Cardiovascular responses to dynamic exercise with acute anemia in humans

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Koskolou, Maria D., Robert C. Roach, José A. L. Calbet, Göran Rådegran, and Bengt Saltin. Cardiovascular responses to dynamic exercise with acute anemia in humans. Am. J. Physiol. 1787–1793, 1997.—We hypothesized that reducing arterial O2 content (CaO2) by lowering the hemoglobin concentration ([Hb]) would result in a higher blood flow, as observed with a low PO2, and maintenance of O2 delivery. Seven young healthy men were studied twice, at rest and during two-legged submaximal and peak dynamic knee extensor exercise in a control condition (mean control [Hb] 144 g/l) and after 1–1.5 liters of whole blood had been withdrawn and replaced with albumin (mean drop in [Hb] 29 g/l (range 19–38 g/l); low [Hb]). Limb blood flow (LBF) was higher (P < 0.01) with low [Hb] during submaximal exercise (i.e., at 30 W, LBF was 2.5 ± 0.1 and 3.0 ± 0.1 l/min for control [Hb] and low [Hb], respectively; P < 0.01), resulting in a maintained O2 delivery and O2 uptake for a given workload. However, at peak exercise, LBF was unaltered (6.5 ± 0.4 and 6.6 ± 0.6 l/min for control [Hb] and low [Hb], respectively), which resulted in an 18% reduction in O2 delivery (P < 0.01). This occurred despite peak cardiac output in neither condition reaching >75% of maximal cardiac output (~26 l/min). It is concluded that a low CaO2 induces an elevation in submaximal muscle blood flow and that O2 delivery to contracting muscles is tightly regulated.

red blood cell; hemoglobin; skeletal muscle; vasodilatation; cardiac output

THE ACUTE AND CHRONIC cardiovascular and metabolic responses to low arterial PO2 (PaO2) during exercise are well documented. In contrast, the responses to low arterial O2 content (CaO2) due to an acute lowering of hemoglobin concentration ([Hb]) are much less studied, which is surprising in view of how common anemia is in the world today.

Maximal cardiac output (CO) during exercise in acute anemia is not elevated or not elevated to an extent to compensate for the impaired O2 delivery (3, 16). At submaximal work, CO is elevated and partly compensates for the impaired O2 delivery (3, 16). No studies are available on the regional responses to acute anemia during work. In a collection of cases with a range of [Hb] levels, summarized in the proceedings of a conference honoring Lars Hermansen (13), there were indications that the low CaO2 was countered at submaximal exercise by an increase in muscle blood flow, so that O2 delivery was maintained. At peak exercise, a final conclusion could not be reached. In at least two cases, there was a suggestion of increased blood flow at peak exercise that, in part, maintained O2 delivery. This notion is supported by the classic study of Sproule et al. (15) on cardiovascular function during exercise in chronic anemic patients as they reached very high CO levels at low peak power outputs. Chronic anemia may have induced adaptations on the systemic as well as on the cellular level, obscuring effects of low [Hb] per se. Thus the question remains of how O2 delivery is maintained on the regional level in response to an acute reduction in [Hb]. The hypothesis is that compensation occurs with an elevated muscle perfusion matched by an equal increase in CO or by reducing the blood flow to nonexercising tissues and organs. We further hypothesize that, in contrast to hypoxia, in acute anemia limb blood flow (LBF) is increased at peak exercise with small muscle mass exercise.

We used a two-legged knee extensor exercise model that allows for a fairly large muscle mass (~6–7 kg) to perform the exercise without taxing the capacity of the heart to match a possible elevation in LBF, even at the highest workloads. The effect of a lowered [Hb] was examined by repeating the studies twice, once with the subjects having a normal [Hb] (control [Hb]) and the second time after withdrawing whole blood and substituting it with an equal amount of albumin to reduce [Hb] by ~20% (low [Hb]).

