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Sweating and Sweat Decline of Resting Men in Hot Humid Environments

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Summary. Time courses of the rates of sweating, drippage and evaporation were studied in hot humid environments. Resting subjects wearing only briefs were exposed to humid conditions, before, during and after humid heat acclimation, so that different levels of skin wettedness could be studied on the entire body. In addition, local sweat rate was measured on the right upper limb, which was enclosed in a highly ventilated arm-chamber. Thus, the arm remained drier than the rest of the body surface. The results confirm that sweating efficiency is related to the skin wettedness level, and that the decline in intensity of sweating is linked to maximal inefficient sweat drippage before the onset of hidromeiosis. Comparison of general and local sweat decreases confirms that hidromeiosis originates from skin hydration. However it is likely that some factor related to blood content acts on the hidromeiotic process, at least after humid heat acclimation.

Key words: Dripping sweat – Skin wettedness – Local sweat rate – Hidromeiosis

Introduction

The evaporative cooling rate of a fully wetted skin is expressed as the maximum evaporative power (E_{max}). In fact, the homeothermic mechanisms of man exposed to hot environments induce an evaporation of excreted sweat at a lower rate than E_{max}. The observed skin evaporative rate is classically described as, (Gagge 1937):

$$E_{sk} = h_e \cdot w \cdot (P_{sk} - P_a)$$

where: E_{sk} is the skin evaporation; h_e, the evaporative heat transfer coefficient; w, the skin wettedness and $(P_{sk} - P_a)$ the difference between skin and water vapour pressure.

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In all ambient conditions, the degree of skin wettedness (w) is calculated from the ratio between the actual skin evaporation (E_{sk}) and the maximum evaporative capacity (E_{max}).

If skin evaporation is less than maximum, the skin wettedness, when varying from 0 to 1, is representative of the intensity of the thermal strain and therefore, the concept of wettedness or that of relative humidity of the skin (Mole 1948) becomes important in thermophysiological studies.

For humans, it has been shown (Clifford et al. 1959; Hall 1963; Hénane 1972; Kamon et al. 1978); and quantified (Givoni 1963; Kerslake 1972; Candas et al. 1979a, b) that the degree of skin wettedness reached in humid heat conditions, contributes to some oversweating which is lost by drippage, and which is ineffective for body cooling. In addition, it has been hypothesized that, due to the film of water on the skin, all heat loss is not effective in human body cooling (Kobayashi et al. 1980). Also, reports have demonstrated the important role of skin wettedness and of skin hydration in sweat secretion (Peiss et al. 1956; Nadel and Stolwijk 1973), and in consecutive evaporative heat loss (Givoni 1963; Kobayashi et al. 1980).

It has been found that high degrees of skin wettedness induce epidermal skin hydration which is associated with a progressive decrease in sweating, called hidromeiosis (Ladell 1945; Randall and Peiss 1957; Hertig et al. 1961; Brebner and Kerslake 1964; Brown and Sargent 1965). This phenomenon, traditionally considered to be due to sweat gland fatigue (Gerking and Robinson 1946; Thaysen and Schwartz 1955; Wyndham et al. 1966), has also been often considered as a dysfunction of the thermoregulatory processes. Sargent (1962) stated that hidromeiosis could be the reflection of an overshoot in sweating in severely humid atmospheres. We described an increase in the sweat decline rate (Candas et al. 1980) with acclimation, and this sweat decline rate was very well correlated with the rate at which the unevaporated sweat was dripping off the body before this sweating decline occurred. Thus, because it has a beneficial effect by saving inefficient water loss, hidromeiosis would not reflect functional disturbances but would appear as a regulatory feedback from the wetted skin surface to prevent excessive dehydration.

Our experiments have had as their objective the identification of the mechanisms involved in the hidromeiosis phenomenon. The main purpose of these experiments was to determine both the sweat rate of the whole body surface and the sweat rate of the right upper limb surface, each being experimentally maintained at different levels of wettedness.

