The Role of Non-Thermal Factors in the Control of Skin Blood Flow During Exercise

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Arguments in favor of the importance of non-thermal factors in the control of skin circulation are presented. Such factors include exercise, posture, water and electrolyte balance, state of training, and acclimatization. The first three factors probably elicit their effects via high- and low-pressure baroreceptors, while the mechanisms involved for the remainder are unknown.

During exercise, the skin circulation is increased in response to the increasing core temperature. The magnitude of vasodilation is influenced by skin temperature, but core temperature is more important for reflex control of skin circulation. Furthermore, several non-thermal factors are determinants for skin blood flow in a given situation: exercise intensity, body posture during exercise, water and electrolyte balance, degree of acclimatization, and state of training. All of these factors will modify the forearm blood flow to core temperature relationship, FBF/Tc. This relationship has become the most common model for studying the stimuli for cutaneous vascular responses. Whether this model is appropriate will be considered after the discussion of non-thermal factors.

EXERCISE FACTORS, NEUROMUSCULAR REFLEXES INFLUENCING SKIN CIRCULATION

At the onset of exercise, the skin circulation is reduced. This fact was shown by Stewart [1], who demonstrated that heat elimination in a resting hand was reduced during exercise with the other hand. A problem for studies during exercise is that most current methods for measuring skin blood flow are very difficult to apply during work, due to motion artefacts. The most common method at present, venous occlusion plethysmography, can also be used during exercise. By such measurements on the finger, Christensen et al. [2] showed that at the onset of exercise an immediate reduction in finger blood flow was elicited (Fig. 1), which was more sustained the larger the exercise intensity. The initial fall was followed by an increase in finger blood flow if the exercise was continued for more than five to six minutes. These early observations have been also confirmed with other methods, for the forearm and hand as well as the finger blood flows (e.g., [3,4,5,6]). The differences between the innervation and control in proximal (forearm) and distal (hand, finger) skin areas have been pointed out [6] and summarized recently by Rowell [7]. It seems clear that at the onset of exercise non-thermal factors have an importance influence on skin circulation.

The crucial question is whether such exercise-related factors persist during continued exercise and in steady-state exercise. This question has been evaluated in experiments where different types of exercise have been studied and in which the

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neuromuscular and metabolic conditions in the working muscle groups have been varied during exercise [8–11]. At comparable core and skin temperatures, work with the arms was compared with leg work, and positive (uphill, concentric) exercise was compared with negative (downhill, eccentric) exercise. In concentric contractions, the muscle is shortening and performing external work; in eccentric, the muscle is stretched by external forces (gravity) and heat is liberated in the muscle. Skin circulation in these studies has been calculated from the heat conductance of the peripheral tissues [12,13]. The results show that for the same esophageal temperature ($T_{es}$) and mean skin temperature ($T_{sk}$) conductance is higher during arm work than during leg work, and higher during negative work than during positive work at the same rate of oxygen uptake ($V_{O_2}$) (Fig. 2). In the conditions where conductance was higher, the heart rate was increased by some ten beats per minute, while cardiac output

![FIG. 1. Variations in finger blood flow ml x min$^{-1}$) with bicycle exercise and non-load bicycling. ■, no load; □, actual work [2].](image1)

![FIG. 2. Skin circulation expressed as conductance (W/m$^2$ x °C) plotted against esophageal temperature during steady state of positive: ▲, and negative: △ O work. Symbols for two subjects. Unpublished data from [8].](image2)
per l V\textsubscript{O\textsubscript{2}} was the same in positive and negative work. From the conductance values, the minimal skin flow in l/minute can be estimated, assuming that the blood arrives at the skin with T\textsubscript{es} temperature and is cooled to skin surface temperature. It then appears that skin circulation is about six times higher in negative work at 20°C (0.6 versus 0.1 l/minute in positive work) (see Fig. 2) and more than double at 30°C (2.2 versus 0.9 l/minute) [11].

