JOURNAL OF APPLIED PHYSIOLOGY
Vol. 31, No. 1, July 1971. *Printed in U.S.A.*

Importance of skin temperature in the regulation of sweating

ETHAN R. NADEL, ROBERT W. BULLARD, AND J. A. J. STOLWIJK
John B. Pierce Foundation Laboratory and Department of Epidemiology,
Yale University School of Medicine, New Haven, Connecticut 06519

NADEL, ETHAN R., ROBERT W. BULLARD, AND J. A. J. STOLWIJK. *Importance of skin temperature in the regulation of sweating.* J. Appl. Physiol. 31(1): 80–87. 1971.—The major thermal inputs to the thermoregulatory center, internal and skin temperatures, were independently varied to evaluate their interaction and relative contributions toward the regulation of sweating in resting man. Average skin temperature ($\bar{T}_s$) was modified by rapid application and removal of radiant heat. Sweating rate from the thigh, measured by resistance hygrometry, was found to be directly related to the $\bar{T}_s$ during skin heating; during skin cooling, however, local sweating rate was a function of the rate of change of $\bar{T}_s$ as well. Increased internal temperatures were achieved by interposing a brief bout of heavy exercise between heating intervals. The relationship between internal and mean skin temperatures in the control of sweating rate was described by a summation model, where sweating rate was linearly related to internal (esophageal) temperature and the level of $\bar{T}_s$ shifted this relationship in the appropriate direction. Clamping local skin temperature at different levels during skin heating revealed the local skin temperature as exerting a modifying effect on the output from the central controller, acting as a multiplier in the determination of local sweating rate. The following model described the major influences on local sweating rate:

$$\text{local sweating rate} = [\alpha(T_{es} - T_{es_0}) + \beta(\bar{T}_s - \bar{T}_{s_0} + \gamma[d\bar{T}_s/dt - r_0])]e^{(T_{s1} - \bar{T}_{s_0})/\delta}$$

local sweating rate; temperature regulation; sweating rate; internal temperature

---

VARIOUS MODELS describing the regulation of sweat secretion have been proposed (9, 14–16, 29, 30, 33), with most of these predicting the regulatory output from an interaction between internal (hypothalamic) and skin temperatures. Recently, the input from the skin has been investigated more thoroughly (7, 22, 23, 30, 33); however, varied and sometimes conflicting interpretations of experimental data have appeared.

The nature of the interaction between internal temperature and the average temperature of the skin in the determination of sweating rate in resting man has been difficult to assess because of the difficulty of forcing internal temperature beyond a very narrow range. Consequently, both additive (14, 29, 31) and multiplicative (16, 33) models have been derived to define the interaction between these primary thermal inputs.

Bullard et al. (9, 10, 21) have established the importance of the local skin temperature in the determination of loca sweating rate and have suggested that its effect was related to the internal temperature drive via some multiplicative mechanism. They theorized that the local effect occurred outside the central integrator, probably in the vicinity of the sweat glands themselves as a result of a temperature dependence of release of transmitter substance per neural impulse at the neuroglandular junction (10). If the local skin temperature effect is mediated peripherally, its influence may modify the output from the thermoregulatory center under certain circumstances. This local influence, heretofore unrecognized, may offer a partial explanation for the variability of the models describing the regulation of the heat dissipation response.

Several recent studies (2, 32) have established a basis for the inclusion of a rate of change of skin temperature component in the model, suggesting a connection with the results obtained by Hensel and co-workers (17, 18) with peripheral nerve fibers which were responsive to both the level and the rate of change of local skin temperature.

To evaluate the relative contributions of these factors which have been implicated and their interaction in the regulation of sweating, it became necessary to cause independent variations of average skin temperature, internal temperature, local skin temperature, and rate of change of skin temperature. To avoid the complications inherent in evaporative rate measurements during transients (5), rate of sweat secretion was measured as the variable under physiologic control within the regulatory mechanism. The synchronous cyclical discharge of sweat over the body (1) strongly suggests a single controlling center, with different skin areas requiring different levels of threshold stimulation from this controlling center (19). Thus, by measuring local sweating rate as the response to the partitioning of these various thermal inputs, the efferent outflow from the thermoregulatory center could be effectively characterized and a comprehensive model constructed.

METHODS

Six male subjects, described in Table 1, were exposed to fixed ambients between 25 and 35° C for 1.5–2 hr. Relative humidity was constant at 35% and air movement was minimal. Each subject, minimally clothed, lay supine on a 5-cm fish netting suspended from a rectangular aluminum frame (2.1 x 0.6 m) which was supported on a Potter beam

balance. A continuous record of body weight provided total evaporative loss per minute by sensing averaged 1-min weights on an IBM 1131 on-line computer. The balance had a 1-g sensitivity.

Rapid alterations in skin temperature were superimposed on the relatively steady state by manipulating a polished aluminum shutter which shielded two Chromalox heating lamps situated 1.6 m above the subject. The energy output from these lamps could be readily controlled by a voltage transformer. Irradiance from the lamps was determined by wide-angle radiometer, which had been calibrated by a Bureau of Standards radiation lamp. Gagge and Hardy (13) had previously reported the irradiated body area in a similar design to be about 32%. Total irradiance most often used in the present study was 750 W/m² of projected area, with irradiance to the subject (effective radiant flux) amounting to 215 W/m² of skin surface area. Irradiance was applied stepwise or exponentially and removed in stepwise, exponential, or linear manners. Varying the mode of application and removal provided wide variations in rate of change of skin temperature during skin warming and cooling. Irradiance was continually measured during each exposure by means of a wide-angle radiometer positioned at the level of the subject.

