RELATIONSHIP BETWEEN PRESSURE-RATE PRODUCT
AND MYOCARDIAL OXYGEN CONSUMPTION
OF NORMAL AND HYPERTROPHIC
RIGHT VENTRICLES IN OPEN-CHEST DOGS

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There are few reports on the relationship between right ventricular performance and its myocardial oxygen consumption (RVMVO₂). The present study was conducted to investigate the relationship between RVMVO₂ and the mechanical performance of normal and hypertrophic right ventricles in open-chest dogs. Right ventricular hypertrophy (RVH) was induced by producing chronic right ventricular pressure overload by banding the pulmonary arteries of 8 puppies for 6 months. The experiment was performed under basal conditions and after increasing the RVMVO₂ in the eight dogs with RVH as well as in 20 normal dogs. The RVMVO₂ showed significant positive relationships with right coronary (RCA) flow, right ventricular systolic pressure, and right ventricular pressure-rate product (PRP) in both the normal right ventricle and RVH hearts. However, the slope between the PRP and RVMVO₂ was significantly steeper in the normal right ventricle (RV) than in the hypertrophic RV. When the PRP was normalized for the thickness of the right ventricular free wall, the slope of the two regression lines merged into a single line of fit. These results suggest that the pressure-rate product can be used to predict myocardial oxygen demand not only in the normal RV but also in well-compensated, hypertrophic RV. Isoproterenol induced smaller increases in cardiac output in the dogs with RVH than in those with normal RV. It also appears that the cardiac output of the hypertrophic RV is less sensitive to β-adrenoceptor stimulation than that of the normal RV.

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There have been few reports concerning right ventricular oxygen metabolism because of the technical difficulty in measuring right ventricular oxygen consumption. Sinha et al.¹,² developed a microphotometric method for studying regional myocardial oxygen consumption. This technique enables the investigation of regional RV oxygen metabolism. Using this technique, it was found that the oxygen metabolism of the right ventricle (RV) is essentially the same as that of the left ventricle (LV)³,⁴ However, when we used the anterior cardiac veins as drainage vessels for the right ventricular myocardium, myocardial oxygen uptake varied over a wide range and was substantially

Key words: Right ventricular hypertrophy RV oxygen usage Pressure-rate product PA bandage

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lower in the normal RV than in the normal LV\textsuperscript{5,6} while oxygen metabolism in the well-compensated hypertrophic RV was essentially the same as that in the LV\textsuperscript{7}. Furthermore, stimuli which raised right ventricular myocardial oxygen demand also increased myocardial oxygen uptake in association with an increase in the coronary blood flow in the normal RV. However, the hypertrophic RV showed minimum additional increases in its oxygen uptake\textsuperscript{7}. These results suggest that the oxygen demand-supply relationship and oxygen metabolism may be different in normal and hypertrophic RV. Although many indices for predicting the oxygen consumption of the LV have been proposed, few indices are available for predicting right ventricular oxygen consumption. Previous studies of right ventricular oxygen metabolism have used the indices obtained from studies on the LV, and have assumed that the relationship between oxygen demand and mechanical performance in the RV is identical to that in the LV. However, the geometry of the RV is quite different from that of the LV. Furthermore, there is a major difference between the regional deformation and local contractile function of the thin-walled right ventricle and the thick-walled left ventricle\textsuperscript{8}. This suggests that indices having left ventricular geometry or volume in the formulas may not simply be applied to the right ventricle for predicting myocardial oxygen consumption (MVO\textsubscript{2}). Thus, the relationship between oxygen demand and ventricular work in the normal and hypertrophic RV remains unclear and warrants further investigation. The present study was conducted to elucidate the relationship between coronary blood flow, oxygen demand and ventricular performance in normal and hypertrophic RV.