Methods

1. Subjects

Experiments were carried out on four healthy male subjects whose physical characteristics are set out in Table 1.

Subjects S1 and S3 were exposed to humid heat from 9:00 to 11:30 and S2 and S4 from 15:00 to 17:30. For all experiments, the subjects wore only briefs and were exposed before and after passive

Table 1. Physical characteristics of subjects. Evaporative heat transfer coefficient (h_e) was calculated from experimental results obtained in acclimated subjects exposed to condition H6 (Table 2), assuming that in this conditions the skin was fully wetted

Subject (no)	Age (yr)	Height (m)	Weight (kg)	A_D (m^2)	h_e $W \cdot m^{-2} \cdot mmHg^{-1}$
S_1	27	1.77	65	1.80	8.0
S_2	27	1.71	66	1.77	8.3
S_3	23	1.84	74	1.96	7.7
S_4	25	1.77	63	1.78	8.1

Table 2. Ambient conditions with increasing humidity. It has been considered that condition H6 imposed a fully wetted skin after acclimation, due to high ambient vapor pressure

Condition	H1	H2	H3	H4	H5	H6
T_a, °C			43			
V_a, $m \cdot s^{-1}$			0.4			
P_a, mmHg	15.0	23.7	27.5	30.0	32.0	34.8

humid heat acclimation. Prior to acclimation, experiments were performed twice a week, and after acclimation they were carried out every day.

During 10 consecutive days, acclimation consisted of daily exposures (165 minutes) to the following ambient conditions: $T_a = T_w = 48°$ C; $P_a = 28$ mmHg and $V_a = 0.3$ $m \cdot s^{-1}$. These conditions produced acclimation at high levels of skin wettedness (w # 100%).

During their stay in the climatic chamber, subjects were asked to keep their body movement to a minimum. No drinking was allowed inside the chamber, but before and after heat exposures, subjects drank ad libidum. No measurement of urinary volume was made, and subject's hydration was not controlled.

2. *Experimental Conditions*

The routine for each experimental day was the following: before being exposed to hot humid conditions, the subject laid on the hammock in the climatic chamber for 45 min under a thermoneutral condition: $T_a = T_w = 28°$ C; $P_a = 15$ mmHg and $V_a = 0.3$ $m \cdot s^{-1}$.

Two series of experiments were performed: the first consisted of a series during which body sweating was measured as a whole; and the second consisted of a series during which local arm sweating was measured separately from the body sweat rate.

a. First Series. During these experiments, air humidity was the only variable that changed from one experimental day to another. The humid environments to which subjects were exposed are given in Table 2. For technical reasons, we were unable to experiment on unacclimated subjects in the H3 condition.

b. Second Series. The second series of experiments (Table 3) was carried out specifically to determine the local arm sweat rate. The right upper limb was enclosed in a plexiglas chamber, and the moisture content of the effluent air was measured with a dew-point hygrometer (Libert et al. 1979). The air which passed over the enclosed arm was heated, so that the arm skin temperature was kept constant at 38° C. In contrast to the low air velocity around the body surface (0.3 $m \cdot s^{-1}$), the air velocity in the arm-chamber was high (equal to 1.3 $m \cdot s^{-1}$ around the arm surface).

Table 3. Ambient conditions imposed before and after acclimation. Local sweat rate was measured for the study of hidromeiosis. Arm skin temperature was kept constant at 38° C to avoid local temperature variation effect

	$T_a = T_w$, °C	P_a, mmHg	V_a, $m \cdot s^{-1}$
A1	43	32.0	0.3
A2	48	28.0	0.3

3. Physiological Recordings

During acclimation as well as during all experimental days, core and 15 local skin temperatures were continuously recorded from thermistors (sensitive to 0.01° C variation). Mean skin temperature ($\bar{T}_{sk}$) was calculated by the weighting method of Hardy and Dubois.

This calculated value of $\bar{T}_{sk}$ led to the determination of the skin vapor pressure (P_{sk}) which allowed us to calculate E_{max}. Skin wettedness was then derived by E_{sk}/E_{max}.

