Eur J Appl Physiol (1989) 58:865-872

European Journal of Applied Physiology and Occupational Physiology

Venous return from distal regions affects heat loss from the arms and legs during exercise-induced thermal loads

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Summary. To study the role of venous return from distal parts of the extremities in influencing heat loss from the more proximal parts, changes in mean skin temperature ($\bar{T}_{sk}$) of the non-exercising extremities were measured by color thermography during leg and arm exercise in eight healthy subjects. Thirty minutes of either leg or arm exercise at an ambient temperature (T_a) of 20° C or 30° C produced a greatly increased blood flow in the hand or foot and a great increase in venous return through the superficial skin veins of the extremities. During the first 10 min of recovery from the exercise, blood flow to and venous return from the hand or foot on the tested side was occluded with a wrist or ankle cuff at a pressure of 33.3 kPa (250 mm Hg), while blood flow to the control hand or foot remained undisturbed. During the 10-min wrist occlusion, $\bar{T}_{sk}$ increased significantly from 28.3° ±0.41° C to 30.1° ±0.29° C in the control forearm, but remained at nearly the same level (28.0° ±0.34° C to 28.2° ±0.25° C) in the occluded forearm. In the legs, although $\bar{T}_{sk}$ on both sides was virtually identical (32.0° ±0.31° C, control vs 32.0° ±0.36° C, tested) before occlusion, $\bar{T}_{sk}$ on the control side (32.6° ±0.27° C) was significantly higher than that on the tested side (32.2° ±0.21° C) after ankle occlusion. As monitored by a laser-Doppler flowmeter, skin blood flow in both forearms and legs did not increase but rather decreased during the 30-min recovery. Thus, the increase in $\bar{T}_{sk}$ in the control forearm or leg cannot be explained by the change in forearm- or leg-skin blood flow. We estimated the contribution of the heat transferred from the venous blood of the hand to be 89% of the increase in heat loss from the forearm during occlusion at T_a of 20° C, and to be 67% from the occluded leg at T_a of 30° C. The present results suggest that heat loss from proximal parts of the extremities is greatly affected by the change in blood flow through the distal parts of the extremities, and such venous blood flow plays an important role in the regulation of heat dissipation during exercise in cool (20° C) to warm (30° C) environments.

Key words: Venous blood flow — Heat loss — Thermography — Exercise — Hand and foot

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Introduction

In constant temperature environments, when there is no evaporative heat loss, skin temperature in immobile regions of the body depends on the rate of blood flow through the skin, as well as the rate of blood flow through both distal and subjacent tissues. At the onset of exercise, forearm skin temperature decreases, and this fall in skin temperature is proportional to work intensity during exercise (Nakayama et al. 1977). However, it has been observed that forearm blood flow is independent of exercise intensity (Wenger et al. 1975). Therefore, the change in forearm skin temperature may not reflect the alteration of forearm-skin blood flow and, instead, may reflect venous blood flow returning from the hand. Grant and Pearson (1938) have demonstrated that venous blood flow returning from the hand is a significant factor in controlling forearm skin temperature during body warming. If changes in heat loss determined by skin temperature in the proximal parts are caused mainly by venous blood returning from the distal parts of the extremities, an increase in the distal blood flow of the extremities will play by far the most important role in heat loss from the human body. In the present study, we have attempted to confirm the influence of venous blood returning from the hand and foot on heat loss from the forearm and lower leg during exercise-induced thermal loads.

Methods

This study consisted of thermographic observation of the forearm during thermal load induced by leg exercise (experiment 1) and observation of the lower legs during arm exercise (experiment 2), and involved eight healthy, male volunteers, aged 30±4.4 years (means±SE), height 169±1.5 cm and weighing 61±3.0 kg in both experiment 1 and 2. Seven subjects (nos. 1–7) participated in experiment 1 and five subjects (nos. 4–8) in experiment 2. Procedures were carefully explained and all subjects gave their informed consent.