Temperatures from 10 skin surface locations were obtained once per minute from thermocouple recordings and average skin temperature ($\bar{T}_s$) was calculated from the following modification of the Hardy-DuBois equation:

$$\bar{T}_s = .07\,T_1 + .07\,T_2 + .09\,T_3 + .09\,T_4 + .09\,T_5 + .09\,T_6 + .07\,T_7 + .11\,T_8 + .16\,T_9 + .16\,T_{10}$$

where

T_1 = forehead temperature
T_2 = dorsal bicep temperature
T_3 = right scapular temperature
T_4 = left scapular temperature
T_5 = lateral lumbar temperature
T_6 = chest temperature
T_7 = lateral forearm temperature
T_8 = palm temperature
T_9 = ventral thigh temperature
T_{10} = dorsal calf temperature

Care was taken to measure T_1, T_6, and T_9 from skin surfaces exposed to irradiation and all other skin temperatures from nonirradiated surfaces. The percentage of irradiated body surface (13) was equal to the sum of the weighting factors for T_1, T_6, and T_9, thereby providing a continuously accurate calculation of mean skin temperatures during application and removal of radiant heat. Observations of irradiated skin temperature by thermocouple were in close agreement with those from a radiometer, after correcting for reflectance of the infrared radiation by the skin.

Tympanic membrane temperature (T_{ty}) was also recorded each minute. The tympanic probe consisted of tightly coiled leads which were held firmly in place by an ear plug incorporated onto the wire; this design permitted unrestricted movement on the part of the subject with consistent placement on the tympanum and minimal discomfort. Esophageal temperature (T_{es}) was continuously recorded from a thermocouple positioned at the level of the heart in many, but not all, experiments. T_{es} was used to represent internal temperature when available, since its response during the transient of exercise was observed to be faster than that of T_{ty}, suggesting a closer approximation to blood temperature; otherwise, T_{ty} was used as the representation of internal temperature.

TABLE 1. *Physical characteristics of subjects*

Subj	Age, yr	Ht, cm	Wt, kg	DuBois Body Surface Area, m²
DS	23	176	70.6	1.87
RL	21	188	77.1	2.05
CJ	26	170	56.7	1.67
DB	24	181	74.1	1.93
RP	26	188	95.1	2.19
PO	24	178	77.0	1.95

Local sweating rate was recorded from a 12-cm² skin area on each ventral thigh surface by parallel resistance hygrometry circuits (7, 10). Air of known humidity was drawn at 1.5 L/min through a sweat collection capsule on the thigh and then past a hygrosensitive element housed in a constant-temperature chamber (49° C) 1 m downstream from the capsule. Any water appearing on the skin surface underneath the capsule would be immediately evaporated into the airstream; thus, a change in the humidity of the airstream was resultant from sweating underneath the capsule and was detected as a resistance change in the hygrosensitive element. Each element was calibrated directly by pumping distilled water at known rates into the sealed capsules from a Harvard constant-infusion pump with a synchronous motor and variable speed control. Calibrations were checked periodically. Time lag of the system due to transport delay was 3 s.

At the beginning of each experiment, the subject was placed on the netting and, after all instrumentation was attached, initial base lines were established for all variables. After this period of lying quietly in the near neutral ambient, the subject was exposed to a preconditioning period of intense irradiation that lasted 4–10 min until obvious sweating activity was established. Gagge and Hardy (13) had reported that under the chosen experimental conditions a preconditioning, or "priming," period was necessary to elevate internal body temperature and stimulate sweat gland activity. Bickford (4) and Bullard (7) have attributed the lag in sweat secretion in an initial electrical stimulation of a population of sweat glands to the time required for filling the sweat ducts and hydrating the epidermis. After the preconditioning period, the subject was exposed to intense irradiation for 2–4 min, followed by 3- to 6-min recovery intervals between irradiations.

The relationships between $\bar{T}_s$, internal T, and local sweating rate were studied in five of the subjects in a number of experiments. After a minimum of six resting irradiation intervals, the subject mounted a bicycle ergometer adjacent to the bed and worked for 10–15 min at 60–80% $\dot{V}O_{2\,max}$ to elevate his internal temperature. He then immediately resumed the supine position and was again exposed to intermittent irradiation. With this technique, rapid alterations in skin temperature could be achieved in

the presence of a wide range of internal temperatures in resting man.

The influence of local skin temperature (T_{sl}) on local sweating rate at different levels of $\bar{T}_s$ was evaluated in three of the subjects. A two-chambered copper sweat collection capsule was placed on one thigh surface and the skin temperature underneath that capsule, continuously monitored by thermocouple, was clamped at different levels by perfusing the copper chamber of the copper capsule with warm or cold water. These subjects were then exposed to on-off irradiation as previously described and local sweating rate from the thermally clamped thigh recorded. Local sweating rate from the contralateral thigh, shielded from the radiant energy, was simultaneously obtained as a representation of control activity.

RESULTS

Sudden exposure to intense radiant heat caused an immediate increase in the temperature of irradiated skin. Nonirradiated skin areas did not show any consistent temperature alterations during the same brief intervals. T_{sl} under the capsule also remained relatively constant ($\pm 0.1^\circ$ C). The typical pattern of average skin temperature change during three consecutive heating-cooling cycles appears in Fig. 1. The rate of change of skin temperature, always greatest at the onset of heating or cooling, approached rates of 12° C/min for ventral surface temperature and 4° C/min for average skin temperature within the initial 10 s, and with time during both heating and cooling. Chest skin temperatures as high as 41.2° C were recorded, but $\bar{T}_s$ increases rarely exceeded 1.0° C during a 2-min irradiation and 1.4° C during 4 min of irradiation.

