Effect of Exercise on Left Ventricular Mechanical Efficiency in Conscious Dogs

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Background We studied the effect of exercise (7.2 to 8.0 km/h) on the efficiency of the conversion of metabolic energy to work (SW) by the left ventricle (LV).

Methods and Results Energy use was calculated from LV myocardial oxygen consumption per beat (MVo2). LV volume was calculated from orthogonal dimensions and coronary flow measured with ultrasonic flow probes. The total mechanical energy of the LV was calculated as the pressure-volume area (PVA). At rest, the MVo2-PVA point fell on the MVo2-PVA relation determined by steady-state changes in arterial pressure produced by graded infusions of phenylephrine. Exercise increased the slope (Ees) of the LV end-systolic pressure-volume (PV) relation by 29%. During exercise, the MVo2-PVA point shifted upward and rightward only slightly above the control MVo2-PVA relation by 0.007±0.005 mL O2·beat⁻¹·100 g LV⁻¹. Despite the increase in ventricular contractility with exercise, the PVA/MVo2 ratio was unchanged because of the marked increase in PVA. During exercise, the transmission of total mechanical energy to work (SW/PVA) increased from 65±5% to 72±4% (P<.01) as the ratio of the arterial end-systolic elastance to Ees decreased from 1.1±0.2 to 0.8±0.1 (P<.05). Thus, LV mechanical efficiency (SW/MVo2=SW/PVA·PVA/MVo2) improved from 12.9±1.5% to 14.3±1.1% (P<.05) during exercise.

Conclusions Exercise increases the efficiency of conversion of metabolic energy to external work by the LV due to alteration in LV arterial coupling resulting in increased production of mechanical energy and enhanced transmission of mechanical energy to external work, which more than offsets any increased metabolic cost of the enhanced contractility. (Circulation. 1994;90:3047-3054.)

Key Words • oxygen consumption • stroke work • metabolic energy • contractility • exercise

In the absence of ischemia, the energy consumed by the LV can be calculated from its oxygen consumption. The external work produced by the LV during each beat is the stroke work (SW), the area contained within the pressure-volume (PV) loop. Thus, the efficiency of the conversion of energy to useful work by the LV can be determined from the ratio of SW to myocardial oxygen consumption per beat (MVo2). During exercise, the efficiency of the energy transmission to external work (ie, increased mechanical efficiency) is still unknown. Accordingly, this study was undertaken to determine the effect of exercise on MVo2, SW, and LV PV relations to assess the effect of exercise on the efficiency of LV conversion of metabolic energy to mechanical energy (PVA/MVo2), the transmission of mechanical energy to external work (SW/PVA), and the resulting mechanical efficiency of the LV (SW/MVo2).

Methods

Preparation

Seven healthy mongrel dogs weighing 23 to 38 kg were instrumented while they were under anesthesia induced with xylazine (2 mg/kg) and sodium thiopental (6 mg/kg IV)
were calibrated with a mercuric manometer. The signal from the micromanometer was adjusted to match that of the catheter. The transit time of 5 MHz sound between the crystal pairs was determined and converted to a distance assuming a constant velocity of sound in blood of 1.55 m/s. The coronary flow probes were connected to an ultrasonic flowmeter (model T201, Transonic System Inc). The flow probe was calibrated at the factory with confirmed accuracy within ±10%. Coronary arterial and venous oxygen contents were measured with a hemoximeter (Co-Oximeter 482, Instrumentation Laboratory).

Protocol
Before exercise, steady-state data were collected during 12- to 15-second periods at rest to obtain heart rate, LV pressure and volume, and coronary flow while the dogs stood on a treadmill (Quinton, Inc). At the same time, LV and coronary sinus blood samples were taken for measurement of oxygen content. Then, transient vena caval occlusions were performed for 6 to 12 seconds to obtain the LV ESPVR. The animals were unsedated, and autonomic reflexes were intact.

After we collected the resting data, the dogs ran on a motorized treadmill. The treadmill speed was gradually increased from 4.0 km/h over 1 to 2 minutes to the submaximal level, 7.2 to 8.0 km/h, in steps of 0.8 km/h. We collected steady-state data and blood samples approximately 3 minutes after the last increase in exercise speed during steady-state submaximal exercise (Fig 1). Then, a transient caval occlusion was created for 6 to 12 seconds during exercise (Fig 2). This submaximal exercise level was sustained during data collection for both steady state and caval occlusion.

