Influence of skin temperature on sweating and aerobic performance during severe work

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DAVIES, C. T. M. *Influence of skin temperature on sweating and aerobic performance during severe work.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 47(4): 770–777, 1979.—Two male subjects were measured over a range of work intensities at dry-bulb temperature (T_{db}) = 21°C (relative humidity, rh <50%) and at approximately 65 and 85% $\dot{V}O_{2\,max}$ for 1 h at T_{db} at 5, 10, 15, 21, and 25°C with high convective airflow (2.5–5 m/s). The results showed that mean skin temperative ($\bar{T}_{sk}$) was related to T_{db} and unaffected by rh over the range studied. $\bar{T}_{sk}$ was dependent on the relative work load and was 2.5°C lower at 85% than 65% $\dot{V}O_{2\,max}$ in the cooler environments. During submaximal work the relative sweat rate ($\dot{M}_{sw}$ expressed as $\%\dot{M}_{sw,\,max}$) was a linear function of rectal temperature (T_{re}) and $\bar{T}_{sk}$ for each subject and thus $\%\dot{M}_{sw,\,max}$ could be predicted from these two variables with a standard deviation of ±12%. For a given $\bar{T}_{sk}$, T_{re} appeared to rise to meet the requirement of heat loss by stimulating set $\%\dot{M}_{sw}$ response. However, during severe work (85% $\dot{V}O_{2\,max}$) this mechanism appeared to become saturated, T_{re} (except for a very narrow prescriptive range) was dependent on T_{db}. These results suggest that under moderate environmental conditions the maximal aerobic and evaporative (cooling) power outputs of an individual are closely matched and only during extremely hard work does thermoregulation become passive and effectively physical (rather than physiological) in nature.

evaporative sweat loss; maximum aerobic power; rectal and skin temperatures; exercise; thermal regulation; control of sweating

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IT HAS BEEN SUGGESTED that during prolonged severe exercise in moderate environments the heat dissipating mechanisms become saturated probably as a result of cardiovascular overload (3, 20). In a study from this laboratory (3) at work loads beyond 85% maximal aerobic power ($\dot{V}O_{2\,max}$), which could be sustained for 1 h, there was evidence of vasoconstriction; the skin remained cool (mean skin temperature [$\bar{T}_{sk}$] rarely exceeded 28°C), but as work progressed there was a spiraling increase on rectal temperature (T_{re}). Thermal control during the latter stages of this type of exercise (equivalent to marathon running) appeared to be "passive", thus we postulated that it would be extremely sensitive to small changes in climatic conditions. Because the dry-bulb temperature (T_{db}) in our experiments did not exceed 22°C and relative humidity (rh) was <50%, it was thought of interest to extend the observations of temperature regulation during exercise of high intensity and prolonged duration to a wider range of environments. The present investigation is therefore concerned with the influence of T_{db} on T_{re}, $\bar{T}_{sk}$, sweating, and aerobic performance during work at constant speed on a motor-driven treadmill.

METHODS

Two male subjects were studied. *Subject 1* (wt, 65 kg; ht, 173 cm; $\dot{V}O_{2\,max}$, 4.72 l/min) was an international ultralong-distance runner in regular training. *Subject 2* (wt, 62 kg; ht, 178 cm; $\dot{V}O_{2\,max}$, 3.8 l/min) ran regularly for pleasure, but not competitively. Twenty-four exercise experiments were carried out at various relative work loads in a constant environment of T_{db} 21°C and 16 experiments were conducted ~65% $\dot{V}O_{2\,max}$ and ~85% $\dot{V}O_{2\,max}$ at 5, 10, 15, and 25°C. Relative humidity was always less than 50% and the tolerance limits for environmental temperatures in the climatic chamber was of the order of ±1°C. Airflow was maintained to ensure the evaporation of sweat from the skin and ranged from 2.5–5 m/s in the two subjects at the higher environmental temperatures, but was reduced to <2 m/s in the cooler conditions. In some additional experiments on *subject 2*, whose maximal sweat rate was ~two-thirds that of *subject 1*, the skin was sprayed with a thin film of water at a temperature to match the existing $\bar{T}_{sk}$ and at a frequency sufficient to allow full evaporation. The air velocity was maintained at a constant rate of 2.5 m/s. The exact volume of water added to the skin throughout the experiment was monitored; the data for these observations are presented separately in Fig. 8. In all experiments the subjects exercised for 1 h and the following measurements were taken.

Metabolism. The metabolic heat production (*M*) was calculated from oxygen intake ($\dot{V}O_2$) measured by the open-circuit technique at the 20th and 50th min of exercise using the calorific equivalent of O_2 for a given exchange ratio (R) from standard tables.

Body temperatures. Deep body temperature was measured by a probe inserted 8 cm into the rectum. Skin temperatures were measured using a thermocouple mounted across the open end of a plastic applicator held lightly against the skin. The T_{sk} was measured at 13 sites as previously described (3).

Body weight. Nude and clothed weight was measured immediately prior to exercise on a beam balance accurate to ±5 g. Clothed weight was taken after 30 min of exercise and again immediately on cessation of effort. Nude weight was measured within 5 min of the end of exercise

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following the removal of any unevaporated sweat with a towel. Evaporative sweat loss ($\dot{M}_{sw}$) was calculated as the total clothed weight loss after correction for metabolic gas exchange and respiratory water loss and expressed in $W \cdot m^{-2}$.

