Progressive Hypoxemia Limits Left Ventricular Oxygen Consumption and Contractility


To study the cardiac effects of progressive hypoxemia, we measured the left ventricular end-systolic pressure-volume relation (ESPVR), myocardial oxygen consumption (MVO₂), and myocardial oxygen delivery (MQO₂) in eight thoracotomized dogs anesthetized with fentanyl and droperidol. We specifically looked for evidence of oxygen supply limitation of MVO₂ and depressed contractility (altered ESPVR) during stepwise decreases in inspired oxygen fraction. We hypothesized that the reported relation between MVO₂ and left ventricular pressure-volume area (PVA) may hold when inadequate MQO₂ determines MVO₂, which then may limit PVA, manifested partly as a change in the ESPVR. Initially, as arterial oxygen saturation was decreased from 95 ±3% to 64 ±14%, coronary blood flow increased so that MQO₂ was maintained with no change in myocardial extraction ratio (ERₘ = MVO₂/MQO₂). During this first phase, lactate utilization, PVA, and ESPVR did not change. When oxygen saturation was further reduced, coronary flow rose no higher and ERₘ increased, but not enough to maintain MVO₂. Lactate consumption decreased and ST segments rose, signaling a change from aerobic metabolism. MVO₂ decrease was associated with a fall in PVA, which was due to a fall in blood pressure and a significant depression of the ESPVR. Specifically, the volume intercept of the ESPVR increased in all dogs (6.5-20.1 ml, p<0.0001), accounting for two thirds of the increase in end-systolic volume. The slope of the ESPVR decreased during hypoxia (13.3-6.1 mm Hg/ml, p<0.02), accounting for only one third of the observed increase in end-systolic volume. We believe that the evidence of anaerobic metabolism, the decrease in PVA, and the depression of the ESPVR demonstrates onset of oxygen supply limitation of MVO₂. Our data are consistent with the hypothesis that limited MVO₂ may limit PVA. The hypoxic volume intercept alteration of the ESPVR is different from changes in the slope of ESPVR seen with other interventions. This may be analogous to recent observations in isolated muscle that show hypoxic depression in contractility to be different from other interventions. (Circulation Research 1988;63: 849-859)

Evidence of depressed cardiac function is frequently found in patients with acute hypoxic respiratory failure. In this study, we attempted to demonstrate potential adverse effects of arterial hypoxemia on left ventricular mechanics and to quantitatively show the limit of aerobic myocardial metabolism during acute hypoxemia. Gremels and Starling demonstrated that hypoxia results in a dilated, poorly contracting heart. More recent studies have demonstrated hypoxic depression of indexes of contractility in myocardial tissue and isolated hearts, but similar findings in intact animals are obscured by reflex adjustments of preload, afterload, and sympathetic tone associated with hypoxia. Indeed, intact animals have been shown to maintain or increase cardiac output, heart rate, blood pressure, and the change in left ventricular pressure over time (dP/dt) in the face of progressive hypoxia. To accomplish our goal yet avoid these pitfalls, we used indexes of contractility that are relatively invariant to changes of preload and afterload within wide physiological limits, namely, the left ventricular end-systolic pressure-volume relation (ESPVR).

Whole-body oxygen consumption is maintained constant when oxygen delivery is progressively reduced by increased oxygen extraction. Further reductions in oxygen delivery eventually exceed the...
ability of the body or tissue to maintain a constant oxygen consumption, which then falls, and blood lactic acid levels increase.\textsuperscript{11,12} The heart is very different from the whole body in that the myocardial extraction ratio (ER\textsubscript{m}) is high even at normal myocardial oxygen delivery (MQ\textsubscript{O2}), and myocardial oxygen consumption (MVO\textsubscript{2}) is maintained or increased largely by changes in coronary blood flow\textsuperscript{13-15} and, to a lesser extent, by changes in ER\textsubscript{m} (note that ER\textsubscript{m} = MVO\textsubscript{2}/MQ\textsubscript{O2}).\textsuperscript{16-19} Conceivably, at high work loads or at some low myocardial oxygen delivery, the limit of myocardial aerobic metabolism is reached as it is in other organs, so that MVO\textsubscript{2} is determined by inadequate MQ\textsubscript{O2}. Of course, this does occur in ischemic heart disease, but it has not been demonstrated in the well-perfused left ventricle exposed to global hypoxemia. Accordingly, we examined our data for evidence of onset of oxygen supply limitation of MVO\textsubscript{2}.

If, at some level of hypoxemia, MVO\textsubscript{2} is determined by MQ\textsubscript{O2} rather than by its usual determinants—loading conditions and contractility—it is conceivable that loading conditions and contractility may themselves be affected (as they are with regional ischemia). Pressure-volume area (PVA) has been shown to closely correlate with MVO\textsubscript{2} in an isolated heart model and provides a useful energetics framework to examine the effects of hypoxia (Figure 1).\textsuperscript{20,21} All experimental studies confirming and extending this relation vary PVA to determine the MVO\textsubscript{2} response. In contrast, we are concerned with the PVA response when MVO\textsubscript{2} becomes limited by inadequate oxygen supply. Conceivably, the MVO\textsubscript{2}-PVA relation may hold in this circumstance with consequences on pumping function. We discuss our results in this innovative context to show that our data are consistent with (though not proof of) the notion that part of the hypoxic depression of left ventricular contractility is due to energy supply limitation. That is, if supply-limited MVO\textsubscript{2} limits PVA, then one or more of the boundaries of PVA must change. An increase in diastolic stiffness, a decrease in end-diastolic volume, a decrease in systolic pressure, and a shift to the right of the ESPVR would decrease PVA (Figure 1). A shift to the right of the ESPVR is interpreted as depressed contractility, which may be accomplished by a decrease in the slope of the ESPVR (E\textsubscript{max}) or by an increase in the volume intercept of the ESPVR (V\textsubscript{o}). Previous work has shown that E\textsubscript{max} is increased by positive inotropic agents but there is no significant change in V\textsubscript{o}.\textsuperscript{22} Since hypoxia may not have acted like previously studied myocardial depressants, we tested for changes both in E\textsubscript{max} and V\textsubscript{o}.