METHODS

Subjects. Seven young men (age 24 yr, range 21–30 yr) healthy men participated in the study. Their physical characteristics averaged (range) 183 cm (167–187 cm) in height, 85.1 kg (67.3–102.3 kg) in weight, 3.3-kg (2.8–4.1 kg) knee extensor mass of one leg, and a mean capillary count of 404 capillaries/mm2 (266–491 capillaries/mm2). Their maximal O2 uptake (V̇O2max) was 54.6 ml·kg−1·min−1 (41–70 ml·kg−1·min−1) and maximal CO during ordinary maximal bicycle exercise was 26.0 l/min (22.7–28.4 l/min). Six of the subjects had a [Hb] within the normal range for young men (mean 148 g/l, range 139–155 g/l), and one had a [Hb] of 126 g/l. All subjects had a normal iron status (ferritin > 33 mg/l and transferrin > 2.0 g/l). They were informed regarding possible risks and discomfort associated with the experiments and volunteered to participate, giving their signed consent. The study had the approval of the Copenhagen and Frederikssberg Ethical Committee.

Methodology. Blood volume (BV) was determined after the subjects had been supine for a minimum of 45 min, at 10, 20, and 30 min after injection of the tracer (131I-radioisotope serum albumin, ~ 250 kBq). The [Hb] and blood O2 saturation (SO2) were measured with a CO-oximeter (AVL 912 CO-Oxyline). PO2, PCO2, and pH were determined by standard techniques (AVL Compact 2) and corrected for measured blood temperature. The coefficients of variation calculated for the measurements of [Hb], SO2, PO2, PCO2, and pH were 4.3, 1.3, 3.8, 2.4, and 1.4%, respectively. Hematocrit (Hct) determinations were made in triplicate with microcentrifugation and corrected for trapped plasma (1.5%). Plasma K+ was measured with ion-sensitive electrodes (AVL 983-S). Lactate
LOW HEMOGLOBIN AND EXERCISE

Pulmonary O₂ uptake (V\textsubscript{O\textsubscript{2}}), CO\textsubscript{2} production (V\textsubscript{CO\textsubscript{2}}), and ventililation (V\textsubscript{E}) were measured with an on-line system (Medical Graphics CPX). Gases with known O\textsubscript{2} and CO\textsubscript{2} concentrations (micro-Scholander) were used for gas analyzer calibration. CO was measured by the dye-dilution technique with indocyanine green dye as the tracer. Arterial blood was withdrawn (Harvard pump), and the dye concentration was determined (Waters densitometer CO-10). The withdrawn blood was reinfused after each determination. Blood pressure was monitored by a transducer at the femoral level (mean distance from the heart 58 cm). Mean arterial pressure was estimated as two-thirds diastolic plus one-third systolic pressure. Heart rate (HR) was obtained either from the pulsatile pressure curve or from the continuously recorded electrocardiogram. Thoracic aortic blood flow was measured by the flow probe technique described previously (11). The withdrawal of arterial blood was reinfused into the subject.

RESULTS

Systemic response. Removal of whole blood reduced [Hb] from 144 ± 3.8 to 115 ± 1.9 g/l, with an individual variation of 19–38 g/l (P < 0.01; Table 1). This reduction in [Hb] was accompanied by a decrease in Hct from 43.5 ± 0.9 (control [Hb]) to 34.4 ± 0.4% (low [Hb]; P < 0.01) and a 22% (20–26%) decrease in red blood cell concentration ([Hb]) from 144 ± 3.8 to 115 ± 1.9 g/l, with an individual variation of 19–38 g/l (P < 0.01) and a 22% (20–26%) decrease in red blood cell concentration ([Hb]) from 144 ± 3.8 to 115 ± 1.9 g/l, with an individual variation of 19–38 g/l (P < 0.01) and a 22% (20–26%) decrease in red blood cell concentration ([Hb]) from 144 ± 3.8 to 115 ± 1.9 g/l, with an individual variation of 19–38 g/l (P < 0.01). The afternoon before the low [Hb] experiment, a light breakfast with control [Hb] and at least 1 wk later with low [Hb] was obtained. From the morning of the day on which the low [Hb] experiment was performed, the subject remained fasting for 13 h and was deprived of all beverages (except water) during the period of peak effort.

