SUMMARY The effects of diltiazem treatment (40–50 mg/kg/day orally for 8 weeks) of left ventricular hypertrophy on systemic and coronary hemodynamics and mechanical cardiac performance were investigated in renovascular hypertensive rats (Goldblatt, two-kidney, one clip). Systemic and coronary hemodynamics were determined by using radioactive microspheres in conscious, unrestrained rats. Mechanical performance was measured on isolated papillary muscle from the same animal. Nine treated hypertensive rats were compared with control groups: 12 untreated hypertensive and nine sham-operated rats. Diltiazem treatment led to an effective but incomplete control of blood pressure (from 208 ± 5 mm Hg in the untreated hypertensive group to 155 ± 3 mm Hg in the treated hypertensive group; \( p < 0.01 \)) associated with a significant but incomplete decrease of the left ventricular mass (from 3.10 ± 0.19 mg/g in untreated hypertensive rats to 2.35 ± 0.04 mg/g in treated hypertensive rats; \( p < 0.01 \)). A close correlation was found between left ventricular mass and systolic blood pressure in untreated, treated, and pooled groups (\( r = 0.84, p < 0.001, n = 30 \)). The left ventricular weight to systolic blood pressure ratio was equivalent in all three groups, so that the reduction of left ventricular mass in diltiazem-treated rats was commensurate with the reduction of blood pressure. At rest, treated hypertensive rats showed a rise in cardiac output (426 ± 12 vs 298 ± 22 ml/min/kg in sham-operated rats; \( p < 0.001 \)) and in coronary blood flow (598 ± 17 vs 453 ± 19 ml/min/100 g; \( p < 0.05 \)) related to the decrease in total peripheral resistance and in total left ventricular coronary resistance. A reversal of impaired myocardial mechanical parameters toward control values was observed except for time to half-maximal relaxation (92 ± 2 msec in the treated group vs 79 ± 5 msec in sham-operated rats) and time to peak force. Our results demonstrate that even incomplete control of blood pressure with diltiazem is associated with significant but partial reduction of left ventricular mass and improvement of mechanical function.

(Hypertension 11: 495–501, 1988)

KEY WORDS • calcium antagonist • diltiazem • renovascular hypertension • left ventricular mass • myocardial perfusion • myocardial contraction

Calcium channel blocking agents are well known to have antihypertensive effects in humans1–5 and in experimental hypertensive animal models.6–8 However, these drugs exhibit substantial differences in their antihypertensive potency, site of action, and degree of sympathetic stimulation. The 1,4-dihydropyridines are very potent antihypertensive drugs, with a proven ability to lower blood pressure and left ventricular mass.9–11 Less data are available about the effects of other antihypertensive calcium antagonist compounds on left ventricular hypertrophy. The present study was undertaken to evaluate the effects of diltiazem, a less vascular selective calcium entry blocker, on left ventricular hypertrophy, systemic and coronary hemodynamics, and isolated muscle mechanical performance in renovascular hypertensive rats (RHR; two-kidney, one clip, Goldblatt model).

Materials and Methods
Preparation of Renal Hypertensive and Sham-Operated Rats
Thirty male Sprague-Dawley rats, aged 40 to 50 days with weights ranging between 150 and 180 g, were purchased from Janvier Laboratory (Genet
Saint-Berthevin, France). Two-kidney, one clip hypertension (Goldblatt model) was induced in 21 of them (RHR) by placing a silver clip (aperture, 0.25 mm) on the left artery while the rats were under ether anesthesia. The contralateral kidney was left untouched. Nine rats had a similar operation without vascular clipping (sham operation) and were used as controls (SHC). Systolic blood pressure (SBP) was measured by the tail-cuff method before operation and at 1-week intervals thereafter. Rats were considered hypertensive when SBP reached 160 mm Hg, which generally occurred within 2 weeks of clipping. RHR and SHC were housed at constant temperature in environmental facilities and were given standard laboratory chow and water ad libitum.