Procedure

Before the test, the relationship between heart rate (HR) and work load was determined during exercise using a cycle ergometer (Monark, Varberg, Sweden) with each subject in a semi-supine posture in a reclining chair. From these data the work load was set at HR of 120 beats·min^{-1} for both leg and arm exercises for each subject. The mean work loads were 96±9.1 W for leg exercise in experiment 1 and 33±3.2 W for arm exercise in experiment 2. Having been familiarized with all test procedures, the subjects reported to the laboratory at approximately the same time each morning after an overnight fast. The subjects wore bathing suits and were fitted with an esophageal temperature (T_{es}) sensor and ECG electrodes.

Experiment 1. To cool the forearms and hands, the subjects immersed both arms for 10 min in a water-bath, at a water temperature of 20° C. After immersion, all traces of water on the skin were wiped off with towels. Each subject then rested quietly in a semi-supine posture with both arms extended and placed on a small table below a thermocamera. Laser-Doppler flow probes were fixed to the middle of the lateral sides of the forearms with a black plastic disk affixed to the skin surface by an adhesive ring. Rest-period data were obtained during the last 10 min of a 20-min rest period. The subject then exercised on the cycle ergometer in the semi-supine posture for 30 min, then recovered for 30 min after the exercise. Immediately following the exercise period, one or other wrist was occluded by inflating a wrist cuff, 5 cm wide, at 33.3 kPa (250 mm Hg) for 10 min. The wrist cuff had been placed on the wrist 30 s before the end of the exercise and was removed after a 10-min occlusion period. For experiment 1, all subjects were tested twice on separate days, alternating the wrist to be occluded with each study.

Experiment 2. After the subjects had pedaled the cycle ergometer in an upright posture for 30 min to increase body temperature, their legs were stretched out below the thermocamera in a semi-supine posture for the remainder of the experiment. The laser-Doppler flow probes were attached to the middle of the lateral sides of both lower legs as described for the arms. Rest period data were obtained during the last 2 min of a 5-min rest period. The subjects then exercised, using the arm ergometer for 30 min, then recovered for 30 min. Immediately following the exercise period, the ankle was occluded by inflating an ankle cuff, 5 cm wide, at 33.3 kPa (250 mm Hg) for 10 min. The cuff had been placed on the ankle 30 s before the end of the arm exercise and was removed after a 10-min occlusion period. The ankle cuff was set on the right side for three subjects and the left side for two subjects. Each subject was tested once.

Measurements

The T_{es} was measured with a thermistor probe (Takara Thermistor Instruments Co. Ltd., Yokohama) introduced via the nose into the esophagus to the level of the left atrium, which was verified by showing the highest temperature in the esophagus. The T_{es} data were recorded every 30 s on a personal computer (PS80, TEAC, Tokyo) through a data logger (K923, Takara Thermistor Instruments Co. Ltd., Yokohama) with an A/D converter. The HR was measured from the ECG output and computed to 30 s averages by a personal computer through a HR counter (AT 600G, Nihon, Kohden, Tokyo), a DC amplifier (SA15U, TEAC, Tokyo), and an A/D converter.

The thermography system (Infra-Eye 160, Fujitsu, Tokyo) consisted of a thermocamera, a controller, a monitor color TV, a personal computer (FM16B FD1, Fujitsu, Tokyo), and a color printer (IO-720, Sharp, Osaka). This system produced a 25-color isotherm display for a temperature range of 22° to 32° C for experiment 1, and 26.5° to 36.5° C for experiment 2, on a 13-in. Braun tube. Colored thermographic recordings of a 3.7-s scanning period of the areas of the palmar side of the hands and forearms, and the medial side of the lower legs and feet were taken and recorded each minute by the thermography system. For data analysis, hand (hand $\bar{T}_{sk}$) and forearm (forearm $\bar{T}_{sk}$) mean skin temperatures on both sides were computed by the personal computer from the thermographic recordings of the forearm (52 cm^2) and hand (17 cm^2) areas; in the same manner, foot (foot $\bar{T}_{sk}$) and leg (leg $\bar{T}_{sk}$) mean skin temperatures on both sides were computed from thermographic recordings on the leg (36 cm^2) and the foot (28 cm^2) areas. Thermal exchange by radiation (R) and convection (C) from the forearm or leg areas was then calculated as follows:

$$(R+C)=h_{r+c}\cdot(\text{forearm or leg } \bar{T}_{sk}-T_a)$$

where,

$(R+C)$ = heat exchange by R and C in W·m^{-2} of body surface

h_{r+c} = combined heat transfer coefficient for R and C. The value of h_{r+c} has been experimentally determined to be 8.60 W·m^{-2}·°C^{-1} at rest in still air (Nadel 1979)