Also represented in Fig. 1 are the typical local sweating responses to rapid alterations in $\bar{T}_s$. In the "primed" subject, the onset of increased local sweating (and increased whole-body evaporative losses) occurred in conjunction with elevated $\bar{T}_s$, and rapid decreases in local sweating rates were associated with the cooling cycle. Energy dissipation calculated from both local evaporative losses and whole-body evaporation approximated the radiant energy added during the brief intervals. During rapid cycling of

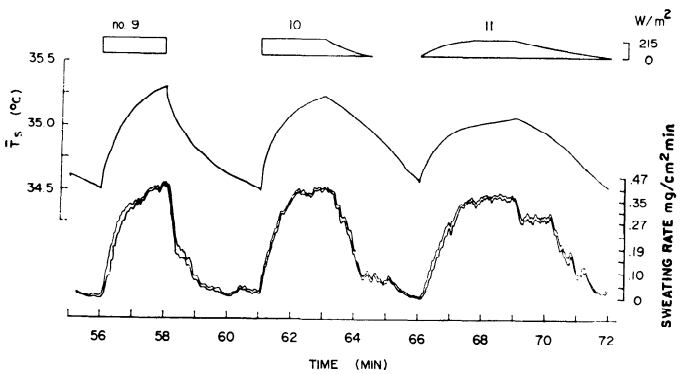

FIG. 1. Mean skin temperature and local sweating rate responses from 12 cm² of both ventral thigh surfaces during three consecutive exposures to 215 W/m² irradiation. Rate of cooling in the three exposures was progressively decreased by varying the mode of removal of irradiation. T_a = 27° C, T_{es} = 36.95° C.

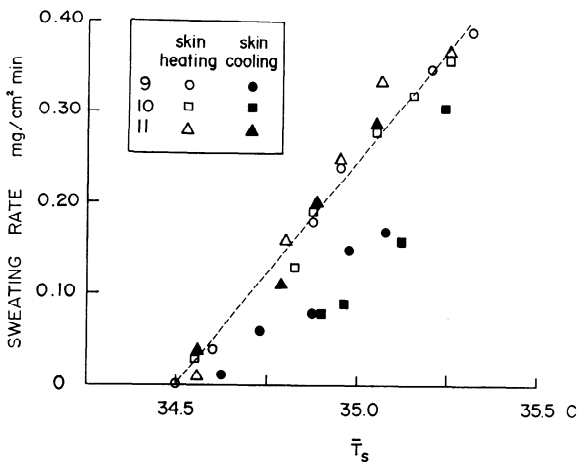

FIG. 2. Linear relationship between local sweating rate and mean skin cooling at low rate (filled triangles). Other filled symbols illustrate depression of sweating during increased rates of skin cooling. Data points taken at 20-s intervals from the three curves in Fig. 1.

$\bar{T}_s$, internal temperatures (T_{ty} and T_{es}) remained essentially constant.

The initial intervals during which local sweating rate did not follow increased $\bar{T}_s$ at the onset of irradiation were not utilized in the analysis, since these most likely represented conditions where the internal temperature-$\bar{T}_s$ relationship at the onset of skin heating was sufficiently below the combined threshold for sweating and/or the sweat ducts or epidermal layers were depleted of fluid and a finite time lag was necessary for their hydration. Once the onset of sweating coincided with the initiation of skin heating, this coincident relationship was maintained in subsequent intervals.

During skin heating, local sweating rate was directly related to the instantaneous value of $\bar{T}_s$ over wide ranges of $\bar{T}_s$ and sweating rate (Fig. 2), and independent of the rate of increase of skin temperature. During skin cooling, however, the proportional decline in sweating rate was greater than the decline in $\bar{T}_s$ in nearly all cases, as is also illustrated in Fig. 2. There was a good relation between the rate of decrease of T_s and the reduction in sweating rate from the steady-state $\bar{T}_s$-sweating rate regression line at lower and moderate levels of sweating, but this relation tended to fail during skin cooling in the presence of elevated internal temperatures where the sweating rate decrease became more linearly related to or even lagged the fall in $\bar{T}_s$. Elevated internal temperatures ($T_{ty} > 37.5^\circ$ C) during rest were usually the result of repeated heating intervals in ambients above thermoneutrality (28–30° C), where dissipation of heat by convection was reduced and $\bar{T}_s$ remained higher. In these circumstances, the sweating drive from internal temperature signals became increasingly important and, therefore, the drive from the skin relatively less important; hence, the drive from $d\bar{T}_s/dt$ information was likewise diminished in importance.

Deviations from the linear sweating rate-$\bar{T}_s$ graphs for each subject were tabulated at 15- to 30-s intervals from at least 2 separate days and plotted against $d\bar{T}_s/dt$. Figure 3 illustrates the absence of any effect of $+d\bar{T}_s/dt$ on local sweating rate and the inhibitory effect of $-d\bar{T}_s/dt$. The

instantaneous sweating rate-$\bar{T}_s$ points in Fig. 3 were gathered at 15-s intervals on 3 separate experimental days from a number of heating-cooling cycles. Ambients on these days were 25°, 28°, and 32° C. Without exception, when $-d\bar{T}_s/dt$ was greater than 0.2° C/min, local sweating rate was reduced in comparison to sweating during the steady state, when $d\bar{T}_s/dt = 0$. During $+d\bar{T}_s/dt$, local sweating rate was not affected by the rate component over a wide range in any subject. The slope of this relationship for subject *DS* (Fig. 3) was found to be −0.40 mg/cm²·min per −1.0° C per min of $\bar{T}_s$ change, when the rate of change exceeded −0.1° C/min. The similar relationship for the other subjects appears in Table 2.