Treatment of Hypertension

Eight weeks after clipping, the RHR were divided randomly into two groups: The first group (n = 12) was left untreated (RHR-U), and the second group (n = 9) was treated with diltiazem (LERS Laboratory, Synthelabo, Paris, France; RHR-T). Evolution of blood pressure was carefully monitored each day during the first week of treatment. The criterion used to establish dosage was effective blood pressure control. RHR-T were given diltiazem in drinking water at an initial dose of 30 mg/kg/day. The dosage was gradually increased to 40–50 mg/kg/day and adjusted for each animal to maintain blood pressure levels near 150 mm Hg. Rats were then given the adjusted dose during 8 weeks of treatment before the final hemodynamic and mechanical measurements were performed. During this period, blood pressure was measured twice a week by the same person at the same time of day.

Hemodynamic and Mechanical Myocardial Performance

RHR and SHC were studied 16 weeks after operation and 12 hours after the final administration of diltiazem. Simultaneous hemodynamic and mechanical measurements were performed on each animal according to the technique developed in our laboratory.

Systemic and Coronary Blood Flow Determination

Cardiac output and coronary blood flow were measured at rest and after coronary dilation by carbocromen in conscious, unrestrained rats by using left atrial injection of radioactive microspheres as described in detail by Wicker and Tarazi. Briefly, a No. 1 polyethylene catheter (Biotrol Pharma, Paris, France) was placed into the left atrium and exteriorized on the back of the neck while the rats were under pentobarbital anesthesia (30 mg/kg i.p.). Twelve hours before the study, another catheter (Biotrol No. 3) was inserted through a femoral artery into the abdominal aorta. Just before experimentation, this catheter was connected to a pressure transducer and an infusion withdrawal pump (Harvard Apparatus, Natick, MA, USA). This system allowed us to record blood pressures just before and after hemodynamic measurements and to withdraw reference blood samples for determination of cardiac output. Before injection, radioactive microspheres (15 μm in diameter) labeled with either cerium-141 or strontium-85 (3M Company, Saint Paul, MN, USA) were prepared as previously described.

A total of 0.15 ml of microsphere suspension was withdrawn in a Biotrol No. 3 catheter corresponding to 300,000 spheres and counted for radioactivity determination. The microspheres were injected into the left atrium over a period of 10 seconds, and the catheter was rapidly flushed with 0.2 ml of saline. Starting 10 seconds before the injection, a blood sample was withdrawn for 70 seconds through the femoral catheter at a constant rate of 0.425 ml/min. The rat was then given 0.2 ml of saline so that blood mass remained unchanged after hemodynamic determinations.

After the baseline measurement, coronary vasodilation was induced by carbocromen, 9 mg/kg, infused at a constant rate of 0.17 ml/min through the left atrial catheter. Five minutes after the end of the carbocromen infusion, hemodynamic measurements were repeated with a second batch of differently labeled radioisotope microspheres.

After hemodynamic data were collected, the animals were killed with an air bolus and their hearts removed immediately. This killing method also allowed mechanical performance to be measured on isolated papillary muscle. After rapid removal of the papillary muscle from left ventricle, right ventricle, endocardium, epicardium, and septum were dissected away, prepared for gamma counting, and weighed with precision. Tissue and blood samples were placed in separate plastic tubes and counted in a gamma counter (LKB Wallac Clinigamma, Paris, France).

Mechanical Cardiac Performance Measurements

Muscles removed from left ventricles were suspended at 29°C in a organ bath (50 ml) containing 50 ml of a modified, normotonic Krebs-Ringer solution (290 mosm): 118 mM NaCl, 4.7 mM KCl, 1.1 mM MgSO4-7H2O, 1.1 mM KH2PO4, 24 mM NaHCO3, 2.5 mM CaCl2-2H2O, and 4.5 mM glucose, buffered at pH 7.4. A gas mixture of 95% O2 and 5% CO2 was bubbled through this solution (oxygen tension, 630 mm Hg). The muscles were electrically stimulated (Roucaire T stimulator, Velizy, France) at a frequency of 6/min, with rectangular pulses of 5 msec. The voltage of these pulses exceeded the stimulation threshold by about 10%. The stimulus was provided through two parallel platinum electrodes. Perfect stabilization was obtained after at least 3 to 4 hours of isotonic beating against a moderate afterload (1–3 g according to initial developed tension). The muscle was then "stretched" to the peak of its length active force curve (i.e., Lmax).

