Is postexercise hypotension related to excess postexercise oxygen consumption through changes in leg blood flow?

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Submitted 26 October 2004; accepted in final form 12 December 2004

Williams, Jay T., Mollie P. Pricher, and John R. Halliwill. Is postexercise hypotension related to excess postexercise oxygen consumption through changes in leg blood flow? J Appl Physiol 98: 1463–1468, 2005. First published December 17, 2004; doi:10.1152/japplphysiol.01211.2004.—After a single bout of aerobic exercise, excess postexercise oxygen consumption remains elevated above preexercise levels [excess postexercise oxygen consumption (EPOC)]. Similarly, skeletal muscle blood flow remains elevated for an extended period of time. This results in a postexercise hypotension. The purpose of this study was to explore the possibility of a causal link between EPOC, postexercise hypotension, and postexercise elevations in skeletal muscle blood flow by comparing the magnitude and duration of these postexercise phenomena. Sixteen healthy, normotensive, moderately active subjects (7 men and 9 women, age 20–31 yr) were studied before and through 135 min after a 60-min bout of upright cycling at 1463–1468 l/min. Resting and recovery VO2 were measured with a custom-built dilution hood and mass spectrometer-based metabolic system. Mean arterial pressure was measured via an automated blood pressure cuff, and femoral blood flow was measured using ultrasound. During the first hour postexercise, VO2 was increased by 11 ± 2%, leg blood flow was increased by 51 ± 18%, leg vascular conductance was increased by 56 ± 19%, and mean arterial pressure was decreased by 2.2 ± 1.0 mmHg (all P < 0.05 vs. preexercise). At the end of the protocol, VO2 remained elevated by 4 ± 2% (P < 0.05), whereas leg blood flow, leg vascular conduc-
tance, and mean arterial pressure returned to preexercise levels (all P > 0.7 vs. preexercise). Taken together, these data demonstrate that EPOC and the elevations in skeletal muscle blood flow underlying postexercise hypotension do not share a common time course. This suggests that there is no causal link between these two postexercise phenomena.

Address for reprint requests and other correspondence: J. R. Halliwill, 122 Esslinger Hall, 1240 Univ. of Oregon, Eugene, OR 97403-1240 (E-mail: halliwill@uoregon.edu).
60% of \( V\dot{O}_2 \) peak. This workload was used on the study day for the Study Day Protocol.

Subjects

A total of 16 healthy, moderately active, nonsmoking, normotensive subjects between the ages of 20 and 31 yr participated in this study (7 men, 9 women). None of the subjects was taking medications other than oral contraceptives. All female subjects had a negative serum pregnancy test on the screening day. Because the effects of the menstrual cycle on postexercise hypotension are unknown, female subjects were studied during the early follicular phase (1–4 days after the onset of menstruation) or during the placebo phase of oral contraceptives to control for this potential influence.

Screening Visit

Subjects reported to the laboratory for a screening visit the night before reporting to the laboratory. The temperature sensing pill was used to assess internal temperature as an index of core body temperature. After visiting the restroom, subjects were instrumented on a table for measurement of heart rate via a five-lead electrocardiogram and mass spectrometry system (Marquette MGA 1100, MA Tech Services, St. Louis, MO). All subjects reached subjective exhaustion within 8–12 min. Whole body \( V\dot{O}_2 \) uptake was measured via a mixing chamber (Parvomedics, Sandy, UT) integrated with a mass spectrometry system (Marquette MGA 1100, MA Tech Services, St. Louis, MO). All subjects reached subjective exhaustion (rating of perceived exertion = 19–20) within 12–16 min. After the subjects rested for 15–20 min, they returned to the cycle ergometer for assessment of the workload corresponding to a steady-state \( V\dot{O}_2 \) of 60% of \( V\dot{O}_2 \) peak. This workload was used on the study day for the 60-min exercise bout. Subjects self-reported activity levels on two questionnaires (1, 27). Finally, subjects were instructed to ingest the temperature sensing pill the night before reporting to the laboratory for the study day visit. Subject characteristics are presented in Table 1.