Materials and Methods

Instrumentation

Ten mongrel dogs weighing 22.8±2.0 kg were anesthetized with fentanyl (200 μg/kg) and droperidol (2.5 mg/kg). Anesthesia was maintained with an infusion of fentanyl (1 μg/kg/min)\textsuperscript{23} as well as with supplemental doses of droperidol as needed. This anesthetic combination was chosen to avoid the cardiac depression and tachycardia associated with pentobarbital and chloralose.\textsuperscript{24,25} The dogs were intubated and mechanically ventilated with a tidal volume of 15–20 ml/kg at a rate adjusted to maintain arterial PCO\textsubscript{2} at 32 to 40 mm Hg. Sodium bicarbonate was infused as necessary to maintain pH at 7.35 to 7.45. A femoral arterial line was established to draw arterial blood samples and to monitor arterial pressure. A left-ventricular catheter (Millar, Houston, Texas) was placed through a left carotid arterial cut-down. A Swan-Ganz catheter was inserted via the left external jugular vein to draw mixed venous blood samples and to monitor cardiac output through use of the thermodilution technique.

A midline thoracotomy and pericardiotomy were performed and 3 cm of positive end-expiratory pressure were applied to maintain end-expired lung volume. A pair of ultrasonic crystals were sewn to the anterior and posterior epicardium. An epicardial crystal sutured to the apex was paired with a crystal implanted through a small stab wound at the base of the left ventricle, about 3 mm below the atrioventricular sulcus.\textsuperscript{26} Auffed, wide-bore (3.5 mm i.d.) balloon catheter was placed in the coronary sinus by direct palpation to collect all coronary sinus flow. The coronary sinus venous effluent was continuously pumped back into a right femoral venous catheter with a roller pump.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Myocardial oxygen consumption (MVO\textsubscript{2}) has been shown to be related to pressure-volume area (PVA) according to the linear relation illustrated in the left-hand panel. PVA is the shaded area in the right-hand panel on a left ventricular pressure-volume diagram. If the relation shown in the left-hand panel holds when MVO\textsubscript{2} is limited by progressive hypoxia, from a to b, then PVA would also decrease. The decrease in PVA could be accounted for by a shift of one or more of the boundaries of PVA. For example, the upper boundary (systolic pressure) and the left-hand boundary may change, from a to b as shown in the right hand panel, to account for the decreased PVA. Note that the left-hand boundary of PVA is a line connecting baseline V\textsubscript{o} with the end-systolic point.\textsuperscript{21} Thus, if in condition b the end-systolic pressure-volume relation has an increased V\textsubscript{o}, then the end-systolic pressure-volume relation obtained from a vena caval occlusion will not coincide with the left-hand boundary of PVA. P\textsubscript{LV} left ventricular pressure; V\textsubscript{LV} left ventricular volume.}
\end{figure}
Immediately after the animals died, we confirmed the placement of the coronary sinus catheter and determined the vascular bed drained by a retrograde injection of dye. Dye stained 86% of left ventricles (89 ± 17 g were stained of 104 ± 18 g total left ventricular weight, which included the septum) and 19% of right ventricles (7 ± 3 g of 38 ± 7 g), suggesting that the coronary sinus flow reflected most of the left ventricular blood flow and probably was not contaminated significantly with right ventricular blood flow. Almost all of the unstained left ventricle was accounted for by a region of the septum that was always unstained.

**Measurements**

Left ventricular pressure, $P_{lv}$, was measured with the intraventricular Millar catheter. Left ventricular chamber volume ($V_{lv}$) was estimated as

$$V_{lv} = \pi/6 \times D_{long} \times D_{ap} \times D_{af} - V_{myocardium}$$

where $D_{long}$ is the apex–base diameter, $D_{ap}$ is the anterior–posterior diameter, $D_{af}$ is the unmeasured septal–freewall diameter estimated as $D_{ap}$, and $V_{myocardium}$ is the myocardial muscle volume. To improve this volume estimate, we used the following additional information. At the end of every experiment, the heart was excised and a thin-walled latex balloon was sewn in the mitral anulus. Fluid and air between the balloon and endocardium was evacuated so that the known balloon volume equaled left ventricular volume. The heart was floated in saline to avoid nonhomogeneous distortion of ventricular shape. Ultrasonic crystal dimensions were measured at many known balloon volumes to calibrate the ventricular volume estimate (Figure 2). Furthermore, we used the information that the left ventricular volume does not change during the isovolumic phases of the cardiac cycle. The “improved” estimate of ventricular volume is

$$V_{lv} = G \times D_{long} \times D_{ap} \times D_{af} - V_{myocardium}$$

where $G$ is not assumed to be $\pi/6$ but is determined in each heart as the slope of the volume calibration curve. $D_{long}$ and $D_{ap}$ are measured in Equation 1. $D_{af}$ is a dimensionally correct combination of $D_{long}$ and $D_{ap}$ that takes into account the impossibility of exact crystal placement and best fits the condition of constant isovolumic volumes (see “Appendix”). $V_{myocardium}$ is determined from the intercept of the volume calibration curve in each heart. The entire analysis was done using both volume estimates with no difference in the conclusions. Because the second volume estimate contained more information and correlated best with independent stroke volume measurements, we report volumes estimated using the second method.