Table 1. Workload, [Hb], arterial and femoral venous oxygenation, and limb blood flow for the 2 Hb conditions

<table>
<thead>
<tr>
<th>Stage</th>
<th>Workload, W</th>
<th>[Hb], g/l</th>
<th>P\textsubscript{O\textsubscript{2}}, Torr</th>
<th>S\textsubscript{O\textsubscript{2}}, %</th>
<th>CO\textsubscript{2}, mM</th>
<th>Limb Blood Flow, l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Arterial</td>
<td>Venous</td>
<td>Arterial</td>
<td>Venous</td>
<td>Arterial</td>
</tr>
<tr>
<td>Control [Hb]</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>0–0</td>
<td>144.4 ± 3.8</td>
<td>99.7 ± 2.8</td>
<td>27.8 ± 0.8</td>
<td>98.1 ± 0.2</td>
<td>49.3 ± 1.7</td>
</tr>
<tr>
<td>30 W</td>
<td>0–0</td>
<td>144.6 ± 4.1</td>
<td>103.3 ± 3.6</td>
<td>22.0 ± 0.7</td>
<td>98.1 ± 0.2</td>
<td>33.4 ± 1.4</td>
</tr>
<tr>
<td>WL\textsubscript{50}</td>
<td>73 ± 6 (40–85)</td>
<td>146.0 ± 4.2</td>
<td>109.8 ± 2.5</td>
<td>23.9 ± 0.4</td>
<td>97.5 ± 0.8</td>
<td>29.1 ± 1.5</td>
</tr>
<tr>
<td>WL\textsubscript{peak}</td>
<td>143 ± 11 (80–170)</td>
<td>154.4 ± 3.6</td>
<td>119.2 ± 1.2</td>
<td>23.6 ± 0.8</td>
<td>97.7 ± 0.7</td>
<td>25.6 ± 1.1</td>
</tr>
<tr>
<td>Low [Hb]</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>0–0</td>
<td>114.7 ± 1.9*</td>
<td>94.9 ± 3.4</td>
<td>25.0 ± 0.7</td>
<td>98.1 ± 0.4</td>
<td>43.2 ± 2.8</td>
</tr>
<tr>
<td>30 W</td>
<td>0–0</td>
<td>116.4 ± 1.7*</td>
<td>103.9 ± 3.5</td>
<td>21.8 ± 0.8</td>
<td>98.0 ± 0.4</td>
<td>32.1 ± 2.0</td>
</tr>
<tr>
<td>WL\textsubscript{50}</td>
<td>55 ± 3 (40–65)</td>
<td>117.1 ± 1.5*</td>
<td>102.8 ± 3.0</td>
<td>22.2 ± 1.2</td>
<td>97.8 ± 0.3</td>
<td>31.1 ± 1.6</td>
</tr>
<tr>
<td>WL\textsubscript{peak}</td>
<td>118 ± 11 (60–155)</td>
<td>123.3 ± 1.0*</td>
<td>115.1 ± 1.5</td>
<td>23.0 ± 0.8</td>
<td>98.0 ± 0.3</td>
<td>24.6 ± 0.7</td>
</tr>
</tbody>
</table>

Values are means ± SE; nos. in parentheses, range. [Hb], hemoglobin concentration; S\textsubscript{O\textsubscript{2}}, O\textsubscript{2} saturation; CO\textsubscript{2}, O\textsubscript{2} content; WL\textsubscript{50}, 50% of preestablished peak workload (WL\textsubscript{peak}). *P < 0.01 compared with the same stage with control [Hb].
Mean arterial $\text{SO}_2$ ($\text{SaO}_2$) was between 97 and 98% and $\text{PaO}_2$ was $\gtrsim 90$ Torr in all conditions (Table 1). As the result of hyperventilation, $\text{PaO}_2$ reached $119.2 \pm 1.2$ and $115.1 \pm 3.1$ Torr during peak exercise for control [Hb] and low [Hb], respectively, with a concomitant fall in arterial $\text{PCO}_2$ ($\text{PaCO}_2$) to $34.7 \pm 1.2$ and $35.1 \pm 0.5$ Torr in control [Hb] and low [Hb], respectively (Table 2). As a function of the drop in [Hb], mean $\text{CaO}_2$ was ~20% lower at rest and during exercise ($P < 0.01$; Table 1). At peak effort, $\text{CaO}_2$ was 7% higher in both conditions (not significant) as a result of an increase in Hb ($\Delta 10$ g/l).