(forearm or leg $\bar{T}_{sk}-T_a$) = the forearm or leg skin ($\bar{T}_{sk}$) to ambient (T_a) temperature gradient, in °C.

Skin blood flow (LDF) in forearms and legs was measured by a laser-Doppler flowmeter (PeriFlux, PF-1d, Perimed KB, Stockholm) (Holloway and Watkins 1977; Öberg et al. 1979). The device had a 2 mW He-Ne laser and emitted monochromatic light at a wavelength of 632.8 nm. The light was delivered to the skin surface via an optic fiber probe. Reflected light was gathered by another optic fiber and processed by analog computation of the power-spectral density of shifted light (Nilsson et al. 1980a, b). The same gain, upper frequency cut off (12 kHz), and time constant (3 s) were used for each of the tests in this study. After each test, to obtain an LDF value for zero blood flow, blood flow to the forearm or leg was occluded by an upper arm cuff (13 cm wide) or a tigh cuff (17 cm wide), at a pressure of 33.3 kPa (250 mm Hg). All tests were conducted in a climatic chamber (TBL-6-s, Tabai MFG Co. Ltd., Osaka) at T_a of 20° ±0.5° C and a relative humidity (rh) of 30%±3% for experiment 1, and at T_a of 30° ±0.5° C and rh of 30%±3% for experiment 2.

Data analysis

Results obtained from the two tests in experiment 1 were averaged for each subject and, then, the grand mean values were calculated from all seven individual averages for statistical analysis. In experiment 2, mean values were calculated from all five individual data for statistical analysis. Statistical analysis was carried out by a one-way analysis of variance (ANOVA) and a paired *t* test ($p<0.05$). Mean values are given with their standard errors (±SE).

Results

Experiment 1

The T_{es} increased significantly by 0.62° C from 36.78° ±0.12° C to 37.40° ±0.06° C during 30-min leg exercise, and decreased to 36.82° ±0.06° C by the end of the recovery period. The HR increased significantly by 59.5 beats·min^{-1} from 64.9±1.7 beats·min^{-1} to 124.4±5.4 beats·min^{-1} during 30-min exercise, and decreased to 66.2±1.5 beats·min^{-1} during the 30-min recovery period.

Figure 1 shows typical changes in hand $\bar{T}_{sk}$, forearm $\bar{T}_{sk}$, forearm $(R+C)$, and forearm LDF in experiment 1. Changes in hand $\bar{T}_{sk}$ were approximately the same in the control and tested hands, at rest and during exercise. During the first 10-min recovery, hand $\bar{T}_{sk}$ increased further with a concomitant increase in forearm $\bar{T}_{sk}$, and gradually decreased thereafter. During the 10-min wrist occlusion, when hand $\bar{T}_{sk}$ apparently decreased, the increase in forearm $\bar{T}_{sk}$ was concomitantly inhibited on the tested side. Forearm LDF, being slightly higher at the end of exercise, decreased significantly and remained at a low level on both sides during occlusion. After the release of wrist occlusion, hand and forearm $\bar{T}_{sk}$ recovered, but forearm LDF showed no change on the tested side. Forearm $(R+C)$ remained at a level near zero at rest and during exercise, and markedly decreased by 16.4 W·m^{-2} as a result of wrist occlusion. After the release of wrist occlusion, forearm $(R+C)$ increased, reaching the pre-occlusion level.