Figure 2 shows a typical calibration plot of postmortem left ventricular volume versus the volume estimated as the product of ultrasonic crystal dimensions. The slope of this regression line is $G$ from Equation 2. The standard deviation in estimating $G$ is small, suggesting that changes in estimated volume very accurately reflect changes in actual volume. Since the $Y$ intercept ($V_{myocardium}$ from Equation 2) is an extrapolation, the standard deviation in estimation of this value is relatively larger even though this value correlated ($r=0.49$) with myocardial mass (Table 1). For all sets of data from all dogs, the ultrasonic crystal volume correlated with stroke volume calculated from cardiac output and heart rate (ultrasonic crystal stroke volume = 0.63 × Fick stroke volume + 4.8 cm$^3$, $r=0.63$, $p<0.05$) (Table 1).

$E_{max}$ and $V_{o}$ were determined at each stage during a vena caval occlusion (Figure 3). A steady-state pressure-volume loop was also recorded at each stage. PVA was determined exactly as previously described.$^{20,21}$ That is, PVA is the area on the left ventricular pressure-volume diagram bounded below by diastole, on the right by isovolumic systole, above by the ejection phase of systole, and on the left by a line connecting the end-systolic point to $V_{o}$ determined during the baseline set (Figure 1). Note that the left-hand boundary of PVA is the same as the ESPVR only when $V_{o}$ is equal to the normoxic baseline $V_{o}$.

$MVO_2$ and $MQO_2$, were determined from coronary sinus flow and arterial and coronary venous oxygen content. Coronary sinus flow was determined directly by a timed collection. Coronary sinus pressure may influence the pressure-flow characteristics of the coronary circulation unless coronary sinus pressure is maintained below the coronary venous vascular waterfall pressure.$^{20,29,30}$ Accordingly, we kept the outflow level of the coronary sinus catheter below the right atrium. To demonstrate that coronary sinus pressure was below the waterfall pressure, we repeated the timed collection in all exper-
Protocol

In eight dogs, sets of measurements were collected first on room air and subsequently at progressively lower inspired oxygen fraction ($F_{IO_2}$). The dog was allowed to stabilize at the new $F_{IO_2}$ for 20 minutes prior to each set of measurements. At each set coronary sinus flow, arterial oxygen content, mixed venous oxygen content, coronary sinus oxygen content, $F_{IO_2}$, mixed expired oxygen fraction, and minute ventilation were measured. Then $P_a$ and the ultrasonic crystal diameters were sampled at 500 Hz and stored in digital format during a 5-second apnea at end expiration. Finally, both the superior and inferior venae cavae were occluded and $P_a$ and diameters were sampled at 100 Hz during a 10-second apnea at end expiration. Typically, seven to 10 sets were collected in each dog before death, which occurred at an $F_{IO_2}$ of 10.6% (range, 6.8%–12.4%).

Two additional dogs were not made hypoxic and identical measurement sets were collected on room air over a time course identical to the hypoxic experiments to rule out major time-related changes in this surgical preparation. These two animals were stable with no change in blood pressure or cardiac output over 4 hours. $V_o$ deviated from the baseline measurement by 0.3 ± 0.9 ml on all sets while $E^s$, slope of the line; $V_o$, volume intercept.

Statistical Analysis

To summarize our data, we present it in seven stages, for which steady-state measurements were obtained in all eight studies. Compared with the first set of values obtained on room air, most of the observed changes occurred in the final three sets, with few statistically significant changes prior to this. For experiments that lasted for more than seven sets, data from stage 2 up to the final three sets were averaged pairwise. For example, set 2 and 3, set 4 and 5, and set 6 and 7 were averaged in a manner described below.

Table 1

<table>
<thead>
<tr>
<th>Dog</th>
<th>r</th>
<th>G</th>
<th>$V_{oxygen}$ intercept</th>
<th>LV mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.991</td>
<td>0.48</td>
<td>72</td>
<td>108</td>
</tr>
<tr>
<td>2</td>
<td>0.936</td>
<td>0.56</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>0.996</td>
<td>0.55</td>
<td>66</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>0.994</td>
<td>0.76</td>
<td>108</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>0.992</td>
<td>0.64</td>
<td>116</td>
<td>111</td>
</tr>
<tr>
<td>6</td>
<td>0.983</td>
<td>0.63</td>
<td>118</td>
<td>128</td>
</tr>
<tr>
<td>7</td>
<td>0.976</td>
<td>0.75</td>
<td>88</td>
<td>112</td>
</tr>
<tr>
<td>8</td>
<td>0.999</td>
<td>0.55</td>
<td>118</td>
<td>124</td>
</tr>
<tr>
<td>9</td>
<td>0.977</td>
<td>0.56</td>
<td>61</td>
<td>83</td>
</tr>
<tr>
<td>10</td>
<td>0.977</td>
<td>0.56</td>
<td>89</td>
<td>120</td>
</tr>
<tr>
<td>Mean</td>
<td>0.982</td>
<td>0.60</td>
<td>91</td>
<td>104</td>
</tr>
<tr>
<td>SD</td>
<td>0.018</td>
<td>0.09</td>
<td>22</td>
<td>19</td>
</tr>
</tbody>
</table>

$V_b$, left ventricular chamber volume; G, slope; $D_{ap}$, anterior-posterior diameter; $D_{rf}$, unmeasured septal-free wall diameter estimated as $D_{ap}$; $V_{oxygen}$, myocardial muscle volume intercept; LV, left ventricular; $SV_{decomp}$, ultrasonic crystal stroke volume; m, slope; $SV_{max}$, stroke volume calculated with Fick principle; b, intercept.