Table 2. Arterial and femoral venous values for $[\text{Lac}]$, $\text{PCO}_2$, pH, and $K^+$ for the 2 Hb conditions

<table>
<thead>
<tr>
<th>Stage</th>
<th>[Lac], mmol/l</th>
<th>Arterial</th>
<th>Venous</th>
<th>$\text{PCO}_2$, Torr</th>
<th>Arterial</th>
<th>Venous</th>
<th>pH</th>
<th>Arterial</th>
<th>Venous</th>
<th>$K^+$, mmol/l</th>
<th>Arterial</th>
<th>Venous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control [Hb]</td>
<td>Low [Hb]</td>
<td></td>
<td>Control [Hb]</td>
<td>Low [Hb]</td>
<td></td>
<td>Control [Hb]</td>
<td>Low [Hb]</td>
<td></td>
<td>Control [Hb]</td>
<td>Low [Hb]</td>
</tr>
<tr>
<td>Rest</td>
<td>0.9 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>38.5 ± 0.9</td>
<td>46.6 ± 1.6</td>
<td>7.37 ± 0.01</td>
<td>7.34 ± 0.01</td>
<td>4.2 ± 0.1</td>
<td>4.1 ± 0.1</td>
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</tr>
<tr>
<td>30 W</td>
<td>0.8 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>39.6 ± 2.6</td>
<td>55.2 ± 2.7</td>
<td>7.38 ± 0.02</td>
<td>7.30 ± 0.01</td>
<td>4.5 ± 0.1</td>
<td>4.5 ± 0.1</td>
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</tr>
<tr>
<td>WL$_{50}$</td>
<td>1.3 ± 0.1</td>
<td>1.6 ± 0.2</td>
<td>42.5 ± 1.1</td>
<td>61.4 ± 1.7</td>
<td>7.34 ± 0.01</td>
<td>7.27 ± 0.01</td>
<td>4.8 ± 0.1</td>
<td>4.7 ± 0.0</td>
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<tr>
<td>WL$_{peak}$</td>
<td>4.9 ± 0.2</td>
<td>6.0 ± 0.3</td>
<td>34.7 ± 1.2</td>
<td>69.2 ± 1.2</td>
<td>7.32 ± 0.01</td>
<td>7.17 ± 0.01</td>
<td>6.0 ± 0.2</td>
<td>6.2 ± 0.2</td>
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</tr>
<tr>
<td>Rest</td>
<td>0.9 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>40.0 ± 1.3</td>
<td>48.0 ± 0.8</td>
<td>7.39 ± 0.01</td>
<td>7.34 ± 0.01</td>
<td>4.3 ± 0.1</td>
<td>4.2 ± 0.1</td>
<td></td>
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</tr>
<tr>
<td>30 W</td>
<td>1.2 ± 0.3</td>
<td>1.2 ± 0.3</td>
<td>40.2 ± 1.6</td>
<td>54.7 ± 1.9</td>
<td>7.38 ± 0.01</td>
<td>7.31 ± 0.01</td>
<td>4.5 ± 0.1</td>
<td>4.5 ± 0.2</td>
<td></td>
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</tr>
<tr>
<td>WL$_{50}$</td>
<td>1.6 ± 0.6</td>
<td>1.8 ± 0.7</td>
<td>40.9 ± 0.8</td>
<td>58.0 ± 2.2</td>
<td>7.36 ± 0.01</td>
<td>7.28 ± 0.02</td>
<td>4.6 ± 0.1</td>
<td>4.5 ± 0.1</td>
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</tr>
<tr>
<td>WL$_{peak}$</td>
<td>5.7 ± 1.2</td>
<td>6.7 ± 1.1</td>
<td>35.1 ± 0.5</td>
<td>69.7 ± 2.1</td>
<td>7.33 ± 0.01</td>
<td>7.16 ± 0.02</td>
<td>5.7 ± 0.3</td>
<td>6.0 ± 0.3</td>
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</table>