One or 2 days before the exercise study, the resting cardiac oxygen consumption per beat (MVo2)/PVA relation was measured in all seven dogs. To avoid the influence of autonomic reflexes during changes in loading conditions, autonomic
blockade was induced for this protocol with only hexamethonium chloride (5 mg/kg) and atropine sulfate (0.1 mg/kg), followed by their continuous infusions at rates of 0.1 mg/kg and 0.005 mg/kg per minute, respectively. LV loading conditions were widely varied with three or four graded doses of phenylephrine. After stabilization of all signals, steady-state data were recorded during 12 to 15 seconds, and thereafter the transient occlusions of venae cavae were created to obtain the ESPVR. The baseline data from five of these animals are reported elsewhere.9

Data Processing and Analysis

Data were digitized, using an on-line analog-to-digital converter (Data Translations Devices) at 200 Hz during each 12- to 15-second collection period. The LV volume was calculated as a modified general ellipsoid using the following equation:

$$V_{LV} = (\pi/6) \cdot D_{AP} \cdot D_{SL} \cdot D_{LA}$$

where $$V_{LV}$$ is LV volume, $$D_{AP}$$ is the anteroposterior LV diameter, $$D_{SL}$$ is the septolateral diameter, and $$D_{LA}$$ is the long-axis LV diameter. We have previously demonstrated that this method gives us a consistent measure of LV volume despite changes in LV loading conditions, configurations, and heart rate.13,14,15

End systole was defined as the time of the peak instantaneous ratio of LV pressure to volume. The PVA was determined as the area under the ESPVR line and the systolic PV trajectory and above the end-diastolic PV relation curve. The ESPVR obtained during transient vena caval occlusion was superimposed on the steady-state PV loop that was averaged over the 12- to 15-second recording period (Fig 2). We assumed that end-diastolic PV relation curve was reasonably approximated by a third-order polynomial. Then, the small area of PVA between the straight line connecting the volume axis intercept ($$V_0$$) of ESPVR and end-diastolic point ($$V_{ed}, P_{ed}$$) and the downward convex end-diastolic PV curve was given by $$P_{ed} \cdot (V_{ed} - V_0)/4$$.16 To evaluate the effect of nonlinearity of the ESPVR, the end-systolic points were also fitted by a quadratic function curve ($$P_{es} = a \cdot V_s^2 + b \cdot V_s + c$$ [a, b, and c are constants, respectively]), and PVA was calculated from this nonlinear ESPVR. The product of the coronary flow (mL/min) and coronary arteriovenous oxygen content difference (vol%) divided by 100 gives oxygen consumption rate in milliliters of O2 per minute. This was divided by the heart rate to yield oxygen consumption in milliliters of O2 per beat. Total LV oxygen consumption was calculated as (total LV weight)/ (perfused LV weight distal to both LCx and LAD flow probes) multiplied by the measured oxygen consumption. To make PVA/MVO2 and SW/MVO2 dimensionless, we converted mm Hg mL of PVA and SW and O2 mL of MVO2 to joules by using 1 mm Hg mL=1.33×10⁻⁶ J and 1 mL O2=20 J.

In the preliminary study with the same instrumentation, we measured arterial and coronary sinus lactate levels before and during exercise (7.2 km/h) in two dogs. The lactate extraction ratio (ie, coronary arteriovenous lactate difference/coronary artery lactate) was 35.8±1.5% at rest and 37.8±8.6% during exercise. A systemic adenosine infusion at rest increased both LCx and LAD coronary flows more than threefold. These results demonstrate that our instrumentation did not limit coronary flow or produce cardiac ischemia during exercise.

At the conclusion of the experiments, the dogs were anesthetized with sodium thiopental (6 mg/kg) and halothane (0.5% to 2%) and a thoracotomy was performed to determine the perfusion territories of LCx and LAD using saturated Evans’ blue solution. The dogs were euthanized with T-61 euthanasia solution (0.3 mL/kg IV) after the injection of the Evans’ blue solution. The hearts were examined to confirm the proper positioning of the instrumentation. Then, the stained
Fig 3. A, Plot of rest (○) and exercise (●) data points superimposed on baseline blocked 
MVO2-PVA relation (● and dotted lines). The 95% confidence limits of the regression line are 
shown. Data from one animal. B, Data from other six animals. MVO2 indicates myocardial 
oxxygen consumption per beat; PVA, pressure-volume area; and LV, left ventricle.

and nonstained portions of the LV were weighed. The ratio of the perfused LV weight to the total LV weight was 0.57±0.05.

Statistical Analysis
Data obtained from dogs at rest and during exercise were compared using two-tailed paired t tests. Linear regression analysis was applied to obtain the regression line of MVO2 on PVA. Values are given as mean±SD.

Results
Fig 1 shows analog recordings of LV pressure (LVP), ventricular diameters (Dap, anteroposterior diameter; Dsl, septolateral diameter; Dla, long-axis diameter), ventricular volume (LVV), coronary flows (for LCx or LAD) in dogs at rest and during exercise. During exercise, the heart rate, LVP, and both coronary artery flows increased.

