Blood Flow, Temperature, and Heat Loss of Skin Exposed to Local Radiative and Convective Cooling

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The relationship between skin blood flow (SBF) and temperature was evaluated and the heat loss calculated for locally applied thermal stimuli. In 10 subjects the palm was exposed to room climate, pure convective air currents, and pure radiation, which resulted in skin temperatures between 23 and 36°C. Skin blood flow was estimated by laser Doppler flowmetry and local skin temperature was measured by a thermistor probe. Linear regression of SBF on skin temperature revealed significant correlations ($r = 0.87$, $p < 0.05$) within subjects and large variations in estimated slopes (s/m = 34%) between subjects. Therefore, SBF was normalized to the room climate value in each separate experiment. When skin temperature and normalized SBF from all subjects were included in the regression analysis, a nearly linear relationship was confirmed ($r = 0.88$, $p < 0.0005$).

Radiative cooling (17°C) doubled the heat loss, reduced skin temperature by 3.7°C, and left SBF virtually unchanged compared with room climate values. When convective cooling (19°C) was applied at 2 air current velocities (0.5 and 1.0 ms^{-1}), palm blood flow diminished to 60 and 53%, respectively, of room climate values. Corresponding heat losses with convective cooling decreased to 68 and 70%, respectively, of room climate values. Linear regression of local heat loss on normalized SBF gave a significant correlation coefficient of 0.79 ($p < 0.001$). *J Invest Dermatol 88:586–593, 1987*

The human body loses heat to the environment by 4 heat transfer modes: radiation, convection, evaporation, and conduction. A nude individual, resting in still air of 20°C, produces 50–60 Wm^{-2}. Sixty percent of the heat is lost through radiation, 25% by evaporation, 12% by convection, and 3% by conduction [1]. These proportions vary considerably, depending on the subject's activity level and environmental conditions. Skin temperature is an important parameter in the estimation of all heat loss modes from the skin surface. Environmental factors such as temperature, relative humidity and velocity of the surrounding air, as well as endogenous factors such as deep body temperature, conduction of heat by the tissue, and transfer of heat by the circulation all influence skin temperature. By regulating skin blood flow (SBF), the heat transfer from the body core to the skin can be controlled to meet varying heat loss demands. When all heat brought to the skin surface is lost to the environment, SBF must be assumed to be closely related to skin temperature and heat loss.

In many laboratory and clinical studies, SBF has been estimated by skin temperature measurements [2]. Reported SBF values have been qualitative, since skin temperature does not depend on perfusion alone. Thermography measures surface temperature by detecting the infrared radiation from the body [3,4]. This method is best suited for scanning purposes and qualitative comparisons of adjacent skin segments. With careful environmental control, quantitative estimates of blood flow are also possible, from the correlation between skin surface temperature and total blood flow [5]. Thermal clearance methods have been developed to assess microvascular blood flow. These methods have been applied in 3 different ways: to assess the rate at which heat from an applied source is removed by the tissue [6,7], to determine the effect required to maintain a fixed temperature difference between probe and skin [8], or to evaluate the time constant of temperature equilibration [9]. However, the first 2 techniques use heated probes, which may cause vasodilatation, thus affecting the blood flow to be measured. The latter method requires a long measuring period.

Because skin temperature can be affected by factors other than SBF, the potential of skin temperature itself as an index of blood flow must be evaluated in vivo alongside other methods that measure SBF. Venous occlusion plethysmography has been frequently used together with skin temperature and heat loss measurements [10–12]. This method estimates total blood flow to an extremity by measuring the volume change per unit of time. Total blood flow, however, approximates SBF only for the fingers [13]. The skin temperature/blood flow relationship has also been studied using models [14–17]. How the superficial blood flow contributes to the heat loss and temperature profile of skin has recently been demonstrated [18,19]. Results from both in vivo and model studies have revealed a near exponential relationship between local blood flow and skin temperature [16,17,20,21]. However, most of these studies covered a broad skin temperature range from 15–40°C, and additive heat loss regulation mechanisms probably occurred.

Injection and epicutaneous isotope washout techniques, Xenon-133 [22], are discontinuous, and injection trauma itself affects the microvascular bed under study [23,24]. Capillaroscopy [25] is limited to measurements from one or a few intact nailfold cap-

illaries. Laser Doppler flowmetry (LDF) [26,27] offers the opportunity to continuously measure SBF within a depth of approximately 1 mm [28,29]. The measuring probe does not heat the tissue, nor does it directly contact the skin surface. Thus, it should not affect the blood flow.

The aim of the present study was to characterize the mutual relationships between skin temperature and blood flow as well as between blood flow and local heat loss during moderate cooling of the palm. In addition, the effect of radiative and convective cooling was studied using well-defined thermal stimuli.

MATERIALS AND METHODS

Subjects Ten healthy male subjects, ranging in age from 16–37 years, volunteered for the experiments (29.3 ± 6.0 years, mean ± SD). Each subject was exposed to 3 different thermal stimuli on different occasions. All the subjects were nonsmokers and none was taking any medication. They were informed of the nature of the study and told to refrain from food intake for 1 h before the experiments.