Values are means ± SE. $[\text{Lac}]$, lactate concentration.
2.3 ± 0.1 l/min (low \([\text{Hb}]\); Fig. 3) as a result of attainable peak power output being reduced 17\% (range 9–25\%; from 143 to 118 W; \(P < 0.01\)). The CO tended to be higher at a given \(\text{VO}_2\) in low \([\text{Hb}]\) compared with control \([\text{Hb}]\). The difference amounted to 1.2–1.7 l/min higher CO per liter per minute of \(\text{VO}_2\) at the three exercise levels. The difference in mean values for CO at a given absolute workload was similar to the difference in leg blood flow, resulting in similar estimated blood flows to the noncontracting tissues. This was also the case at peak effort in the two conditions. CO reached 20–21 l/min, and contracting muscle blood flow averaged 15–16 l/min (see DISCUSSION), leaving close to 5 l/min of blood flow for noncontracting tissues. The HR tended to be higher in low \([\text{Hb}]\) compared with control \([\text{Hb}]\) during exercise, reaching 155 beats/min at peak effort. Stroke volume was unaffected by \([\text{Hb}]\).

Regional response. With low \([\text{Hb}]\), LBF was unchanged at rest but higher when exercising at 30 W (Fig. 3). At peak effort, LBF reached the same level in both conditions (−13 l/min for two legs); as a result, \(\text{O}_2\) delivery was reduced (18\%; \(P < 0.01\)) in low \([\text{Hb}]\). Two-legged blood flow at peak effort amounted to 63 and 65\% of CO in control \([\text{Hb}]\) and low \([\text{Hb}]\), respec-

tively. Of note is that when expressing LBF relative to the workload (two-legged blood flow/W), the difference was 0.02 l·min\(^{-1}\)·W\(^{-1}\) (\(P < 0.01\)), resulting in the same \(\text{O}_2\) delivery in control \([\text{Hb}]\) and low \([\text{Hb}]\) (Fig. 4).

Moreover, with an unaltered systemic blood pressure, limb vascular conductance was lower at a given absolute workload.

Femoral venous \(\text{SO}_2\) (Sfv\(\text{O}_2\)) was barely affected by the lowering of \([\text{Hb}]\) at rest or at submaximal exercise. This is also the case at peak effort when Sfv\(\text{O}_2\) reached 25.6 and 24.6\% in the control and low \([\text{Hb}]\) conditions, respectively (Table 1). Also, femoral venous \(\text{PO}_2\) (Pfv\(\text{O}_2\)) was only moderately and nonsignificantly lower, reaching at peak effort 23–24 Torr in both conditions (Table 1). The femoral venous \(\text{O}_2\) content (Cfv\(\text{O}_2\)) was reduced at rest and all exercise intensities (\(P < 0.01\)) when \([\text{Hb}]\) was lowered but not to the extent of C\(\text{aO}_2\) (Table 1). The femoral a-v \(\text{O}_2\) difference was then reduced (−20\%) at all exercise levels (\(P < 0.01\)). The \(\text{O}_2\) extraction by the working muscle expressed in relation to \(\text{O}_2\) delivery
was similar in the two [Hb] conditions, increasing with exercise intensity and reaching ~75% at peak effort (Fig. 4).

Leg \( \dot{V}O_2 \) was identical in the two conditions at rest (0.02 l/min) and at 30 W (0.3 l/min; Fig. 5). At peak effort, leg \( \dot{V}O_2 \) was lower with low [Hb] (~20%; \( P < 0.01 \)). Leg \( \dot{V}O_2 \)-to-workload ratios, however, were the same regardless of [Hb] and exercise level. The elevation in leg \( \dot{V}O_2 \) during submaximal exercise was accounted for fully by the observed increase in LBF in both conditions (Fig. 5). Going from submaximal to peak effort, leg \( \dot{V}O_2 \) only contributed 55–60% of the pulmonary \( \dot{V}O_2 \), reflecting that additional muscle became engaged in the exercise.

Low [Hb] had little effect on the [Lac] response (Table 2). The release of [Lac] from the contracting muscles resulted in similar arterial and venous [Lac] levels at the same workloads in both conditions. Arterial and venous pH corresponded to the femoral venous PCO2 and [Lac] (Table 2). Also, the K1 concentration increased with exercise, reaching 6.0–6.2 mmol/l in the femoral vein at peak effort in the two conditions (Table 2).

**DISCUSSION**

The major finding of this study was that during submaximal work LBF was elevated and matched by an increase in CO, compensating for the reduction in \( CaO_2 \) caused by a 20% decrease in [Hb]. It is of note that blood pressure was identical in the two conditions, which means that the larger LBF was due to local vasodilatation and not to an increased perfusion pressure. However, neither LBF, CO, nor \( O_2 \) extraction compensated for a low [Hb] at peak effort.

