Regional hemodynamics during postexercise hypotension.

II. Cutaneous circulation

Brad W. Wilkins, Christopher T. Minson, and John R. Halliwill
Department of Human Physiology, University of Oregon, Eugene, Oregon 97403-1240

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A single bout of dynamic exercise elicits a persistent reduction in arterial pressure lasting nearly 2 h in healthy individuals (11, 13–15). This postexercise hypotension occurs after exercise bouts of 30–60 min performed at a moderate intensity [50–70% peak aerobic capacity; peak \( \dot{V}O_2 \) consumption \( \dot{V}O_{2\text{peak}} \)]. Shorter duration and higher intensity exercise produces inconsistent responses in postexercise blood pressure (11). Generally, postexercise hypotension is due to a sustained elevation in systemic vascular conductance that is not completely offset by increases in cardiac output (11, 14, 15). The persistent vasodilation is known to be due to a reduction in sympathetic neural outflow to skeletal muscle vascular beds (14), as well as a diminished vascular responsiveness to a given sympathetic outflow (12, 14). However, the altered neural and vascular components in skeletal muscle cannot explain the persistent vasodilation in its entirety (13).

One possibility is that vascular beds other than those in the skeletal muscle (e.g., splanchnic, renal, or cutaneous circulations) may contribute to the overall increase in total vascular conductance. In our companion paper, the potential contributions of the splanchnic and renal circulations during postexercise hypotension are examined (28). In the context of the cutaneous circulation, Halliwill et al. (14) demonstrated persistent vasodilation in both the forearm and the leg using venous occlusion plethysmography. This vasodilation paralleled the increase in systemic vascular conductance after cycle exercise (14). This suggests that vasodilation in the nonexercising limb contributes to the lingering hypotension. A potential limitation with the use of venous occlusion plethysmography to determine whole limb blood flow is that this method cannot distinguish between those changes in vascular conductance of the cutaneous circulation and those in the underlying skeletal muscle vasculature. Thus it is possible that a persistent vasodilation in the cutaneous vasculature contributes to postexercise hypotension.

Under thermoneutral environmental conditions, core body temperature remains elevated after an acute exercise bout (2, 9, 23, 31). This postexercise elevation in core body temperature is intensity dependent, because higher postexercise temperatures were found to be associated with higher exercise intensities (23). It is possible that a persistent postexercise thermal load from an increased core body temperature would elevate cutaneous blood flow compared with preexercise. In turn, this elevation in cutaneous vascular conductance would contribute to the sustained systemic vascular conductance during postexercise hypotension.

In addition to the thermoregulatory inputs of core body temperature and skin temperature (17, 27, 29), sympathetic active vasodilator control of skin blood flow is influenced by important nonthermoregulatory influences such as the baroreflex (6, 7, 19) and exercise (18, 21, 22). During exercise, the core temperature threshold for the onset of active vasodilation may be elevated (18, 20, 22). In addition, the rise in skin blood flow during exposure to heat stress is influenced by baroreceptor unloading, where lower body negative pressure (5, 6, 19) reduces skin blood flow responses during passive heating. Recent evidence suggests altered sympathetic control of the cutaneous vasculature after an acute bout of dynamic exercise. Specifically, the threshold for the onset of active vasodilation during passive heating increases to higher core temperatures

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after an acute exercise bout (24). It is not known whether this alteration in active vasodilation is due to the exercise per se or due to the reduction in arterial pressure occurring postexercise. However, increasing mean arterial pressure with lower body positive pressure after exercise causes the threshold for active vasodilation during passive heating to return to core temperatures similar to those obtained without exercise (16). Although studies have examined the alterations in sympathetic control of the cutaneous circulation postexercise, no study has determined whether these changes translate into persistent elevations in cutaneous blood flow. Importantly, no study has examined the contribution of the cutaneous circulation to the sustained elevations in systemic vascular conductance and postexercise hypotension using an exercise paradigm shown to consistently elicit postexercise hypotension.

Therefore, the purpose of this study was to examine the potential contribution of the cutaneous vasculature to postexercise hypotension under thermoneutral environmental conditions. Specifically, we hypothesized that the continued thermal stress, from an elevated postexercise core body temperature, leads to a sustained vasodilation in the cutaneous vasculature. We further hypothesized that the time course of this elevated cutaneous vascular conductance parallels the postexercise reduction in arterial pressure.

METHODS

The Institutional Review Board at the University of Oregon approved all study protocols, and subjects gave informed, written consent before participation.

Subjects

Ten subjects (6 men and 4 women) within an age range of 20–30 yr volunteered to participate in this study. Subjects were healthy, normotensive, and nonsmokers, and they had no history of cardiovascular disease. No subjects were taking medications, with the exception of oral contraceptives, and they were instructed to abstain from alcohol and caffeine at least 24 h before the study day. Female subjects were studied in the early follicular phase of the menstrual cycle or the placebo phase of oral contraceptives and had a negative pregnancy test on both the screening and study day.