Ambient Conditions The experiments were performed under conditions that most individuals would find comfortable [30,31]. Subjects were resting quietly in a supine position in a climate-controlled room at temperatures of 25–28°C, and relative humidities ranging from 40–50%. They were clothed in shorts, t-shirt, and light socks.

Stimulation and Measurements The palm of the subject's right hand was exposed to 2 types of thermal stimuli: pure convective air flows of 2 different velocities, and pure radiation (Table I). The skin was exposed to the stimuli inside a microclimate chamber, made of acrylic plastic (Perspex) and thermally insulated by urethane plastic (Frigolite), designed to minimize the influence from the room climate on the local (stimulus) climate. The hollow chamber (Fig 1) had the following geometrical dimensions: 38 mm (width), 78 mm (length), and 35 mm (height). A wall at 23 mm height divided the chamber into a water-containing side and an open side (38 × 78 mm) facing the palm skin. The chamber had rounded corners and the edges were covered with an elastic sealing strip to make the application to the skin air tight.

A fan generated the convective air flows and a fluidistor controlled the magnitude [21]. The volume flow was measured at the inlet of the microclimate chamber, and the air velocity (v) was calculated from this measured value. In a temperature-regulating unit [21] the temperature of the air was set to desired values. Available flow and temperature ranges were 0–100 liter/
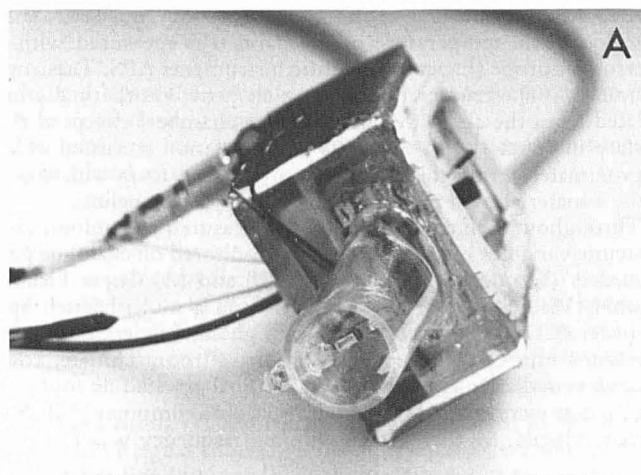
Figure 1. *A*, Microclimate chamber. *B*, Photograph showing the right hand and the microclimate chamber, to make clear the dimensional relations of the palm, the chamber, and the measuring probes.

Table I. Description of the Stimuli Used

Stimulus	T_{air} (°C)	T_{rad} (°C)	P_{air} (kPa)	v_{air} (ms^{-1})
Radiation				
Comfort mean	30.1	35.6	1.32	—
range	28.9–31.3	34.8–36.0	1.07–1.52	—
Cooling mean	29.1	17.0	1.45	—
range	28.1–30.3	16.2–17.9	1.12–1.63	—
Convection 0.5 ms^{-1}				
Comfort mean	30.1	35.4	1.28	—
range	29.0–30.8	34.6–36.4	0.99–1.47	—
Cooling mean	19.5	26.8	0.64	0.5
range	18.2–22.2	25.0–28.4	0.59–0.73	0.4–0.5
Convection 1.0 ms^{-1}				
Comfort mean	29.3	35.4	1.17	—
range	26.9–30.2	35.0–36.2	0.99–1.43	—
Cooling mean	18.4	23.8	0.75	1.0
range	17.3–19.0	20.4–25.6	0.59–1.00	0.9–1.1

In every experiment a room climate (comfort) exposure preceded the actual stimulation (cooling) and served as a reference.

T_{air} = temperature of the air in the microclimate chamber
T_{rad} = temperature of radiating surface
P_{air} = water vapor pressure in the microclimate chamber
v_{air} = fluid (air) velocity

min (accuracy ± 5%) and +5–+50°C (accuracy better than ± 1°C), respectively. During stimulations by convective air currents the radiating surface temperature (see below) was controlled equal to the measured skin temperature. Radiative heat loss was therefore eliminated.

To generate the radiative stimulus, the dividing wall in the microclimate chamber was used as a radiator. The wall surface temperature was regulated by circulating the water in the chamber through a temperature-controlled water bath (Julabo, Juchheim Labortechnik KG, Lahr/Schwarzwald, B.R.D.). For optimal heat conduction and radiation, the wall (radiating surface) was made of brass and painted flat black. The surface temperature of the radiator was measured by a thermistor probe (Exacon, Scientific Instruments APS, Taastrup, Denmark) mounted in a measuring cup. During radiative stimulations the air temperature was regulated to approximate that of the skin. The convective heat loss was thus diminished.