METHODS

To induce right ventricular hypertrophy in dogs, eight mongrel puppies of both sexes were anesthetized with sodium pentobarbital (30 mg/kg, i.v.). After endo-tracheal intubation, the dogs were ventilated and prepared for sterile surgery. A thoracotomy through the 4th intercostal space exposed the heart for pulmonary artery banding. A cotton tape (10 mm wide) was placed around the main pulmonary artery and constricted until the right ventricular systolic pressure was approximately 40 mmHg above control. The chest was then closed in layers and the lung was re-expanded under water seal drainage. All dogs were placed on a one-week postsurgical regimen of antibiotics. At least 6 months later, experiments were conducted in the 8 dogs with chronic pulmonary artery banding, and in 20 normal dogs that served as controls. To perform the RV studies, each of the 28 dogs was sedated with ketamine-HCl (0.1 mg/kg, s.c.), and anesthetized with pentobarbital sodium (30 mg/kg, i.v.). Each animal was ventilated with a mixture of oxygen and room air. A median sternotomy and the construction of a pericardial cradle exposed the heart for implantation of an electromagnetic flow probe and a pneumatic occlusive cuff on the proximal right coronary artery (RCA). We used a special flow probe (Nihon-Koden Kagyo Co., Tokyo) to minimize any changes in the contact between the vessel and the probe. The probe has a small head (about 0.7 g) and a very soft and light leadline which allows the probe head to move freely with each heart beat. This probe permitted us to obtain a RCA flow pattern without significant noise. Two to four cardiac veins in the central region of the RV were canulated with small polyethylene tubes (OD=0.86 mm). The anterior cardiac veins which receive blood from the pulmonary conus were excluded from this study. Blood from the veins was collected anaerobically by gravity drainage into tubes containing paraffin oil held at the level of the right atrium. This method allowed collection of 20–30% of the blood flow of the right coronary artery. The data regarding oxygen saturation of the blood in these veins were stored and averaged for each dog. Measurements of the RCA flow and the oxygen content in the anterior cardiac veins were used to calculate the RVMVO\textsubscript{2}. The cardiac output was measured with an electromagnetic flow probe positioned around the ascending aorta. Catheters in the right ventricle and the aortic root were used to monitor the intracavitary and coronary artery perfusion pressures. The arterial oxygen and carbon dioxide tensions (PO\textsubscript{2}, PCO\textsubscript{2}) and the pH were maintained within physiologic ranges by adjusting
TABLE I CARDIAC ANATOMIC AND HEMODYNAMIC MEASUREMENTS AT REST IN NORMAL DOGS AND PA-BANDED DOGS WITH MODERATE RIGHT VENTRICULAR HYPERTROPHY

<table>
<thead>
<tr>
<th></th>
<th>normal (n=20)</th>
<th>RVH (n=8)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV weight (g)</td>
<td>35.3±2.7</td>
<td>48.6±7.8</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>RV wall thickness (mm)</td>
<td>5.2±0.28</td>
<td>9.8±0.84</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RV/body weight ratio (×10^{-3})</td>
<td>1.68±0.10</td>
<td>2.82±0.26</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RV/LV weight ratio</td>
<td>0.39±0.03</td>
<td>0.86±0.05</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mean aortic pressure (mmHg)</td>
<td>100±7.2</td>
<td>94±6.3</td>
<td>ns</td>
</tr>
<tr>
<td>RV systolic pressure (mmHg)</td>
<td>23±1.0</td>
<td>49±11.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Heart rate (beat/min)</td>
<td>148±6.4</td>
<td>152±6.6</td>
<td>ns</td>
</tr>
</tbody>
</table>

Values are mean ± SEM.
PA=pulmonary artery, RVH=right ventricular hypertrophy,
RV=right ventricle, LV=left ventricle, ns=not significant.

the respiratory rate and/or the intravenous infusion of 7% NaHCO₃.

The experimental protocol compared the coronary blood flow rate and myocardial oxygen consumption under basal conditions and during the following interventions which increased RVMVO₂: 1) continuous intravenous infusion of isoproterenol at a rate of 0.1 µg/min/kg, and 2) constriction of the pulmonary artery by a special metal clip which was able to raise the right ventricular systolic pressure by 30 to 50%. After sampling the blood and recording the coronary flow and blood pressure, the stimulus was discontinued, and each animal was allowed to recover for at least 30 min. After each dog fully recovered, the second intervention was commenced. The order of the interventions was completely randomized. Prior to, and during, an intervention, a zero flow was obtained by inflating a pneumatic occlusive cuff positioned around the coronary artery, which ensured that there was no flow. After completion of the experiments, a 0.1% solution of Evans blue dye was infused into the left anterior descending coronary artery (LAD) at a rate of 1.5 mL/min to estimate the contamination of blood from the LAD into the anterior cardiac veins. After these experiments were completed, each dog was killed with an intracardiac injection of a saturated KCl solution. A 2% solution of Congo red dye was injected into the RCA to stain the myocardium. The heart was excised, the dye-stained myocardium was cut, and the weight and thickness of the RV and LV were measured. The MVO₂ and the coronary artery flow were expressed per 100 g of the myocardium.

