Eur J Appl Physiol (1992) 65:550–554

European Journal of Applied Physiology and Occupational Physiology

Thermographic studies on patterns of skin temperature after exercise

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Accepted August 18, 1992

Summary. In six subjects thermograms of the thighs and the forearms were taken before, during and after 10 min ergometer exercise at 100 W at an ambient temperature of 23 °C. During exercise, an intraindividually constant and reproducible skin temperature pattern with local temperature differences exceeding 3 °C evolved. Reactions after external local cooling or after occlusion of blood flow and measurements with a laser Dopplerflowmeter showed dispersed convective heat transport to be the source of this irregular pattern. Temperature differences of 3.6 °C and deviations of blood flow in the skin microcirculation of 300% within a distance of a few centimetres reduce the value of single-spot measurements of skin temperature with reference to the whole extremity.

Key words: Thermovision – Skin blood flow – Skin temperature – Thermocouples

Introduction

Many parameters in human physiology are assigned definite values, regardless of the fact that the parameter does not exist physically. This is mostly true for parameters with integrative characteristics due to the measuring technique (e.g. plethysmography for determination of peripheral blood flow) or for parameters computed from several single measurements (e.g. skin or core temperature as an average of several measurements at different sites).

Undoubtedly, parameters like core or skin temperature may be considered as integrative inputs referring to the physiological controller, composed of a large number of receptor measurements at sites distributed all over the body. On the other hand, skin temperature (T_{sk}) plays an important role in heat exchange with the environment. In both cases, the real value of skin temperature may not be measured correctly if only a few single values not representing the neurological input or the thermal interface of the total skin are measured.

In the past, many proposals have been made to take this fact into account by making representative temperature measurements. Several models have been developed to determine a mean T_{sk} by a number of single temperature measurements in different parts of the body: 3 points (Burton 1934; Roberts et al. 1977), 4 points (Ramanathan 1964), 6 points (Teichner 1958), 7 (Hardy and Dubois 1938), 8 (Wenger et al. 1975), 9 (Hanna and Smith 1975), 10 (Burton 1934) and 12 points (Hardy and Dubois 1938). The accuracy of mean T_{sk} increases with the number of temperature probes applied (Teichner 1958; Veghte 1965). All these models have in common that the data used for the calculation of the mean T_{sk} are obtained by several spot probes which are fixed on the test subject. Obviously, the number of probes is limited. In most cases only one probe is attached to each part of the body. The temperature obtained by this probe can be taken as representative of this part of the body, assuming homogeneous temperature distribution in which case the exact position of the probe is not important.

However, studies by Livingstone et al. (1987) indicate that temperature distribution, even on a limited body surface, is not homogeneous at all. In studies on working men, emphasis is laid on investigation of those parts of the body where most of the metabolic heat stressing the whole organism is produced. In this investigation we used surface thermography to examine the change in T_{sk} pattern on the extremities during exercise. Additionally, the influence of this pattern on the spot measurements of skin blood flow with a laser Dopplerflowmeter was examined.

Methods

Six volunteers (5 men, 1 woman) participated in this study after being well informed about the aim and type of the experiment.

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Measuring techniques

Thermography. We used thermovision equipment (Thermovision Agema, Danderyd, Sweden) consisting of a scanner and a computer for display of the thermograms on a monitor and further evaluation of the acquired data. This system has an accuracy of 0.1 °C. The thermograms were printed on a colour printer or photographs were taken from the monitor. Colour or grey tone display could be chosen.

Thermocouples. Spot temperature measurements of the skin were taken with copper-constantanthermocouples with an accuracy of 0.05 °C.

Laser Dopplerflowmeter. The microcirculation in the skin was assessed by a laser Dopplerflowmeter (Periflux PF 2 B, Perimed, Sweden). In this method laser light transmitted into the skin and reflected from the moving erythrocytes undergoes a Doppler effect, the magnitude of which is dependent on erythrocyte velocity. A tissue volume of about 1 mm^3 is "seen" by the laser beam.