The local SBF of the palm was measured by a laser Doppler flowmeter (Periflux, Perimed KB, Stockholm, Sweden). The operating principle of the instrument [26,27] is based on the fact that laser light scattered in moving blood cells is frequency broadened (Doppler shifted), whereas light scattered in static structures is not. The LDF output is a continuous electrical signal, which is linearly related to the product of the number of blood cells and their average velocity [27]. The cutoff frequency of the band-pass filter was set to 4 kHz, because relatively low flows were measured. This bandwidth gives a better signal to noise ratio compared with the other available bandwidth (12 kHz). In order to suppress the pulsatile components and record average blood flow

levels, the time-constant of the output amplifier was set to 3 s. The local skin temperature of the palm was measured with a thermistor probe (Exacon, Scientific Instruments APS, Taastrup, Denmark). The temperature-sensing element was thermally insulated from the air in the microclimate chamber, except at the surface in contact with the skin. The insulation consisted of an approximately 2 mm-thick cover of polyurethane foam with closed cells, a material used to insulate cold and warm pipelines.

Throughout each experiment all the measured physiologic and systemic variables were continuously monitored on analogue pen recorders (Servogor recorders 460, 120 and M, Goerz Electro GmbH, Vienna, Austria) and recorded on a multichannel tape recorder (SE7000, SE Labs Ltd, Nottingham, England). During the last 4 min of each experimental phase (room climate, convective or radiative exposures, and the final arrested flow phase, Fig 2), data were entered on flexible disks via a computer (ABC80, Luxor, Motala, Sweden). The sampling frequency was 1 Hz.

Experimental Protocol Each experiment lasted about 70 min, which was divided into 4 phases (Fig 2). The first constituted 30 min of adaptation to the room climate. Next, the subject's right hand was placed tightly on top of the microclimate chamber and the SBF and skin temperature probes were applied. A 15-min recording was made under room climate conditions. During the third phase, a cooling (radiative or convective) local climate was applied and the recording continued for another 15 min. Finally, a 4-min arrested flow phase was obtained when a cuff around the upper arm was inflated to above systolic pressure.

Heat Loss Calculations Heat balance in humans is determined by the relationship between heat produced within the body and heat exchanged with the environment. The heat balance equation (Eq. 1), gives the components involved in the heat exchange process from the entire body.

$$M \pm W \pm R \pm C \pm K - E \pm H_{res} \pm S = 0 \qquad (1)$$

M is metabolic energy production, W external work, R radiative heat loss, C convective heat loss, K conductive heat loss, E evaporative heat loss, H_{res} respiratory heat losses, and S the rate of heat storage (all in units of Wm^{-2}). In the present study, in which a local skin segment was examined during exposure to cold and to comfortable conditions, Eq. 1 was modified to Eq. 2 according to the model in Figure 3.

$$H_{bi} + H_c + M + S = R + C + E + K + H_{bo} \qquad (2)$$

Heat from the deep body tissues is transferred to the skin segment by the circulating blood (H_{bi}) and by tissue conduction (H_c). H_{bi} depends on the rate of blood flow, the physical properties of the blood, the temperature difference between blood and surrounding tissue, and the heat transfer properties between them. Heat loss from the segment to the environment takes place through radiation (R), convection (C) and evaporation (E). The conductive (K) heat loss is considered negligible compared to the other heat loss components. The segment also loses heat through exiting blood (H_{bo}) if the blood temperature is above that of the surrounding skin tissue. For the local thermal conditions investigated, H_{bo}, M, and S rates were considered negligible. Components R, C, and E were therefore assumed to monitor the thermal state of the examined body segment. These heat loss components could
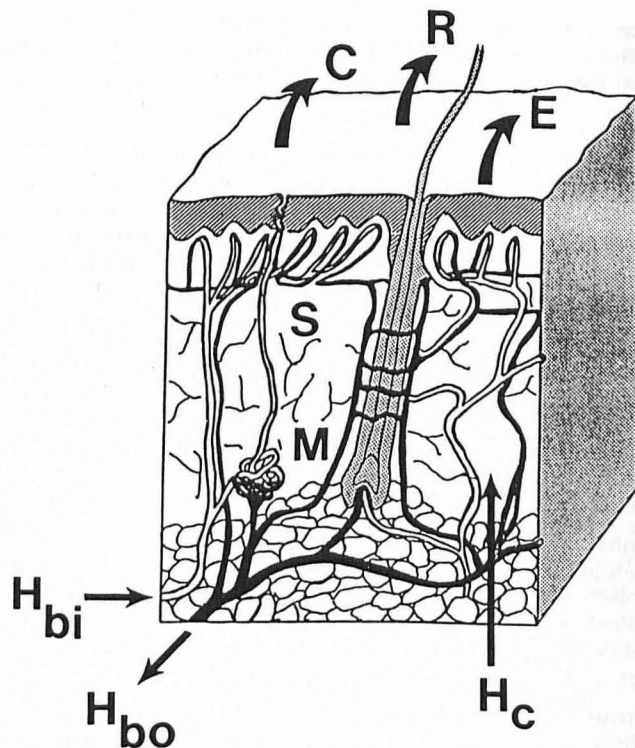

Figure 3. Heat flow model of a local skin segment.

be estimated from measurements on human subjects in a controlled environment.