The blood gas tensions and the pH were estimated with a Corning Model 165/II gas analyzer calibrated with reference gas mixtures and known pH buffer solutions between each sample measurement. Duplicate estimates of PO₂ and PCO₂ differed by 1 mmHg or less, while those of the pH differed by less than 0.05 units. The oxygen saturation of hemoglobin (SO₂) was estimated immediately after sampling with an Erma Optical Works Model PWA-100 Oximeter. The oximeter was calibrated against a AVL 990 gas analyzer, and with blood equilibrated with 100% O₂ gas. The hemoglobin (Hb) concentration was measured using the cyanomethemoglobin method. The oxygen content (O₂ cont) was calculated by the formula: O₂ cont= 1.34 × Hb (g/dl)×SO₂ (%) + 0.0031×PO₂ (mmHg). The concentration of Evans blue dye in the blood from the anterior cardiac veins and the aorta was measured spectrophotometrically with a Hitachi Spectrophotometer, model 220A. The procedures were approved by the institution's Animal Care and Use Committee.

Data analysis
These experiments compared the ventricular wall thickness, ventricular weight, coronary blood flow, and MVO₂ in normal and hypertrophic RVs. The slopes of the relationships between RVMVO₂ and heart rate, RCA flow, RV systolic pressure, and pressure-rate product, were also compared.

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between normal and hypertrophic RVs using analysis covariance. An unpaired Student’s t-test was used to compare the data between the two groups. Group data are presented as mean ± SEM.

RESULTS

Anatomic and hemodynamic characteristics of right ventricular hypertrophy (RVH)

The cardiac geometry and hemodynamic characteristics of the 8 dogs with pressure-overloaded RVH are summarized in Table I. Chronic pulmonary artery obstruction caused increases in the right ventricular systolic pressure, the right ventricular wall thickness measured in the middle of the anterior wall (the right ventricular outflow tract), the RV/body weight ratio, and the RV/LV weight ratio. The mean aortic pressure, heart rate, and cardiac output of the two groups during the baseline control were similar.

Baseline coronary blood flow and oxygen metabolism under basal conditions

The concentration of Evans blue dye in the anterior cardiac veins was the same as that in the aorta, indicating that there was no significant contamination of blood from

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**TABLE II  EFFECTS OF INTRAVENOUS INFUSION OF ISOPROTERENOL**

<table>
<thead>
<tr>
<th></th>
<th>normal (n=20)</th>
<th>RVH (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>control</td>
<td>isoproterenol</td>
</tr>
<tr>
<td>RCA flow (ml/min/100 g)</td>
<td>46 ± 6</td>
<td>114 ± 13**</td>
</tr>
<tr>
<td>RVMVO₂ (ml/min/100 g)</td>
<td>4.2 ± 0.4</td>
<td>10.9 ± 1.4**</td>
</tr>
<tr>
<td>mean AoP (mmHg)</td>
<td>102 ± 8</td>
<td>91 ± 11</td>
</tr>
<tr>
<td>RVSP (mmHg)</td>
<td>26 ± 3</td>
<td>30 ± 5</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>146 ± 12</td>
<td>175 ± 16*</td>
</tr>
<tr>
<td>Cardiac output (ml/min/kg)</td>
<td>132 ± 9.2</td>
<td>174 ± 11.9**</td>
</tr>
</tbody>
</table>

Data are mean ± SEM. RVH=right ventricular hypertrophy, RCA flow=right coronary blood flow, RVMVO₂=right ventricular oxygen consumption, mean AoP=mean aortic pressure, RVSP=right ventricular systolic pressure. Significantly different from the control; *p<0.05, **p<0.01. Increases due to stimulation significantly different from the corresponding values in normal hearts; * p<0.05, ** p<0.02.