After exercise, subjects maintained elevated levels of internal temperature and local sweating rate. In the presence of elevated T_{es}, local sweating rate was again linearly related to $\bar{T}_s$ during skin heating, but the slope of the sweating rate-$\bar{T}_s$ relationship was reduced. Replotting these data along T_{es} isotherms revealed that local sweating rate

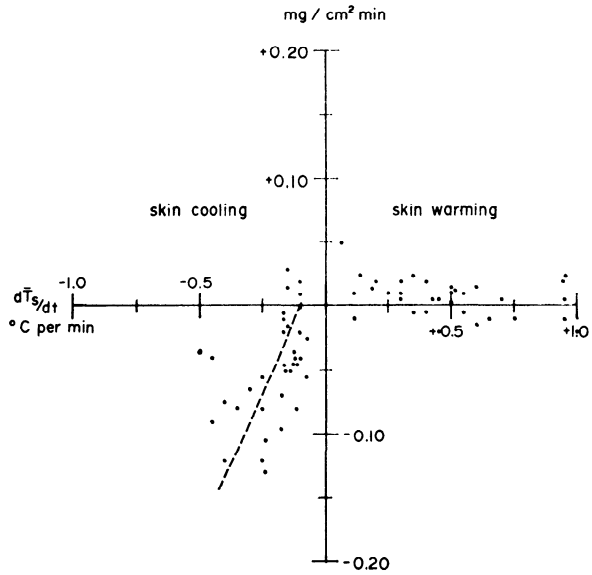

FIG. 3. Illustration of sensitivity of rate of sweating to rate of change of $\bar{T}_s(d\bar{T}_s/dt)$ in *subject DS*. Points represent the deviation from the linear sweating rate-$\bar{T}_s$ relationships at 15- to 30-s intervals from a number of irradiation cycles in ambients of 25°, 28°, and 32° C. Characteristics of rate sensitivity for all subjects appears in Table 2.

TABLE 2. *Average deviation from linear sweating response of six resting (T_{tu} < 37.5° C) subjects during skin cooling*

Subj	Rate Control Constant (γ), mg/cm²·min per °C per min	Rate Threshold (r_0), °C per min	Resting $\bar{T}_s$ Below Which No Sweating Occurs ($\bar{T}_{s_0}$), °C
DS	−0.40	−0.10	35.5
RL	−0.50	−0.10	34.0
CJ	−0.32	−0.19	34.3
DB	−0.22	−0.18	33.7
RP	−0.18	−0.35	34.3
PO	−0.16	−0.22	34.5

Instantaneous $\bar{T}_s$-sweating rate points obtained at 15- to 30-s intervals over 2–3 min from no fewer than 10 cooling cycles in at least two different ambients.

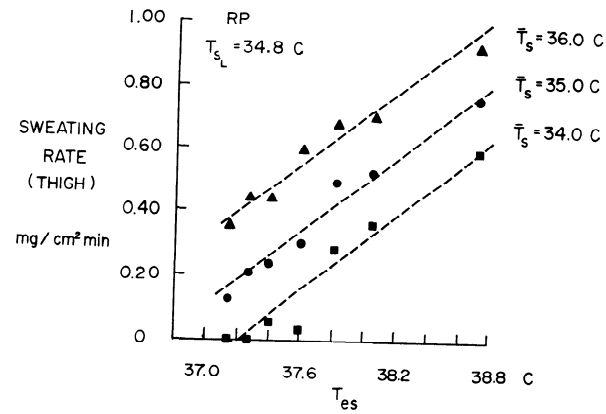

FIG. 4. Effect of T_{es} and $\bar{T}_s$ on local sweating rate with local (under sweat collection capsule) skin temperature = 34.8° C.

was directly related to T_{es}, with the effect of $\bar{T}_s$ shifting this relationship in the appropriate direction (Fig. 4).

Clamping T_{s_l} at different levels during skin heating altered the slope of the linear sweating rate-$\bar{T}_s$ relationship, but not the T_{s_l} threshold at constant internal temperatures (Fig. 5). This verified that the primary drive affecting the rate of local sweat secretion during skin heating in the presence of constant $T_{internal}$ was provided by $\bar{T}_s$, with T_{s_l} modifying this drive. Replotting these data revealed a nonlinear relationship between local sweating rate and T_{s_l} at any level of $\bar{T}_s$, verifying previous observations of Bullard et al. (9, 10). There was interindividual consistency in the local sweating rate-T_{s_l} relationship, since the data from all subjects could be described by a single exponential function.

DISCUSSION

Once the sweating mechanism had been sufficiently primed in the presence of a constant internal thermal drive, sweating rate was related either directly to the average temperature of the skin or to a derivative thereof. By effectively separating the peripheral and central thermal inputs to the thermoregulatory center, the modifications in rate of sweat secretion caused by irradiation were clearly mediated entirely through peripheral thermoreception. The relationship between sweating rate and $\bar{T}_s$ confirmed Gagge's (12) report of increased evaporative losses in subjects exposed to high radiant heat, and supported Gagge and Hardy's (13) observation that under conditions where heat storage was negligible, the change in evaporative loss caused by thermoregulatory sweating was quantitatively related to the effective radiant flux. These observations also verified Kerslake's (20) report of a 1.6-s physiological delay between cyclical irradiation and sweat production. The present data are added evidence in contradiction of Benzinger's (3) conclusions regarding the noninvolvement of peripheral thermoreceptors at skin temperatures greater than 33° C in the control of sweating.

By independently varying $\bar{T}_s$ and T_{es}, local sweating rate was shown to be linearly related to $(\bar{T}_s - \bar{T}_{s_0})$ when T_{es} and T_{s_l} were constant (only during skin heating) and linearly related to $(T_{es} - T_{es_0})$ when $\bar{T}_s$ and T_{s_l} were constant (Fig. 4). The interaction between T_{es} and $\bar{T}_s$ represented a