Radiative heat loss was calculated from the Stefan-Boltzmann law for radiation:

$$R = s \times \epsilon_1 \times \epsilon_2 \times (T_{skin}^4 - T_{rad}^4) \qquad (3)$$

where s is Stefan–Boltzmann's constant ($5.7 \times 10^{-8}\ Wm^{-2}\ K^{-4}$), ϵ_1 the emissivity of the skin, 0.99 [32], ϵ_2 the emissivity of the black radiating surface (1.00), T_{skin} the skin temperature (K), and T_{rad} the temperature of the radiating surface (K).

Convective heat loss occurs between a surface and a moving fluid in contact with it. In this study, the fluid (air) near the skin was exchanged rapidly, implying that steady state can be assumed. The expression for heat exchange by convection is

$$C = h_c \times (T_{skin} - T_{air}) \qquad (4)$$

where h_c is the convective heat transfer coefficient ($Wm^{-2}\ °C^{-1}$), T_{skin} the skin temperature (°C), and T_{air} the temperature of the air in the microclimate chamber (°C), calculated as the mean of the inlet and outlet temperatures.

During the stimulations with convective air flows, conditions of forced convection existed in the chamber. The exposed skin area was assumed to be a flat segment heated over its entire length, for which h_c could be calculated from Holman [33] according to classical physics.

$$h_c = Nu \times \frac{k}{L} = 0.332 \times \frac{k}{L} \times Pr^{1/3} \times \left(\frac{L \times v}{\nu}\right)^{1/2} \qquad (5)$$

where Nu is the Nusselt number ($= 0.332 \times Pr^{1/3} \times Re^{1/2}$ for a flat segment heated over its entire length), k the thermal conductivity ($Wm^{-1}\ °C^{-1}$), L a characteristic dimension, i.e., the length of the skin segment (m), Pr the Prandtl number 0.71 [34], Re the Reynolds number ($= L \times v \times \nu^{-1}$), v the fluid velocity (ms^{-1}), and ν the kinematic viscosity (m^2s^{-1}).

When parameter values, valid for the selected stimuli [35], were inserted in Eq. 5 the convective heat transfer coefficient became

$$h_c = 7.05 \times v^{1/2} \qquad (6)$$
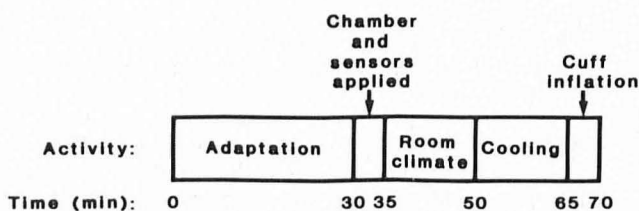

Figure 2. Protocol for the experimental procedure.

Activity:	Adaptation		Room climate	Cooling	
Time (min):	0	30	35	50	65 70

Chamber and sensors applied

Cuff inflation

During exposures to room climate conditions and pure radiative cooling, the convection was not forced but free. Under these circumstances, convective currents were generated because the air near the warm skin surface was heated and expanded. Because the air currents are generated by the heat transfer process and are not imposed from outside, the air velocity is not involved in the calculation of the heat transfer coefficient. The influencing parameters for air are combined in the product of the Grashof (Gr) and the Prandtl (Pr) numbers, which according to Holman [33] can be written

$$GrPr = \frac{g \, \beta \, \rho^2 c_p L^3}{\mu k} \times (T_{skin} - T_{air}) \tag{7}$$

where g is the gravitational acceleration (ms^{-2}), β the coefficient of expansion ($°C^{-1}$), ρ the density (kgm^{-3}), c_p the heat capacity ($Wskg^{-1}°C^{-1}$), μ the dynamic viscosity (Nsm^{-2}), k the thermal conductivity ($Wm^{-1}°C^{-1}$), L a characteristic dimension, i.e., the mean of length and width of the skin segment (m), T_{skin} the temperature of the skin (°C), and T_{air} the temperature of the air in the microclimate chamber (°C).

With parameter values valid for the room climate and radiative conditions, the GrPr-product was about 10^5. For GrPr-products in the interval 10^4–10^9, the heat transfer coefficient for free convection can be calculated as [33]

$$h_c = 1.32 \times \left(\frac{T_{skin} - T_{air}}{L}\right)^{1/4} \tag{8}$$

Evaporative heat loss was the third component to be considered. During cooling, the skin temperature varied between 23 and 32°C. Within this range active sweating controlled by the thermoregulatory system is not present [36,37]. According to Olesen [31] the evaporative heat loss, attended by passive water vapor diffusion through the skin, can be calculated from

$$E = 3.05 \times 10^{-3} \times (p_{skin} - p_{air}) \tag{9}$$

where p_{skin} is the saturated water vapor pressure at skin temperature (Pa) and p_{air} the water vapor pressure in the chamber (Pa), calculated as the mean of the inlet and outlet pressures.