The sweat rate was assumed to be equal to the reduction in body weight which was recorded by a balance. No correction was made for respiratory water loss or for the mass of sweat lying on the skin surface. An illustration of this balance in addition to the hammock used in our study, can be found in a previous publication (Candas et al. 1979b). The drippage rate was deduced from continuous recordings of the total amount of sweat dripping from the body. Sweat drippage was collected in an oil pan which was also attached to a balance. These two balances had a 2 g sensitivity and a 1 g precision. Whole body sweat rate and dripping sweat rate were calculated minute by minute with a linear regression for 19 consecutive minutes (the slope of each regression gives the instantaneous sweat rate at the 10th minute of regression, which is the central point of the regression lines). The evaporative rate (E_{sk}) was then obtained by substracting the dripping rate from the body sweat rate.

In addition, during the second series of experiments in which the subject had his right arm in an arm chamber, the calculated local arm sweat rate (or the evaporative rate, since there was no drippage from this enclosed arm) was always substracted from the whole body sweat rate, in order to give the sweat rate for the rest of the body.

Results

Sweat Rate Evolution

During each humid exposure, after the onset of sweating, the sweat rate increased during the first hour and than remained relatively constant for 10–15 min. In all cases where dripping sweat was observed, a decrease in sweat rate was obtained after 60–80 min of heat exposure, and this sweat decline represents the hidromeiosis phenomenon. The typical time course examples of sweat, evaporative and drippage rates given in Fig. 1, were recorded during the acclimation exposures.

The two phases of sweat rate evolution appear clearly in this illustration; after the initial increase in sweating during the first hour, the sweat rate decreased continuously with time. The sweat decline always reduced the unevaporated output; however, the evaporative sweat rate remained constant throughout the heat exposure. The greater rate of sweating on the last two days of acclimation (compare Fig. 1a–b) was accompanied by a greater rate of

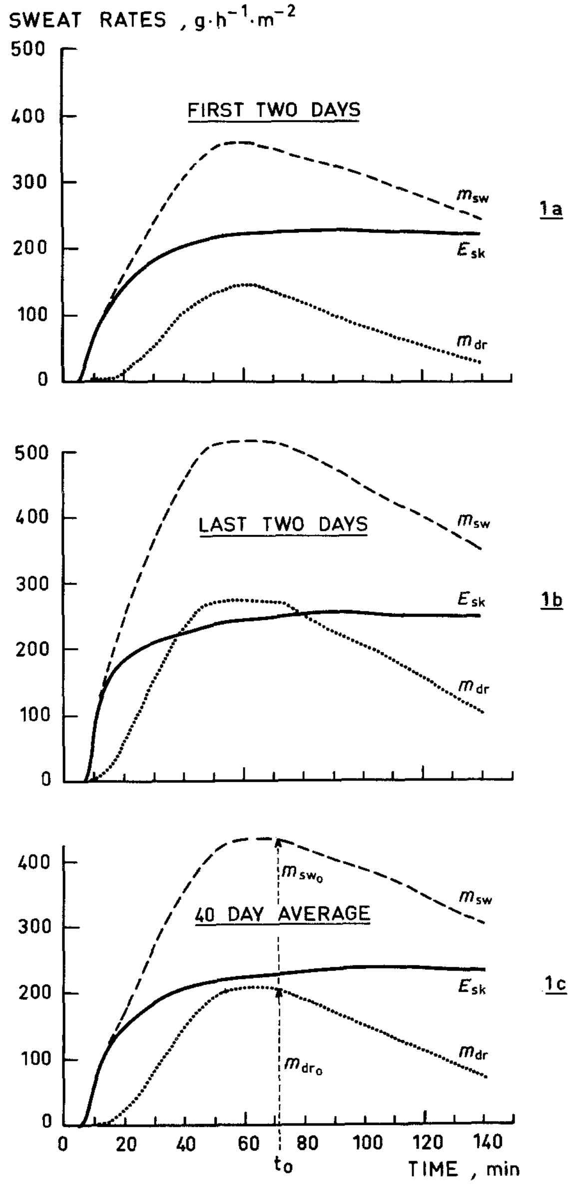

Fig. 1. Time course of sweating rates (m_{sw}) evaporative rates (E_{sk}) and dripping rates (m_{dr}). **a** average during the first two days of acclimation (four subjects); **b** average on the ninth and tenth days, and **c** mean time course from the acclimation period (four subjects during 10 days)