Group values of hemodynamic, PV, and cardiac oxygen consumption indexes are summarized in Tables 1, 2, and 3. An example of PV loops at steady state and transient caval occlusion before and during exercise are shown in Fig 2. Exercise increased the heart rate by an average of 45 beats per minute and end-systolic pressure by an average of 20 mm Hg. During exercise, LV end-diastolic volume slightly but significantly increased.

Table 1. Hemodynamic Data at Rest and During Exercise

<table>
<thead>
<tr>
<th></th>
<th>HR, bpm</th>
<th>EDV, mL</th>
<th>ESV, mL</th>
<th>SV, mL</th>
<th>EDP, mm Hg</th>
<th>ESP, mm Hg</th>
<th>dP/dtmax, mm Hg/s</th>
<th>−dP/dt, mm Hg/s</th>
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whereas end-systolic volume was unchanged; thus, the
stroke volume increased significantly by 16%. Exercise
enhanced the LV contractile state as determined by a
29% increase in Ees and a 37% increase in dP/dt max.
Both external work (SW) and PVA increased signifi-
cantly during exercise.

Coronary flow at rest was 81.5±10.6 mL · min⁻¹ · 100
g⁻¹ · LV and increased significantly by 51% during exer-
cise. Coronary artery hemoglobin concentration in-
creased from 11.0±0.9 to 11.8±0.6 g/dL during exercise
(P<.05). Coronary artery oxygen saturation was
96.1±1.0% at rest and was unchanged. Coronary ve-
nous oxygen saturation decreased from 21.7±3.6% to
14.9±1.9% during exercise (P<.01). The coronary ar-
teriovenous oxygen content difference increased sig-
nificantly during exercise due to a decrease in coronary
venous oxygen content and an increase in arterial
oxygen content. Exercise increased cardiac oxygen
consumption per minute by 72% and per beat (MVVo2)
by 25%.

As shown in Table 4 and Fig 4, the ratio of SW to
PVA (SW/PVA) was 65.0±5.0% at rest and increased
significantly to 72.1±3.9% during exercise. The ratio of
PVA to MVVo2 was 19.8±1.3% at rest and unchanged
(19.9±1.3%) during exercise. The ratio of SW to MVVo2
(SW/MVVo2), ie, the mechanical efficiency, was 12.9±1.5
% at rest and increased to 14.3±1.1% during exercise
(P<.05). PVA values calculated from nonlinear ESPVR
were only slightly smaller than those from a linear
approximation of its ESPVR. The SW/PVA ratio were
slightly (<5%) increased and the PVA/MVVo2 ratio was
slightly decreased (<2%) at both rest and exercise
compared with that obtained (P=NS) from the linear
ESPVR (Table 4).

The MVVo2-PVA relation was obtained at rest by chanc-
ing LV loading conditions with phenylephrine after au-
tonomic blockade to prevent reflex changes in contractile
state. Ees was nearly constant (P=NS) regardless of
changes in loading conditions in each heart, and the
coefficient of variation (standard deviation/mean value)
was .06±.03. The value of the blocked Ees (8.3±1.7
mm Hg/mL) was almost identical to the value (8.2±2.1
mm Hg/mL) at rest before exercise. After blockade, MVVo2
was linearly correlated with PVA in all dogs with the cor-
correlation coefficient of .986±.014 (Fig 3). The slope
and MVVo2 intercept of the MVVo2-PVA regression line was
(2.19±0.30)·10⁻⁵ mL O₂ · mm Hg⁻¹ · mL⁻¹ and
0.0247±.0038 mL O₂/100 g LV, respectively. The slope
and MVVo2 intercept calculated from the nonlinear ES-
PVR were similar to the linear values, 2.32±.31·10⁻⁵
mL O₂ · mm Hg⁻¹ · mL⁻¹ and 0.0246±.0046 mL O₂/100 g
LV, respectively, with the correlation coefficient of
.986±.014.

Fig 3 shows the response to exercise in the MVVo2-PVA
plane in all hearts. Before exercise, each data point was
on or near the blocked MVVo2-PVA relation. MVVo2 at
rest was 0.073±0.0195 mL O₂ · beat⁻¹ · 100 g⁻¹ · LV and was
very close to the value calculated from the MVVo2-PVA
regression line at the same PVA value before exercise
(0.073±0.0179 mL O₂ · beat⁻¹ · 100 g⁻¹ · LV, P=NS). In 6 of
the 7 animals, the resting MVVo2-PVA point fell within
the 95% confidence intervals of the blocked MVVo2-PVA
relation. During exercise, the MVVo2-PVA point shifted
to the right with increases in both MVVo2 and PVA.
In 2 animals, the MVVo2-PVA point during exercise
was above the 95% confidence limits of the blocked
MVVo2-PVA relation, and in the other 5 it fell within
the 95% confidence limits. MVVo2 during exercise
was 0.0916±0.0191 mL O₂ · beat⁻¹ · 100 g⁻¹ · LV and was
slightly but significantly (P<.05) higher than the value
calculated from the resting MVVo2-PVA line at the same
PVA value (0.0851±0.0178 mL O₂ · beat⁻¹ · 100 g⁻¹ · LV).