Most studies on skin perfusion have been made at high skin temperatures, where plethysmographic measurements of forearm blood flow (FBF) have been used to investigate the relationship between FBF and the assumed main stimulus for the skin vasodilation, the rise in core temperature. The core temperature can be raised by exercise, by heat stress (e.g., using a water-perfused suit), or by both. Johnson and co-workers [14] found that in exercise the slope of this relationship was reduced as compared to rest, probably through a vasoconstrictor drive to the skin. However, in later work by this group [15] no difference was found in the FBF/T\textsubscript{es} relationship with work intensities between 150 and 750 kpm/minute, nor did Roberts and Wenger [16] find effects of exercise at lower skin temperatures during short-lasting work bouts of three minutes' duration. Taylor et al. [5] again affirm that the vasoconstriction at the onset of exercise is independent of skin temperature but also that the effect of exercise is different at different local T\textsubscript{es} of the limb (forearm).

Hirata et al. [17] used a gradient-layer hand calorimeter to measure hand skin blood flow, calculated as hand heat loss divided by the temperature difference between esophagus and hand skin temperature (Fig. 3). Their results indicated a sustained vasoconstriction in response to increasing exercise loads. The authors argue that the constrictor reflex may be maximal at relatively low exercise intensities <50 percent of maximal aerobic power, V\textsubscript{O\textsubscript{2}} max, and this may be the reason for the failure of others (e.g., [16]) to find graded effects of exercise at 50 and 70 percent of V\textsubscript{O\textsubscript{2}} max, on finger blood flow.

**CARDIOVASCULAR REFLEXES AND SKIN CIRCULATION**

An upright body position must usually be maintained in order to perform physical exercise. Even under resting conditions, a change from the supine position to the
upright posture is associated with a shift of blood to vascular beds below heart level, resulting in an increased hydrostatic pressure and filtration of fluid from dependent capillary beds and a reduced filling of the heart [18,19]. These events elicit arterial and low-pressure baroreceptor reflexes which increase sympathetic tone and heart rate. Vasoconstriction in arterioles and veins is elicited, and, in addition, local reflexes constrict the veins [20]. Thus some or all influences on skin circulation during exercise may be ascribed to postural reflexes which maintain arterial blood pressure, rather than to exercise per se—i.e., the neuromuscular events during work. Influences of posture on skin circulation during exercise have been demonstrated in a large number of studies [14,21,22,23]. The results show that, for a given increase in core temperature, the FBF is reduced in upright compared to reclined or supine positions. Similar effects on FBF can be produced by experimental stimulation of baroreceptors by neck suction, lower body negative pressure, or positive pressure breathing [24,25,26]. In hypertensive patients, the baroreceptor influences also seem to be involved in their reduced FBF response to the thermal stimulus during exercise [27].

In addition, the plasma volume loss which occurs as a consequence of thermal sweating has effects on the FBF/T_core relationship during exercise. This result has been tested in a number of studies where hypo- or hyperhydration, with or without changes in plasma osmolality, have been produced. Plasma volume has been reduced by diuresis, bloodletting, and sweating, and plasma volume has been expanded by excess water intake, infusion of blood or volume expanders, and water immersion [4,28,29,30]. These investigations show that any decrease of volume in the vascular system or reductions in central venous filling lead to a decrease in skin circulation, most often described as a higher threshold for the vasodilation response to increased core temperature, a reduced slope of the FBF/T_core relationship, and a reduced maximum blood flow [29] (Fig. 4). The reflexes involved are probably the same as those which are activated by changes in posture.
"CHEMICAL" FACTORS: OSMOTIC AND IONIC EFFECTS ON SKIN CIRCULATION