Study Day Protocol

Subjects reported for the study between 6 and 10 AM at least 8 h postprandial and abstained from caffeine, alcohol, and exercise for 24 h before this visit. Subjects performed an incremental bicycle exercise test (Lode Excaliber, Groningen, The Netherlands) comprised of 1-min workload increments to determine \( V\dot{O}_2 \) peak. Specifically, after a 2 min warm-up period of easy cycling (20–30 W), workload increased at 20, 25, or 30 W every minute. Selection of the workload increment was subjective, with the goal of producing exhaustion within 8–12 min. Whole body \( V\dot{O}_2 \) uptake was measured via a mixing chamber (Parvomedics, Sandy, UT) integrated with a mass spectrometry system (Marquette MGA 1100, MA Tech Services, St. Louis, MO). All subjects reached subjective exhaustion (rating of perceived exertion = 19–20) within 12–16 min. After the subjects rested for 15–20 min, they returned to the cycle ergometer for assessment of the workload corresponding to a steady-state \( V\dot{O}_2 \) of 60% of \( V\dot{O}_2 \) peak. This workload was used on the study day for the 60-min exercise bout. Subjects self-reported activity levels on two questionnaires (1, 27). Finally, subjects were instructed to ingest the temperature sensing pill the night before reporting to the laboratory for the study day visit. Subject characteristics are presented in Table 1.

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>21.7±2.6</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>23.8±3.7</td>
</tr>
<tr>
<td>( V\dot{O}_2 ) peak, mL/kg·min⁻¹</td>
<td>40.4±7.4</td>
</tr>
<tr>
<td>Exercising workload, W</td>
<td>127.1±42.2</td>
</tr>
<tr>
<td>Exercising heart rate, beats/min</td>
<td>139.3±15.7</td>
</tr>
<tr>
<td>Percentage of heart rate reserve, %</td>
<td>64.9±13.5</td>
</tr>
<tr>
<td>Baecke sport index, arbitrary units</td>
<td>9.3±2.2</td>
</tr>
<tr>
<td>Index of physical activity, MET-h/wk</td>
<td>158.4±86.5</td>
</tr>
</tbody>
</table>

Values are means ± SD; \( n = 16 \) subjects. BMI, body mass index; \( V\dot{O}_2 \) peak, peak oxygen consumption; MET, metabolic equivalents.

Measurements. Preexercise and postexercise measurements were made with subjects in the supine position and consisted of consecutive recordings of heart rate, arterial pressure, internal temperature, and leg blood flow every 15 min for 60 min preexercise and 135 min postexercise.

\( V\dot{O}_2 \) was measured continuously using a custom-built dilution hood and mass spectrometer-based metabolic system (Parvomedics, Sandy, UT). Ambient air was drawn through a loosely fitting hood past the subject’s nose and mouth at a rate sufficient to prevent escape of expired gas (i.e., up to 60 l/min). The rate was adjusted to maintain flow-through carbon dioxide concentrations between 1 and 1.5%.

Femoral artery diameter and velocity were measured by using an ultrasound probe (10-MHz linear vascular probe, GE Vingmed System 5, Horten, Norway). The entire width of the artery was imaged with an angle of 60°. Velocity measurements were taken immediately after diameter measurements and were corrected for the angle of insonation. Leg blood flow was calculated as artery cross-sectional area multiplied by femoral mean blood velocity, doubled to represent both legs, and reported as milliliters per minute. Leg vascular conductance was calculated as flow for both legs divided by mean arterial pressure and expressed as milliliters per minute per millimeters of mercury.

Exercise. Subjects exercised upright on a stationary cycle at 60% of \( V\dot{O}_2 \) peak for 60 min. Exercise of this intensity and duration consistently produces a sustained (~2 h) postexercise hypotension in healthy normotensive subjects (21). Heart rate, arterial pressure, and internal temperature were recorded every 15 min throughout the exercise period. During exercise, subjects drank 15 ml of water/kg of initial body weight to offset volume loss.