The lack of a compensatory elevation in LBF with low [Hb] at peak effort is puzzling, at least in view of the finding by Sproule et al. (15) of a CO of 23 l/min in chronically anemic patients, resulting in only 1.8 l/min \( VO_2max \). An explanation of the present findings could then be that the pump capacity of the heart may have set a limit. This is hardly the case. Peak LBF was close to 7 l/min in both conditions, putting a demand for the two legs at 13 l/min. The heart pumped an additional 7 l/min, of which 2 l/min can be estimated to have perfused contracting skeletal muscle in the hip region, not accounted for in the measurements over the legs, and the respiratory muscles. This leaves ~5 l/min to the remaining body, which is a high value considering that the exercise effort is maximal. In ordinary two-legged exercise, blood flow to the noncontracting tissues is reduced at the onset of exercise in relation to the relative exercise intensity, being as low as ~3 l/min at exhaustive exercise (12). From the perspective of the performing muscle, especially in the low [Hb] condition of the present study, an additional 1 l/min of blood flow to each leg would have been enough to compensate for the low \( CaO_2 \). This amount would have been available if noncontracting tissue blood had been reduced as in ordinary two-legged exercise (12).

Another and very critical finding is that the \( C_{fv}O_2 \) is high not only at normoxia and submaximal exercise but also at peak effort with low [Hb], when it is 41.3 ml/l with a \( P_{fvO_2} \) of 23 Torr. This is quite different from observations by Sproule et al. (15). They found a low \( C_{fv}O_2 \) of 13.5 ml/l with a \( P_{fvO_2} \) of 23 Torr, which is explained by a shift to the right of the \( O_2 \) dissociation curve (Fig. 6), which is not observed in acute anemia. Thus the leg a-v \( O_2 \) differences constitute 86% in chronically and severely anemic patients compared with 75% in acute anemia (low [Hb] in present study), with no difference in the latter study compared with control [Hb]. The findings of the present study point to a diffusion limitation in the contracting muscle that can be due to 1) a short MTT, 2) limited mitochondrial respiration, 3) restricted off-loading of the \( O_2 \) from the Hb molecule, and 4) capillary red blood cell spacing and heterogeneity in flow. The number of capillaries varied among subjects, as expected, considering the large range in \( VO_2max \). The higher degree of capillarization in the trained subjects matched their larger muscle perfusion, giving a similar estimated MTT of 525 ms. Although there was a tendency for the subjects in the upper range of MTT (600–650 ms) to have a slightly larger femoral a-v \( O_2 \) difference, it is questionable whether the MTT explains the low \( O_2 \) extraction because the femoral a-v \( O_2 \) difference is less in the low [Hb] condition despite an unchanged MTT. It could possibly be explained by an enlarged spacing of red

![Fig. 5. Individual values for limb blood flow (A) and \( O_2 \) delivery to working muscles (B) vs. limb \( \dot{V}O_2 \) at rest and during submaximal and peak exercise.](http://ajpheart.physiology.org/)
blood cells in the capillary with a low Hct (2). On the other hand, the blood flow distribution within the capillary beds of contracting skeletal muscles may be improved with low Hct or [Hb] (8). Moreover, although CaO₂ is lower with low [Hb], the pressure gradient for O₂ diffusion into the cell was maintained, which should favor a larger O₂ flux to the contracting muscles. The limitation could be in the capacity for mitochondrial respiration, which, however, is unlikely because the peak V̇O₂ with low [Hb] is lower than with control [Hb]. When the control [Hb] is compared with the low [Hb] in regard to Pfv O₂, they are almost identical in the corresponding conditions, which may be a reflection of Pfv O₂ and Cfv O₂ being regulated variables. Of note is that almost as low a Pfv O₂ is observed during the submaximal exercises as at peak effort, but O₂ extraction is elevated as Sfv O₂ is gradually lowered with increasing exercise intensity. The lower Sfv O₂ with increasing exercise intensity is a function of the acidification of the blood. It is of note that a lowering of CaO₂ to 150–160 ml/l by lowering the [Hb] and maintaining PaO₂ at a normal level does not affect the submaximal and maximal lactate responses. With [Lac] and Pco₂ levels being the same in the two conditions, pH is reduced in an identical manner in control and low [Hb]. Taken together, the PaO₂, SaO₂, and pH data point to the off-loading of O₂ from Hb as possibly limiting O₂ extraction.