The heat production (H) was calculated as M minus the vertical work performed (W) on the motor-driven treadmill. For *subject 1* at 21°C the gradient of the treadmill ranged from 0–4% and the speed from 9.7–14.5 km/h. In *subject 2* the respective figures were 0–15% and 6.4–11.2 km/h. The 65% and 85% $\dot{V}O_{2\,max}$ loads in the different environmental conditions corresponded to 0% (14 km/h) and 3% (14.5 km/h) in *subject 1* and 1% and 5% at 11.3 km/h in *subject 2*. The tissue heat conductance (K) was calculated from the formula

$$K = \frac{H_{sk}}{(T_{re} - \bar{T}_{sk}) \times A_D} \qquad (W \cdot m^{-2} \cdot {}^\circ C^{-1}) \qquad (1)$$

A_D, body surface area; H_{sk}, the heat dissipated from the skin, namely H corrected for respiratory heat loss from the lungs and body heat storage (S). The mean skin temperature ($\bar{T}_{sk}$) was computed from the 13 sites using the formula and weighting factors given by Hardy and Dubois (6). Value of T_{re} and $\bar{T}_{sk}$ at the 45th and 60th min of exercise were used in the equation. Heat storage was calculated from the equation: $S = 0.83\ W\ (0.9\ \Delta\ T_{re} + 0.1\ \Delta\ \bar{T}_{sk})$, where 0.83 is the specific heat of the body tissues in kcal and W is body weight in kg and then converted to $W \cdot m^{-2}$. Maximal aerobic power output ($\dot{V}O_{2\,max}$) was determined in separate experiments using the criteria and methods previously described (3).

RESULTS

Figure 1 shows plot of T_{re} against time for work of 85 and 65% $\dot{V}O_{2\,max}$ at 5 and 21°C in *subject 2*. At the lower relative work load, T_{re} reaches a plateau value independently of T_{db}, but at 85% $\dot{V}O_{2\,max}$ this is no longer true. At 21°C, T_{re} rises after 20 min of exercise as a linear function of time to reach a final value approximately 1.4°C higher than observed at 5°C. When plotted against T_{db} (Fig. 2), T_{re} at 85% $\dot{V}O_{2\,max}$ shows an 'S'-like curve suggesting a very narrow prescriptive (cf. Lind, Ref. 9) range over which T_{re} is actively regulated during this severe form of work. At T_{db} <10°C and >20°C, T_{re} is affected by changes in ambient temperature. This effect is not apparent at 65% $\dot{V}O_{2\,max}$ (Fig. 2). The effect of T_{db} is to linearize the relationship of T_{re} to %$\dot{V}O_{2\,max}$ (Fig. 3).

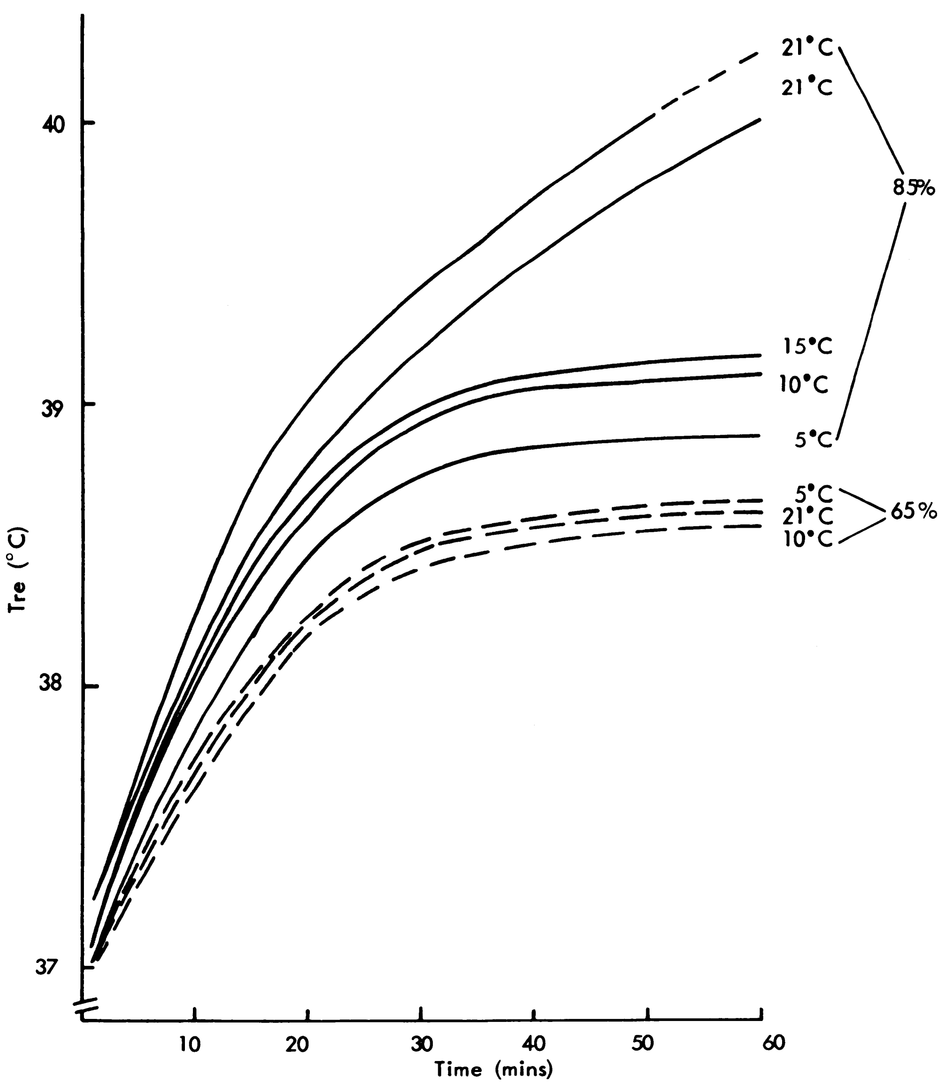

FIG. 1. Relationship of rectal temperature (T_{re}) to time at approximately 85% (*solid line*) and 65% (*dotted lines*) $\dot{V}O_{2\,max}$ for T_{db} of 5, 10, 15 and 21°C. *Subj 2* was unable to exercise at 25°C at 85% $\dot{V}O_{2\,max}$ for 1 h. At 21°C he failed at the 50th min of exercise on 1 occasion, hence dotted portion of the curve.