Whole-body oxygen consumption was calculated by measuring minute ventilation with a Collins spirometer and by measuring inspired and mixed expired oxygen fractions with a mass spectrometer. Cardiac output was calculated using the Fick principle. Stroke volume was calculated as Fick cardiac output divided by heart rate. Serum lactate concentration was measured spectrophotometrically. Myocardial lactate consumption was estimated as the product of coronary sinus flow and the difference in lactate concentrations between arterial and coronary sinus blood. Lead II of an ECG was recorded.

To summarize our data, we present it in seven stages, for which steady-state measurements were obtained in all eight studies. Compared with the first set of values obtained on room air, most of the observed changes occurred in the final three sets, with few statistically significant changes prior to this. For experiments that lasted for more than seven sets, data from stage 2 up to the final three sets were averaged pairwise. For example, set 2 and 3, set 4 and 5, and set 6 and 7 were averaged in a manner described below.

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TABLE 2. Variables Affecting Arterial Oxygenation in Eight Dogs

<table>
<thead>
<tr>
<th>Stage</th>
<th>( F_{10} ) (%)</th>
<th>Paco₂ (mm Hg)</th>
<th>Arterial oxygen content (mlO₂/dl)</th>
<th>Paco₂ (mm Hg)</th>
<th>pH</th>
<th>Hct (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.0±0.5</td>
<td>81±3</td>
<td>13.7±3.7</td>
<td>38±2</td>
<td>7.40±0.05</td>
<td>32±8</td>
</tr>
<tr>
<td>2</td>
<td>16.6±1.7*</td>
<td>61±13*</td>
<td>12.1±2.8</td>
<td>37±2</td>
<td>7.42±0.02</td>
<td>31±5</td>
</tr>
<tr>
<td>3</td>
<td>14.0±0.5*</td>
<td>50±6*</td>
<td>11.2±2.6</td>
<td>35±1</td>
<td>7.42±0.04</td>
<td>32±7</td>
</tr>
<tr>
<td>4</td>
<td>12.7±1.0*</td>
<td>43±6*</td>
<td>10.6±1.6*</td>
<td>36±3</td>
<td>7.42±0.03</td>
<td>34±6</td>
</tr>
<tr>
<td>5</td>
<td>12.0±1.2*</td>
<td>41±8*</td>
<td>9.9±1.3*</td>
<td>36±2</td>
<td>7.41±0.03</td>
<td>34±6</td>
</tr>
<tr>
<td>6</td>
<td>11.3±1.4*</td>
<td>36±8*</td>
<td>8.8±1.6*</td>
<td>36±3</td>
<td>7.38±0.03</td>
<td>34±6</td>
</tr>
<tr>
<td>7</td>
<td>10.6±1.6*</td>
<td>36±9*</td>
<td>9.0±2.2*</td>
<td>34±6</td>
<td>7.41±0.08</td>
<td>36±5</td>
</tr>
</tbody>
</table>

Mean ± SD.
*Different from baseline stage 1 \( p<0.01 \).

10-set experiment, resulting in seven stages where the important data from the first room air stage and the final three stages remain intact.

We tested the null hypotheses that hypoxia does not change \( E_{max} \) and \( V_{O} \) with a nonparametric repeated-measures analysis of variance (Friedman test). When a significant difference was found \((p<0.05)\), a Mann-Whitney test with a Bonferroni correction identified specific differences. The same analysis with parametric statistics was performed for the data shown in Table 2, Table 3, and Figure 4 to highlight changes in measured parameters. Data are summarized as mean ± SD throughout.

Results

The reductions in \( F_{10} \), were chosen to produce approximately equal reductions in arterial oxygen content at each stage (Table 2). Paco₂, pH, and hematocrit were maintained constant. As \( F_{10} \) was decreased from 21% to 12%, heart rate and cardiac output were relatively constant and arterial pressure fell slightly (Table 3). During this initial phase of hypoxia, \( MVO_{2} \) was maintained by an increase in coronary blood flow so that \( ER_{m} \) did not change from the initial value of 65% (Figure 4). On the average, \( MVO_{2} \) and PVA were constant at 53±2 ml O₂/kg/min and 197,000±16,000 mm Hg/ml/min. There were no significant changes in lactate consumption, ST segments, or contractility as measured by \( V_{O} \) and \( E_{max} \) during this initial phase.

Further reduction of \( F_{10} \), below 12% during the final two stages resulted in significant changes in many variables signaling a change in both metabolism and function. During this extremely hypoxic phase, coronary blood flow did not increase further to maintain \( MVO_{2} \) (Figure 4). Indeed, coronary blood flow decreased in part because of the fall in blood pressure. \( MVO_{2} \) and PVA decreased (by 17% and 23%, respectively, at stage 7), associated with reduced cardiac output and blood pressure (Table 3). Extraction ratio finally rose when the coronary flow fell in stage 6, associated with a fall in lactate consumption (Figure 4). In four of eight dogs the myocardium became a lactate producer, signaling anaerobic metabolism. ST segments rose in seven of eight dogs and fell in the other dog so that the average deviation from baseline in the second phase was significant and probably reflected myocardial ischemia. The ESPVR became acutely depressed. Thus, when coronary blood flow could no longer increase to maintain \( ER_{m} \), there was an approximately simultaneous change in oxygen metabolism.