When the subjects were resting in a reclining position in room climate (approximately 27°C and 45% relative humidity), they were allowed to reach thermal steady state with minimal active sweating from a dry skin surface. Under these conditions the heat production (M) can be assumed approximately 50 Wm^{-2} [38] and the evaporative heat loss can be calculated according to Kerslake [35]

$$E = M + h_o \times (T_o - T_{skin}) + 1.2$$
$$\times \left[p_{skin} - p_{air} - \frac{h_o \times (T_o - T_{skin}) + M}{h_e} \right] \tag{10}$$

where

$$h_o = h_r + h_c \tag{11}$$

$$T_o = \frac{h_c}{h_o} \times T_{air} + \frac{h_r}{h_o} \times T_{rad} \tag{12}$$

h_r, h_c, and h_e are the radiative, convective, and evaporative heat transfer coefficients, respectively.

The total heat loss from the skin segment to the environment was calculated as the sum

$$H_{tot} = R + C + E \tag{13}$$

for the different climatic conditions.

The heat gained by the air when it passed the chamber was not used as an estimate of the heat dissipated from the palm, because the conductivity of poorly perfused (cooled) tissue is similar (0.1 $Wm^{-1}°C^{-1}$ [39]) to that of the chamber materials [40]. Heat from the room could have contributed to the rise in air temperature.

Data Treatment The SBF value was calculated as the flowmeter output signal subtracted by the output signal obtained at arrested flow conditions. Mean values of the data collected during the last 4 min of each experimental phase (Fig 2), when steady state was assumed to have been established, were used as individual values in the analysis. Room climate values were defined as those obtained when the palm was exposed to the climate occurring in the temperature-controlled room, i.e., approximately 27°C and 45% relative humidity. Normalized blood flow values were calculated as the ratios between values obtained during cooling and the corresponding room climate value. The analysis of skin temperature and local heat loss for the strongest convective stimulus (v = 1.0 ms^{-1}) included only 9 subjects, because the skin thermometer was in poor contact with the skin in one experiment, resulting in unreliable values.

Differences in SBF, skin temperatures, and heat losses obtained for the various stimuli were statistically evaluated using two-way analysis of variance and Student's t-test. The null hypothesis, that values obtained for the different climatic conditions were equal, was tested and rejected at the 5% level. A linear regression model was applied to test the relationships between the physiologic variables [41,42]. The calculations and the statistical analysis were made on a computer (ABC80, Luxor, Motala, Sweden).

RESULTS

Within the temperature range 23–36°C, a linear relationship between skin temperature and SBF was apparent for all the examined subjects. When the individuals were analyzed separately, correlation coefficients between 0.77 and 0.94 (mean, 0.87) were calculated (Table II). Values obtained for cooling and room climate conditions (n = 6) were included. From the linear regression model the individual slopes ranged from 60–104 mV °C^{-1}, except for subject 4, whose blood flow decreased with 20 mV for every °C decrease in skin temperature. The coefficient of variation (s/m) for the estimated slopes was 34%. Therefore, analysis of the relationship between SBF and skin temperature, including data

Table II. Individual Correlation Coefficients (r), and Linear Regression Slopes (b) for the Relationships Between Skin Temperature (T_{skin}) and Skin Blood Flow (SBF) as Well as Between SBF and Local Heat Loss (H_{tot})

Subject	T_{skin} vs SBF			SBF vs H_{tot}		
	r	p	b (mV°C^{-1})	r	p	b ($Wm^{-2}V^{-1}$)
1	0.942	<0.005	79.7	0.995	<0.05	106.7
2	0.768	<0.05	59.6	0.980	<0.05	85.8
3	0.894	<0.01	61.2	0.725	>0.10	232.3
4	0.772	<0.05	19.8	0.992	<0.05	280.1
6	0.883	<0.01	85.6	0.987	<0.05	76.7
7	0.906	<0.01	103.8	0.967	<0.05	115.8
8	0.874	<0.01	64.4	0.984	<0.05	106.8
9	0.914	<0.005	66.7	0.497	>0.25	71.6
10	0.852	<0.05	87.9	0.674	>0.25	73.8

Significance levels (p) are shown for each r value. b = linear regression slope.
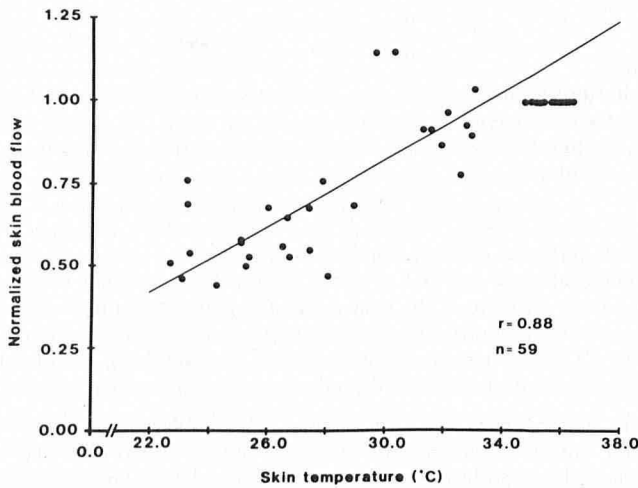
Figure 4. Normalized SBF vs skin temperature for the room climate and cooling conditions.

from all the subjects, was based on normalized blood flow values. An overall correlation coefficient of the same order as those obtained for individual subjects ($r = 0.88$, $n = 59$, $p < 0.0005$) confirmed a linear relationship (Fig 4).