An electromagnetic lever similar to that previously described by Brutsaert and Claes but with a smaller moving mass (155 mg) allowed the automatic adjustment of the preload constraint and the imposition of different loads during the contractions. The force transducer (manufactured by Dr. Claes, University of Antwerp, Antwerpen, Belgium) was similar to the
DILTIAZEM AND EXPERIMENTAL CARDIAC HYPERTROPHY/Grellet et al.

Systemic and Coronary Hemodynamics

Cardiac output did not differ between SHC and RHR-U, but it was elevated significantly in RHR-T compared with SHC (p < 0.01; see Table 1). The high blood pressure level in RHR-U was supported by a significant increase in total peripheral resistance compared with SHC (p < 0.01; see Table 1). Diltiazem therapy resulted in an important decrease of total peripheral resistance. Its average value was significantly smaller in RHR-T than in RHR-U (p < 0.01) and in SHC (p < 0.05).

There were no significant differences in heart rate among the three experimental groups.

Left ventricular coronary blood flow per unit mass did not differ at rest among SHC and RHR-U (Table 2). Diltiazem administration resulted in a significant

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sham-operated rats (n = 9)</th>
<th>Untreated (n = 12)</th>
<th>Treated (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (g)</td>
<td>388 ± 17</td>
<td>345 ± 20</td>
<td>345 ± 6</td>
</tr>
<tr>
<td>LVW (mg/g)</td>
<td>2 ± 0.09</td>
<td>3.10 ± 0.19*</td>
<td>2.35 ± 0.04*†</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>416 ± 14</td>
<td>426 ± 17</td>
<td>404 ± 5</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>137 ± 6</td>
<td>208 ± 5*</td>
<td>155 ± 3*†</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>106 ± 6</td>
<td>156 ± 7*</td>
<td>125 ± 3*†</td>
</tr>
<tr>
<td>CO (ml/min/kg)</td>
<td>298 ± 22</td>
<td>314 ± 16</td>
<td>426 ± 12*†</td>
</tr>
<tr>
<td>TPR (mm Hg·ml^{-1}·min^{-1}·kg^{-1} )</td>
<td>0.363 ± 0.025</td>
<td>0.489 ± 0.024*</td>
<td>0.295 ± 0.008†</td>
</tr>
</tbody>
</table>

Values are means ± SE. LVW = left ventricular mass normalized for body weight; HR = heart rate; CO = cardiac output; TPR = total peripheral resistance.

*p < 0.01, †p < 0.05, compared with values for sham-operated controls.

**p < 0.01, compared with values for untreated hypertensive rats.
increase of left ventricular coronary flow at rest in RHR-T compared with SHC ($p < 0.01$) that was associated with a significant reduction in total coronary vascular resistance ($p < 0.05$). Following carbochromen infusion, coronary flow significantly increased in all rats. The maximal left ventricular coronary flows and the minimal coronary vascular resistances were not significantly different in SHC, RHR-U, and RHR-T (see Table 2).

Coronary flow reserve, in terms of capacity to increase flow in response to a coronary vasodilator stimulus, was not modified in RHR-T and RHR-U (see Table 2). However, when expressed as percent change from resting values, coronary flow reserve was lower in RHR-T than in the other two groups ($p < 0.05$). In addition, coronary vasodilator reserve, computed either in absolute units (mm Hg/ml/min) or as percent change from resting values, was significantly lower in RHR-T than in RHR-U and SHC ($p < 0.05$).