TABLE 3. Effects of Hypoxia on Hemodynamics and Ventricular Mechanics in Eight Dogs at Each Stage

<table>
<thead>
<tr>
<th>Heart rate</th>
<th>Cardiac output</th>
<th>P at V, V (Vat + 20 ml) (mm Hg)</th>
<th>Emax (mm Hg/ml)</th>
<th>AVa (ml)</th>
<th>ΔE (ml)</th>
<th>PVA (mg Hg/ml)</th>
<th>PVA per beat (mg Hg/ml)</th>
<th>MVO₂ (ml O₂/kg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td>(beats/ min)</td>
<td>(l/min)</td>
<td>(mm Hg)</td>
<td>(ml)</td>
<td>(ml)</td>
<td>(ml)</td>
<td>(thousands)</td>
<td>(ml O₂/kg/min)</td>
</tr>
<tr>
<td>1</td>
<td>132±23</td>
<td>2.19±0.45</td>
<td>87±7</td>
<td>6.9±1.6</td>
<td>8.0±1.8</td>
<td>23.5±7.3</td>
<td>13.3±15.1</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td>2</td>
<td>131±28</td>
<td>2.49±0.40</td>
<td>81±7</td>
<td>7.4±2.5</td>
<td>7.9±1.5</td>
<td>23.3±5.2</td>
<td>13.3±13.8</td>
<td>0.7±1.6</td>
</tr>
<tr>
<td>3</td>
<td>123±28</td>
<td>2.18±0.42</td>
<td>80±11</td>
<td>7.2±1.9</td>
<td>8.2±2.1</td>
<td>23.9±5.1</td>
<td>11.3±9.3</td>
<td>1.2±1.9</td>
</tr>
<tr>
<td>4</td>
<td>125±27</td>
<td>2.18±0.49</td>
<td>74±11</td>
<td>6.4±2.2</td>
<td>8.2±2.0</td>
<td>26.7±3.9</td>
<td>11.1±7.2</td>
<td>4.0±3.5</td>
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<tr>
<td>5</td>
<td>116±33</td>
<td>2.00±0.43</td>
<td>70±121</td>
<td>6.4±2.4</td>
<td>8.2±1.3</td>
<td>25.6±4.1</td>
<td>8.7±6.8</td>
<td>4.3±2.1</td>
</tr>
<tr>
<td>6</td>
<td>127±18</td>
<td>1.93±0.52</td>
<td>69±131</td>
<td>5.9±1.7</td>
<td>8.5±1.7</td>
<td>28.8±2.9</td>
<td>9.8±1.8</td>
<td>10.4±3.5</td>
</tr>
<tr>
<td>7</td>
<td>118±30</td>
<td>1.53±0.77†</td>
<td>59±221</td>
<td>6.4±1.7</td>
<td>10.6±4.2</td>
<td>36.5±8.6</td>
<td>6.1±7.7</td>
<td>13.6±7.3</td>
</tr>
</tbody>
</table>

P, pressure; V, volume; \( V_{O} \), volume intercept of end systolic pressure-volume relation; \( E_{max} \), slope of the end systolic pressure-volume relation; PVA, pressure-volume area; \( MVO_{2} \), myocardial oxygen consumption.
*Different from baseline stage 1 \( p<0.05 \).
†Different from baseline stage 1 \( p<0.01 \).
Coronary Blood Flow (ml/min)

Myocardial Extraction Ratio (%)

Lactate Consumption (mmol/kg/min)

ST segment Change (mm)

Vo (ml)

Emax (mmHg/ml)

F102 (%)

94 89 84 75 72 64 63

Arterial Saturation (%)

Progressive Hypoxia

Death

≤ SEM * p < 0.05, † p < 0.01 different from first set.

FIGURE 4. Seven stages of progressively decreasing inspired oxygen fraction (F102) and arterial oxygen saturation are shown on the x axis. Coronary blood flow initially increases to maintain the other displayed variables unchanged. When coronary blood flow can increase no further (and falls because of decreased blood pressure) oxygen metabolism changes (increased myocardial extraction ratio), lactate consumption falls, ST segments rise, and dilated cardiac dysfunction ensues (increased Vo and decreased Emax). All changes occur at approximately the same time, thereby defining two distinct phases: aerobic and anaerobic, as indicated by the dashed line. The fifth stage appears intermediate between the two phases.

lactate metabolism, electrophysiological function, and contractility of the left ventricle.

These metabolic and functional changes define two parts to the MVo2–MQO2 relation similar to the aerobic and anaerobic phases of the whole body (Figure 5). Whole body oxygen consumption became supply limited at a critical oxygen delivery of 9.3 ml O2/kg/min consistent with published values. The heart differs from the whole body during the initial phase in that oxygen consumption is not a constant (the plateau of Figure 5) but variable (top panel of Figure 6). Analogous to the whole body, the anaerobic second phase of the MVo2–MQO2 relation is distinguished from the first by an increased Emax, altered lactate metabolism, and a decrease in MVo2 associated with a decrease in MQO2 (Figure 4 and the bottom panel of Figure 6).

In each experiment the reduction in PVA at stages 6 and 7 was associated with the reduction in MVo2. The units of PVA and MVo2 can be converted to joules (1 mm Hg · ml = 1.33 × 10^-4 J and 1 ml O2 = 20.2 J approximately). Therefore, the fraction of MVo2 that is converted to PVA can be calculated. The efficiency ratio, PVA/MVo2, decreases slightly as MVo2 decreases (first stage, 27%, to last stage, 17%), consistent with published results in isolated hearts. To account for the decrease in PVA, we examined its four boundaries (as illustrated in Figure 1). There was no measurable change of the diastolic pressure-volume relation (the bottom boundary) in this open-chest, open-pericardium preparation. Specifically, there was no change in diastolic pressure when measured at a volume of 20 ml greater than baseline Vo (pressure at volume = Vo + 20 ml in Table 3). The right-hand boundary, marked by end-diastolic volume, increased in the late stages (Table 3) and therefore influenced the calculated value of PVA but did not account for the observed decrease in PVA. Indeed, an isolated increase of the right-hand boundary would increase PVA. Therefore, the observed decrease in PVA was due to concurrent changes of the other boundaries. The top boundary, related to end-systolic pressure, decreased slightly with progressive hypoxia because of a decrease in systemic vascular resistance and, preterminally, because of a decrease in cardiac output. This accounts for part of the decrease in PVA. The rest of the reduction in PVA
is caused by a rightward shift of the left-hand boundary, which is related to a fall in contractility. 