**TABLE III  EFFECTS OF PULMONARY ARTERY (PA) CONstriction**

<table>
<thead>
<tr>
<th></th>
<th>normal (n=20)</th>
<th>PA constriction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>control</td>
<td>PA constriction</td>
</tr>
<tr>
<td>RCA flow (ml/min/100 g)</td>
<td>44 ± 4</td>
<td>51 ± 6**</td>
</tr>
<tr>
<td>RVMVO₂ (ml/min/100 g)</td>
<td>3.9 ± 0.3</td>
<td>5.0 ± 0.5**</td>
</tr>
<tr>
<td>mean AoP (mmHg)</td>
<td>100 ± 9</td>
<td>94 ± 8</td>
</tr>
<tr>
<td>RVSP (mmHg)</td>
<td>24 ± 2</td>
<td>38 ± 2**</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>148 ± 10</td>
<td>150 ± 12</td>
</tr>
<tr>
<td>Cardiac output (ml/min/kg)</td>
<td>138 ± 10</td>
<td>122 ± 11*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>RVH (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>control</td>
</tr>
<tr>
<td>RCA flow (ml/min/100 g)</td>
<td>49 ± 8</td>
</tr>
<tr>
<td>RVMVO₂ (ml/min/100 g)</td>
<td>4.4 ± 0.5</td>
</tr>
<tr>
<td>mean AoP (mmHg)</td>
<td>86 ± 7</td>
</tr>
<tr>
<td>RVSP (mmHg)</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>148 ± 6</td>
</tr>
<tr>
<td>Cardiac output (ml/min/kg)</td>
<td>128 ± 8</td>
</tr>
</tbody>
</table>

Data are mean ± SEM. RVH=right ventricular hypertrophy, RCA flow=right coronary blood flow, RVMVO₂=right ventricular oxygen consumption, mean AoP=mean aortic pressure, RVSP=right ventricular systolic pressure. Significantly different from the control; *p<0.05, **p<0.01. Increases due to stimulation significantly different from the corresponding values in normal hearts; * p<0.05.
the LAD to the veins. The baseline right coronary flow and oxygen consumption of the hypertrophic RV were 51±8 mL/min/100 g and 4.3±0.6 mL/min/100 g, respectively, which were not significantly different from corresponding values in normal dogs: 45±6 mL/min/100 g and 4.1±0.5 mL/min/100 g for the RCA flow and RVMVO$_2$, respectively.

Hemodynamic responses to increased oxygen consumption

Tables II and III compare the responses of normal and hypertrophic RVs to isoproterenol and acute pulmonary constriction, respectively. In both groups, isoproterenol infusion increased the heart rate by 20% and lowered the mean aortic blood pressure by 15%. The RCA flow and RVMVO$_2$ in the RVH group increased by 67±21.6% and 59±25.5%, respectively, above the baseline controls with the isoproterenol infusion. The increases were significantly smaller than those of the normal group: 141±35.6% (p<0.02) and 157±30.1% (p<0.01) for the RCA flow and RVMVO$_2$, respectively. During isoproterenol infusion, the cardiac output of the normal dogs increased by 29±11.5% (p<0.01) while that in the dogs with RVH showed an insignificant increase (5.5±3.1%). In the RVH group, increasing the pulmonary artery constriction further raised the right ventricular systolic pressure by 30 to 50%, but did not affect the heart rate or the aortic blood pressure. The RCA flow and RVMVO$_2$ increased concomitantly with the elevation of right ventricular pressure. The rates of increase in RCA flow and RVMVO$_2$ tended to be greater in the hypertrophic RV, although the differences were not statistically significant. While cardiac output decreased with increased pulmonary artery narrowing in both groups, the magnitude of the cardiac output reduction was slightly, but significantly greater in the hypertrophic group than in the normal group.

**Relationship of MVO$_2$ to right ventricular systolic pressure and heart rate**

The pooled data from 8 dogs were used to analyze the relation between hemodynamic parameters and RVMVO$_2$. Linear regression analysis revealed a significant relationship between RVMVO$_2$ and right ventricular systolic pressure (RVP) in normal dogs and in those with hypertrophic RV (Fig. 1). The relationship can be expressed by the following formulae: MVO$_2$=0.07RVP+0.26 (r=0.71, p<0.01) for the dogs with normal RV and MVO$_2$=0.097RVP+0.44 (r=0.73, p<0.01) for the dogs with hypertrophic RV. The slopes and Y-intercepts of the linear relationships between RVMVO$_2$ and each hemodynamic parameter are presented in Table IV. The relationship between RVMVO$_2$ and heart rate over the range of 120 to 170 beats per minute was not significant. The PRP, which is the product of the heart rate and right ventricular systolic pressure, showed significant correlation to RVMVO$_2$ in both the normal dogs and in those with hypertrophic RV (Fig. 2). The slope of the regression line was significantly steeper (p<0.02) in the normal dogs than in the dogs with hypertrophic RV. However, after normalization of PRP for the right ventricular weight or the thickness of the right ventricular free wall, the differences between the groups disappeared. The regression equation between RVMVO$_2$ and PRP/(RV weight) was MVO$_2$=24.6×10$^{-3}$ (PRP/RV weight)+1.30 (r=0.72, p<0.01) for the hypertrophied RV, and MVO$_2$=30.3×10$^{-3}$ (PRP/RV weight)+1.46 (r=0.73, p<0.01).
Fig. 2. Relationship between pressure rate product (PRP) and myocardial oxygen consumption (MVO₂). The right panel shows the relationship in the overall right ventricle, and the left panel shows the results after normalization of the PRP for the thickness of the right ventricular free wall. Note that after normalization, the difference between the slopes of the regression lines which was seen in the overall RV disappeared (see text). Solid line, hypertrophic RV; dashed line, normal RV. Open symbols, normal RV; closed symbols, hypertrophic RV. ○● control; □■ isoproterenol infusion; △▲ pulmonary artery constriction.