Table 1 summarizes the effects of exercise and wrist occlusion on hand $\bar{T}_{sk}$, forearm $\bar{T}_{sk}$ and forearm LDF, while Fig. 2 shows the time course of mean forearm $\bar{T}_{sk}$ and forearm LDF in seven subjects during occlusion. The 10-min wrist occlusion significantly inhibited increases in forearm $\bar{T}_{sk}$. Forearm LDF did not increase but rather decreased significantly on both sides during occlusion.

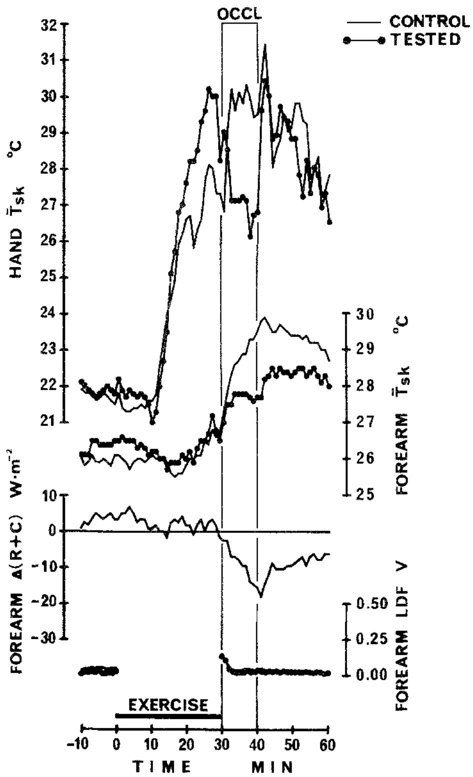

Fig. 1. Changes in mean skin temperatures of the hands (*Hand* $\bar{T}_{sk}$) and forearms (*Forearm* $\bar{T}_{sk}$), difference of dry heat loss from the *control* and *tested* forearms [*Forearm* $\Delta(R+C)$], and skin blood flow (*Forearm LDF*) in the *control* and *tested* forearms for subject 4 before, during and after leg *exercise*. *OCCL:* wrist occlusion at 33.3 kPa (250 mm Hg). *R*, radiation; *C*, convection

Figure 3 shows the relationship between changes in hand $\bar{T}_{sk}$ and forearm $\bar{T}_{sk}$ during the 10-min wrist occlusion in all subjects. The relationship showed a significant positive correlation, having the regression line of $y=0.30x+1.23$ ($r=0.86$).

Experiment 2

The T_{es} significantly increased from 37.12° ±0.02° C to 37.34° ±0.02° C during arm exercise lasting for 30 min and had decreased to 36.90° ±0.03° C by the end of the recovery period. The HR also increased significantly from 85.6±3.2 beats·min^{-1} to 112.6±5.5 beats·min^{-1} during exercise and then returned to 80.0±1.7 beats·min^{-1} during the 30-min recovery period.

Table 2 and Fig. 2 show changes of mean foot $\bar{T}_{sk}$, leg $\bar{T}_{sk}$ and leg LDF in all subjects. With the

Table 1. Effects of wrist occlusion on mean skin temperatures of the hand (Hand $\bar{T}_{sk}$) and forearm (Forearm $\bar{T}_{sk}$), and laser-Doppler blood flow in the forearm skin (Forearm LDF) at rest, during leg exercise, and in recovery

Time (min)	Rest	Exercise			Recovery		
	0	10	20	30	40[a]	50	60
Hand $\bar{T}_{sk}$ (° C)							
Control	23.1 ±0.99	23.2 ±0.75	28.4 ±0.83	31.3 ±0.79	32.4 ±0.52	31.4 ±0.52	29.7 ±0.64
Tested	23.2 ±0.80	23.2 ±0.70	28.1 ±0.87	30.8 ±0.89	27.9* ±0.44	30.7 ±0.52	29.1 ±0.62
Forearm $\bar{T}_{sk}$ (° C)							
Control	27.6 ±0.44	27.2 ±0.41	27.1 ±0.36	28.3 ±0.41	30.1 ±0.29	30.2 ±0.28	29.7 ±0.29
Tested	27.7 ±0.45	27.2 ±0.46	27.0 ±0.35	28.0 ±0.34	28.2* ±0.25	29.2* ±0.34	29.1* ±0.33
Forearm LDF (V)							
Control	0.018 ±0.003	—	—	0.125 ±0.016	0.028 ±0.006	0.019 ±0.005	0.019 ±0.005
Tested	0.024 ±0.005	—	—	0.172 ±0.045	0.031 ±0.006	0.021 ±0.003	0.021 ±0.004