\( V_o \) did not remain equal to baseline \( V_o \) \((p<0.0001)\) when the dogs became severely hypoxemic (Table 3 and Figure 7). Thus, the left-hand boundary of PVA (a line joining baseline \( V_o \) to the hypoxic end-systolic pressure-volume point) did not coincide with the measured ESPVR in this circumstance. Table 3 demonstrates that when compared at the same end-systolic pressure, end-systolic volume increased compared with baseline. (For comparison, at the same end-systolic pressure, a baseline end-systolic volume was determined from the baseline ESPVR read at the hypoxic end-systolic pressure.) The increase in \( V_o \) was equal to two thirds of the increase in end-systolic volume. Only the remaining third of the increase in end-systolic volume was caused by a decrease in \( E_{\text{max}} \) \((p<0.05)\). In fact, at hypoxic stage 5, \( E_{\text{max}} \) increased in four dogs even when an increase in \( V_o \) had resulted in a dilated, depressed left ventricle.

**Discussion**

These observations suggest that progressive hypoxemia reaches the limits of myocardial aerobic metabolism when coronary blood flow is maximized. Further reduction in arterial oxygen saturation reduces \( \text{MDO}_{2} \) and \( \text{MVO}_{2} \) decreases associated with anaerobic metabolism despite increased oxygen extraction. In turn, this oxygen supply limitation and anaerobic metabolism is associated with reduced PVA output of the ventricle in accord with the conservation of energy. The associated depression of the ESPVR is largely due to an increase in \( V_o \) with some decrease in \( E_{\text{max}} \).

**Measurement of Volumes and Coronary Sinus Blood Flow**

As Slinker and Glantz\(^3^\) point out, measurement of left ventricular volume is difficult since this signal cannot be transduced directly but can only be inferred from dimension measurements. Our volume estimate, calibrated in every dog by postmortem examination and in vivo (Table 1 and Figure 2), compares favorably with other measures of left ventricular volume made in intact dogs.\(^2^\)\(^6^\)\(^3^\) \( V_o \) deviated \( 0.3\pm0.9 \) ml over seven normoxic sets in two time-control dogs. This difference and the standard deviation of the difference are more than an order of magnitude less than the change in \( V_o \) reported here. Thus, we believe that our methods are capable of detecting the difference in \( V_o \) even though the measurement of \( V_o \) is more difficult as it is an extrapolation. We measured coronary sinus blood flow by direct collection because we believe it is the most accurate measure of absolute flow.\(^3^\) Measurement of flow at different downstream pressures confirmed that we maintained downstream pressure below the coronary venous waterfall pressure\(^2^\)\(^6^\)\(^3^\)\(^3^\)\(^0^\) so that the measurement did not alter
Progressive Hypoxemia Limits Left Ventricular Aerobic Metabolism

Progressive hypoxemia resulted in supply limitation of whole-body oxygen consumption (Figure 5) as in Cain’s whole-body studies. The analogous relation of $\text{MV}_2$ to $\text{MQ}_2$, as found in Cain’s whole-body studies, has not previously been directly reported but can be determined in part by examining published data. Some investigators find no change in $\text{ER}_n$ while others find an increase in $\text{ER}_n$ in moderate hypoxemia or when $\text{MV}_2$ is increased by exercise. However, no previous global left ventricular investigation has examined the full range of the $\text{MV}_2$-$\text{MQ}_2$ relation to demonstrate the onset of limitation of $\text{MV}_2$ by inadequate $\text{MQ}_2$, the coincident onset of anaerobic metabolism, and the critical limit of myocardial oxygen extraction. Similar to the whole-body oxygen delivery-oxygen consumption relation there appears to be an aerobic and an anaerobic phase. During the initial phase of hypoxia, coronary blood flow is increased and the left ventricle is functioning aerobically. We think that during this initial phase $\text{MV}_2$ determined $\text{MQ}_2$ through autorregulation of coronary blood flow. Like the whole body, the anaerobic second part of the $\text{MV}_2$-$\text{MQ}_2$ relation is distinguished from the first by increasing $\text{ER}_n$, lactate production, and $\text{MV}_2$ decreasing with $\text{MQ}_2$ (Figure 4 and Figure 6 bottom panel). Accordingly, we believe that during this second phase $\text{MV}_2$ demonstrates oxygen supply limitation similar to that seen in the whole body and in other isolated tissues. We also found that with decreasing $\text{MV}_2$ during this oxygen supply limited phase left ventricular contractility decreased, cardiac output fell, and the ECG demonstrated ischemic changes. In no dog did we find significant depression of contractility before onset of supply limitation of $\text{MV}_2$ nor did we find preservation of contractility after onset of supply limitation of $\text{MV}_2$ and anaerobic metabolism. This is consistent with the notion that function is largely dependent on energy from aerobic metabolism and function is limited when $\text{MV}_2$ is limited by inadequate oxygen supply.