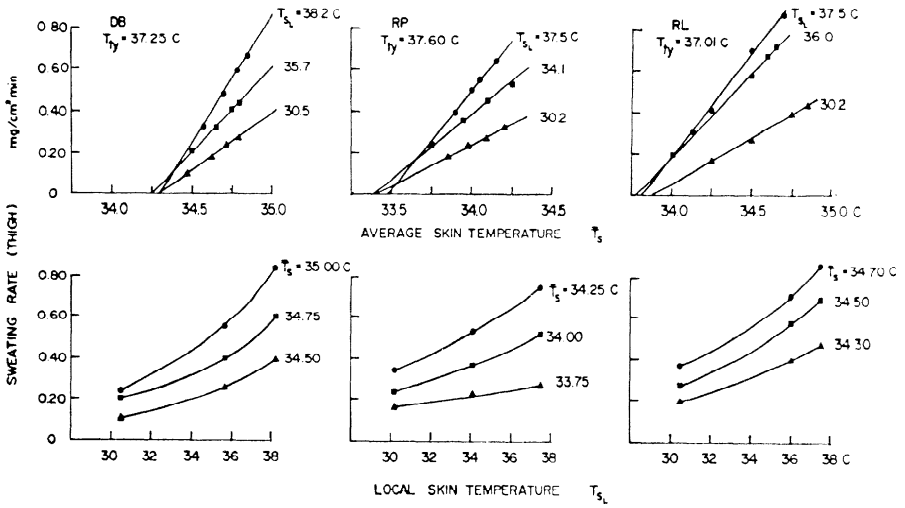

FIG. 5. Influence of local skin temperature (T_{s_l}) on linear sweating rate-$\bar{T}_s$ relationships during skin heating in three subjects (*upper graphs*). Replotting these data illustrates exponential influence of T_{s_l} on local sweating rate at any level of $\bar{T}_s$.

summation of temperature signals in the determination of efferent activity. A summation model for evaporative heat loss has been proposed by Stolwijk and Hardy (29) for rest and by Stolwijk et al. (31) for exercise. However, they noted that other relationships such as multiplicative ones have been suggested and that internal and average skin temperatures may not be the only factors influencing evaporative losses in man. This summative relationship between T_{es} and $\bar{T}_s$ in the determination of sweating rate when T_{s_l} variations were clamped at a constant level was observed in all five subjects studied, despite individual differences in the proportional control constants α and β. The mathematical expression of this interrelation between these temperatures was as follows:

$$\text{local sweating rate} = (\alpha[T_{es} - T_{es_0}] + \beta[\bar{T}_s - \bar{T}_{s_0}]) \quad (1)$$

where T_{es_0} and $\bar{T}_{s_0}$ represent threshold temperatures for sweating in the steady state of rest.

The effect of varying the average skin temperature by skin heating in the presence of different, fixed local skin temperatures (with internal temperature constant) is shown in the upper graphs of Fig. 5. Rather large modifications in local sweating rate were observed in the presence of a constant sweating drive from internal and average skin temperature signals in response to moderate alterations in local skin temperature. This observation offered a partial explanation for the diversity in the models describing the regulation of sweating, because it was apparent that the model contained both additive and multiplicative elements, as follows:

$$\text{local sweating rate} = (\alpha[T_{es} - T_{es_0}] + \beta[\bar{T}_s - \bar{T}_{s_0}])L \quad (2)$$

where L represents the local skin temperature effect. The inclusion of both additive and multiplicative elements in this model tends to unify the viewpoints of Hammel (14), Stolwijk and Hardy (29), and Stolwijk et al. (31), whose descriptions of the heat loss response can be readily represented as a summation between the primary thermal inputs, with the observations of Bullard et al. (9, 10), Hardy and Stolwijk (16), and Wyndham and Atkins (33) that there is a multiplicative effect of these thermal inputs. Stitt et al. (28) have described the control of sweating in the squirrel monkey as a summation between thermal inputs from the hypothalamus and the skin, and Nadel and Stitt (24) have reported that the sweating rate from the foot of squirrel monkeys was related to local temperature in the presence of constant internal and average skin temperatures; thus, the elements controlling sweating rate in man have been reported as participating in a like manner in another species as well.

The nature of the local skin temperature effect on local sweating rate has been described by Bullard et al. (9) as a nonlinear relationship, with increasing increments in local sweating rate per unit of local temperature increase. The present data describing the T_{s_l}-sweating rate relation (Fig. 5, lower graphs) were relatively consistent with Bullard's data, although the Q_{10} of sweat gland activity in the present study was slightly lower. The average sweating rate Q_{10} when internal temperature was constant for the three subjects in the present study was 3.0 (subject range 2.6–3.5), with each subject showing consistency over a wide range of $\bar{T}_s$. Calculations from Bullard's curves (one subject) show an average Q_{10} between 4 and 5 for different levels of $\bar{T}_s$. This discrepancy may be attributed to *1)* the differential placement of the sweat collection capsule, encompassing a population of sweat glands innervated by a considerably different concentration of nerve branchlets, or *2)* the fact that the calculation of the Q_{10} from the derivative of local sweating rate with respect to local skin temperature is very sensitive to minor alterations in average skin temperature. By deriving the local sweating rate-T_{s_l} functions from the linear sweating rate-$\bar{T}_s$ relations at given levels of T_{s_l}, the small variations in $\bar{T}_s$ which would occur over the time course of an experiment and the effects of these variations have been minimized. Calculations from the whole-body data of Wyndham and Atkins (33) using our model revealed a Q_{10} effect of 2.7, a surprisingly close fit with the calculated Q_{10} from this study considering the differences between local sweating and total evaporative measurements.

The local temperature effect (L in *eq 2*) was determined to be an exponential, with the local temperature error signal in the numerator of the exponent and the Q_{10} constant, δ, in the denominator. The calculation from the three subjects revealed $\delta = 9.1$ when $L = e^{(T_{s_l} - \bar{T}_{s_0})/\delta}$. The consistency in the sweating rate-T_{s_l} data between subjects

permitted derivation of δ from the pooled data. The similarity between subjects supported the concept that local temperature has its effect on sweating rate at the neuroglandular junction, where physicochemical laws tend to govern the reaction rate, rather than within the central controller, which shows significant interindividual variability. The mode of action at the neuroglandular junction has yet to be determined, as Ogawa (27) has suggested that high local skin temperature may act on specific receptor mechanisms of glandular cells to increase their sensitivity to specific stimuli, rather than by simply accelerating cellular metabolism.