Screening Day

Subjects performed an incremental bicycle exercise test (Lode Excaliber, Groningen, The Netherlands) consisting of 1-min workload increments to determine VO_{2peak}. After a 2 min warm-up period of easy cycling (20–30 W), workload was 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 O_{2} uptake (VO_{2}) 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 steady-state VO_{2} of 60% VO_{2peak} was determined by VO_{2} measurement. This workload was used on the study day for the 60-min exercise bout. Subjects reported to the laboratory at least 2 h postprandial and abstained from caffeine, alcohol, and exercise for 24 h before the study. Subjects self-reported activity levels from the Baecke sport index arbitrary units (10). In all 10 subjects, internal temperature was assessed by an ingestible pill telemetry system (4, 32) (HQinc, Palmetto, FL).

Exercise protocol. After instrumentation subjects were positioned supine for 30 min before exercise. The exercise consisted of a 60-min period of seated upright cycling at 60% of VO_{2peak}. Exercise of this intensity and duration consistently produces a sustained (~2 h) postexercise hypotension in healthy normotensive subjects (11). Immediately after the exercise bout, subjects were instructed to remain still while remaining seated on the bicycle ergometer. Skin blood flow was assessed for a 30-s period at this time to determine the skin blood flow response to the exercise bout in the absence of movement artifacts. Subjects were then returned to the supine position for 90 min. The ambient temperature in the laboratory was carefully controlled at ~23°C.

Data Acquisition and Analysis

Data were digitized and stored at 20 Hz on a computer and were analyzed offline by using signal-processing software (Windaq, Dataq Instruments, Akron, OH). Skin blood flow was assessed by averaging laser-Doppler flux values over stable 2-min periods (with the excep-

| Subject characteristics | Age, yr | 23±1 | Height, cm | 175±3 | Weight, kg | 74±2 | Body mass index, kg/m\(^2\) | 24±2 | VO_{2peak}, ml/kg·min\(^{-1}\) | 45±2 | Workload at 60% VO_{2peak}, W | 149±16 | Baecke sport index arbitrary units | 10.5±0.8 | Index of physical activity, MET·h\(^{-1}\)·wk\(^{-1}\) | 150.5±36.3 |

Values are ± SE for 10 subjects. VO_{2peak}, peak O_{2} consumption; MET, metabolic equivalents.
tion of the end of exercise, described above). Skin blood flow was expressed as cutaneous vascular conductance, calculated as laser-Doppler flux (mV)/mean arterial pressure (mmHg), and normalized to the maximal levels achieved during local heating to 43°C.

To compare the responses during postexercise to preexercise values, mean arterial pressure, cutaneous vascular conductance, weighted mean skin temperature, and internal temperature values were obtained at the end of the 30-min preexercise period, during the final minute of exercise (cutaneous vascular conductance assessed immediately after exercise), and every 10 min during the postexercise period. Values were compared by repeated-measures ANOVA, and a Fischer’s least significant difference post hoc test was used to determine where differences occurred.

To examine any alterations in the internal temperature-skin blood flow relationship, the decay in cutaneous vascular conductance and internal temperature was determined for each subject by nonlinear regression described by the equation $Y = Y_0 + ae^{-bx}$, where $Y_0$ is the baseline conductance, $a$ is $Y_{\text{max}} - Y_0$ ($Y_{\text{max}}$ is conductance at the cessation of exercise), and $-b$ is the decay constant. The half-life (min) for the decay in cutaneous vascular conductance at each site and for the decay in internal temperature was determined by $\ln(2)/b$. From the equation above, the disappearance of cutaneous vasodilation was calculated relative to the peak conductance at the cessation of exercise through the postexercise period. In addition, the time to the nadir in mean arterial pressure after exercise from each subject was used to determine the average time to the nadir in mean arterial pressure. Differences were considered significant when $P < 0.05$. All values are reported as means ± SE.

RESULTS

Exercise

The goal was to have each subject exercise for 60 min at 60% $\dot{V}O_2$ peak. The percentage of heart rate reserve (heart rate reserve is defined as maximal heart rate achieved during $\dot{V}O_2$ peak testing minus the resting supine heart rate) reached during exercise (67 ± 4%) were consistent with the target workloads. Mean arterial pressure increased from 82 ± 2 mmHg during supine rest to 96 ± 2 mmHg during bicycle exercise ($P < 0.05$). Internal temperature during supine rest was 36.7 ± 0.1°C and increased to 38.0 ± 0.1°C by the final minute of exercise ($P < 0.05$). Whole body skin temperature was 31.9 ± 0.3°C during supine rest, and it decreased to 31.4 ± 0.3°C by the final minute of exercise ($P < 0.05$).