Values are means ±SE
* Significantly different from the corresponding control values ($p<0.05$)
[a] The values at 40 min in the tested side are those at the end of the 10-min wrist occlusion from 30 to 40 min

10-min ankle occlusion, foot $\bar{T}_{sk}$ on the tested side was significantly lower than that of the control side ($p<0.05$). Leg $\bar{T}_{sk}$ on the tested side was also significantly lower than on the control side ($p<0.05$). Leg LDF, which during the first 10 min

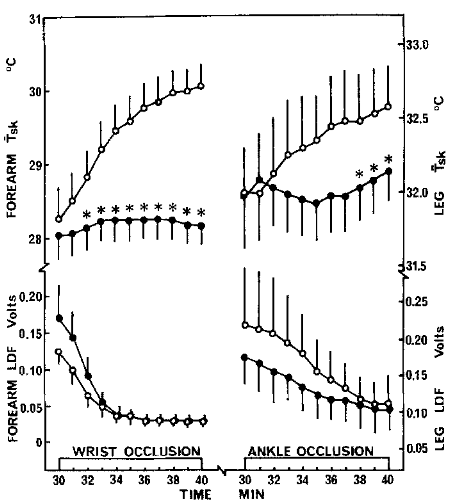

Fig. 2. Changes in mean skin temperature (*Forearm $\bar{T}_{sk}$*) and skin blood flow (*Forearm LDF*) in the *control* (○) and *tested* forearms (●) during *wrist occlusion* (left). Changes in mean skin temperature (*Leg $\bar{T}_{sk}$*) and skin blood flow (*Leg LDF*) in the control (○) and *tested* legs (●) during *ankle occlusion* (right). Values are means ±SE. *Significantly different from the corresponding control values, $p<0.05$

of recovery was nearly the same as the pre-exercise values, gradually decreased on both sides thereafter (Fig. 2).

Figure 4 shows the estimated contribution of venous blood flow returning from the hand or foot to the increase in dry heat loss ($R+C$) from the forearm or leg during the 10-min recovery following exercise. In the forearm, 89% of $\Delta(R+C)$ of 15.5 $W \cdot m^{-2}$ was attributed to the venous blood returning from the hand at 20° C and, in the leg, 67% of $\Delta(R+C)$ of 5.3 $W \cdot m^{-2}$ to the venous blood returning from the foot at 30° C.

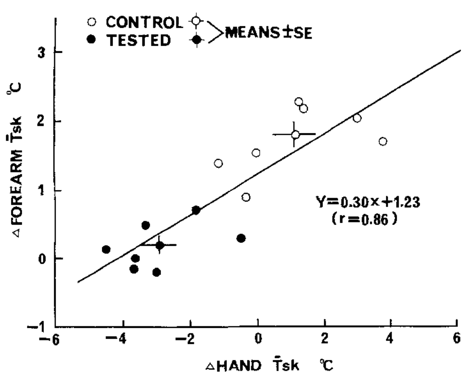

Fig. 3. Relationship of change in forearm mean skin temperature (*Δ Forearm $\bar{T}_{sk}$*) to change in hand mean skin temperature (*Δ Hand $\bar{T}_{sk}$*) for the first 10 min of recovery in the *control* and *tested* sides

Table 2. Effects of ankle occlusion on mean skin temperatures of foot (Foot $\bar{T}_{sk}$) and leg (Leg $\bar{T}_{sk}$), and laser-Doppler blood flow in the leg skin (Leg LDF) at rest, during arm exercise, and in recovery