The distribution of coronary blood flow between endocardium and epicardium was measured by means of the endocardial/epicardial flow ratio. At rest, this ratio approximated unity in all groups (see Table 2). Carbochromen vasodilation resulted in a reduction of the endocardial/epicardial flow ratio. The intergroup differences for this parameter were not significant at rest and after carbochromen infusion.

### Mechanical Cardiac Performance Data

Our experimental model allowed successive measurements of hemodynamics and mechanical performance parameters, so that all the data were recorded from each animal tested. Mechanical performance data obtained from papillary muscle preparations at Lmin in all three groups are summarized in Table 3. Developed isometric tension was significantly higher in RHR-U than in SHC ($p < 0.01$; see Table 3). Isometric timing parameters — TPF and THR — reached higher levels in RHR-U, resulting in an increased time of total contraction (TPF, $p < 0.01$; THR, $p < 0.05$) compared with SHC. Duration of isotonic contraction was also longer in RHR-U in relation to a significant decay of peak velocity of shortening ($p < 0.01$) and peak relaxation velocity ($p < 0.05$; see Table 3), but the time to relaxation index, an index of load-sensitivity of relaxation, remained similar in all groups (see Table 3).

Mechanical performance data following 8 weeks of treatment with diltiazem approximated values in SHC. Developed tension, velocity of shortening, and velocity of relaxation decreased toward values slightly higher than but not significantly different from those of SHC (see Table 3). The decrement of isometric timing parameters (THR and TPF) was less marked, since a statistically significant difference was maintained between RHR-T and SHC following treatment, as shown in Table 3.

### Table 2. Coronary Hemodynamic Effects of 8 Weeks of Diltiazem Treatment (40-50 mg/kg/day) in Renovascular Hypertensive Rats

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sham-operated rats ($n = 9$)</th>
<th>Untreated rats ($n = 12$)</th>
<th>Treated rats ($n = 9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVCF (ml/min/100 g) At rest</td>
<td>$453 \pm 19$</td>
<td>$549 \pm 48$</td>
<td>$598 \pm 17^*$</td>
</tr>
<tr>
<td></td>
<td>After carbochromen infusion</td>
<td>$1521 \pm 153$</td>
<td>$1618 \pm 77$</td>
</tr>
<tr>
<td>Coronary flow reserve (ml/min/100 g)</td>
<td>$1102 \pm 168$</td>
<td>$1068 \pm 109$</td>
<td>$909 \pm 79$</td>
</tr>
<tr>
<td></td>
<td>Percent increase</td>
<td>$242 \pm 41$</td>
<td>$209 \pm 38$</td>
</tr>
<tr>
<td>TCVR (mm Hg/ml/min) At rest</td>
<td>$31.5 \pm 3$</td>
<td>$29.7 \pm 3.5$</td>
<td>$26.0 \pm 0.8^\dagger$</td>
</tr>
<tr>
<td></td>
<td>After carbochromen infusion</td>
<td>$8.38 \pm 0.53$</td>
<td>$8.56 \pm 0.60$</td>
</tr>
<tr>
<td>Coronary vasodilator reserve (mm Hg/ml/min)</td>
<td>$-23.1 \pm 2.9$</td>
<td>$-21.1 \pm 3.3$</td>
<td>$-16.3 \pm 0.8^\dagger$</td>
</tr>
<tr>
<td></td>
<td>Percent change</td>
<td>$-73.3 \pm 3.0$</td>
<td>$-71.0 \pm 3.3$</td>
</tr>
<tr>
<td>Endocardial/epicardial flow At rest</td>
<td>$1.015 \pm 0.050$</td>
<td>$1.040 \pm 0.031$</td>
<td>$1.041 \pm 0.032$</td>
</tr>
<tr>
<td></td>
<td>After carbochromen infusion</td>
<td>$0.823 \pm 0.037$</td>
<td>$0.852 \pm 0.039$</td>
</tr>
</tbody>
</table>

Values are means ± SE. LVCF = left ventricular coronary flow; TCVR = total coronary vascular resistance.

*$p < 0.01$, $^\dagger p < 0.05$, compared with values for sham-operated controls.