The mechanisms for elevating V̇E, CO, and LBF in hypoxia are understood because there are sensors for alterations in PaO₂ (9). In contrast, a sensor for CaO₂ located centrally or in the peripheral tissues has been sought, but none has yet been identified. Novel proposals for CaO₂ to have a regulatory function have been put forward by Ellsworth et al. (4) and Jia et al. (5). The former authors suggest that there is a release of ATP from the red blood cells when they pass through peripheral vascular beds that is related to the number of occupied O₂ binding sites on the Hb molecules. The other possibility as proposed by Jia et al. is that the Hb molecule functions as a scavenger of nitric oxide (NO) in the peripheral vascular bed, with low [Hb] causing more NO to be available to induce vasodilatation. An attractive feature with these two proposals is that they take into consideration a role for the variable amount of [Hb], a key to explain our findings. We are left then with the phenomenon that acute lowering of CaO₂, either by low [Hb] or hypoxia, elevates LBF and CO during submaximal exercise, but how it is brought about in the low [Hb] condition is unknown.

When CaO₂ is lowered by inhaling hypoxic gas, the usual response is an increase in ventilation regulated by increased peripheral chemosensor activation. Although the aortic peripheral chemosensor is capable of sensing changing CaO₂ (9), it makes a negligible contribution to the overall ventilatory response. This is apparent in the present study by the lack of an increase in V̇E even though CaO₂ was decreased 20% in the low [Hb] condition. For example, at 30 W, V̇̇E was nearly identical between the two conditions despite a difference in CaO₂ of ~40 ml/l. The increase in [Lac] and fall in pH during exercise were also similar between conditions and thus provided no extra central drive to breathe. The lack of increase in peripheral chemoreceptor stimulation is explained in the present study by the nearly identical PaO₂ values in the two conditions at rest and exercise. In comparison, in a recent study, Koskolou et al. (7) showed that when CaO₂ was lowered by breathing hypoxic gas, the same magnitude of drop in CaO₂ caused by a decrease in inspired Po₂ resulted at 30-W exercise in a 10 l/min higher V̇E and a 5 Torr lower PaCO₂. The function of the heart measured as stroke volume is also differentially affected by hypoxia and low [Hb]. In hypoxia, stroke volume is reduced (7), whereas this is not the case in acute (present study) or severe, chronic anemia (15).

The present study was performed in the morning 12–18 h after reduction of [Hb], which allowed for fluid adjustments but hardly any adaptation on a cellular level including the red blood cells, which may occur with slowly developing chronic anemia. In this respect, it is of interest to note that in the few cases studied (13), it appears that their LBF elevation at submaximal work is similar to the one found in the present study. At peak exercise, however, chronically anemic subjects had a 1 l/min higher LBF than that observed in our subjects with low [Hb] despite a slightly higher CaO₂ (172 vs. 162 ml/l). On the other hand, the femoral a-v O₂ difference was slightly smaller (7 ml/l) in the chronically anemic subjects. This resulted in a similar relationship between O₂ delivery to the exercising limb and leg V̇O₂ in acute and chronic anemia, but at peak exercise, it was brought about by a higher blood flow in the chronically anemic subjects (13, 15).

In summary, this study has demonstrated that O₂ delivery to exercising muscles and V̇O₂ were well maintained at the submaximal level even though [Hb] was 20% lower. This was accomplished by a compensatory elevation in LBF and CO. Equally clear is that at peak exercise...
exercise, LBF and CO did not increase with low [Hb], resulting in a reduced peak O₂ delivery and V˙O₂. This lack of compensation, either by increasing the blood flow or O₂ extraction, is surprising because 1) only a limited fraction of the muscle mass was engaged in the exercise, 2) the subjects’ maximal CO was not reached, and 3) the venous blood draining the contracting muscles still contained ample amounts of O₂. This being the case, it is of interest that, even with low [Hb], the previously well-documented tight coupling among O₂ delivery to the exercising limbs, performed work, and V˙O₂ still exists (Fig. 4).

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