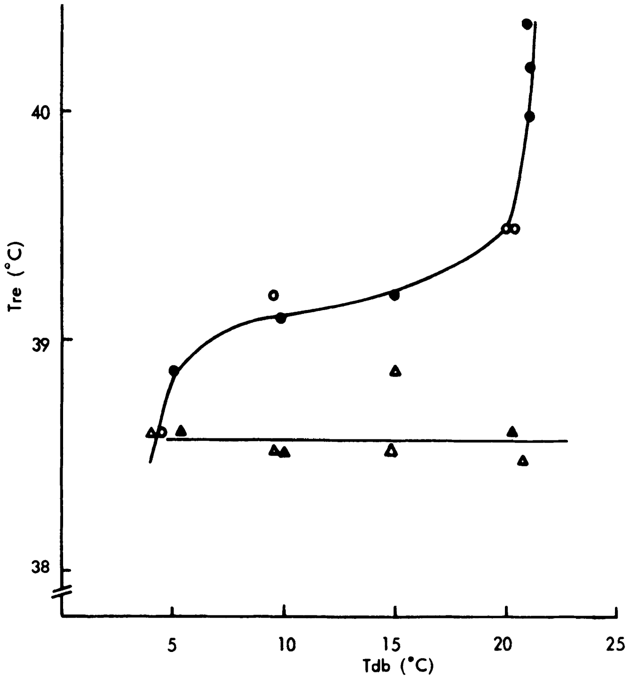

FIG. 2. Rectal temperature (T_{re}) in relation to dry-bulb (T_{db}) temperature at approximately 85% (●, *subj 2*; ○, *subj 1*) and 65% $\dot{V}O_{2\,max}$ (▲, *subj 2*; △, *subj 1*).

Skin temperature. Figure 4 shows the relationship of $\bar{T}_{sk}$ to T_{db} at moderate (65% $\dot{V}O_{2\,max}$) and the most severe (85% $\dot{V}O_{2\,max}$) work loads. In both cases the relationship is linear. The effect of increasing the work output is to increase the slope of the $\bar{T}_{sk}/T_{db}$ relationship so that at 5°C the $\bar{T}_{sk}$ is 2.5°C lower at 85% $\dot{V}O_{2\,max}$ than at 65% $\dot{V}O_{2\,max}$. Humidity, in the presence of high airflow, over the limited range (see METHODS) studied in this investigation, appears to have no effect on the $\bar{T}_{sk}/T_{db}$ relationship. During exercise $\bar{T}_{sk}$ invariably fell at the onset of work then rose slightly, but was usually constant from the 15th–60th min of work. However, there were large regional variations in skin temperature, particularly during work in the cool and cold environments.

Tissue heat conductance. Tissue heat conductance varied from 25.8 to 39.3 $W \cdot m^{-2} \cdot °C^{-1}$ in *subject 2* and 31.8 to 50.4 $W \cdot m^{-2} \cdot °C^{-1}$ in *subject 1* over the range of exercise intensities studied. In both subjects *K* was associated with $\bar{T}_{sk}$ and metabolism and curvilinearly related to T_{re}. At T_{re} higher than 39.3°C, *K* tended to plateau with no further significant rise (Fig. 5).

Evaporative sweat loss. Evaporative sweat loss was linearly related to *H*; thus $\dot{M}_{sw}$ ($W \cdot m^{-2}$) = − 66.11 + 0.38 *H* (*W*), *r* = + 0.64 (*Eq. 1*) and showed the same relationship to T_{re} as *K* (Fig. 5). Thus the relationship of evapo-