Total heat losses and SBFs were also fitted to a linear model. Significant correlations were found for 6 of 9 subjects, when data were analyzed individually (Table II). Only values obtained for cooling conditions ($n = 3$) were included, since the heat loss in room climate conditions reflected a completely different process of thermal regulation. The calculated correlation coefficients varied between 0.50 and 0.99 (mean, 0.87). The coefficient for subject 9 was markedly lower than for the other individuals. Similar to the blood flow/temperature relationship, large individual variations in the slope were observed when SBF and heat loss data were fitted to linear equations. The range was 72–280 $Wm^{-2}V^{-1}$ and the coefficient of variation 62% (Table II). Using normalized blood flow values, the overall correlation coefficient was calculated to be 0.79 ($n = 29$, $p < 0.001$).

The bar diagrams in Fig 5 show the resulting mean levels ($\pm$ SEM) of the physiologic variables: SBF (A), normalized SBF (B), skin temperature (C) and total heat loss (D), measured on the palm for different climatic conditions. The normal room climate bars include data from recordings preceding all the 3 cooling stimulations ($n = 30$). These room climate values, recorded before the various cooling exposures, did not differ mutually for any of the variables ($p > 0.05$, $n = 10$). Significance levels, for differences between values obtained at various climatic conditions, are listed in Table III.

From Fig 5 it is obvious that both convective stimuli (approximately 19°C in combination with 0.5 or 1.0 ms^{-1}, respectively) caused large reductions in all 4 physiologic variables shown. For those 2 stimulations SBF decreased to 60 and 53%, respectively, of the room climate values. The corresponding skin temperatures decreased by 8.5 and 12.0°C on the average. Decreases in SBF and temperature, compared with room climate values, were significantly different for the 2 convective stimuli (Table III). The total heat losses during the 2 convective exposures did not differ (Fig 5D, Table III), but were about 20 Wm^{-2} below the loss achieved during room climate conditions.

Radiative cooling (17°C) caused only minor reductions in SBF, which diminished to 96% of room climate level, while skin temperature decreased by an average of 3.7°C ($p < 0.001$). Total heat loss was approximately twice that lost at room climate conditions. Large differences in all 4 physiologic variables were apparent between the convective and the radiative cooling (Fig 5, Table III).

In Fig 6 the proportions of different heat loss components are presented for the stimuli: radiative cooling (A), convective cooling with air velocity 0.5 ms^{-1} (B), and convective cooling with air velocity 1.0 ms^{-1} (C). The large heat loss (112 Wm^{-2}) from the palm during radiative cooling was to 80% radiative. Free convection caused a heat loss of 13 Wm^{-2} (12% of total loss). The 2 convective stimuli caused similar heat losses, 37 and 38 Wm^{-2}, respectively, for 0.5 and 1.0 ms^{-1}. Convective heat loss constituted, however, different fractions of this total: 75 and 84%, respectively, for the low and high air velocities. The evaporative heat loss was consistently between 7 and 10 Wm^{-2} for the 3 cooling conditions.

Separate analysis of the convective heat loss (Fig 7) revealed a difference (Table III) between the 2 degrees of convective cooling. The changes compared with room climate level were minute in both cases. Compared with all the other stimulations, a small convective heat loss was calculated for the radiative stimulation. The evaporative heat loss amounted to a minor fraction of the total heat loss, for the selected climates (Fig 6), and was not separately analyzed. Also, the radiative heat loss was not treated separately because it was regulated to be zero except for radiative cooling.