$p < 0.05$, compared with values for untreated hypertensive rats.
of adrenergic response. In our study, the regression lines were very close in treated and untreated groups. This superimposition suggests that the incomplete regression of LVW may be related to the incomplete control of blood pressure alone. It is not surprising since the adrenergic response to diltiazem was less important as compared with those to nifedipine and nifedipine. Moreover, this result is inconsistent with a direct effect of diltiazem on left ventricular hypertrophy, as speculated by Tubau et al.

Systemic Hemodynamic Data

Cardiac output did not differ between untreated groups. The rise in blood pressure was related to a proportional increase in total peripheral resistance. Diltiazem treatment led to an increase in cardiac output without any change in heart rate. Since diltiazem itself had a negative inotropic effect on isolated heart muscle, the increased stroke volume cannot be related to a direct effect of this drug on myocardial tissue. Therefore, it is reasonable to assume that the rise in cardiac output was due to the ability of diltiazem to reduce the total peripheral vascular resistance.

Coronary Hemodynamics

Left ventricular coronary flow, expressed per 100 g of myocardial tissue, and total coronary resistance remained unchanged in hypertensive rats under both resting and maximal vasodilating conditions. Except for unchanged coronary flow reserve, these results are in agreement with most of the reported data. The maintenance of total coronary resistance suggests that the functional cross-sectional area of the coronary circulation does not grow in parallel with ventricular mass. In accordance with Wicker and Tarazi, the level of maximal coronary blood flow was closely correlated with the value of the MAP/LVW ratio. In our experiment, maintenance of this ratio could explain the unchanged maximal coronary blood flow.

Under resting conditions, diltiazem produced a significant increase in left ventricular coronary flow. The observed rise in cardiac output was not high enough in terms of myocardial oxygen consumption to explain this change in coronary blood flow. Diltiazem's elimination half-life is short in rats (approximately 1 hour). In this context, low levels of diltiazem were conceivable at the time of the hemodynamic measurements; however, increased stroke volume and coronary blood flow cannot be related to an acute effect of this drug. Under similar conditions, at the time of hemodynamic measurements, diltiazem treatment resulted in an increased coronary blood flow and stroke volume in normal rats (unpublished results, 1987). These data suggest a residual systemic and coronary vasodilating action of diltiazem at the times of the hemodynamic measurements. Hemodynamic data did not allow conclusions with reference to any diltiazem-induced beneficial change in coronary circulation in RHR associated with reversal of the early phase of left ventricular hypertrophy since 1) coronary hemodynamic-
ics remained unchanged in RHR-U and 2) comparable results were obtained in SHC.

Mechanical Performance

Previous studies in both humans and animals have evidenced an impairment of contractility and relaxation in ventricular hypertrophy. Mechanical performance changes in animal models vary according to the stimulus used to induce hypertrophy, the duration of pressure load, and the animal species.

In rats with hypertrophy induced by pressure load, most studies report increased isometric timing parameters (TPF and THR), decreased velocity of shortening, and normal or increased peak tension values. Our experimental data are in agreement with these previous results. In rats, reduced velocity of shortening can be correlated with the decrease in myosin adenosine triphosphatase activity due to an isoenzymatic pattern change. The longer duration of isometric contraction (increase in THR and TPF) may be related to the increased action potential duration observed in hypertrophied muscles.

Delayed relaxation of myocardial fiber (decrease in peak relaxation velocity) cannot be attributed to an alteration of the sarcoplasmic reticulum function, since load dependence of relaxation was not altered. Diltiazem treatment led to a normalization of mechanical parameters except for THR and TPF. The lack of total reversal of isometric timing parameters could be related to the incomplete left ventricular mass regression. However, a similar result was obtained after 8 weeks of treatment with a new converting enzyme inhibitor despite total regression of left ventricular mass. Therefore, an additional factor seems to be involved in the maintenance of a delayed isometric contraction. A possible explanation may be the maintenance of a longer action potential duration.

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