Time (min)	Rest	Exercise			Recovery		
	0	10	20	30	40[a]	50	60
Foot $\bar{T}_{sk}$ (°C)							
Control	33.1 ±0.92	33.3 ±0.98	33.8 ±0.73	34.1 ±0.68	34.7 ±0.47	34.9 ±0.35	35.0 ±0.27
Tested	32.8 ±0.97	33.0 ±1.06	33.2 ±1.06	33.4 ±1.02	32.8* ±0.59	34.3* ±0.52	34.6* ±0.35
Leg $\bar{T}_{sk}$ (°C)							
Control	32.6 ±0.15	32.1 ±0.27	32.0 ±0.27	32.0 ±0.31	32.6 ±0.27	33.2 ±0.35	33.7 ±0.30
Tested	32.9 ±0.16	32.3 ±0.30	32.1 ±0.29	32.0 ±0.36	32.2* ±0.21	33.0 ±0.33	33.5 ±0.30
Leg LDF (V)							
Control	0.206 ±0.101	—	—	0.220 ±0.079	0.112 ±0.039	0.067 ±0.020	0.065 ±0.023
Tested	0.158 ±0.044	—	—	0.178 ±0.038	0.103 ±0.026	0.076 ±0.019	0.076 ±0.018

Values are means ±SE
* Significantly different from the corresponding control values ($p<0.05$)
[a] The values at 40 min in the tested side are those at the end of the 10-min wrist occlusion from 30 to 40 min

Discussion

The present study was designed to determine to what extent venous blood returning from the distal parts of the extremities causes heat loss from the proximal parts of the extremities during exercise. Accordingly, simultaneous measurements of blood flow and temperature of the forearm or leg skin were made during and after blood circulation to the hand or foot was arrested by a wrist or ankle occlusion during thermal load.

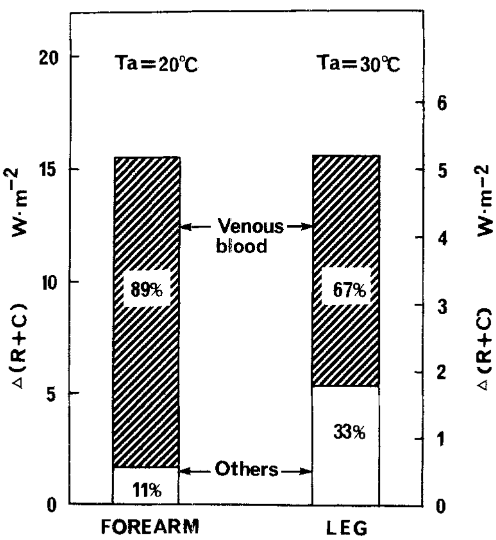

Fig. 4. Contribution of venous blood returning from the distal parts of the extremities for the first 10 min of recovery to the change in heat loss [$\Delta(R+C)$] from the proximal parts of the extremities. Measurements were made in the *forearm* at T_a of 20°C, and in the *leg* at T_a of 30°C. R, radiation; C, convection

Mild exercise at an ambient temperature of 20°C markedly increased forearm skin temperature. However, when the wrist cuff was inflated, arresting circulation to the hand for at least 10 min, forearm $\bar{T}_{sk}$ did not increase on the tested side (Fig. 1 and Table 1). After the wrist cuff was released, forearm $\bar{T}_{sk}$ greatly increased and reached levels attained in the control forearm. However, blood flow, as measured by laser-Doppler flowmetry, did not increase but rather decreased and remained at low levels. It has been reported that the transient change in skin temperature during and immediately following exercise is a sensitive index of change in blood flow through the skin (Veghte et al. 1979). However, the present data do not support this idea, and essentially supports the results and conclusion of Grant and Pearson (1938) that venous return from the hand is a controlling factor in forearm $\bar{T}_{sk}$. In the present study, leg or arm exercise was performed using an ergometer and the unexercised limbs were stationary throughout the experiment. Thus, the effect of heat transfer from an actively contracting muscle by direct conduction could not be a factor in producing our results. Neither could direct vertical, vascular convection of heat from the muscle outwards toward the overlying skin (Cooper et al. 1959) provide an explanation as Johnson and Rowell (1975) have reported that, during leg exercise, forearm-muscle blood flow remains lower than at a resting level.