The observation of a rate of change of $\bar{T}_s$ effect on local sweating rate during skin cooling supported earlier reports of such an effect (2, 32). There was no effect of rate of change of $\bar{T}_s$ on rate of sweat secretion during skin warming. This observation indicated that the thermoregulatory center processed peripheral thermal information somewhat differently during skin heating and skin cooling. The lack of correlation between alterations in skin temperature and weight loss observed by Colin and Houdas (11) during a heating transient in five of eight subjects could be attributed to the time lag associated with the priming phenomenon rather than noninvolvement of skin thermoreceptors.

Although the firing rate of warm and cold sensitive afferents have been shown to be markedly elevated during rate of change of skin temperature (17, 18), Banerjee et al. (2) noted that the temporal characteristics of the neural patterns during the transient have not been shown to correspond with the time course of the inhibition of sweating. Local T_s transients induced by Banerjee et al. (2) were 30 s–2 min, whole $\bar{T}_s$ transients utilized by Wurster and McCook (32) lasted 10–15 min. $\bar{T}_s$ transients in the present study were 2–4 min. Alterations in firing rate of cutaneous thermosensitive afferent fibers during thermal transients were only reported for 2- to 4-s intervals by Hensel and co-workers (17, 18). Firing rate during extended thermal transients, such as used in the above studies, has not been reported. It is likely that the various thermosensitive fibers in any area of skin display a wide diversity in their activity during transient thermal situations. The similarity between firing rate of cold sensors as reported by Hensel and coworkers (17, 18) and pattern of sweating rate during cooling transients may only indicate that there are dynamic overshoots in physiological systems at several levels. The absence of similarity between these parameters on the warm side suggested that the control over rate of local sweat secretion was not exclusively dependent on firing rate of peripheral thermoreceptors during transients. Rather, a combination of input from the thermosensitive afferent fibers, integration in the thermoregulatory center, and mechanical limitations between the motor activity and actual liberation of sweat were responsible for the sweating response during transients and the differences in responsiveness between heating and cooling transients. Further insight into the control of sweating during thermal transients might be attained with a nerve-gland preparation.

If the $d\bar{T}_s/dt$ effect on local sweating rate were mediated centrally, the rapidly changing skin temperature could either be acting to *a*) reduce the gain of the controlling system, thereby assigning the error signal reduced importance, *b*) stimulate an upward shift in hypothalamic threshold temperature for sweating, thereby reducing the error signal which drives sweating activity, or *c*) provide a signal to the integrator in conjunction with the $\bar{T}_s$ error signal. Since the entire sweating variability in the present set of conditions at constant local skin temperature was directly accounted for by the change in $\bar{T}_s$ and its negative rate derivative, the latter would be the most likely explanation. The observation that the rate effect on sweating rate was diminished when the internal temperature was elevated above 37.5° C would support this interpretation, since the total input from the skin was relatively less important in the determination of sweating rate in the presence of an elevated internal temperature.

Other evidence that the $d\bar{T}_s/dt$ effect on sweating rate was of central rather than local origin was that skin temperature under the shielded sweat capsule was relatively constant during the alterations in $\bar{T}_s$. If the rate effect were of local origin, it could not have been observed under such circumstances. Brown and Brengelmann (6) have demonstrated an overshoot in metabolic response during rapid skin cooling, further indicating that the rate effect was through centrally mediated rather than local activities.

Thus, the total influence of the average skin temperature error signal within the central integrator was expanded to include the rate of change information, as follows:

$$\beta(\bar{T}_s - \bar{T}_{s_0} + \gamma[d\bar{T}_s/dt - r_0]) \qquad (3)$$

where the average values of γ (the rate constant), $\bar{T}_{s_0}$, and r_0 for each subject appear in Table 2. The rate component has its effect only when $d\bar{T}_s/dt$ exceeds its threshold value, r_0, during skin cooling. The inclusion of a rate of change component in the model describes a control system that is highly responsive to sudden decreases in ambient and, therefore, average skin temperatures.

A curious phenomenon occasionally observed was a rebound or sudden increase in sweating following the marked depression during rapid skin cooling. As $d\bar{T}_s/dt$ was reduced during the 2nd or 3rd min of cooling, a burst of activity from the sweat glands elevated sweating rate to levels that would have been predicted directly from $\bar{T}_s$. These rebounds were transient in nature and did not persist for intervals greater than 20–30 s. Rebound sweating probably represented the overriding of the rate component influence on sweating rate by the steady state or error component influence. Because of the transience and irregularity of rebound sweating, quantification of this phenomenon was not attempted.

A synthesis of the information described in *equations 1–3* reveals the major determinants of local sweating rate to be interrelated as follows:

$$\text{local sweating rate} = [\alpha(T_{es} - T_{es_0}) + \beta(\bar{T}_s - \bar{T}_{s_0} + \gamma[d\bar{T}_s/dt - r_0])]e^{(\bar{T}_{s_i} - \bar{T}_{s_0})/\delta} \qquad (4)$$

Total evaporative heat loss data obtained in this laboratory during steady-state resting (ref 16, Fig. 11, 13; ref 29, Fig. 17; ref 31, Fig. 2) exposures in a wide range of ambients were compared to the model represented by *equation 4*. These data were readily fit to the skeleton equation by utilizing the following constants:

$$E \text{ in W/m}^2 = (197(T_{in} - 36.7) + 23(\bar{T}_s - 34.0))e^{(\Sigma \text{ weighted } T_{sl} - 34.0)/10} \quad (5)$$

Figure 6 illustrates the dependence of these steady-state evaporative heat loss data on internal and skin temperatures, with the solid lines drawn from *equation 5*. It is apparent that the different $\bar{T}_s$ isotherms have different slopes as well as intercepts. The following conclusions from the local sweating information can then be extended to include the control of total body sweating as estimated from weight loss in a steady state during rest and exercise: *1*) at constant skin temperature, sweating is proportional to internal temperature; *2*) at constant internal temperature, sweating is proportional to mean skin temperature; and *3*) at a given combination of internal and mean skin temperatures, local sweating is dependent on local skin temperature with a Q_{10} of slightly less than 3.