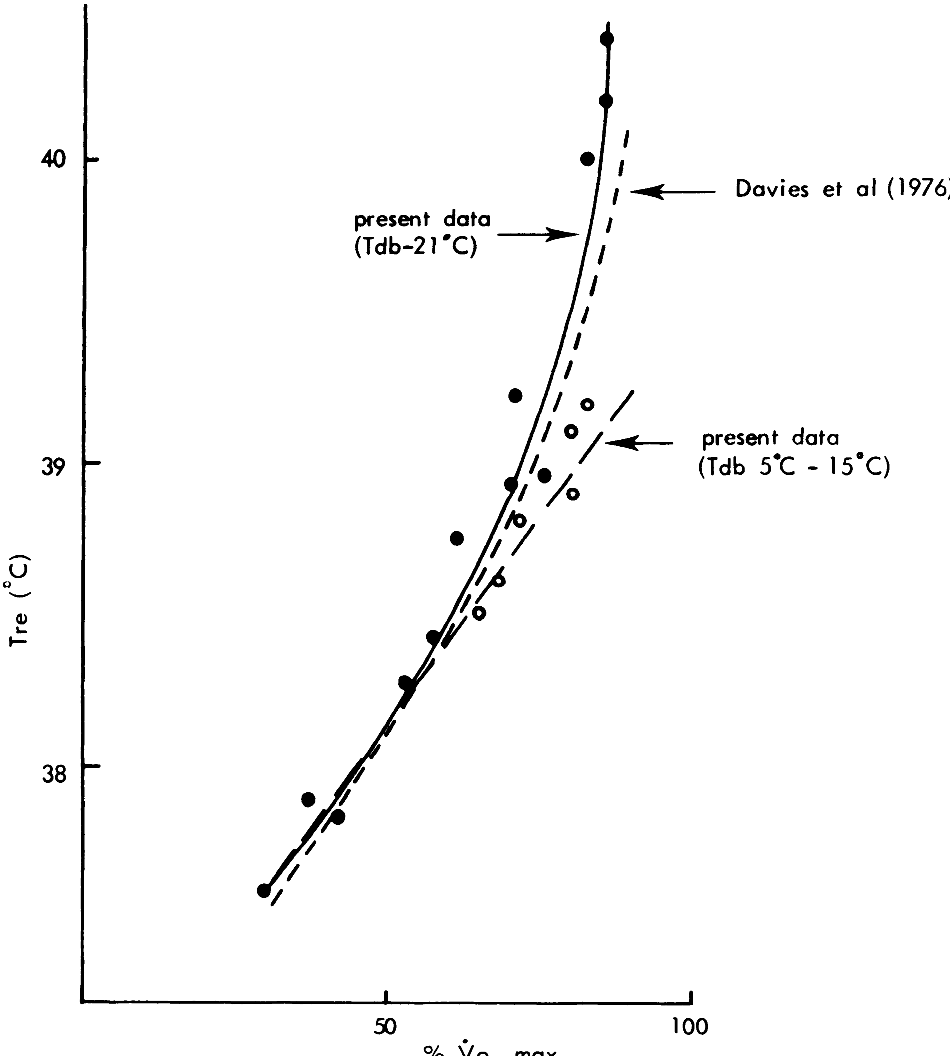

FIG. 3. Rectal temperature (T_{re}) in relation to relative aerobic power output (% $\dot{V}O_{2\,max}$) T_{db} = 21°C (●) and T_{db} = 5–15°C (○) for *subj 2*.

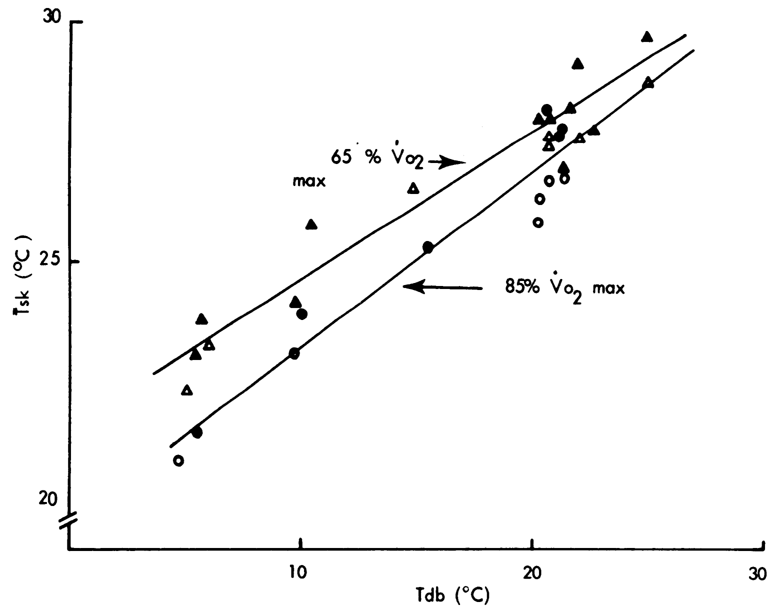

FIG. 4. Mean skin temperature ($\bar{T}_{sk}$) in relation to ambient temperature at 65% $\dot{V}O_{2\,max}$ and 85% $\dot{V}O_{2\,max}$. Symbols same as Fig. 2. Relationship for the 2 relative work loads can be described by the following linear regression equations: $\bar{T}_{sk}$ (°C) = 21.70 + 0.299 T_{db} (°C), r = + 0.96 (65% $\dot{V}O_{2\,max}$) and $\bar{T}_{sk}$ (°C) = 19.60 + 0.367 T_{db} (°C), r = + 0.97 (85% $\dot{V}O_{2\,max}$).

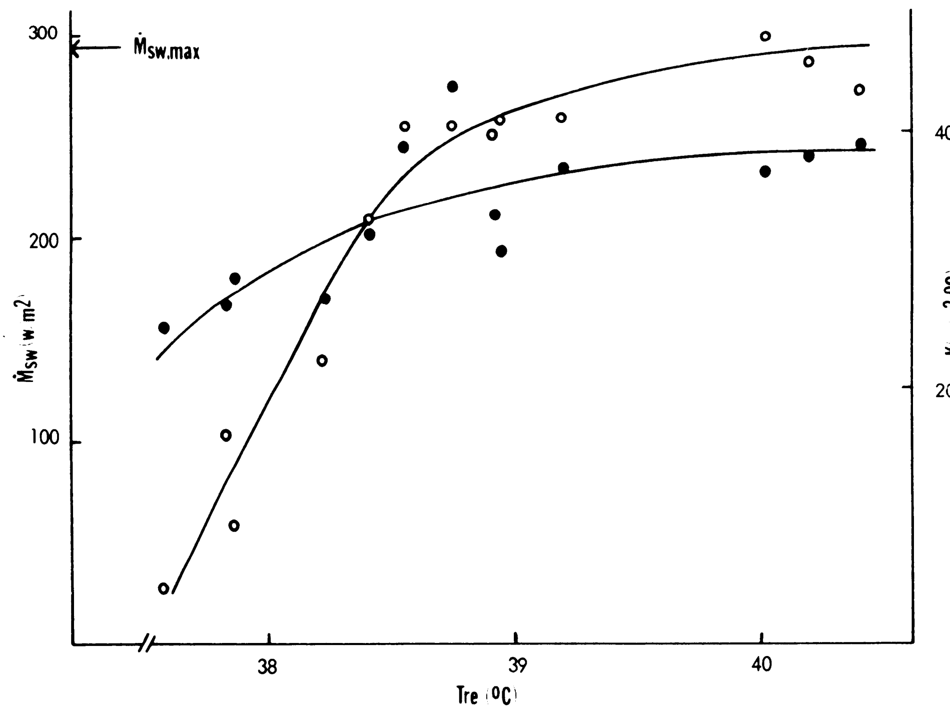

FIG. 5. Evaporative sweat loss (○) and peripheral tissue heat conductance (●) in relation to T_{re}. Data for *subj 2*. *Arrowed line*: predicted $\dot{M}_{sw,\,max}$ for subject (see text).