The experiments were performed in a climatic chamber. At a constant ambient temperature of 23 °C and a relative humidity of 50% subjects worked at 100 W for 10 min in a semi-supine position on a cycle ergometer. Immediately before the exercise started, and 5 and 10 min later, the surface temperature of the thigh and of the supinated forearm were recorded by the thermovision equipment.

The borders of exposed extremities were not taken into account, because only those parts of the thermograms were evaluated where the surface was at an angle of more than 45 °C to the scanner lens. In those parts, the error in measuring on curved surfaces can be disregarded (Watmough et al. 1970).

Following exercise, the dynamics of temperature distribution were determined by two additional measurements. First, blood flow of one arm was completely interrupted by a pneumatic cuff inflated with a pressure exceeding systolic blood pressure for 4 min and then deflated.

Next, a skin area (10 cm in diameter) on the thigh was cooled down to 30 °C using a cooling spray. The effect of these manipulations on the surface temperatrure distribution was observed and recorded.

Each subject repeated the experiment (10 min exercise with recording of the surface temperature distribution) on a different day. The thermograms obtained were compared with those from the earlier experiment. In addition the microcirculation in the skin was measured following the 10 min exercise. Under observation by thermovision, the probe of a laser flowmeter was fixed successively on regions of the skin with different temperatures and the mean values for 20 s were recorded. Some of the subjects repeated the experiment on another day with ten thermocouples attached to different parts of the thigh with medical tape. The exact position of the thermocouples was chosen in accordance to the prior thermography such that five of the thermocouples covered parts of the skin which were known to become warm areas during exercise, and five were fixed over potentially cooler regions. During the course of the experiment the temperatures were recorded every 30 s. Because of interference by the thermocouples, thermography was omitted from this part of the study.

Results

Thermograms

Thermograms taken 5 min after the beginning of exercise show the skin surface to be colder than before exercise started. After 10 min the average T_{sk} was higher than the resting values in all subjects [rest 31.9 °C (SD 0.89), after 5 min 31.52 °C (SD 1.05), after 10 min 32.38 °C (SD 0.72)]. The average temperature of on individual subject from more than 1000 single values was calculated by the computer. The values given here are averages of all subjects. A remarkable temperature pattern consisting of warmer and colder areas was apparent (Fig. 1). The relatively homogeneous temperature distribution at the beginning is replaced by a temperature pattern with distinctly warmer and cooler areas.

Neighbouring warm areas merge partly. Within a single warm area a nearly circular regular temperature gradient with a 2–4 cm diameter is formed (Fig. 2). The mean thermal gradient is 0.8–1.0 °C/cm skin surface with extreme values up to 1.5 °C/cm. If we consider that the mean distance between "thermal peaks" is about 4–6 cm, we found a temperature difference of 3 °C or more within a short distance.

The thermal distribution patterns were constant in repeated experiments for every subject, but differed among subjects. This means that the same picture is obtained if the same experiment is repeated many times.

During a 4-min occlusion of blood flow in a forearm (Fig. 3) the temperature differences and the absolute temperature decreased. After restoring blood flow the skin surface rewarmed. The initial pattern reappeared and those areas which showed the first signs of rewarming were the same as the centres of warm areas before suppression of blood flow.

In a further experiment we uniformly cooled the skin surface using a cooling spray to demonstrate the dynamics of rewarming. Figure 4 shows the position of the 30 °C isotherm at varying times after cooling. A centre of active warming can be seen in the right part of the