It is clear that Fig. 6 has included the local skin temperature multiplier effect from the nonparallel splay of the $\bar{T}_s$ isotherms. If the relationship between internal and skin temperatures were entirely multiplicative, the T_{es} sweating threshold for all levels of $\bar{T}_s$ would be constant; obviously, this is not the case.

The output from the central controller toward the determination of whole-body sweat loss can be found by eliminating the peripheral multiplier influence from *equation 5*, and this relation appears in Fig. 7. This interaction has only been validated for the steady state; the relation during transients such as skin cooling, as illustrated previously, or the onset of exercise introduce new inputs into the control mechanism which must be considered.

In conclusion, the partitioning of the major inputs to the thermoregulatory center coupled with continuous estimates of the efferent outflow from this center (measurement of rate of local sweat secretion) has permitted certain insights into the controlling mechanism. Additive as well as multiplicative aspects of the integration of central and peripheral signals in the determination of the sweating response have been identified. The relationship between internal and mean skin temperatures in the control of local sweating rate was found to be a summation while the local skin temperature contribution was identified as a modifying effect upon the output from the central controller, acting as a multiplier in the determination of local sweating rate. The rate of change of skin temperature was also shown to provide a significant signal to the integrator during skin cooling. Moreover, total evaporative data taken from steady-state experiments of this laboratory (16, 29, 31) and others (26, 33) could readily be described by the equation derived from the interrelations between internal and skin temperatures and local sweating rate. There no doubt are other thermal and/or nonthermal inputs that participate in the regulation of sweating, but these may be difficult to partition and may operate only during exceptional circumstances. Considerably more data are required for a complete description of the regulation of sweating, particularly in the area of regulation during transients.

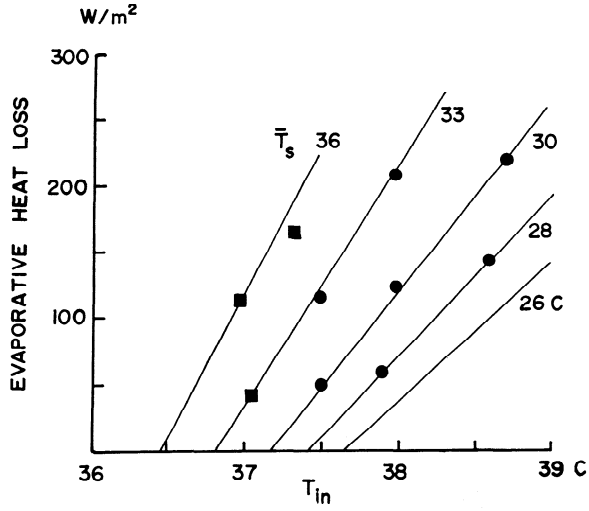

FIG. 6. Dependence of total evaporative heat loss on internal and skin temperatures. Data points obtained from steady-state resting (filled squares) and exercising (filled circles) exposures in a wide range of ambients (16, 29, 31). Solid lines calculated from $E = (197(T_{in} - 36.7) + 23(\bar{T}_s - 34.0))e^{(\Sigma \text{ weighted } T_{sl} - 34.0)/10}$.

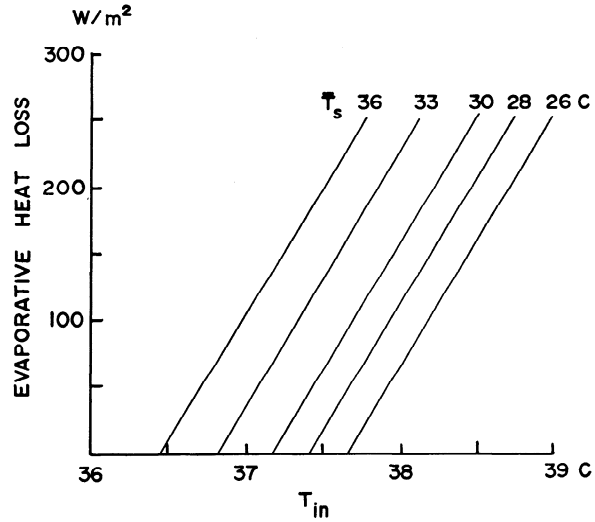

FIG. 7. Output from central controller toward determination of total evaporative heat loss calculated by eliminating local effect. Solid lines calculated from $E = 197(T_{in} - 36.7) + 23(\bar{T}_s - 34.0)$.

The authors acknowledge the many constructive comments of Professor John W. Mitchell.

This study was supported in part by Public Health Service Grants ES-00123 and GM-45192 and National Aeronautics and Space Administration Contract NAS-9-4531.

Present address of R. W. Bullard: Dept. of Anatomy and Physiology, Indiana University, Bloomington, Ind. 47401.

Received for publication 28 January 1971.

REFERENCES

1. ALBERT, R. E., AND E. D. PALMES. Evaporation rate patterns from small skin areas as measured by an infrared gas analyzer. *J. Appl. Physiol.* 4: 208–214, 1951.
2. BANERJEE, M. R., R. ELIZONDO, AND R. W. BULLARD. Reflex responses of human sweat glands to different rates of skin cooling. *J. Appl. Physiol.* 26: 787–792, 1969.
3. BENZINGER, T. H. On physical heat regulation and the sense of temperature in man. *Proc. Natl. Acad. Sci., US* 45: 645–659, 1959.