rative heat loss (E) to K was therefore adequately described by a linear regression relationship of the form $\dot{M}_{sw}$ (W·m^{-2}) = − 209.72 ± 11.36 K (W·m^{-2}·°C^{-1}) r = 0.83 (*Eq. 2*). The effect of reducing T_{db} and thus $\bar{T}_{sk}$ was to effect a linear decrease of $\dot{M}_{sw}$ of the same order of magnitude in both subjects, though the absolute value of $\dot{M}_{sw}$ at each relative work load under the same environmental conditions varied between the two subjects. These differences could be reduced by expressing $\dot{M}_{sw}$ in relative terms, i.e., as percent of the maximal evaporative sweat loss recorded during experiments at 21°C for each subject. This was calculated as the plateau value of $\dot{M}_{sw}$ observed at T_{re} 39.3°C (Fig. 5). The relationship of relative evaporative sweat loss (%$\dot{M}_{sw}$) to $\bar{T}_{sk}$ is shown in Fig. 6. Similarly %$\dot{M}_{sw,\,max}$ could be represented as a linear function of T_{re} over the range of 37.0–39.3°C for each subject (Fig. 7).

The effects of spraying *subject 2* with water on $\dot{M}_{sw}$ and $\bar{T}_{sk}$ in relation to the heat dissipated from the skin (H_{sk}) are shown in Fig. 8. The evaporation of the film of water from the skin resulted in an additional mean heat loss of 117 W·m^{-2} and a fall in $\bar{T}_{sk}$ of approximately 2.5°C. This was associated with a suppression of sweating (67 W·m^{-2}) and a reduction in $C + R$ (45 W·m^{-2}) that almost exactly counterbalanced the increased evaporative water (heat) losses from the skin. The $\bar{T}_{sk}$ decreased to a value governed by the overall cooling capacity of the environment; T_{re} remained unchanged.

DISCUSSION

The results of the present study show that at very high work loads in excess of 85% $\dot{V}O_{2\,max}$, the T_{re} is sensitive to changes in environmental conditions. During severe ex-

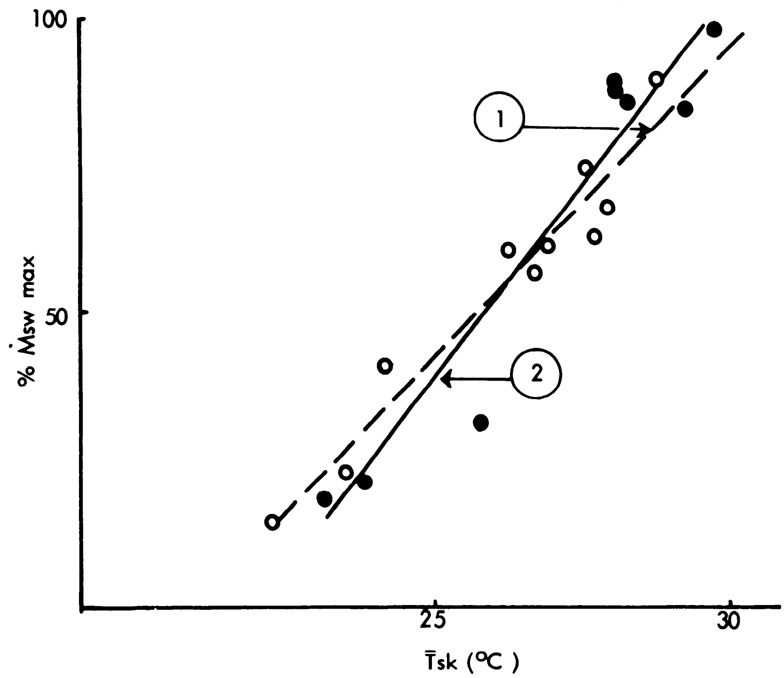

FIG. 6. Evaporative sweat loss expressed at a % of maximal evaporative sweat loss ($\%\dot{M}_{sw,\,max}$—see text) in relation to mean skin temperature ($\bar{T}_{sk}$). Linear regression lines shown are of the form $\%\dot{M}_{sw} = -213.9 + 10.27\ \bar{T}_{sk}$ (°C); $r = +0.97$ (*subj 1*); $\%\dot{M}_{sw} = -287.6 + 13.07\ \bar{T}_{sk}$ (°C); $r = +0.95$ (*subj 2*) exercising at 65% $\dot{V}O_{2\,max}$.