Statistics

The results were analyzed with repeated-measures ANOVA. Significant effects were further tested with Fisher’s least significant difference test, and differences were considered significant when \( P < 0.05 \). All values are reported as means ± SE.

RESULTS

Exercise

During exercise, heart rate increased from 55.0 ± 2.2 to 139.3 ± 4.0 beats/min (average over 60 min; \( P < 0.05 \)). The goal was to have each subject exercise for 60 min at 60% \( V\dot{O}_2 \) peak. The percentage of heart rate reserve (heart rate reserve is defined as maximal heart rate achieved during \( V\dot{O}_2 \) peak testing minus the resting supine heart rate) reached during exercise (64.9 ± 3.5%) was consistent with the target workload. Systolic blood pressure increased from 108.0 ± 2.8 mmHg during supine rest to 141.3 ± 4.4 mmHg (\( P < 0.05 \)), whereas diastolic blood pressure was unchanged (60.8 ± 1.6 vs. 64.3 ± 2.2 mmHg) over the 60-min bout of exercise. Therefore, mean arterial pressure increased from 77.4 ± 1.5 mmHg during supine rest to 90.7 ± 8.2 mmHg during exercise (\( P < 0.05 \)). Internal body temperature increased from 36.7 ± 0.1°C during supine rest to 37.9 ± 0.1°C by the final min of exercise (\( P < 0.05 \)).

Postexercise

Figure 1 shows mean arterial pressure, whole body \( V\dot{O}_2 \), and leg blood flow preexercise and through 135 min postexercise. Notably, whole body \( V\dot{O}_2 \) was increased by 11% during the first hour postexercise compared with preexercise (\( P < 0.05 \)). This elevated \( V\dot{O}_2 \) was maintained throughout the study protocol, such that \( V\dot{O}_2 \) at the end of the protocol remained 4%
greater than preexercise values ($P < 0.05$). Leg blood flow increased from 207 ± 30 ml/min before exercise to 280 ± 39 ml/min during the first hour postexercise ($P < 0.05$). By 105 min postexercise, leg blood flow decreased to within preexercise levels ($P = 0.82$).

Table 2 presents combined hemodynamic and metabolic observations at several key time points during the protocol. Notably, arterial pressures were decreased at 45 min postexercise relative to preexercise ($P < 0.05$) but returned to preexercise levels by the end of the protocol. Leg vascular conductance was elevated during recovery from exercise but returned to preexercise levels by the end of the protocol.

Figure 2 shows the simultaneous values for $\dot{V}O_2$ vs. leg blood flow throughout the protocol. At 15 min postexercise, both leg blood flow and $\dot{V}O_2$ exhibited high values. However, by 30 min postexercise, there was a substantial decline in $\dot{V}O_2$ with little change in leg blood flow. Through the remainder of the protocol, leg blood flow progressively returned to resting preexercise levels, but $\dot{V}O_2$ remained elevated.

Figure 3 shows the preexercise to postexercise change in mean arterial pressure and leg vascular conductance vs. the change in $\dot{V}O_2$ across individuals for the representative time point of 45 min postexercise. Individual responses were variable. The change in mean arterial pressure ranged from $-11.4$ to $+3.7$ mmHg, the change in leg vascular conductance ranged from $-27.2$ to $+209.4\%$, and the change in $\dot{V}O_2$ ranged from $-18.0$ to $+26.1\%$ at this time point. There did not appear to be an association between the degree of pressure reductions and elevations in $\dot{V}O_2$ ($r = 0.40, P = 0.13$). Similarly, there did not appear to be an association between the degree of leg vasodilation and elevations in $\dot{V}O_2$ ($r = 0.37, P = 0.16$).

DISCUSSION

The goal of this study was to determine whether an association exists between postexercise hypotension and EPOC. In our study, moderately active subjects were examined to test the hypothesis that EPOC would correlate closely with the changes in leg blood flow over time during recovery from exercise, suggesting a link between the elevated postexercise metabolism and hyperemia in the previously active skeletal muscle (21, 37, 40). In contrast to our hypothesis, no association between these two postexercise phenomena was observed; thus they appear to be unrelated.