**Discussion**

During exercise, both the LV SW and heart rate
increased. It would be advantageous if the increased SW
During exercise, the increase in MVo2 at constant PVA during exercise is small, and although the mean value was significantly increased, in only 2 of the 7 animals did the exercise point fall outside of the 95% confidence limits of the control MVo2-PVA regression line. Thus, the present study does not have the power to define whether the MVo2-PVA relation is shifted during exercise in conscious animals. However, the present study does clearly demonstrate that PVA/MVo2 is not altered during exercise. This ratio, PVA/MVo2, representing the overall efficiency of production of mechanical energy, should be differentiated from the slope of the MVo2-PVA relation. This slope indicates the increment of metabolic energy required to produce an increment of mechanical energy. The total MVo2 consumed at a given PVA consists of the sum of the MVo2 intercept and the incremental MVo2 to generate PVA. Thus, PVA/MVo2 increases with increasing PVA. The marked increase in PVA we observed during exercise offset any upward shift of the MVo2-PVA relation so that PVA/MVo2 (indicating the efficiency of conversion of metabolic energy to mechanical energy by the myocardium) was not altered during exercise (Fig 3).

The other factor that influences SW/PVA is SW/PVA, the portion of the total mechanical energy that results in external work. SW/PVA is determined by the coupling of the LV and the arterial system. This coupling can be quantitated as the ratio of the effective arterial elastance (Ea) to Ees. Ea is calculated as the end-systolic pressure/stroke volume and is approximated by the product of peripheral vascular resistance and heart rate. If the ejection portion of the LV PV loop is assumed to be flat and the end-diastolic pressure is negligible, Burkhoff and Sagawa showed that SW/PVA = 1/(1 + 0.5 · Ees/Ea). We have recently found that despite the limitations of the simplifying assumptions, this prediction is a very accurate description of the intact cardiovascular system of conscious animals. In the present study, Ees increased during exercise, whereas Ea remained constant. Thus, during exercise SW/PVA increased. Because PVA represents the total mechanical energy produced by each LV contraction, this indicates that more of this mechanical energy is expressed as useful external work (SW) during exercise.

Thus, during steady-state, submaximal exercise, the efficiency of the conversion by the LV of metabolic energy (MVo2) to external work (SW) was enhanced by the increase in PVA and the expression of more of the mechanical energy (PVA) as external work (SW).

There are several methodological issues to be considered. First, we measured LAD flow distal to the large first septal branch and assumed that coronary flow per unit mass is uniform within the LV. Consistent with this assumption, both LCx and LAD flows changed in a parallel manner during exercise. The resting coronary flow was 81.5 mL · min⁻¹ · 100 g⁻¹ LV, consistent with earlier studies. Furthermore, we have found that adenosine increases both coronary flows more than three times and that coronary arteriovenous lactate...
The full M\textsubscript{Vo2}-PVA relation cannot be determined in a conscious animal in the presence of intact reflexes because the required steady-state alterations in load result in reflex alterations in contractility. Accordingly, we defined the control M\textsubscript{Vo2}-PVA relation after autonomic blockade. The resting M\textsubscript{Vo2}-PVA point, determined with intact reflexes, fell close to the blocked M\textsubscript{Vo2}-PVA relation. This is consistent with previous observations of the lack of an effect of adrenergic tone on LV function in conscious animals at rest.

We studied the effect of submaximal steady-state exercise (7.2 to 8.0 km/h), so our results may not apply to more strenuous exercise. At higher levels of exercise, we would expect greater increases in heart rate, arterial pressure, E\textsubscript{es}, SW, PVA, and M\textsubscript{Vo2}. We speculate that this would result in an even greater increase in LV mechanical efficiency as a more marked decrease in E\textsubscript{es}/E\textsubscript{es} resulted in a higher SW/PVA and PVA, which would continue to offset the more marked upward shift of the M\textsubscript{Vo2}-PVA relation due to a greater increase in contractility.

We were only able to measure one M\textsubscript{Vo2}-PVA point during exercise, so we are not able to detect whether exercise altered the slope of the M\textsubscript{Vo2}-PVA relation. Burkhoff et al\textsuperscript{34} recently observed that an increase in ejection fraction in physiologically loaded isolated canine hearts decreased the slope. Such an effect may occur during exercise.

We conclude that exercise increases the efficiency of conversion of metabolic energy to external work by the LV due to alteration in LV arterial coupling resulting in increased production of mechanical energy and enhanced transmission of mechanical energy to external work, which more than offsets the increased metabolic cost of the enhanced contractility.

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References


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