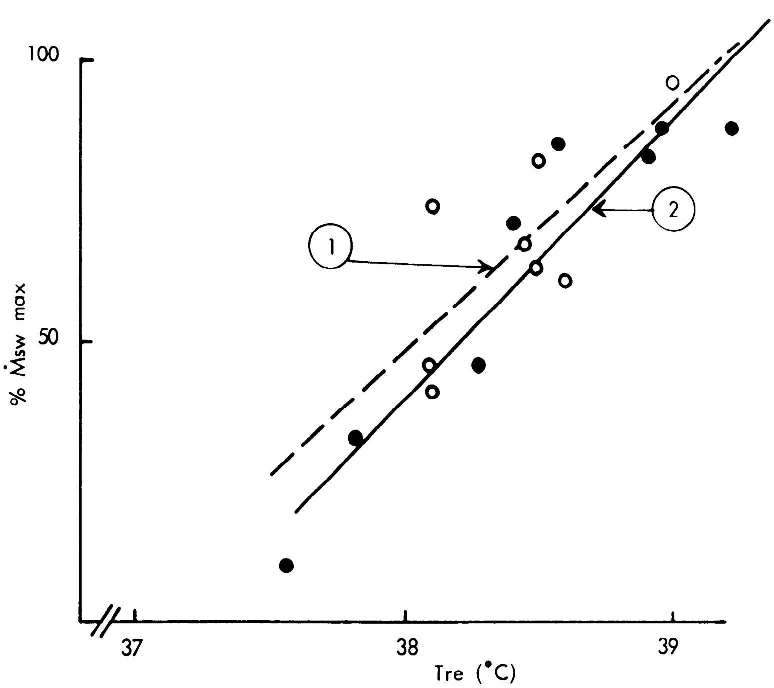

FIG. 7. Relative evaporative sweat loss ($\%\dot{M}_{sw,\,max}$) in relation to T_{re} at a given $\bar{T}_{sk}$ of approximately 28°C. T_{re} range 37 − 39.3°C see text. $\%\dot{M}_{sw} = -1583 + 42.96\ T_{re}$ (°C); $r = +0.73$ (*subj 1*) $\%\dot{M}_{sw} = -1875 + 50.39\ T_{re}$ (°C); $r = +0.93$ (*subj 2*).

ercise T_{re} rose as a linear function of time (Fig. 1) beyond the 20th min of work to reach values approaching and often exceeding 40°C even in moderate conditions (T_{db} = 21°C, rh <50%) with high convective airflow. Equally at T_{db} below 10°C T_{re} fell and values observed in the two subjects were similar to those recorded in moderate and warm environments at lower relative loads (Fig. 2). These findings are contrary to those of Nielsen (14) and several later authors (9, 13, 24), who have found the rise in T_{re} during exercise to be independent of ambient temperature from 5 to 30°C at lower relative work loads and less convective cooling.

In a previous paper (3), we have argued that at very high relative work loads that can be sustained for 1 h, the skin becomes partially vasoconstricted, resulting in a fall of $\bar{T}_{sk}$. This will inhibit sweating and though $\dot{M}_{sw}$ appears to reach a maximal value (Fig. 5) with apparent saturation of the sweat loss mechanism, we have argued that $\dot{M}_{sw}$ is not the limiting factor for thermal equilibrium under these conditions. The present observations serve to underline this view. The changes in $\bar{T}_{sk}$, which can be achieved in relation to the large increase in heat production, are small due to the high cooling capacity of the environment, thus one might expect (11, 13, 24), as has been found (Fig. 4), $\bar{T}_{sk}$ to be a linear function of T_{db}. However, it should be noted that the slope of the $\bar{T}_{sk}/T_{db}$ line is significantly steeper at 85% than 65% $\dot{V}O_{2\,max}$, which is indicative of a greater degree of vasoconstriction

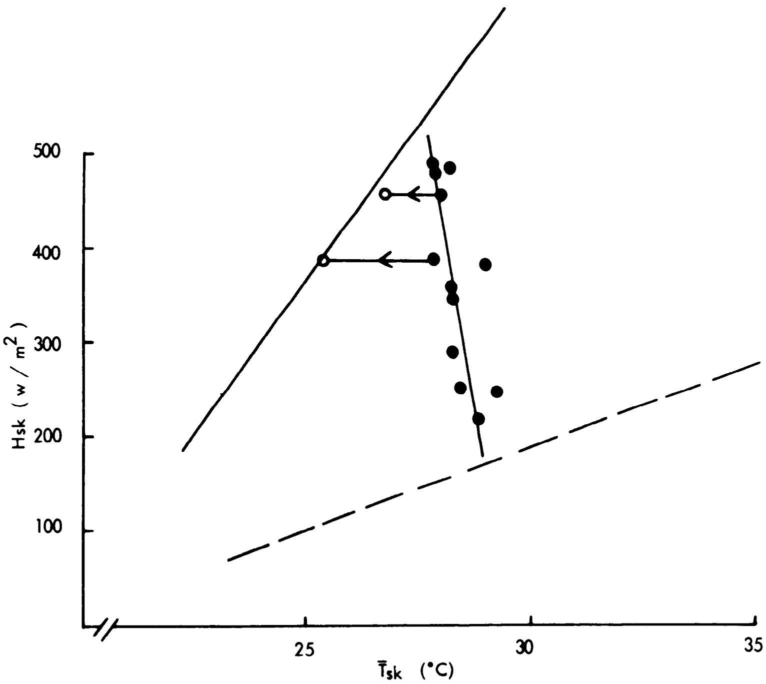

FIG. 8. Effect of skin wetting on $\bar{T}_{sk}$ in relation to heat dissipated from skin (H_{sk}) and total (——) cooling capacity of environment provided by evaporation and convection plus radiation ($C + R$ - - -). Values were calculated using heat exchange coefficients given by Kerslake (8), Appendix 4. (○) skin wetting, (●) normal data; *subj 2.*