We assessed changes in metabolism via changes in $\dot{V}O_2$. These data indicate that the preceding exercise caused a modest but prolonged increase in metabolism, requiring an additional $2.86 \pm 0.93$ liters of oxygen through 135 min of recovery. This observation is consistent with prior reports on EPOC (2, 3, 16, 26, 30). Several factors have been implicated in the generation of EPOC, including the metabolism of lactate and replenishment of creatine phosphate (5, 7, 8, 14, 16, 19, 26, 30, 35), muscle glycogen resynthesis (8), increased body temperature (6, 9, 12, 20), increased heart rate (12), increased ventilatory rate (19), increased circulating concentrations of catecholamine hormones (4, 10, 11, 17), and replenishing the body’s resting oxygen levels (18, 39). Some of the metabolic products created during exercise whose oxidation may contribute to the EPOC may also stimulate increases in blood flow to previously active skeletal muscle (38), creating a “postexercise hyperemia.”

Our subjects demonstrated a reduction in blood pressure through 60 min after the cessation of exercise consistent with prior reports on postexercise hypotension (21–25). Underlying this postexercise hypotension, we observed an elevated leg blood flow through 90 min postexercise. This rise in skeletal muscle blood flow after exercise is well documented but poorly understood. Although there is clear evidence of reduced sympathetic outflow to skeletal muscle vascular beds in humans (15, 24) and rats (28) during postexercise hypotension, blockade of $\alpha$-adrenergic receptors is unable to reproduce the mag-
nitude of postexercise vasodilation in skeletal muscle. There is evidence of vascular $\alpha_1$- and $\alpha_2$-adrenergic hyporesponsiveness in rats (32), but $\alpha_1$- and $\alpha_2$-adrenergic vascular responsiveness is intact in humans (22). Finally, although nitric oxide contributes to postexercise vasodilation in rats (31), independent inhibition of either nitric oxide synthase (23) or cyclooxygenase (29) does not reduce the postexercise vasodilation in humans. Thus additional factors appear to mediate the persistent vasodilation during postexercise hypotension and could be related to ongoing release of metabolic signals from the previously exercised muscle.

We have considered the possibility that this elevation in blood flow to previously active muscles could subserve a continued demand for oxygen delivery and perhaps be linked to EPOC. However, our data appear inconsistent with this model for the following reasons. First, if the elevation in leg blood flow were related to an increase in oxygen utilization in the leg, we would have expected a linear relation between $V_{\dot{O}_2}$ and leg blood flow, which we did not find (Fig. 2). Second, individual differences in the metabolic and hemodynamic responses to exercise exist (Fig. 3), yet we found no association between changes in $V_{\dot{O}_2}$ and changes in either arterial pressure or leg vascular conductance after exercise. In fact, some pairs of subjects had very similar reductions in mean arterial pressure despite dissimilar metabolic responses after the exercise.