Thermometric data showed that, at a T_a of 20° C, a 1° C rise of hand $\bar{T}_{sk}$ caused a 0.3° C increase in forearm $\bar{T}_{sk}$ (Fig. 3). This means that, if hand vessels dilate and hand $\bar{T}_{sk}$ is increased by 1° C, heat loss would be enhanced by 8.60 $W \cdot m^{-2}$ from the hand and, additionally, by 2.58 $W \cdot m^{-2}$ from the forearm through the venous blood originating from the hand (see Methods). As shown in Fig. 4, we estimated that 89% of 15.5 $W \cdot m^{-2}$ of heat would be dissipated from the forearm as a result of direct heat transfer from the venous blood returning from the hand. Likewise, at T_a of 30° C, 67% of the increase in heat loss from the leg would be attributed to venous blood returning from the foot. Thus, we conclude that this heat dissipation process is quantitatively important in regulating body temperature during exercise-induced thermal load in cool environments.

Changes in forearm-skin blood flow were measured by a laser-Doppler flowmeter, a recently introduced technology for measuring the superficial capillary flow of the tissues (Holloway and Watkins 1977; Öberg et al. 1979; Nilsson et al. 1980a, b). The output of the laser-Doppler flowmeter correlates well with forearm blood flow as measured by venous occlusion plethysmography (Johnson et al. 1984; Saumet et al. 1986), although there are intra- and inter-individual variations. While laser-Doppler flowmetry can be quite accurate in qualitatively assessing differences in blood flow within the same organ or vascular bed of the same subject (Smits et al. 1986), we did not measure forearm or leg skin blood flow during leg or arm exercise, as shown in Table 1 and 2, because recordings are disturbed by mechanical movement of the optic fiber system.

To verify the relationship of blood flow and skin temperature in the forearm and hand, forearm venous blood flow velocity, finger blood flow, forearm and finger $\bar{T}_{sk}$, and HR were measured during and after 40-min leg exercise with and without wrist occlusion (Fig. 5). To measure the mean velocity of blood flow in a forearm vein, a Doppler ultrasonic velocity detector (Dual-Frequency Directional Doppler, Model 909, Parks Medical Electronics, Oregon, USA) was placed on the skin just above a superficial vein of the forearm. Ultrasound of 10 MHz was scattered by moving blood particles inside the vein and the reflected signal shifted in frequency in proportion to the blood flow velocity. Finger blood flow (FBF) on the same side was measured at 30-s intervals by venous occlusion plethysmography using a mercury-in-Silastic strain gauge compensat-

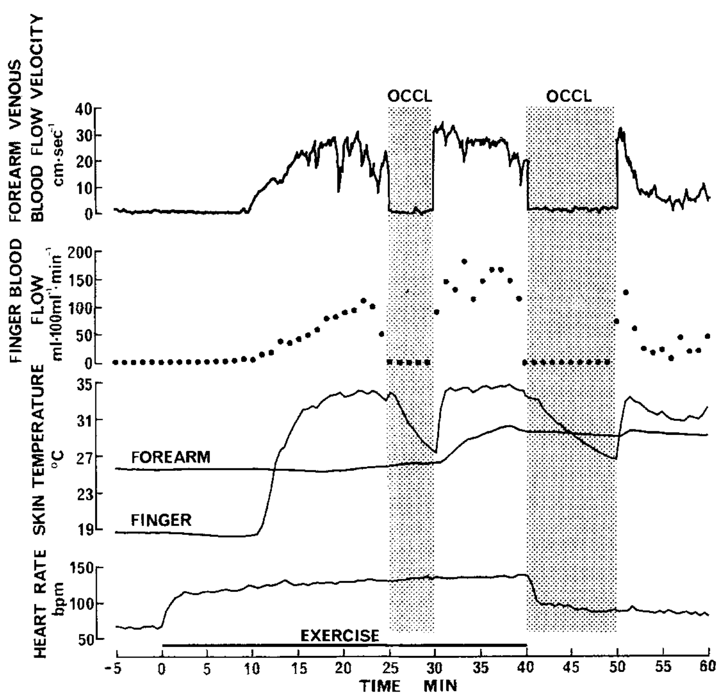

Fig. 5. Effects of wrist occlusion (*OCCL*) at a pressure of 33.3 kPa (250 mm Hg) on the *forearm venous blood flow velocity*, *finger blood flow*, *finger* and *forearm skin temperatures*, and *heart rate* during a 40-min leg *exercise* and recovery for subject 2