at the higher work load. The degree of inhibition of $\dot{M}_{sw}$ at high work loads at a T_{db} of 21°C can be judged from the results on *subject 1*, working at a lower work load with an environment sufficiently warm to ensure peripheral vasodilatation, he achieved 30% increase in $\dot{M}_{sw}$ (1.5 l/h–2.0 l/h) compared with his severe work experiments in a moderate environment. Thus the sweat mechanism becomes saturated in moderate environments at high work loads only in the sense that a higher $\dot{M}_{sw}$ cannot be achieved due to the cool skin imposed by the requirements of exercise. This is clearly illustrated by the skin-wetting experiments (Fig. 8) performed on *subject 2*, whose sweating capacity at the existing $\bar{T}_{sk}$ was of the order of 1.0 l/h. The water, which was sprayed on the skin during exercise, served to cool the skin further but did not reduce T_{re}. The evaporation of water from the skin exactly compensated for the reduction of $\dot{M}_{sw}$ and heat loss by $C + R$. It subjectively aided performance, but its only contribution to the achievement of thermal equilibrium was qualitative rather than quantitative. The major problem at high levels of exercise would seem to be the maintenance of an adequate convective flow of heat from the core to the periphery. In the face of restricted peripheral blood flow, this can only be achieved by changes in core temperature. However, the disadvantage of this mechanism as shown by Wyndham (25) is that the T_{re} becomes very sensitive to small changes in the environment (Fig. 2). Due to the body's small thermal capacity, at high rates of heat production the changes in central temperature are rapid. The subject becomes effectively poikilothermic.

Of course, the question may be raised as to why the $\bar{T}_{sk}$ is not allowed to rise during exercise when T_{re} reaches 39.3°C (Fig. 3 and 5). At high absolute levels of heat production with a high T_{re} and low $\bar{T}_{sk}$, the rise in $\bar{T}_{sk}$ required to effect a given heat transfer to the environment is small. For instance, a rise in $\bar{T}_{sk}$ of only 1°C would produce a substantial rise in $\dot{M}_{sw}$ (Fig. 6), and increased heat loss by $C + R$. The answer is probably as pointed out by Rowell et al. (21) that at high levels of work metabolic considerations are given priority over the body's requirements for heat dissipation. A rise in $\bar{T}_{sk}$ can only be achieved by an increase in skin blood flow at the expense of muscle blood flow. This would inevitably compromise the level of exercise being performed and ultimately result in a reduction in the speed of running. Certainly, it is our experience in the laboratory that at high work loads if one suddenly forces the skin to dilate using only small amounts of radiant heat, the subject's performance immediately suffers and he is unable to sustain the work. Similarly, outdoors it is a common observation of marathon runners (including *subject 1*) that they become extremely sensitive to small changes in environmental conditions during a race, particularly on sunny days when there is limited cloud cover and intermittent shade, which result in adjustments of pace.

At low environmental temperatures (T_{db} 5°C), one observes a similar, but essentially opposite, thermal behavior when severe work is performed. The $\bar{T}_{sk}$ is further reduced, $\dot{M}_{sw}$ inhibited, and T_{re} actually falls (Fig. 2). At 5°C the $\bar{T}_{sk}$ is of the order 21.5°C, though even under these conditions the large metabolic heat production sustains $\dot{M}_{sw}$ at approximately 40% of maximum (Fig. 6). The observation underlines the enormous potentiating effect of exercise on $\dot{M}_{sw}$ (19) and the inherent difficulty of suppressing sweat completely during work (24). From Fig. 6 it would seem that a $\bar{T}_{sk}$ of ~15.5°C would be required to totally inhibit sweating; this would prove unacceptable to most subjects and one doubts if one could achieve a physiological condition under which sweating ceased at very high levels of exercise. At the low T_{db}, K was higher at 5 than at 10°C, and though the skin was probably maximally vasoconstricted, there were greater regional variations in skin temperature than observed at higher T_{db}. Because one must assume that the requirements of the muscles for blood flow remain large and constant during severe exercise, these observations would suggest that forced enlargement of the body's core under conditions of low T_{db} facilitate the transfer of heat by conduction directly from the working muscles through the overlying tissue to the skin. The "forced" heat loss results in a lowered T_{re} for a given M (cf. Nielsen and Davies, Ref. 15). The two subjects in the present experiments were extremely thin (the conventional sum of four-skinfold thicknesses was <25 mm), and indeed this may be one reason why they were able to complete the strenuous series of experiments. The high 'minimal' and relatively low 'maximal' K values recorded at 5 and 21°C, respectively, suggest that in both subjects a large proportion of the heat produced was eliminated by direct transfer from the working muscles to the overlying skin. The maximum mean values of K recorded in these experiments, 39.3 $W \cdot m^{-2}$ (*subject 2*) and 50.4 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$ (*subject 1*) should be compared with those recorded in athletes (16, 17) and nonathletes (26) working in hot chambers. Of course, the maximum K values recorded are critically associated with M and T_{db}, both of which influence $\bar{T}_{sk}$. At high work loads and low $\bar{T}_{sk}$, the change in K necessary to maintain T_{re} is small compared to conditions in the heat. Working in hot conditions, the present subjects could easily achieve higher values of K, but only at lower work loads. They could not achieve their highest work output for 1 h if $\bar{T}_{sk}$ exceeded ~28°C.

In the present experiments with high convective air flow, K was closely associated with $\dot{M}_{sw}$ at all levels of work. This suggests, if we accept the work of Nielsen (13), which shows K may be taken as an indication of peripheral blood flow, that the control of evaporative sweat loss and skin circulation are closely matched. Indeed, the common thermal input may be central core temperature (27). Clearly, if this is so, direct heat transfer not involving peripheral blood flow would be a distinct advantage for high performance. In our thin subjects, one would expect a higher $\dot{M}_{sw}$ for a given K than seen in normal subjects working in environments with lower airflows and there is some evidence of this (cf. *Eq. 2* with Kerslake (8), p. 169, and Fig. 7 of Ref. 22). The low K value and relatively high sweat rates at low $\bar{T}_{sk}$ (Fig. 6) during severe work suggest that sweating can be initiated and sustained at minimal peripheral blood flow levels. The magnitude and importance of direct heat transfer and the level of skin blood flow necessary to elicit a given sweat rate in subjects who vary in body size and composition would be an interesting field for further research.