Effects of Hypoxia on Contractility Mediated via $\text{MV}_2$-$\text{PVA}$ Relations

Hypoxia depresses isolated myocardial tissue contractility and in the limit some level of hypoxia must depress cardiac contractility in situ. Yet our hemodynamic results are similar to previously published results and do not necessarily imply any cardiac depression until the terminal set. The basis of hemodynamic changes is complex and may be due to reflex changes of preload, peripheral vascular properties, and cardiac performance. To distinguish between these possibilities, we measured left ventricular pressure, volume, and the ESPVR—a measure of contractility that is relatively invariant to changes of preload and afterload within wide physiological limits.

We make novel use of the recently described relation between $\text{MV}_2$ and PVA to develop an energetics analysis of our data to help test the possibility that the observed depression of the ESPVR can be accounted for by oxygen (and therefore energy) supply limitation. All studies confirming and extending this relation vary PVA to determine the $\text{MV}_2$ response. Here we explore the PVA response (and the ventricular mechanics comprising the boundaries of PVA) when $\text{MV}_2$ becomes limited by an inadequate oxygen supply. Since $\text{MV}_2$ is related to metabolic energy input (1 ml $\text{O}_2 = 20.2$ J) and PVA has been identified as total mechanical energy output, we speculate that at a given contractile state PVA may correspond one-to-one to $\text{MV}_2$ (that is, a change in PVA will force a change in $\text{MV}_2$ and a change in $\text{MV}_2$ will force a change in PVA). Thus, when progressive hypoxia begins to limit $\text{MV}_2$ then PVA must also decrease. Indeed, we found that decreases in $\text{MV}_2$ were associated with decreases in PVA. The observed decrease of PVA was due to depression of contractility, as measured by the left-hand boundary of PVA, and a decrease of systolic ejection pressure, the upper boundary of PVA. The right-hand boundary of PVA, marked by end-diastolic volume, increased and positively influenced the calculated value of PVA but less than the decrease in PVA effected by the left-hand and upper boundaries.
Suga and associates\textsuperscript{20,21} demonstrated the relation between MV\textsubscript{O}\textsubscript{2} and PVA as illustrated in Figure 1 by artificially varying PVA over a wide range in isolated hearts. Note that at an extrapolated PVA of zero a basal MV\textsubscript{O}\textsubscript{2} remains. We did not independently try to manipulate PVA thus we did not define the MV\textsubscript{0}-PVA relation nor the MV\textsubscript{O}\textsubscript{2} intercept accurately. Nevertheless, our PVA/ MV\textsubscript{O}\textsubscript{2} ratios through the range of normoxia to extreme hypoxia are in accord with published data\textsuperscript{20,21} Because we did not subtract a basal MV\textsubscript{O}\textsubscript{2} in calculating PVA/MV\textsubscript{O}\textsubscript{2}, we observe an expected decrease in this ratio as MV\textsubscript{O}\textsubscript{2} and PVA decrease with hypoxia.

The MV\textsubscript{O}\textsubscript{2} intercept has been shown to increase with positive inotropic agents\textsuperscript{21} Thus, the MV\textsubscript{O}\textsubscript{2}-PVA relation data collected under a variety of loading and contractility conditions indicate that if contractility is significantly increased, PVA may decrease while MV\textsubscript{O}\textsubscript{2} stays approximately the same. Alternatively, if contractility decreases, PVA may increase while MV\textsubscript{O}\textsubscript{2} stays the same. Applied to this hypoxia study, when MV\textsubscript{O}\textsubscript{2} is limited by inadequate MVO\textsubscript{2} contractility could increase at the expense of decreased PVA or contractility could decrease associated with an increase in PVA. Our data indicate that the latter strategy is followed in that contractility is observed to decrease, possibly with the benefit of maximizing PVA. However, even with a decrease in the MV\textsubscript{O}\textsubscript{2} intercept, the PVA would eventually have to decrease as MV\textsubscript{O}\textsubscript{2} became very low. Thus, the speculation that the relation between MV\textsubscript{O}\textsubscript{2} and PVA may hold during progressive hypoxemia can account for the observed decrease in contractility based on this energetics analysis. That is, either contractility decreases as a strategy to preserve PVA (from the MV\textsubscript{O}\textsubscript{2}-PVA relation) or as PVA is forced to decrease contractility decreases because it is related to the left-hand boundary of PVA. Our data are consistent with, but by no means proof of, this hypothesis.

\textit{Hypoxemia, Increased V\textsubscript{O}, and Contractile Mechanics}

Decrease in contractility due to an increase in V\textsubscript{O} to the extent observed here was a new and surprising result. Virtually all studies have shown that changes in contractility have been due to changes in E\textsubscript{max}\textsuperscript{22} However, a recent study of ischemia from decreased perfusion pressure observes an increase in V\textsubscript{O}.\textsuperscript{37} Schroff et al\textsuperscript{38} have also recently demonstrated that ventricular systolic resistance may result in decreased ejection when ejection velocity increases. Ventricular systolic resistance is consistent with recent observations in isolated hearts\textsuperscript{39} showing an increase of V\textsubscript{O} (although much less than seen here with hypoxia) with decreased afterload. It follows that one explanation for our results is that ventricular resistance increased with hypoxia. Contracture due to hypoxia may account for or be related to such an effect. However, this sort of contracture observed as an increase in resting tension in isolated muscle preparations\textsuperscript{4} occurs at PO\textsubscript{2} values (<6 mm Hg) lower than arterial and coronary sinus PO\textsubscript{2} values measured here. Although major changes of left-ventricular geometry may alter estimates of V\textsubscript{O} and E\textsubscript{max}, we do not think that this is the case in this study. Thoracotomy and pericardiectomy do not substantially alter left-ventricular dynamic geometry\textsuperscript{34} and septal shift was unlikely as right ventricular pressures did not rise.