Postexercise

Mean arterial pressure. Presented in Fig. 1 is mean arterial pressure at preexercise, during the final minute of exercise, and throughout 90 min postexercise. Subjects exhibited postexercise hypotension 20 min after the cessation of exercise (78 ± 2 vs. 82 ± 2 mmHg preexercise; $P < 0.05$). Mean arterial pressure reached a nadir at 46.0 ± 4.5 min postexercise (77 ± 1 mmHg; $P < 0.01$), returning to values not significantly different from preexercise at 71.2 ± 4.1 min postexercise (79 ± 2 mmHg; $P = 0.21$).

Skin blood flow. Presented in Fig. 2 is cutaneous vascular conductance from each skin site at preexercise, immediately after exercise, and throughout 90 min postexercise. Cutaneous vascular conductance decreased to values similar to preexercise within 20 min postexercise at the forearm and the leg skin sites, within 30 min postexercise at the chest skin site, and within 50 min at the thigh skin site (Fig. 2; $P < 0.05$). The elevation in cutaneous vascular conductance at all four skin sites did not parallel the observed reductions in arterial pressure, because the 50-min time point corresponds to the nadir in the postexercise mean arterial pressure. Furthermore, 98.7 ± 0.4% of the elevated cutaneous vascular conductance response after exercise had disappeared at the nadir (46.0 ± 4.5 min) in mean arterial pressure.

Internal and skin temperature. Presented in Fig. 3 is internal temperature at preexercise, during the final minute of exercise, and throughout 90 min postexercise. Core body temperature remained elevated from preexercise values through the entire postexercise period (36.9 ± 0.1°C at 90 min postexercise vs. 36.7 ± 0.1°C preexercise; $P < 0.05$). Weighted mean skin temperature, after decreasing during exercise, returned to values not different from preexercise by 10 min into postexercise recovery (data not shown). Mean skin temperature rose during postexercise recovery and at 50 min postexercise was higher than mean skin temperature before exercise (32.3 ± 0.2°C vs. 31.9 ± 0.3°C preexercise; $P < 0.05$). Mean skin temperature remained greater than preexercise through 90 min after exercise.

Internal temperature-skin blood flow relationship. To examine the relationship between internal temperature and whole body skin blood flow, cutaneous vascular conductance was averaged from values at the four skin sites. Presented in Fig. 4 is the relationship between internal temperature and the average cutaneous vascular conductance values obtained at preexercise, at the end of the exercise bout, and at 10, 30, 60, and 90 min of postexercise recovery. Thirty minutes after the exercise bout, core body temperature was elevated compared with preexercise (37.1 ± 0.1 vs. 36.7 ± 0.1°C; $P < 0.01$). However, the average cutaneous vascular conductance at 30 min postexercise was not significantly higher than the average cutaneous vascular conductance before exercise (11 ± 1 vs. 9 ± 1% maximal cutaneous vascular conductance preexercise; $P > 0.05$). The average postexercise cutaneous vasodilation from all four skin sites had a half-life of 7.5 ± 0.6 min, as determined by the decay in the response immediately after exercise. In contrast, the half-life for the internal temperature response was 16.2 ± 3.3 min from the final minute of exercise ($P = 0.03$ vs. cutaneous vasodilation half-life).
DISCUSSION

The primary finding from this study was that elevated skin blood flow immediately after exercise decreased to values similar to preexercise at the forearm and leg within 20 min, the chest within 30 min, and the thigh within 50 min postexercise. Importantly, under the conditions set in this study, postexercise hypotension persisted through 60 min postexercise. Thus, although there was an increase in skin blood flow after a 60-min exercise bout (60% $\dot{V}O_2$ peak), elevations in cutaneous vascular conductance are short lived relative to postexercise hypotension under thermoneutral environmental conditions. In our companion paper (28), we found that the renal and splanchnic vascular beds do not directly contribute to postexercise hypotension. Combined with the results from this study, this suggests that postexercise hypotension is largely due to vasodilation in the skeletal muscle vascular beds but that there may still be a contribution from an unidentified vascular bed.

Studies examining the postexercise hypotension phenomenon have focused on the vascular beds in exercising and nonexercising limbs as the likely source for the sustained elevations in vascular conductance. In fact, vascular conductance in both the arm and leg parallel the increased systemic vascular conductance after lower body exercise (14). Similarly, in our companion paper, we demonstrate that systemic vascular conductance and leg vascular conductance was elevated through 100 min postexercise (28). On the systemic level,
mean arterial pressure is directly related to total peripheral resistance and inversely related to conductance. However, because the major vascular beds are arranged in parallel, partitioning the contribution of each vascular bed is best achieved by calculating conductances, which summate linearly. Thus, the contribution of cutaneous vasodilation to either limb vasodilation or systemic hemodynamics is proportional to the change in cutaneous vascular conductance (not resistance). As such, the data from this investigation suggest that the elevated limb vascular conductance is not associated with a sustained vasodilation of the cutaneous vasculature. Thus our data suggest that the sustained limb vascular conductance is associated with elevated vasodilation in the skeletal muscle vascular beds.

