td>
<td>Const 0.77 ± 0.08</td>
<td>ns</td>
<td>0.77 ± 0.08</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to peak tension (sec)</td>
<td>Const 6.22 ± 0.43</td>
<td>&lt;0.05</td>
<td>7.56 ± 0.40</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to peak shortening (sec)</td>
<td>Const 0.146 ± 0.004</td>
<td>&lt;0.01</td>
<td>0.165 ± 0.004</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of animals</td>
<td>Control 14</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Constricted 10</td>
<td>13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Values represent means plus or minus one standard error. P values listed horizontally are for differences between values for various days after operation. P values listed vertically are for differences between controls and animals with aortic constriction at any one day after operation.

Mechanical Measurements in Trabecular Muscles of Hypertrophied Hearts Matched Against Controls for Cross-sectional Area

To eliminate changes in mechanics due solely to changes in muscle thickness, muscles of similar cross-sectional area from the control and hypertrophied groups of hearts were evaluated. Data from 14 control and 19 animals with aortic constriction were summarized in Figure 4. There was a highly significant depression of Max V, while maximum isometric tension of muscles from hypertrophied hearts was unchanged from that of controls. Thus, decreases in isometric tension seen in muscles from the total group of hypertrophied hearts may be explained by the presence of thicker muscles. Decreases in Max V, on the other hand, appear to be related to some other property of the hypertrophied muscle.

Relation Between Degree of Hypertrophy and Mechanical Parameters of Contracture for Muscles with Matched Cross-sectional Area

The Max V for muscles with the same cross-sectional area showed a high inverse correlation with the extent of hypertrophy as
reflected by the left ventricle to body weight ratio (Fig. 5). On the other hand, no significant correlation was found between developed tension per cross-sectional area and the extent of hypertrophy.

### Duration of Contraction

The duration of contraction was evaluated by measuring time to peak isometric tension and time to peak "unloaded" isotonic shortening (where "unloaded" represents the lightest possible load against which the muscle shortened). Time to peak tension of the overall group of muscles from hypertrophied hearts appeared to be slightly prolonged at 7 and 14 days after aortic constriction, although the statistical significance of this was borderline ($P < 0.10$) (Fig. 6). At 28 days after aortic constriction, there was a 9% prolongation in the time to peak tension with a significant $P$ value ($< 0.001$). This variable was also prolonged for the group of muscles from hypertrophied hearts matched against controls of the same cross-sectional area (Figs. 4 and 6). There was an increase in the time to peak shortening at 7 ($P < 0.02$), 14 ($P < 0.01$), and 28 ($P < 0.001$) days after the aortic constriction. A significant prolongation in time to peak shortening was also present for the muscles matched against controls for cross-sectional area.

### Resting Length-Tension Relationships

In these experiments the resting tension was measured at a muscle length that resulted in peak isometric tension development. There was a statistically significant increase in resting tension in muscles from hypertrophied hearts at three days after aortic constriction (Table 1), and this variable remained elevated at all subsequent times except at two weeks when no difference from controls was found.