### TABLE IV  RELATIONSHIP BETWEEN RIGHT VENTRICULAR MVO₂ AND HEMODYNAMIC PARAMETERS

**Normal right ventricle**

<table>
<thead>
<tr>
<th></th>
<th>slope ($\times 10^{-3}$)</th>
<th>Y-intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SEM</td>
</tr>
<tr>
<td>HR vs. MVO₂</td>
<td>26.6</td>
<td>13.2</td>
</tr>
<tr>
<td>RVP vs. MVO₂</td>
<td>171.1</td>
<td>23.8</td>
</tr>
<tr>
<td>PRP vs. MVO₂</td>
<td>1.30</td>
<td>0.199</td>
</tr>
<tr>
<td>PRP/(RV weight) vs. MVO₂</td>
<td>30.3</td>
<td>3.65</td>
</tr>
<tr>
<td>PRP/(wall thickness) vs. MVO₂</td>
<td>6.62</td>
<td>0.29</td>
</tr>
</tbody>
</table>

HR = heart rate, MVO₂ = myocardial oxygen consumption,  
RVP = right ventricular systolic pressure,  
PRP = pressure rate product.

**Hypertrophied right ventricle**

<table>
<thead>
<tr>
<th></th>
<th>slope ($\times 10^{-3}$)</th>
<th>Y-intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SEM</td>
</tr>
<tr>
<td>HR vs. MVO₂</td>
<td>24.4</td>
<td>12.8</td>
</tr>
<tr>
<td>RVP vs. MVO₂</td>
<td>96.9**</td>
<td>12.7</td>
</tr>
<tr>
<td>PRP vs. MVO₂</td>
<td>0.66**</td>
<td>0.084</td>
</tr>
<tr>
<td>PRP/(RV weight) vs. MVO₂</td>
<td>24.6</td>
<td>4.44</td>
</tr>
<tr>
<td>PRP/(wall thickness) vs. MVO₂</td>
<td>5.34</td>
<td>0.65</td>
</tr>
</tbody>
</table>

HR = heart rate, MVO₂ = myocardial oxygen consumption,  
RVP = right ventricular systolic pressure,  
PRP = pressure rate product.  
Significantly different from values of normal dogs; **p<0.02.
for the normal RV. The equation between RVMVO₂₂ and PRP/(wall thickness) was
MVO₂₂ = 6.34 × 10⁻³PRPc + 1.08 (r = 0.72,
p < 0.01) for the banded dogs and
MVO₂₂ = 6.62 × 10⁻³PRPc - 0.52 (r = 0.74,
p < 0.01) for the normal dogs, where PRPc
was the PRP after normalization for the right
ventricular wall thickness.

DISCUSSION

This experiment was conducted to elucidate the relationship between the mechanical
performance and myocardial oxygen consumption in the hypertrophic right ventricle.
The results indicate that the pressure rate product (PRP), which is the product of the
heart rate and right ventricular systolic pres-
sure, varied with RVMVO₂₂. This suggests that
the PRP is a useful index of the RVMVO₂₂ in the hypertrophic, as well as in
the normal, RV. We used blood which had
been drained from the central region of the
right ventricular free wall to study oxygen metabolism in the RV, because in dogs this
area of the RV is perfused only by the RCA.
The region adjacent to the left ventricle,
approximately 37% of the right ventricular
free wall, receives its blood supply from the
left coronary artery. Pressure overload-
induced RVH did not change the blood flow
distribution of the RV from the left coronary
artery, but did result in an increase in the
RCA flow relative to the total perfusion of
the right ventricular free wall. In addition,
any significant contamination of blood from
the LAD to the veins used in this study was
excluded by the finding that the plasma con-
centration of Evans blue dye in the anterior
cardiac vein was not different from that in
the aorta. Thus, it is reasonable to use blood
drained from the anterior cardiac veins for
studying oxygen metabolism of the hyper-
trophic RV, although we cannot exclude the
possibility of contamination of blood sup-
plied by the left circumflex coronary artery
to the veins.