DISCUSSION

For the subjects examined in this study, linear relationships between skin temperature and SBF of the palm were revealed within the skin temperature range 23–36°C (Table II). However, large intraindividual variations (s/m = 34%), in the blood flow reduction per °C skin temperature decrease, were observed (Table II). Differences in perfusion capacity among subjects exposed to cooling are suggested to cause the variability. Spatial and temporal variations in blood flow during an experiment [43] are abolished by the methodology used. In separate experiments on the same subject, the LDF probe may have been positioned over different vessels that varied in their regulatory capacity. This lack of standardization may have contributed to some intraindividual variation. Evaluation of the interconnection between blood flow and temperature is partly concealed and thereby complicated by this variation. Therefore, normalization of the SBF values should be done before data from several individuals can be compared or
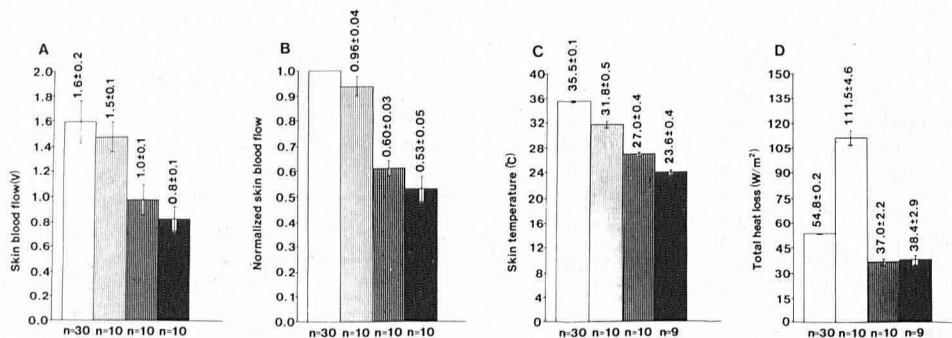
Figure 5. Skin blood flow (A), normalized SBF (B), skin temperature (C), and total heat loss (D), (mean $\pm$ SEM) obtained from the palm for locally applied room climate (*white bars*), radiative cooling (*light gray bars*) and convective cooling by 0.5 ms^{-1} (*dark gray bars*) and 1.0 ms^{-1} (*black bars*), respectively.

Table III. Significance Levels (p) for Differences in the Physiologic Variables Obtained Between Different Thermal Conditions

| Test Variable	Thermal Condition	Cooling					
		Radiative		Convective 0.5 ms^{-1}		Convective 1.0 ms^{-1}	
		p	n	p	n	p	n
Blood flow	Room clim.	NS	10	<0.001	10	<0.001	10
	Rad.			<0.001	10	<0.001	10
	Conv. 0.5 ms^{-1}	<0.001	10			<0.05	10
	Conv. 1.0 ms^{-1}	<0.001	10	<0.05	10		
Skin temperature	Room clim.	<0.001	10	<0.001	10	<0.001	9
	Rad.			<0.001	10	<0.001	9
	Conv. 0.5 ms^{-1}	<0.001	10			<0.001	9
	Conv. 1.0 ms^{-1}	<0.001	9	<0.001	9		
Total heat loss	Room clim.	<0.001	10	<0.001	10	<0.001	9
	Rad.			<0.001	10	<0.001	9
	Conv. 0.5 ms^{-1}	<0.001	10			NS	9
	Conv. 1.0 ms^{-1}	<0.001	9	NS	9		
Convective heat loss	Room clim.	<0.001	10	NS	10	NS	9
	Rad.			<0.001	10	<0.001	9
	Conv. 0.5 ms^{-1}	<0.001	10			<0.05	9
	Conv. 1.0 ms^{-1}	<0.001	9	<0.05	9		

analyzed. When blood flow values were normalized, the relationship between skin temperature and SBF data from the 10 subjects followed a linear equation ($r = 0.88$, n = 59, $p < 0.0005$, Fig 4). The correlation coefficient for a similar analysis based on absolute blood flow values was 0.54 (n = 59, $p < 0.0005$). An approximately linear relationship between palm blood flow and temperature was reported by Hertzman [15]. He suggested a direct effect of temperature on the vessels, not representative of other cutaneous beds, to be responsible for the physiologic reactions. Within the temperature range 22–38°C a linear relationship has also been postulated from experimental model studies in the dog [44].

Laser light with a wavelength of 632.8 nm penetrates the skin to approximately 1 mm [28,29]. Since arteriovenous anastomoses (AVAs), capillaries, and arterioles are located within this depth, they can be assumed to have contributed to the flowmeter output signal. The temperature profile and the heat loss from the skin surface are postulated to be strongly influenced by the blood flow within this depth [18,19]. Additionally, palm skin contains numerous AVAs [38], which constitute pathways with high percolation capacity reported to be essential for thermal regulation [45].
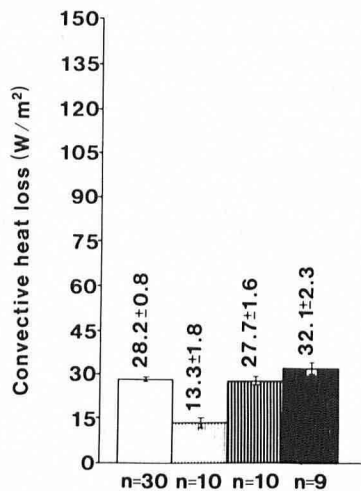
Methods measuring local superficial blood flow have been used sparsely so far in studies of the relationship between skin temperature and blood flow. Bengtsson et al [46], using LDF, found the correlation coefficient between changes in skin temperature and blood flow to be 0.32 under sympathetic blockade by spinal analgesia. Their material contained data from several body segments, i.e., from differently perfused skin tissues. Östergren and Fagrell [47] simultaneously measured the blood velocity in nailfold capillaries by a microscopic technique and skin temperature of the finger with a thermistor probe. Within the skin temperature range 23–36°C the correlation coefficient was 0.52 ($p < 0.001$). This compares favorably with the correlation coefficient ($r = 0.54$) obtained for the absolute values in the present study. Skin temperature and blood flow values obtained by thermography and washout of Xenon-133, respectively, were compared by Tsuchida [4]. He concluded that skin temperature did not reflect SBF. Additionally, skin temperature variations induced by local heat production affected the relationship. The thermal balance of the skin areas investigated was, however, not explicitly calculated or controlled in the above studies.