### BIOCHEMICAL DETERMINATIONS

#### Evaluation for Chronic Hypoxia of Muscle

It has been suggested that hypoxia is present in hypertrophied heart muscle and

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<table>
<thead>
<tr>
<th>T Days</th>
<th>14 Days</th>
<th>28 Days</th>
<th>Same cross-sectional area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.76 ± 0.05</td>
<td>$&lt;0.001$</td>
<td>$0.96 ± 0.06$</td>
<td>$1.17 ± 0.02$</td>
</tr>
<tr>
<td>1.11 ± 0.07</td>
<td>$&lt;0.001$</td>
<td>$1.31 ± 0.07$</td>
<td>$1.14 ± 0.02$</td>
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<tr>
<td>2.06 ± 0.5</td>
<td>$&lt;0.001$</td>
<td>$196 ± 4$</td>
<td>$199 ± 4$</td>
</tr>
<tr>
<td>2.74 ± 10</td>
<td>$&lt;0.001$</td>
<td>$274 ± 6$</td>
<td>$278 ± 9$</td>
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<tr>
<td>2.81 ± 0.6</td>
<td>$&lt;0.001$</td>
<td>$2.83 ± 0.08$</td>
<td>$2.91 ± 0.07$</td>
</tr>
<tr>
<td>2.34 ± 0.13</td>
<td>$&lt;0.001$</td>
<td>$2.36 ± 0.09$</td>
<td>$2.41 ± 0.10$</td>
</tr>
<tr>
<td>0.71 ± 0.27</td>
<td>$&lt;0.001$</td>
<td>$0.76 ± 0.07$</td>
<td>$0.79 ± 0.04$</td>
</tr>
<tr>
<td>1.12 ± 0.09</td>
<td>$&lt;0.001$</td>
<td>$1.08 ± 0.05$</td>
<td>$1.12 ± 0.10$</td>
</tr>
<tr>
<td>0.64 ± 0.25</td>
<td>$&lt;0.001$</td>
<td>$0.87 ± 0.05$</td>
<td>$0.90 ± 0.07$</td>
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<tr>
<td>5.75 ± 0.47</td>
<td>$&lt;0.001$</td>
<td>$5.83 ± 0.30$</td>
<td>$5.90 ± 0.32$</td>
</tr>
<tr>
<td>0.170 ± 0.004</td>
<td>$&lt;0.001$</td>
<td>$0.184 ± 0.004$</td>
<td>$0.186 ± 0.003$</td>
</tr>
<tr>
<td>0.181 ± 0.004</td>
<td>$&lt;0.001$</td>
<td>$0.177 ± 0.006$</td>
<td>$0.180 ± 0.004$</td>
</tr>
<tr>
<td>0.173 ± 0.004</td>
<td>$&lt;0.001$</td>
<td>$0.166 ± 0.003$</td>
<td>$0.168 ± 0.002$</td>
</tr>
<tr>
<td>0.188 ± 0.005</td>
<td>$&lt;0.001$</td>
<td>$0.184 ± 0.013$</td>
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</tr>
</tbody>
</table>

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Circulation Research, Vol. XXVIII, February 1971

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Summary of findings from control and hypertrophied hearts with muscles of similar cross-sectional area (A). In rats with hypertrophy, left ventricular/body weight (LV/BW), time to peak shortening (TPS), and time to peak tension (TPT) are increased; Max V is depressed, and maximum developed isometric tension (DT) is similar in both groups.

It was considered that chronic hypoxia may be present in hypertrophied rat heart muscle, and could play a role in the mechanical changes observed in our studies. To investigate this possibility, trabecular muscles from the left ventricles of animals four weeks after aortic constriction were subjected to a hypoxic environment, and the time course of changes in developed tension was compared with that of trabecular muscles from control animals.

As demonstrated in Figure 7, no enhanced ability of hypertrophied muscles to tolerate hypoxia was observed. Hearts obtained from rats four weeks after aortic constriction were similar in both groups.

TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>Epinephrine</th>
<th></th>
<th>Endothelin</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cont. (µg/mg dry wt)</td>
<td>% Increase above sham</td>
<td>% Increase above sham</td>
<td>% Increase above sham</td>
</tr>
<tr>
<td>Sham (20)</td>
<td>2.32 ± 0.06</td>
<td>-</td>
<td>2.32 ± 0.06</td>
<td>-</td>
</tr>
<tr>
<td>Constricted (16)</td>
<td>2.66 ± 0.12</td>
<td>14.7 &lt;0.1</td>
<td>3.04 ± 0.20</td>
<td>31.0 &lt;0.05</td>
</tr>
</tbody>
</table>

*Mean values plus or minus one standard error are given. The numbers of control animals and those with aortic constriction are indicated in parentheses.
Figure 5
Correlation of left ventricular-body weight ratio with Max V (upper) and developed tension (lower) in trabecular muscles of similar cross-sectional area. Each point represents a determination from a single muscle.