ing for temperature variations (Whitney 1953; Honda 1962), as previously detailed (Hirata et al. 1986). Forearm skin temperature near the Doppler ultrasonic probe and temperatures at the tip of the third finger were measured by thin thermistors. The HR was obtained from an ECG recording. While arresting circulation to the hand, FBF was zero and mean velocity in the forearm vein decreased significantly. After release of wrist occlusion, FBF and the forearm venous blood velocity increased markedly, which corresponded to a rise in forearm skin temperature. These results again suggested that the increase in forearm skin temperature can be attributed to the increase in superficial forearm venous blood returning from the hand.

During leg exercise, hands and arms act as important avenues for vascular heat loss from the central circulation. Aulick et al. (1981) have measured blood temperatures in the axillary artery and vein during exercise for 1 h on a treadmill in a dry, cool environment (24° C dry bulb and 15° C wet bulb). Blood temperature in the axillary vein decreased and was 2.3° to 4.3° C lower than that of the axillary artery at all levels of exercise. There was an inverse relationship between blood temperature in the axillary vein and finger blood flow as suggested by finger pad temperature. These large fluctuations in the axillary venous temperature and blood flow to the finger are related to the synchronous opening and closing of the many arteriovenous anastomoses (AVA) in the finger (Sherman 1963; Thoresen and Walløe 1980). According to Coffman and Cohen (1971), 78% of the finger blood flow passes through arterio-venous shunt vessels at T_a of 20° C. As AVA patency provides a high blood flow to the finger, a great amount of convective heat must be transferred to the upper limb. The opening of hand AVA must be effective in enhancing heat transfer not only from the hand but also from the more proximal part of the arm. With AVA in the hand and foot, the put-through of heat is considerable, and the still warm returning venous blood greatly influences skin temperature of the forearm and lower leg. Moreover, as pointed out by Aschoff and Wever (1959) , the increase of venous blood flow and then skin temperature would be higher than predicted, since the degree of precooling of the arterial blood is reduced when the AVA are open. The arterial and venous obstructions at the wrist and ankle eliminate all these mechanisms, and the effect of blood flow obstruction at the sites distal to the forearm and lower leg is as if the occlusions were proximal to them.

Rübsamen and Hales (1984) examined the role of different microcirculatory compartments (capillaries and AVA) in heat transfer across the hind-leg skin of sheep in a thermoneutral environment. They measured with radioactive microspheres a wide range of blood flows through capillaries and AVA, and, simultaneously, heat loss from the skin using a calorimeter in the form of a stocking consisting of a network of water-perfused thin tubes. They estimated that the maximum heat loss was 0.4 $W \cdot ml^{-1}$ of capillary blood flow and 0.08 $W \cdot ml^{-1}$ of AVA blood flow, which suggests that heat transfer is greatly influenced by different vascular routes. Their results support ours showing that increased AVA blood flow enhances heat loss from the more proximal part of the extremities via venous blood returning from the distal end of the extremities.

In summary, it was confirmed that the venous blood flow returning from the hands and feet greatly influenced the increase in heat dissipation from the forearms and legs during thermal load. The extent of the influence was estimated to be 89% of the increase in the forearm at 20° C and 67% in the leg at 30° C.

Acknowledgements. We gratefully acknowledge the co-operation of Atsuo Hirai, Masami Hirashita, Toshinari Takahata, Yoriko Yoneda, Shin-ichi Yoshida, Hiroyuki Fukatani and Masatoshi Fuji in the present study. This study was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan (Grant nos. 62770113 and 61440027), and by the Japan Foundation for Health Sciences.

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Accepted January 3, 1989