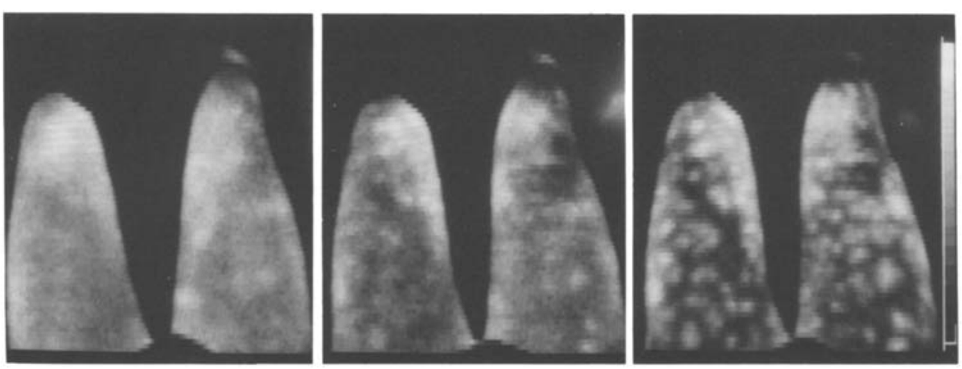

Fig. 1. Temperature pattern of a thigh before (*left*), 5 min after (*middle*) and 10 min after (*right*) the beginning of exercise. Ergometer performance 100 W, ambient temperature 23 °C. Scale from 28.8 °C (dark) to 33.8 °C (bright)

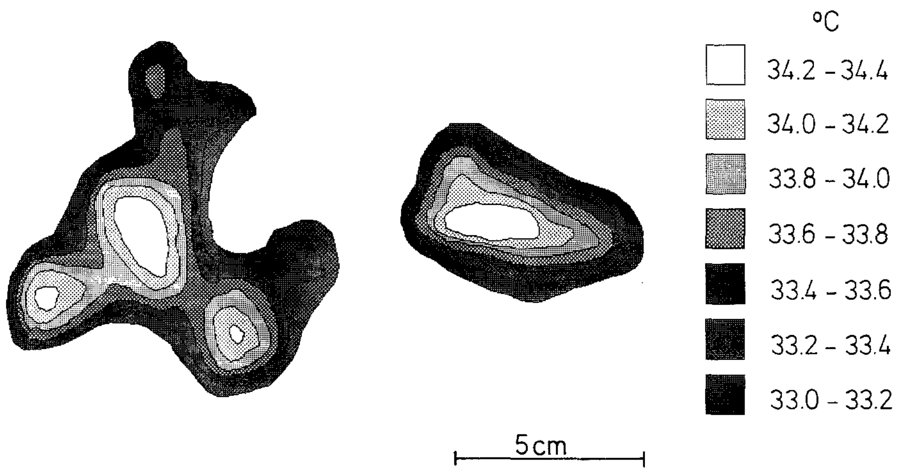

Fig. 2. Magnification of two typical patterns. The grey tones correspond to the indicated skin temperature ranges. Closely neighbouring warm areas merge into more complex patterns (*left*); single warm peaks form regular concentric gradients (*right*). Experimental conditions as in Fig. 1