The linear relationship of $\dot{M}_{sw}$ to K allows prediction of $\dot{M}_{sw}$ with a standard deviation of ± 63 $W \cdot m^{-2}$ in the two subjects. However, if we assume proportionality between $\dot{M}_{sw}$ and K, then for a given relative work load (and therefore T_{re}, Fig. 3) $\dot{M}_{sw}$ should be a curvilinear function of $\bar{T}_{sk}$ as Kerslake (8) has indicated. There is no evidence of this in Fig. 6; $\dot{M}_{sw}$ expressed as a $\%\dot{M}_{sw,\,max}$ is a linear function of T_{re} (Fig. 7). These observations find agreement with those (e.g., Ref. 11) who have stressed the importance of $\bar{T}_{sk}$ in sweat regulation and the extensive work of the Pierce Laboratory (11, 22) that has consistently advocated a model of sweating based on $\bar{T}_{sk}$ and T_{re} (or T_{es}). Their current model takes the form of a multiple regression equation with the addition of an exponential term to account for inhibition of sweating due to local skin cooling. The model has proved useful for predicting sweat rates in positive (12) and negative (10) work in subjects who have similar levels of $\dot{V}O_{2\,max}$ and states of acclimatization. The limitation of the equation without resort to complex and as yet unknown constants is in reconciling $\dot{M}_{sw}$ in subjects who differ in thermal status and fitness. The present analysis suggests that the natural state of acclimatization of subjects living and working in temperate climates may be a function of their exercise capacity (cf. Gisolfi and Robinson, Ref. 4). From the observed data, the following multiple regression equation can be derived

$$\%\dot{M}_{sw} = -1814 + 44.45\ T_{re}\ ({}^{\circ}C) + 5.90\ (\bar{T}_{sk}\ ({}^{\circ}C)); \qquad r = 0.82 \tag{2}$$

Using the equation, $\dot{M}_{sw}$ can be predicted with a standard deviation of ± 12%. If one inserts the set point constants of 36.9°C, i.e., allowing 0.2°C difference between T_{es} and T_{re} (Saltin and Hermansen (23)) for T_{re} and 34°C for $\bar{T}_{sk}$ used by Nadel et al. (11), the relationship of $\dot{M}_{sw}$ to $\bar{T}_{sk}$ and T_{re} is not materially changed. The constant terms are qualitatively of the same order of magnitude though the intercept becomes positive. As a T_{re} of 36.9°C is closely in agreement with our data (Fig. 7) for the set point of sweating with a $\bar{T}_{sk}$ of 28°C, the positive intercept may be in part due to the figure of 34°C given by Nadel et al. (11) for the skin with zero central drive. At rest there is some evidence to suggest that their figure is accurate (5), but during exercise, particularly with high convective air flow, the sensitivity of the skin thermoreceptors may change. Certainly, the present analysis would suggest that the figure is too high, but further detailed experiments would be required before definitive conclusions could be reached. The important factor that emerges from the analysis is that at a set $\bar{T}_{sk}$ a given increase in T_{re} will produce a set rise in relative sweat rate in both the nonathlete and the athlete. The aerobic power output and cooling capacity of the body are seemingly closely matched in both subjects and controlled in a similar way independently of the fitness of the individual. A rise in core temperature of 1°C in a moderate environment with airflow between 2.5–5 m/s will produce a 40% increase in sweat rate (Fig. 7). This effect will be modified by any change in $\bar{T}_{sk}$.

If these observations are taken together, then the rise in T_{re} is seen to meet the requirements of heat dissipation. Though the rise in T_{re} may be related to M, the rate of work and the relative work load, its primary functions are to create a thermal gradient from core to periphery and to elicit a given sweat rate response. Beyond $\dot{M}_{sw,\,max}$, T_{re} rises passively to maintain the convective transport of heat from the core to the skin in the face of an active increase in peripheral vasoconstrictor tone. Therefore, at all times during exercise T_{re} rises or falls to maintain a balance between heat production and heat loss. The environment exerts the greatest influence on $\bar{T}_{sk}$ and both the active and passive roles of $\bar{T}_{sk}$ on thermal regulation can be seen in Fig. 6 and 8. Changes in $\bar{T}_{sk}$ modify the central drive to $\dot{M}_{sw}$ (Fig. 6) and possibly peripheral blood flow (*Eq. 2*). Certainly local temperature is a most important factor in the control of blood flow in the superficial vessels of the skin (1, 7). The passive role of $\bar{T}_{sk}$ is exemplified by the skin-wetting experiments whereby the subject responds in a manner similar to a wet-bulb thermometer (Fig. 8). However, it is clear that at high metabolic rates the intense sympathetic outflow can override thermal stimuli (2, 20) and produce a fall in $\bar{T}_{sk}$ (Fig. 4). Performance at these levels of exercise will depend on $\dot{V}O_{2\,max}$, the maintenance of a low $\bar{T}_{sk}$ (at or below 28°C), and the cooling capacity of the environment. On this basis, given that $\dot{V}O_2$ is a linear function of speed (18) and knowing the $\dot{V}O_{2\,max}$ of an endurance athlete and the environmental heat-transfer coefficients, it should be possible with the aid of plots similar to Fig. 8 to predict optimal performance for different climatic conditions.

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