4. BICKFORD, R. G. The mechanism of local sweating in response to Faradism. *Clin. Sci.* 3: 337–341, 1938.
5. BREBNER, D. F., AND D. McK. KERSLAKE. The relation between sweat rate and weight loss when sweat is dripping off the body. *J. Physiol., London* 202: 719–735, 1969.
6. BROWN, A. C., AND G. L. BRENGELMANN. The interaction of peripheral and central inputs in the temperature regulation system. In: *Physiological and Behavioral Temperature Regulation*, edited by J. D. Hardy. Springfield, Ill., Thomas, 1970, chapt. 47.
7. BULLARD, R. W. Continuous recording of sweating rate by resistance hygrometry. *J. Appl. Physiol.* 17: 735–737, 1962.
8. BULLARD, R. W. Studies on human sweat gland duct filling and skin hydration. *J. Physiol., Paris*. In press.
9. BULLARD, R. W., M. R. BANERJEE, F. CHEN, R. ELIZONDO, AND B. A. MACINTYRE. Skin temperature and thermoregulatory sweating: a control systems approach. In: *Physiological and Behavioral Temperature Regulation*, edited by J. D. Hardy. Springfield, Ill., Thomas, 1970, chapt. 40.
10. BULLARD, R. W., M. R. BANERJEE, AND B. A. MACINTYRE. The role of the skin in negative feedback regulation of eccrine sweating. *Intern. J. Biometeorol.* 11: 93–104, 1967.
11. COLIN, J., AND Y. HOUDAS. Initiation in sweating in man after abrupt rise in environmental temperature. *J. Appl. Physiol.* 20: 984–990, 1965.
12. GAGGE, A. P. Body perspiration on exposure to thermal radiation (Abstract). *Federation Proc.* 23: 473, 1964.
13. GAGGE, A. P., AND J. D. HARDY. Thermal radiation exchange of the human by partitional calorimetry. *J. Appl. Physiol.* 23: 248–258, 1967.
14. HAMMEL, H. T. Regulation of internal body temperature. *Ann. Rev. Physiol.* 30: 641–710, 1968.
15. HARDY, J. D. Physiology of temperature regulation. *Physiol. Rev.* 41: 521–606, 1961.
16. HARDY, J. D., AND J. A. J. STOLWIJK. Partitional calorimetric studies of man during exposures to thermal transients. *J. Appl. Physiol.* 21: 1799–1806, 1966.
17. HENSEL, H. Electrophysiology of thermosensitive nerve endings. In: *Temperature, Its Measurement and Control in Science and Industry*, edited by J. D. Hardy. New York: Reinhold, 1963, vol. 3, part 3, p. 191–198.
18. HENSEL, H., A. IGGO, AND J. WITT. A quantitative study of sensitive cutaneous thermoreceptors with C afferent fibers. *J. Physiol., London* 153: 113–126, 1960.
19. HERTZMAN, A. B., W. C. RANDALL, C. N. PEISS, AND R. SECKENDORF. Regional rates of evaporation from the skin at various environmental temperatures. *J. Appl. Physiol.* 5: 153–161, 1953.
20. KERSLAKE, D. McK. Thermal radiation in the investigation of cutaneous vasomotor and sudomotor control. In: *Thermal Problems in Aerospace Medicine*, edited by J. D. Hardy. Maidenhead, England: Technivision Services, 1968, p. 57–70.
21. MACINTYRE, B. A., R. W. BULLARD, M. BANERJEE, AND R. ELIZONDO. Mechanism of enhancement of eccrine sweating by localized heating. *J. Appl. Physiol.* 25: 255–260, 1968.
22. NADEL, E. R., AND S. M. HORVATH. Peripheral involvement in the thermoregulatory response to an imposed heat debt in man. *J. Appl. Physiol.* 27: 484–488, 1969.
23. NADEL, E. R., S. M. HORVATH, C. A. DAWSON, AND A. TUCKER. Sensitivity to central and peripheral thermal stimulation in man. *J. Appl. Physiol.* 29: 603–609, 1970.
24. NADEL, E. R., AND J. T. STITT. Control of sweating in the squirrel monkey (Abstract). *Physiologist* 13: 267, 1970.
25. NADEL, E. R., AND J. A. J. STOLWIJK. Physiologic control of rate of local sweat secretion in man. *J. Physiol., Paris*. In press.
26. NIELSEN, B., AND M. NIELSEN. Influence of passive and active heating on the temperature regulation of man. *Acta Physiol. Scand.* 64: 323–331, 1965.
27. OGAWA, T. Local effect of skin temperature on threshold concentration of sudorific agents. *J. Appl. Physiol.* 28: 18–22, 1970.
28. STITT, J. T., E. R. ADAIR, E. R. NADEL, AND J. A. J. STOLWIJK. The relation between behavior and physiology in the thermoregulatory response of the squirrel monkey. *J. Physiol., Paris*. In press.
29. STOLWIJK, J. A. J., AND J. D. HARDY. Partitional calorimetric studies of responses of man to thermal transients. *J. Appl. Physiol.* 21: 967–977, 1966.
30. STOLWIJK, J. A. J., AND J. D. HARDY. Temperature regulation in man—a theoretical study. *Arch. Ges. Physiol.* 291: 129–162, 1966.
31. STOLWIJK, J. A. J., B. SALTIN, AND A. P. GAGGE. Physiological factors associated with sweating during exercise. *Aerospace Med.* 39: 1101–1105, 1968.
32. WURSTER, R. D., AND R. D. MCCOOK. Influence of rate of change in skin temperature on sweating. *J. Appl. Physiol.* 27: 237–240, 1969.
33. WYNDHAM, C. H., AND A. R. ATKINS. A physiological scheme and mathematical model of temperature regulation in man. *Arch. Ges. Physiol.* 303: 14–30, 1968.