Figure 6
Effect of hypertrophy on the time to peak isometric tension and time to peak "unloaded" isotonic shortening. Each bar graph indicates the percent change from controls.

Also examined for tissue LDH concentration and subunit distribution. In these experiments no increase in the LDH concentration or shift in the electrophoretically assayed isoenzyme distribution was noted. Thus, these studies provide no evidence for chronic tissue hypoxia in the hypertrophied hearts.

Hydroxyproline

The left ventricle was analyzed for hydroxyproline in control and hypertrophied hearts. As shown in Table 2, there was an increase in the hydroxyproline concentration in hearts from animals with aortic constriction. The increase in concentration was greater in endomyocardial than in epimyocardial samples.

The relationship between tissue endomyocardial hydroxyproline concentration and the...
FIGURE 7

Effect of hypoxia on developed tension of trabecular muscles from unoperated and sham-operated animals and those subjected to aortic constriction. Experiments were carried out so that muscles from each of the four groups indicated by symbols were studied simultaneously in a common gassed medium. There were ten muscles in each group. At zero time, all muscles were exposed to 95% N₂ and 5% CO₂. Changes are expressed as percent of tension at zero time, and standard errors are indicated by brackets.

Max V of trabecular muscles is demonstrated in Figure 8. Although there appeared to be a significant overall inverse correlation between these measurements ($r = 0.48$, $P < 0.001$), there were a large number of trabecular muscles with a depressed Max V from hypertrophied hearts whose hydroxyproline concentrations were within the control range. Conversely, there were several hypertrophied hearts with elevated hydroxyproline concentrations but with Max V within the control range.

Discussion

Our finding of a depressed maximum shortening velocity of the hypertrophied rat left ventricular trabecular muscle is consonant with the studies of Spann et al. (3) on the hypertrophied right ventricular papillary muscle of the cat. As in the studies with the cat and those of Grimm et al. (2) with the rat, we found no alteration in peak isometric tension normalized for cross-sectional area. This finding might appear at variance with that of Kerr and coworkers (1) who reported that developed tension per unit muscle weight was increased in the hypertrophied heart. Normalization of tension on a muscle weight basis, however, is misleading since a short muscle with a given cross-sectional area would be credited with more tension developed than a longer one. The finding that maximum shortening velocity is depressed in hypertrophied heart muscle suggests at first that the contrac-
The state of the muscle is likewise depressed. It should be made clear, however, that the velocities measured in these experiments are those of muscle and not of its contractile element. In the present study two properties of hypertrophied muscle influence the interpretation of the observed depressed shortening velocities. The first is the finding that the resting tension of hypertrophied muscle is increased. In a three-component model of heart muscle, an observed decrease in muscle shortening velocity may be due to an increase in the stiffness of the parallel elastic component without a change in contractile element velocity (13). Since the resting tension of hypertrophied muscle was increased, the depressed muscle velocities observed in this study might be explained on this basis.

Secondly, depressed muscle velocities during early contraction might be due to changes in the time courses of the active state. Thus, delayed onset of the active state would be manifested as a depression of early, lightly loaded shortening velocities. A study of normal and hypertrophied preparations by quick release experiments could better resolve the question of inconstant active state intensity.

The unchanged isometric tension development in the presence of a depression in velocity of contraction can be explained most readily by a prolongation in the duration of contraction. Our studies, contrary to those of Spann et al. (3), show clearly that time to peak isometric tension and time to peak isotonic shortening are prolonged during experimental hypertrophy. Similar changes have been reported to take place in the rat heart during aging (14).