In the present study, no significant differ-
ence in RCA flow per unit weight existed be-
tween hypertrophic RV and normal RV
under basal conditions. This finding agrees
with the report of Wyse et al. who
observed normal right ventricular perfusion
in pigs with severe RVH. However, Murray
and co-workers observed marked in-
creases in the transmural blood flow per
gram in moderately and severely hyper-
trophic RV which were proportional to the
increases in their mass. An important differ-
ence between these studies and ours is the
degree of right ventricular pressure loading.
Our dogs developed moderate right ventricu-
lar hypertension to 49 ± 11.1 mmHg about 6
months after their first operation, while
Murray et al. markedly increased the right
ventricular systolic pressure to 78 ± 3 mmHg
4 to 6 weeks after surgery, and then to
102 ± 9 mmHg 4 to 5 months after surgery.
However, the RV wall thickness was similar
in the dogs in these two studies. Thus, it is
possible that the RV wall stress of Murray’s
dogs could not be normalized completely
because of their higher right ventricular
pressure with only a moderate increase in
their wall thickness. This may have resulted
in an increase in the right ventricular flow
per unit weight. In the LV, Sasayama et al. reported that wall stress increased im-
mediately after raising the pressure load.
However, over a period of several weeks,
the ventricular wall thickness increased, and
returned the wall stress to normal. This find-
ing may be applicable to the RV with
pressure-induced hypertrophy. In the pre-
sent study, long-term elevation of the right
ventricular pressure caused right ventricular
wall thickening, which compensated for the
increased wall stress and consequently re-
turned the RCA flow and RVMVO₂₂ per unit
myocardial weight to their baseline levels.
The finding of normal perfusion per unit
weight of muscle in hypertrophic cardiac
muscle is in agreement with many studies of
chronic left ventricular hypertrophy. An
alternative explanation for the normal RCA
flow in our RVH dogs is that we observed
coronary flow which had already passed
through a phase of elevated right ventricular
perfusion per unit weight and had returned
to its normal value, perhaps during the des-
cent toward right ventricular failure. How-
ever, this explanation seems unlikely
because the hemodynamic data and the right
ventricular responses to stimuli which in-
crease right ventricular work suggested that
the hypertrophic RV functioned in a nearly
normal manner.

Many pieces of evidence have indicated

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that the systolic pressure-volume area (PVA) correlates with ventricular oxygen consumption (MVO$_2$) under a variety of loading and contractile conditions$^{16-18}$. This index of MVO$_2$ enables the measurement of ventricular energy for EC coupling and contractile efficiency independently during various loading conditions. Determination of the pressure-volume relation of the RV is essential for obtaining PVA. However, it is difficult to accurately measure the instantaneous RV volume during a heart beat in the in situ heart, and, therefore, it is difficult to determine the PVA-MVO$_2$ relationship. Thus, in the present study, we used right ventricular PRP to predict RVMVO$_2$ instead of PVA, despite the theoretical superiority of PVA.

Wall stress is one of the major determinants of MVO$_2$. For a spherical RV, the Laplace equation is $WstRV = Pr^{2}h$, where WstRV is the wall stress, P is the pressure, r is the radius, and h is the mean wall thickness of the RV. However, we did not measure the radius of the RV, because the RV is not spherical and it is difficult to measure the radius accurately. Archie et al$^{19}$ calculated the peak systolic wall stress of the RV by assuming that the right ventricular end-diastolic volume at a given end-diastolic pressure was similar in control and banded lambs of equal body weight. We did not determine the right ventricular wall stress in this study because the pressure-volume relationship in hypertrophic RV is different from that in normal RV, and the right ventricular geometry is not so simple that it can be calculated from hemodynamic data, even if we used some simplifying assumptions. Instead of calculating wall tension, we simply utilized the right ventricular systolic pressure as a determinant of RVMVO$_2$. Since the right ventricular systolic pressure is related to the peak systolic wall tension, and an elevation in the systolic pressure could result in an increase in the RV radius, it follows that the right ventricular systolic pressure closely reflects the right ventricular wall tension. In fact, we found a significant relationship between the right ventricular systolic pressure, RVMVO$_2$, and the right coronary blood flow. While heart rate changes were associated with changes in RVMVO$_2$ and the right coronary blood flow, those relationships were not statistically significant, possibly because the heart rate varied only within a relatively narrow range.