As another potential explanation we considered that the global parameters, E\textsubscript{max} and V\textsubscript{O}, may reflect underlying myocardial properties, particularly in this global hypoxia intervention, which did not result in confounding segmental differences in contraction. The integration over space and time of individual myocardial tissue force-length properties results in the global pressure-volume relation. Thus, a shift of the force-length properties would shift the global ESPVR, other things being equal. Therefore, consider the muscle fiber force-length relation as follows. It is well known that increased intracellular calcium frees more actin-myosin fibers of tropinin-tropomyosin so that more force can be generated shifting the force-velocity relation upward. Yet the maximum rate of shortening of each actin-myosin fiber, V\textsubscript{max}, is not increased\textsuperscript{40,41} (Figure 8, left-hand panel, solid lines). Since V\textsubscript{max} does not change with an increase in intracellular calcium, a hypothetically unloaded contraction from the same diastolic point with a similar time course will have the same end point, V\textsubscript{O}. On the other hand, for any nonzero afterload the ventricle will contract further in the same time because an increase in intracellular calcium concentration increases shortening velocity at any given load. The result in a shift to the left of the ESPVR with no change in volume intercept is an increase in E\textsubscript{max} (Figure 8). An increase in E\textsubscript{max} with no change in V\textsubscript{O} is exactly what has been found with interventions that alter myocardial intracellular calcium concentrations.\textsuperscript{22} A second type of change of the ESPVR may occur if V\textsubscript{max} is decreased. Then the hypothetical unloaded contraction starting from the same diastolic point will not contract as far, resulting in an increase in V\textsubscript{O}. At the global level, hypoxic increase in V\textsubscript{O} is exactly what we have observed. At the isolated muscle fiber level, it is conceivable that hypoxia could result in a decrease, in a rate-limiting step represented by V\textsubscript{max}, either by limitation of energy substrate or by other effect on actin-myosin ATPase.

The identification of these two types of dilated cardiomyopathy—decreased E\textsubscript{max} and increased V\textsubscript{O}—is not without precedent in studies of isolated muscle. Allen and Orchard\textsuperscript{42} describe interventions that change myocardial muscle force in two distinct ways. Changes in intracellular calcium concentration produced by inotropic agents such as digitalis glycosides change force by altering intracellular
The conjectured relation between global pressure-volume relation and the muscle force-velocity relation is illustrated here. The muscle force-length relations (center panel) are directly derived from the muscle force-velocity relations (left-hand panel) given the same diastolic conditions and systolic time so that, in effect, the graph is turned on its side. The force-length relation is analogous to the global left ventricular pressure-volume relation (right-hand panel). Using this schema, a change in $E_{\text{max}}$ is related to a shift up of the velocity-force relation with no change in $V_{\text{IKa}}$, as would be produced by recruitment of more actin-myosin fibers. An increase in $V_{0}$ is related to a decrease in $V_{\text{IKa}}$, as would be produced by a decrease in the rate of reaction of the actin-myosin ATPase cycle.

Appendix

During isovolumic contraction and relaxation, volume does not normally change yet shape changes dramatically. This information may be used to test volume estimating procedures or volume estimating procedures may be improved by incorporating this additional information. We estimate

$$V_{\text{V}} = G \times D_{\text{ap}} \times D_{\text{long}} \times D_{\text{ip}} - V_{\text{myocardium}}$$  \hspace{1cm} (1)

with $G$ and $V_{\text{myocardium}}$ measured from a postmortem calibration curve and $D_{\text{ap}}$ and $D_{\text{long}}$ measured directly. Ultrasonic crystal placement can never be exactly along principal directions of shortening since these directions change during the cardiac cycle. Rather than estimate $D_{\text{ip}}$ as $D_{\text{ap}}$ we assume that $D_{\text{ip}}$ is better estimated as a combination of $D_{\text{ap}}$ and $D_{\text{long}}$. To maintain dimensional correctness we write

$$D_{\text{ip}} = D_{\text{ap}}^x \times D_{\text{long}}^{(1-x)}$$  \hspace{1cm} (4)

where $x$ is an exponent between 0 and 1. During an isovolumic phase where volume is a constant ($V_{\text{V}}$), we substitute Equation 4 into Equation 1 and rearrange:

$$(V_{c} + V_{\text{myocardium}}) / G = D_{\text{ap}}^{(1+x)} \times D_{\text{long}}^{(2-x)}$$

Note that the left-hand side of the equation is a collection of constants. When logarithms of both sides are taken and rearranged:

$$\log(D_{\text{ap}}) = \frac{(2-x)}{(1+x)} \log(D_{\text{long}}) + \log(\frac{(V_{c} + V_{\text{myocardium}})}{G})$$  \hspace{1cm} (2)

This is in the linear form \( y = mx + b \) where \( y = \log(D_{\text{ap}}) \) and \( x = \log(D_{\text{long}}) \). A log-log plot of $D_{\text{ap}}$ versus $D_{\text{long}}$ thus has a slope depending only on the unknown $x$.

$$\text{slope} = \frac{(2-x)}{(1+x)} = \frac{\text{change of log}(D_{\text{ap}})}{\text{change of log}(D_{\text{long}})}$$

To find the slope we measured $\frac{\text{change of log}(D_{\text{ap}})}{\text{change of log}(D_{\text{long}})}$ for all isovolumic phases in each dog and took the average value to calculate $x$ for each dog. Now Equation 1 with $D_{\text{ip}} = D_{\text{ap}}^x \times D_{\text{long}}^{(1-x)}$ gave a volume estimate that incorporated the additional averaged information that volume does not change during isovolumic phases.

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Key Words • left ventricle • hypoxia • contractility • myocardial oxygen consumption • pressure-volume area

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