When venous occlusion plethysmography is used, the extremity is often immersed in water, which has completely different heat-conducting properties compared with those of air. Correlation coefficients between skin temperature and blood flow of the size 0.57 have been reported with this method [12]. From graphs presented by Raman and Vanhuyse [11], a linear relationship between water temperature and hand blood flow appears probable in the temperature range 25–40°C. A slope (0.05°C^{-1}) approximately similar to that in Figure 4 (0.04°C^{-1}) is obtained if their blood flow data are normalized to 35.5°C. Raman and Vanhuyse [48] modeled the temperature influence on the distribution of blood in the hand. Above approximately 25°C the blood
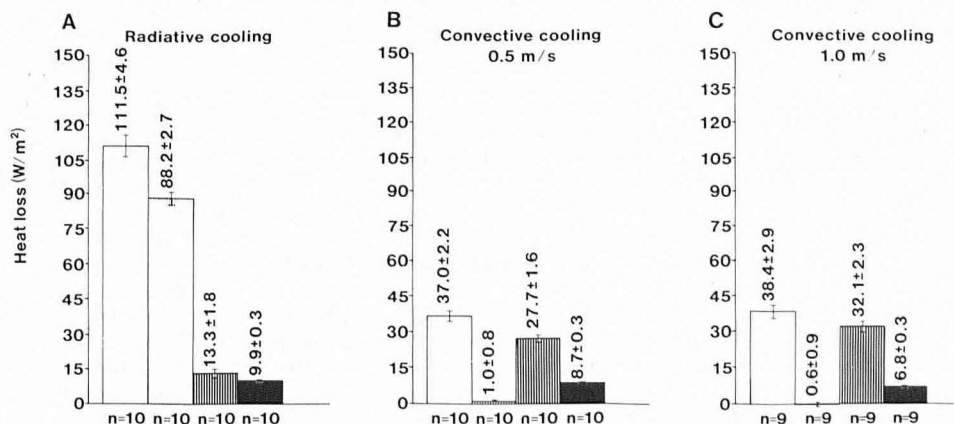
Figure 6. Total heat loss (*white bars*) and the radiative (*light gray bars*), convective (*dark gray bars*), and evaporative (*black bars*) heat loss fractions (mean ± SEM) determined for the radiative cooling (*A*) and convective cooling by 0.5 ms^{-1} (*B*) and 1.0 ms^{-1} (*C*), respectively.

A   Radiative cooling
Heat loss (W/m²)
111.5±4.6
88.2±2.7
13.3±1.8
9.9±0.3
n=10 n=10 n=10 n=10

B   Convective cooling 0.5 m/s
37.0±2.2
1.0±0.8
27.7±1.6
8.7±0.3
n=10 n=10 n=10 n=10

C   Convective cooling 1.0 m/s
38.4±2.9
0.6±0.9
32.1±2.3
6.8±0.3
n=9 n=9 n=9 n=9

Figure 7. Convective heat losses (mean ± SEM) for room climate (*white bar*), radiative cooling (*light gray bar*) and convective cooling by 0.5 ms^{-1} (*dark gray bar*) and 1.0 ms^{-1} (*black bar*), respectively.

returns to the body core primarily through superficial vessels, which facilitates the heat loss. Below this temperature the fraction of blood flow conducted in the cutaneous vessels decreases with temperature. A minimum is reached at 13°C. Blood flow values obtained in the present study support this view, but the large flow reduction occurred between 27 and 32°C.

If one compares the heat losses obtained in this study with those reported by Raman and Vanhuyse [11], a similar response pattern is obvious, although the levels reported by them appear higher. Variations in room climates and cooling procedures are probable origins of the discrepancies. Convective heat loss depends on the air velocity and temperature difference between the skin and surrounding air. When the velocity was increased the temperature difference decreased, a fact that can explain the small heat loss difference between stimulations with the 2 different air currents (Figs 5D, 7).

The resulting linear relationships between skin temperature and SBF as well as between SBF and local heat loss, have been based on measurements within a limited thermal range, representative of cool indoor climates. If the range is extended toward warmer and colder conditions, thermoregulatory mechanisms such as sweating, maximal vasoconstriction, and cold-induced vasodilatation are activated, and introduce nonlinearities in the relationship, which have been proposed to be exponential [21]. In this study a local skin segment has been exposed to pure radiative and pure convective cooling. These 2 stimuli do not simulate real life situations, when the skin surface is usually exposed to a combination of different thermal stimuli. Thus the obtained relationship cannot easily be extended to daily life conditions. The data will, however, contribute to our understanding of how SBF is controlled to preserve thermal balance in varying thermal environments.

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