A recent review by Halliwell (11) outlining the mechanisms of postexercise hypotension suggested exercise and recovery in a hot environment may exacerbate the hypotensive response, in part due to a greater cutaneous vasodilation. Franklin et al. (9) demonstrated that postexercise hypotension was augmented when exercise (30 min) and recovery (60 min) were performed under hyperthermic conditions, whereas decreasing ambient temperature during exercise and recovery attenuated the postexercise hypotension. Because only an index of core temperature (via external auditory meatus) and skin temperature were assessed in that study (blood flow was not measured), it is unclear if high cutaneous blood flows contributed to the augmented blood pressure response under the hyperthermic condition.

As an alternative to greater cutaneous vasodilation, a greater loss of plasma volume due to higher sweat rates may contribute to the augmented postexercise hypotension under hyperthermic environmental conditions (11). In line with this possibility, fluid replacement (8) and preventing plasma volume loss by intravenous saline infusion during exercise (3) may lessen the postexercise hypotension. Regardless, the suggestion that postexercise hypotension is augmented by high cutaneous blood flow under hyperthermic environmental conditions does not imply that an elevated cutaneous blood flow is the cause of postexercise hypotension under other conditions. For example, under the thermoneutral environmental conditions set in this study, postexercise hypotension persisted substantially longer than cutaneous vasodilation at all four skin sites.

The data from the present study show that, in the face of a sustained thermoregulatory drive to elevate skin blood flow (i.e., sustained elevation in internal temperature), skin blood flow rapidly declines to resting levels following exercise. This observation is consistent with a “resetting” of the internal temperature-skin blood flow relationship after exercise, as suggested by Kenny and colleagues (16, 23, 24), and deserves further study.

Limitations

Our measurements of cutaneous vascular conductance were limited to sites of nonglabrous skin. Nonglabrous skin is representative of 95% of body surface area and, in general, exhibits uniform and predictable responses to thermoregulatory inputs. In contrast, the distribution of glabrous skin is limited to the hands, feet, and face regions and is exquisitely sensitive to environmental temperature and emotional inputs. We cannot address the issue of whether glabrous skin contributes to postexercise hypotension. Nonetheless, we recognize that glabrous skin is not likely to contribute to measurements of limb blood flow if the circulation of the hands and feet are excluded by arterial occlusion cuffs located at the wrist and ankle (a common practice during venous occlusion plethysmography). As such, prior reports of calf and forearm vasodilation during postexercise hypotension likely reflect skeletal muscle vasodilation with little or no contribution from glabrous or nonglabrous skin.

Nonglabrous skin vasodilates when directly heated (a locally mediated response). In our study, weighted mean skin temperature was elevated at 50 min postexercise, due to an elevation in temperature recorded by the back thermocouple (37.1 ± 0.3 vs. 36.3 ± 0.3°C preexercise; P < 0.05). Clearly, this is due to heat being trapped between the subject and the mattress on which they laid. The question arises as to whether or not this elevation in skin temperature might mediate a regional (i.e., back) cutaneous vasodilation, thus contributing to postexercise hypotension. On the basis of studies in which we have locally heated skin of the forearm over this same range of temperatures, vasodilation under these conditions would be small (on the order of 3–4% maximal cutaneous vascular conductance). If the entire area of the back was vasodilated this amount, it could contribute to postexercise hypotension. To address this possibility, we had an additional two subjects undergo the present study, but we had these subjects sit upright both pre- and postexercise so that their backs were exposed to ambient temperature. This manipulation prevented the postexercise rise in back skin temperature and weighted mean skin temperature, but it had no effect on postexercise hypotension in these two subjects. This suggests that a sustained regional cutaneous vasodilation in areas of skin not exposed to ambient condition (e.g., back skin temperature) does not contribute to postexercise hypotension.

Conclusion

Elevations in skin blood flow after a 60-min bout of moderate aerobic exercise rapidly declined to preexercise levels. As such, this vasodilation does not parallel the well-documented systemic vasodilation that underlies postexercise hypotension. This rapid decline in skin blood flow suggests there is an alteration in the internal temperature-skin blood flow relationship after an acute exercise bout, such that in the face of a persistent thermal load after exercise, cutaneous blood flow returns to preexercise levels. Therefore, under thermoneutral environmental conditions, postexercise elevations in nonglabrous skin blood flow are short lived and, thus, skin blood flow does not play an obligatory role in postexercise hypotension.

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