Table 2. Hemodynamics and metabolism before and after exercise

<table>
<thead>
<tr>
<th></th>
<th>Preexercise</th>
<th>15 min Postexercise</th>
<th>45 min Postexercise</th>
<th>135 min Postexercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, beats/min</td>
<td>55.0±2.2</td>
<td>65.9±2.9*</td>
<td>61.1±2.6*</td>
<td>56.1±2.4</td>
</tr>
<tr>
<td>Systolic arterial pressure, mmHg</td>
<td>108.0±2.8</td>
<td>109.4±2.5</td>
<td>104.3±2.4*</td>
<td>109.3±3.1</td>
</tr>
<tr>
<td>Diastolic arterial pressure, mmHg</td>
<td>60.8±1.6</td>
<td>62.5±2.1</td>
<td>59.4±1.6</td>
<td>61.8±1.8</td>
</tr>
<tr>
<td>Mean arterial pressure, mmHg</td>
<td>77.4±1.5</td>
<td>78.1±1.8</td>
<td>74.7±1.5*</td>
<td>77.5±1.7</td>
</tr>
<tr>
<td>Leg blood flow, ml/min</td>
<td>207±30</td>
<td>295±40*</td>
<td>269±31*</td>
<td>197±24</td>
</tr>
<tr>
<td>Leg vascular conductance, ml/min/mmHg⁻¹</td>
<td>2.78±0.47</td>
<td>3.76±0.49*</td>
<td>3.60±0.38*</td>
<td>2.52±0.28</td>
</tr>
<tr>
<td>$V_{\dot{O}_2}$, ml/min</td>
<td>267±17</td>
<td>328±24*</td>
<td>282±19*</td>
<td>281±21*</td>
</tr>
<tr>
<td>$V_{\dot{CO}_2}$, ml/min</td>
<td>228±15</td>
<td>306±27*</td>
<td>223±15</td>
<td>224±15</td>
</tr>
<tr>
<td>Respiratory exchange ratio</td>
<td>0.85±0.01</td>
<td>0.92±0.02*</td>
<td>0.79±0.01*</td>
<td>0.80±0.01*</td>
</tr>
<tr>
<td>Internal temperature, °C</td>
<td>36.7±0.1</td>
<td>37.2±0.1*</td>
<td>36.9±0.1*</td>
<td>36.8±0.1</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 16 subjects; $V_{\dot{O}_2}$, oxygen consumption; $V_{\dot{CO}_2}$, carbon dioxide production. *P < 0.05 vs. preexercise.

Some subjects exhibited very high EPOC with virtually no reductions in blood pressure, whereas others had significant blood pressure reductions with no elevation in $V_{\dot{O}_2}$. Taken together, these data suggest that EPOC and the elevation in skeletal muscle blood flow underlying postexercise hypotension are not associated and that it is unlikely there is a causal link between these two postexercise phenomena.

We did not measure the arteriovenous oxygen difference across the leg vascular bed, so we cannot be certain that...
changes in leg blood flow were not accompanied by simultaneous changes in local \( \dot{V}O_2 \). On the basis of the Fick equation relating \( \dot{V}O_2 \), blood flow, and the arteriovenous oxygen difference, and our observation that leg blood flow returns to resting values while \( \dot{V}O_2 \) remained elevated, the only way the excess oxygen could be utilized by the legs would be if there were a progressive rise in the arteriovenous oxygen difference over the 135-min postexercise period. Because this seems highly unlikely, it would appear that the sustained rise in \( \dot{V}O_2 \) was the result of an increased oxygen utilization in some other vascular bed and not in the previously exercised skeletal muscles of the leg.

We were able to document vasodilation in terms of leg vascular conductance in this protocol, despite what can be considered only a modest postexercise hypotension. The magnitude of postexercise hypotension is greater in hypertensive individuals than the normotensive subjects we studied, and we note that our conclusions regarding the absence of an association between EPOC and postexercise hypotension may be limited to healthy individuals of average fitness. Thus it could be that in different populations (e.g., older individuals with hypertension), elevated metabolism during recovery from exercise contributes to the vasodilation that underlies postexercise hypotension.

**Conclusion**

In summary, we assessed the potential relationship between postexercise hypotension and EPOC after a bout of moderate-intensity, dynamic exercise. Our observations suggest that the elevated leg blood flow after exercise is not the result of an increased oxygen utilization in the previously exercised skeletal muscle of the legs. These data also demonstrate that EPOC and the elevations in skeletal muscle blood flow after exercise is not the result of an increased oxygen utilization in some other vascular bed that in different populations (e.g., older individuals with hypertension), elevated metabolism during recovery from exercise contributes to the vasodilation that underlies postexercise hypotension.

**ACKNOWLEDGMENTS**

We thank Dr. Brad W. Wilkins for advice in developing this project. We especially thank the subjects who volunteered for this study. This study was conducted by J. T. Williams in partial fulfillment of the requirements for the degree of Masters of Science at the University of Oregon.

**GRANTS**

This research was supported in part by American Heart Association, Northland Affiliate, Scientist Development Grant 30403Z and National Heart, Lung, and Blood Institute Grant HL-65305.

**REFERENCES**