The pressure rate product, which is the product of the heart rate and systolic pressure, is an index which reflects myocardial metabolic demand and frequently is used clinically to predict the left ventricular oxygen requirement per minute$^{20}$. For the RV, we computed the PRP using the right ventricular systolic pressure instead of the systemic blood pressure. The PRP of the total RV varied with changes in the perfusion and oxygen consumption in both the normal and hypertrophic RVs. When the index was normalized for the right ventricular weight or wall thickness in each animal, the lines of regression nearly merged into a single line. The insignificant difference between the normal and banded animals in the slopes of the regression lines, suggests that the oxygen demand of the right ventricular cardiac muscle per unit weight is unchanged in the well-compensated hypertrophic RV, and that perfusion to the hypertrophic right ventricular muscle is adequate.

Our observation produced a rough relationship between PRP and MVO$_2$ of the right ventricle in both the normal and banded dogs. One possible explanation for the relatively rough correlation is that there may be other important factors, including ventricular volume and myocardial contractility, in addition to heart rate and right ventricular pressure. Ventricular volume, or dimension, and myocardial contractility are the major factors involved in the regulation of myocardial oxygen consumption$^{21,22}$. These factors may vary from dog to dog. Due to the technical difficulty in measuring right ventricular volume and contractility, these factors were not incorporated into the PRP used to predict RVMVO$_2$. Therefore, PRP may not reflect the close relationships with RVMVO$_2$. The other possible explanation for the relatively rough correlation involves a technical problem. In the present study, the pooled data for all of the dogs in each group (inter-heart data) were used to estimate the relation between hemodynamic parameters and MVO$_2$, instead of the averaged slope and intercept data from each dog (intra-heart data). Although a better relationship between hemodynamic parameters and MVO$_2$ would be expected with the intra-
heart data than the inter-heart data, it was difficult to calculate the intra-heart data because we were only able to obtain 2 or 3 points of the relationship for each dog.

In addition, the present study showed that the hypertrophic RV was less able to increase cardiac output in response to \( \beta \)-adrenergic stimulation by isoproterenol infusion. The results of previous studies on the response of the hypertrophic ventricle to \( \beta \)-adrenergic stimulation are equivocal. Some reports\(^{23,24}\) have demonstrated that the work performance of the hypertrophic RV in response to \( \beta \)-adrenergic stimulation remains, normal, while other investigators have noted either a reduction\(^{25}\) or an increase in the work performance\(^{26}\). These different observations appear to reflect differences in the experimental models and/or the degree of hypertrophy. The results from papillary muscle strips, very early hypertrophy, hypertrophy with failure, or hypertrophy in conscious animals cannot be compared directly with the present findings, since our experiments were performed in situ in dogs with chronic compensated RVH. Under these conditions, a less extensive response of cardiac output to infused isoproterenol was found in the hypertrophic RV than in the normal RV. Since the perfusion per unit weight of myocardium both prior to and during the isoproterenol infusion did not differ between the two groups, myocardial ischemia, which would attenuate the mechanical response of the heart to isoproterenol, is not expected to occur during isoproterenol infusion. This finding is consistent with the observations of Wyse et al\(^{10}\) who found that the intravenous infusion of isoproterenol increased the right ventricular peak dP/dt less extensively in the banded animals than in the normal controls. Oxygen wasting with adrenergic stimulation, which may be exacerbated in LVH, has been described in the myocardium\(^{27,28}\). Cimini and Weiss\(^{29}\) also observed impaired cardiac function during isoproterenol stress in hypertrophic left ventricular myocardium independent of a restricted myocardial oxygen supply. Some possible explanations for the reduced response by hypertrophied LV have been proposed. Investigators have shown reduced numbers of \( \beta \)-adrenoceptors in left ventricular hypertrophy\(^{20,31}\). Although \( \beta \)-adre-

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