The findings emphasize the potential error of comparing muscles that have different cross-sectional areas. The inverse relationship between muscle thickness and tension development per unit cross-sectional area has been demonstrated previously (15). The reason for this relationship is not clear, but it may be due to hypoxia of the core of the muscle preparation since the relationship does not hold for very thin strips of muscle. In our experiments the selection of muscles of similar cross-sectional areas obviated the problem of varying muscle thickness.

Contrary to previous reports (2, 3), a significantly elevated resting tension per unit cross-sectional area was found in muscles from hypertrophied hearts in the present study. The measurement of resting tension at a length where peak developed tension is achieved (Lmax) is subject to a sizable potential error since the resting tension curve is rising steeply and Lmax is not always clearly defined. In addition, stress relaxation takes place, resulting in progressively lower values of resting tension. In these experiments the muscle was stretched no further than the peak of the active tension curve. Resting tension was measured at a similar time after stretch in all experiments. Thus, the degree of stress relaxation in all muscles should have been similar. In spite of some variation of the data, a significant elevation of resting tension was generally seen in hypertrophied trabecular muscles. It is possible that an increase in connective tissue, indicated by the increase in hydroxyproline concentration of hypertrophied hearts, could be responsible for the elevated resting tension seen in hypertrophied muscle.

A period of increased tension per unit cross-sectional area of muscle is present after aortic constriction prior to the load normalizing process of hypertrophy. It is of interest that changes in muscle mechanics did not occur during this period but only after cardiac hypertrophy was established. Indeed, a good correlation between Max V and the degree of hypertrophy was noted (Fig. 5). These findings suggest that factors related to hypertrophy itself rather than the immediate effects of an increased work load are somehow responsible for the decreases in muscle shortening velocity.

As reported by others (16, 17), an increase in hydroxyproline concentration in hypertrophied hearts was noted in this study. Although there appeared to be an inverse correlation between hydroxyproline concentration and Max V, there were many hyper-
trophied hearts in which there was a lack of correspondence between these variables. Analysis of hydroxyproline in trabecular muscles might have shown better correlation, especially since the increase in myocardial hydroxyproline was greater in endomyocardial tissue than in epimyocardial samples. This was not possible because of the small size of trabecular muscles.

An increase in work load or muscle mass might result in chronic hypoxia of the muscle cell, which in turn could alter myocardial mechanics. However, our studies failed to demonstrate any evidence for chronic hypoxia as might be manifested by an altered mechanical tolerance of muscle to hypoxia in vitro or by changes in LDH. Our findings of unchanged LDH isoenzymes differ from the report of Fox and Reed (18). It is possible that the changes in LDH which they observed reflect a considerably larger degree of hypertrophy in their studies.

Linzbach has suggested that depressed myocardial performance is seen only with severe degrees of cardiac hypertrophy (19). In this way he explains the apparently normal function of the "physiologically" hypertrophied hearts of athletes. In the present study it was found that relatively moderate degrees of hypertrophy may result in a depression of Max V. These findings may be reconciled with normal cardiac performance in the presence of moderate or "physiological" hypertrophy in several ways. First, shortening velocity of the moderately hypertrophied heart actually may be depressed while performance is unaltered because of a prolonged contraction time, as was found in the present study. Second, the effects of the manner and rate at which hypertrophy developed have not been studied. Thus, hypertrophy after intermittent work exposure, as in "physiological" hypertrophy, is gradual rather than abrupt, and rest periods are interposed so that function at normal loads occurs intermittently. Thirdly, the mechanical properties of the hypertrophied heart resulting from an increased afterload might differ from those of hypertrophy which has been produced by other means, such as increased volume work. This possibility has received recent support from Turina and coworkers (20) who found that left ventricular hypertrophy associated with chronic volume load in intact dogs did not alter the force-velocity relationship.

Finally, in the intact heart a disproportionate increase in the amount of hypertrophy may compensate for the decrease in shortening velocity and enable the hypertrophied heart to function in an apparently normal fashion.

Acknowledgment

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References

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