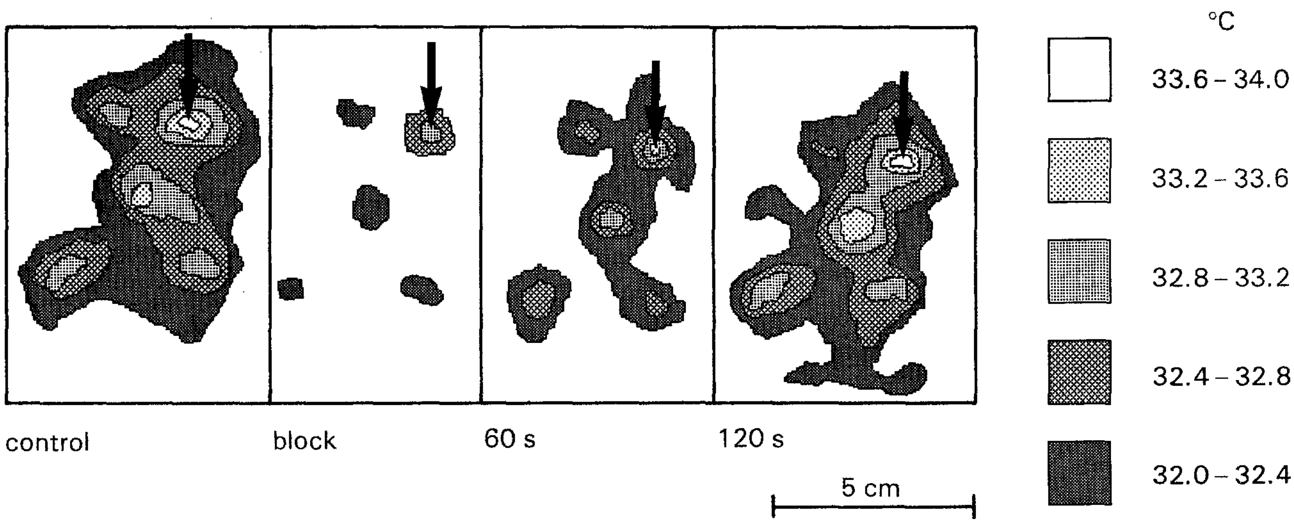

Fig. 3. Detail of a thermogram series of a forearm before complete, 4-min occlusion of blood flow (*control, left*), during occlusion (*block*) and 60 and 120 s after restoring blood flow. Areas with a skin temperature exeeding 32 °C are represented by the grey tones. The warm spot (*arrow*) has the maximum temperature in all images.

cooler surface. The rewarming started from this centre. The isotherm shrinks rapidly on the right in comparison with the negligible displacement on the left border.

Laser Doppler blood flow measurements

The results of the flowmeter measurement of all six subjects show obvious differences in blood flow between cool and warm areas. The blood flow is always higher in warm areas than it is in cool ones (Fig. 5).

Thermocouples

In the experiments using thermocouples temperature differences of more than 3 °C were measured (Fig. 6). The largest temperature difference observed was 3.6 °C, which corresponds to the range of temperature distribution demonstrated by the infrared thermograms. The difference in T_{sk} before exercise due to differing thickness of the subcutaneous adipose layers is apparent. T_{sk} fell initially during the first minutes after exercise started. The difference in temperature measured by neighbouring thermocouples increased due to the dynamic influence of differing local skin blood flows.

Discussion

Under our experimental conditions, a typical temperature pattern on the surface of the limbs was apparent in all subjects. A similar heterogeneous temperature distribution has been described previously (Livingstone et al. 1987). These authors recorded thermograms of resting subjects and suggested that the temperature differences resulted from varying subcutaneous adipose layers. The larger the percentage of insulating body fat of the subject and the lower the ambient temperature the more distinct were the observed differences and the greater the conductive, passive heat transfer between warmer core and cooler shell.

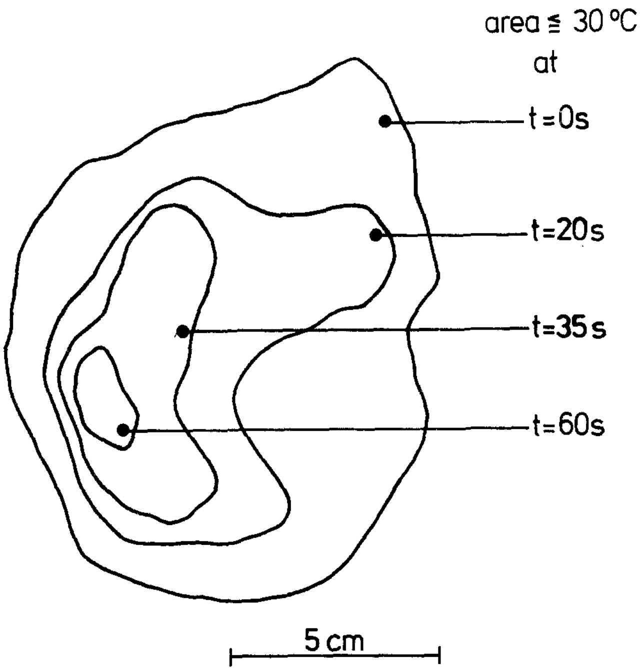

Fig. 4. Position of the 30 °C isotherm at the beginning of rewarming ($t=0$) and 20 s, 35 s and 60 s later. A skin area on the thigh (10 cm in diameter) was cooled by spray after 10 min exercise. Experimental conditions as in Fig. 1