Exercise and sweating lead to changes in the ionic composition as well as in the volume of the body fluids. A loss of hypotonic sweat leads to increased osmolality in the plasma. How changes in osmolality per se affect skin circulation is not clear. Injection of hyperosmotic NaCl into the ear vessels of rabbits [31] produced a vasoconstriction in the other ear, and a reduction in total heat loss. In humans, forearm and calf blood flow measured with impedance plethysmography did not change significantly after intake of hypertonic sodium solution but decreased after Ca$^{2+}$ intake [32]. Perfusion of denervated hind limbs of cats with hyperosmotic blood produced vasodilation [33]. It is possible that the unchanged FBF reported above [32] may be due to an increase in muscle blood flow while skin blood flow is decreased by hyperosmolality. Fortney et al. [34] compared the effects on FBF of dehydration caused by sweating to those of hyperosmolality alone. They infused 3 percent saline into dehydrated subjects, so that initial plasma volume was restored to a higher than normal level of plasma osmolality. In these two conditions, the response of forearm blood flow to increasing core temperature produced by exercise showed a higher threshold for vasodilation in the dehydrated than in the hypertonic states than in the normal condition (Fig. 4). The slope of the relationship did not differ between the control and the hypertonic test, but both were steeper than that after dehydration [34].

The mechanisms for the effects of hyperosmolality or hypernatremia on skin circulation are not clear. For the sweating mechanism, which is also affected by osmolality changes, the effect seems to be electrolyte-specific, the Na$^+$ ion having opposite effects from the Ca$^{2+}$ ion [35]. Whether the actions of osmolality and ions take place directly in the hypothalamic temperature center or on skin vessels, or whether the effects are brought about indirectly through the activation of hormones (e.g., antidiuretic hormone), is at present unknown.

OTHER NON-THERMAL FACTORS

A number of other "factors" may be listed which change sensitivity or threshold for skin circulation. They are not easily classified, and the physiological mechanism of their interference is not proved.

These factors may include, for example, exercise training which increases the slope, and acclimatization to heat, which correlate with a reduction in the threshold in the FBF/T$_{core}$ relationship [36]. A diurnal variation in FBF/T$_{core}$ has also been described [37].

METHODS FOR MEASURING SKIN BLOOD FLOW

No method is available today for quantitative measurements of the circulation through the skin. The premises on which studies of skin blood flow in humans are based are measurements of the heat transfer across the skin, on the assumption that blood is cooled from core temperature to average or local skin surface temperature [1,3,8--13,17,28].

Measurements of the arterial inflow to a segment of an extremity (venous occlusion plethysmography) can be applied on the assumption that the changes in flow in tissues other than the skin represented in the segment are negligible in the experimental situation. Plethysmography was used in most of the investigations discussed above [2,4--6,14--16,19,21--27,29,30,32,34,36].
The rate of removal of heat or of an intracutaneous depot of trace substance, e.g., \(^{133}\)Xenon, is also an index of the skin blood flow [20]. Furthermore, measurements of the velocity of blood corpuscles flowing in a small skin area (laser-doppler technique) have been used to estimate skin capillary blood flow.

The limitations and problems involved in some of the methods mentioned have been discussed [38] and have been recently reviewed [39]. Johnson et al. [40] have compared the laser-doppler technique to plethysmography in resting subjects and Sejrsen [41] has discussed the xenon washout method.

Some of the discrepancies found in the literature about the possible role of non-thermal factors in skin circulation may be due to the use of different methods, especially as innervation varies between proximal and distal skin areas [6,7]. Also of importance, however, is whether the variables which are supposed to represent the input to the temperature centers, e.g., \(T_{\text{core}}\), \(T_{\text{sk}}\), are true representatives of all the thermal stimuli to skin circulation [10].

CONCLUSION

The skin is a large organ with a great capacity for blood flow. In spite of this fact, measurements of skin circulation are based on indirect measurements or on extrapolations from local flow measurements. Studies of forearm blood flow have been extensively used for estimation of the importance of various stimuli. Such studies show that \(T_{\text{core}}\) is the most important stimulus for skin vasodilation, the influence being 10–20 times greater per degree C than that of \(T_{\text{sk}}\) [7]. The various non-thermal factors discussed, i.e., neuromuscular reflexes, cardiovascular reflexes in connection with posture and exercise, electrolyte composition, training, acclimatization, and so on, are claimed to be important because any changes in these may cause a two- to sixfold variation in FBF for a given combination of the thermal stimuli. The exact magnitude of the physiological stimulus, however, may be unknown and cannot be identified by stimulus-response curves.

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