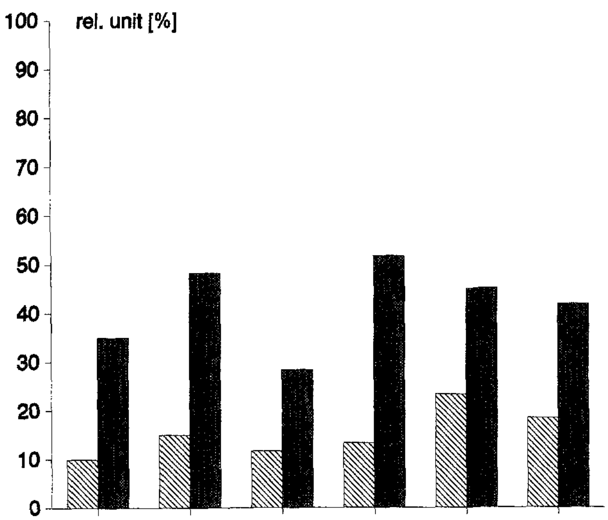

Fig. 5. Skin blood flow of six subjects measured by a laser Dopplerflowmeter. The probe was positioned on warmer or cooler areas under thermographic observation. Each column represents the average of three single measurements of three spots on the thigh over 20 s. Blood flow is given in relative units. ▧ cool; ■ warm

In our experiments with exercising subjects, heat transport by convection seems to be more important. The decline of temperature within 5 min of the start of exercise corresponds well with the vasoconstriction in the skin and in the splanchnic area at the beginning of work. The decreased blood flow results in skin cooling at an ambient temperature of 23 °C. In the skin, vasoconstriction is followed by permanent vasodilatation 5–7

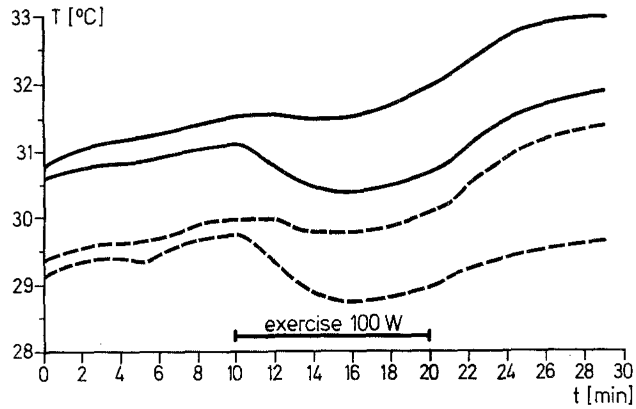

Fig. 6. Time series of skin temperature on the thigh. Experimental conditions as in Fig. 1. The temperatures shown here were measured by two neighbouring thermocouples (no. 1 + 2) fixed over the quadriceps muscle (skinfold 9 mm) and two further neighbouring couples (no. 3 + 4) fixed over the medial part of the thigh (skinfold 24 mm). —— Couples 1 + 2; - - - couples 3 + 4

min after the start of exercise (Johnson 1979). This agrees with our observation that, with a slightly lower T_{sk} as a result of initial vasoconstriction, the prospective temperature patterns appear in outline in the thermograms about 5 min after the start of exercise. Apparently, the beginning of the increase of T_{sk} which we attribute to the beginning of vasodilatation can be observed here. We thus interpret the thermal pattern which can be clearly seen after 10 min as the result of local differences in skin blood flow.

This temperature pattern develops not only on the active extremities (here the thighs), but also on the passive extremities, the arms. This is therefore a central reaction to the heat load, rather than a conductive process due to local muscle heating.

Theoretically the pattern could also result from differing activity or distribution of sweat glands, with higher evaporation in the cooler parts of the skin and lower evaporation in the warmer ones. If this were true, the pattern must also be found after occlusion of arm blood flow, but at a lower level of temperature. This was not observed. The occluded arm cooled down by loss of heat to the environment and the typical pattern disappeared. The changes after the end of blood flow occlusion were due to skin rewarming by the restored blood flow. The time course of the changes in temperature shows that the rewarming of the skin is the active process; those areas of the skin which were originally cool remain cool and are not rewarmed, so their lower temperature is due to a passive effect.

The nature of rewarming after cooling by spray or blocking of blood flow shows the dynamics of heat distribution and the skin blood flow. Rewarming of the immediate vicinity from initially small local centres can only occur by circulatory heat transfer from the depth of the extremity. Thus it is this circulatory heat transfer which dominates the pattern of temperature distribution; passive heat flow by conduction as a result of thermal gradients cannot explain the dynamics of rewarming seen in the thermograms. The higher skin blood flow in the warmer areas, measured with the laser Dopplerflowmeter, provides evidence for the correlation between higher blood flow and higher T_{sk}.

The constancy and reproducibility of this temperature pattern in our investigation makes it unlikely that functional decreases or increases of blood flow in the skin itself produce this pattern.

The thermal peaks within the temperature pattern seem to be those parts of the skin where warm blood is transported to the surface and then distributed into the surrounding areas. In regard to the thermoregulation of the organism, which must dissipate excessive heat produced by exercise through the surface, the opening of those vessels has of course a regulatory function, but the position of the thermal peaks is determined by the position of blood vessels, which conduct the additional blood flow to the skin if required, and is therefore correlated with morphological and anatomical parameters.

In investigations where skin blood flow and T_{sk} have to be measured with a high degree of accuracy, the individual regularity of the skin pattern can be used for mapping the temperature pattern of the test persons, which makes it possible to locate the thermocouples or laser probe on comparable skin spots.

The influence of the observed temperature pattern on measurements of T_{sk} and skin blood flow should not be underestimated. We observed differences of more than 3 °C in T_{sk} and of 300% in skin blood flow. These differences cannot be explained by varying experimental conditions, but rather by differing positions of measuring probes – only a few centimetres apart. In comparative studies the influence of a certain parameter could be falsified by varying positions of a spot probe on a heterogeneous surface, or a real effect, which is comparatively small, could be concealed by the local deviations. This problem is more evident for the measurements of blood flow by laser Dopplerflowmeter. Many devices, especially the older types, have only one optical input. As the area covered by the laser is restricted to 1 mm^2 the value obtained is greatly influenced by the position of the probe and it is not possible to calculate the average of several positions. However, it is feasible to eliminate the rhythmic oscillations of microcirculation (Salerud et al. 1983) by calculating a time integral. Other methods like venous occlusion plethysmography or the strain-gauge (Whitney 1953) determine blood flow as a spatial integral, which may be an advantage.

As shown earlier (Fig. 6) the problems arising from the use of thermocouples can be minimized by increasing the number of probes, but the maximum number is limited by technical factors.

The use of thermography may optimize the applied measuring techniques by facilitating the mapping of the skin surface once for every test subject and thus to determine the optimal position for a probe or thermocouple, even if thermography equipment is not available for everyday use in a laboratory. Moreover, thermography may be used to analyse rapid temperature changes, whereas thermometers need more time to reach thermal equilibrium.

Thermography cannot replace other techniques in experiments where skin temperatures, for example, have to be measured under cooling or protecting suits. Problems can arise in the investigation of wet surfaces like sweating skin. Under certain experimental conditions the measurement of T_{sk} with accurate thermocouples is still suitable.

Acknowledgements. We gratefully acknowledge the support of the Deutsche Forschungsgemeinschaft (We 919/2) and thank Prof. Dr. Eysel (Ruhr-Universität Bochum) for the permission to use the thermographic device (also provided by the DFG).

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