drippage. However, a small increase in the rate of evaporation ($18\ g \cdot h^{-1} \cdot m^{-2}$) was observed during repeated heat exposures. This is probably due to a slight increase in convective and radiative heat gains resulting from a decrease in $\bar{T}_{sk}$ with acclimation. In addition, this increase may be partly due to a slight increase in metabolic heat production, which is linked to a higher sweat output. It is obvious that evaporation could not be greatly increased in our conditions since high ambient vapor pressure leads to fully wetted skin.

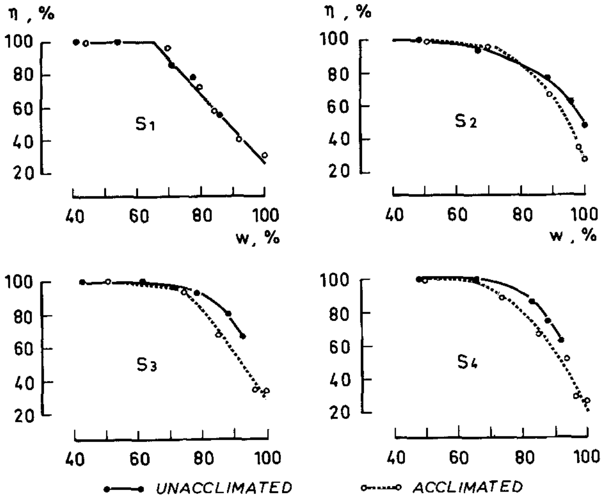

Fig. 2. Relationship between evaporative sweating efficiency (η) and skin wettedness (w)

The day to day constancy of the observed skin evaporation allowed us to average the 10 days spent in the humid condition for all subjects. The last example (Fig. 1c) corresponds to this mean time course obtained from the first day to the 10th day of acclimation.

For each experimental day, the relatively "steady state" in sweating was assumed to be obtained when the sweat rate reached its maximum value, for instance, at time 72 min in Fig. 1c (t_o). During this relatively steady state, at time t_o, we determined sweat rate, m_{sw}, dripping rate, m_{dr}, and consequently evaporative rate, E_{sk}. At this moment, skin wettedness was calculated from E_{sk}/E_{max}, E_{max} having been calculated by the use of h_e from Table 1 and P_{sk} which is equal to saturated water pressure at the observed $\bar{T}_{sk}$.

Evaporative – Sweat Ratio

The evaporative efficiency of sweating (η) is defined as the ratio between evaporative rate and sweat rate (E_{sk}/m_{sw}). Figure 2 gives the relationships between evaporative sweat efficiency and skin wettedness (w) for the four subjects. Results confirm that efficiency of sweating is strongly related to skin wettedness requirements. For subjects S2, S3 and S4, acclimation induced a decrease in the evaporative efficiency of sweating at the same level of skin wettedness. Because Subject S2 and S3 showed a fully wetted skin in condition H5, results of condition H6 are not reported here.

Generally speaking, it appears that some sweat becomes ineffective for body cooling at skin wettedness levels which are greater than 60% to 70%. The decrease in sweat efficiency which was linked to the increase in skin wettedness, is larger here than in our earlier studies (Candas et al. 1979a, b). This could be explained by the difference in the acclimation conditions, which were more humid than those of our previous studies. Consequently, subjects presented a greater maximum sweating capacity, which induced a larger decrease in sweating efficiency. This finding does not imply that sweat efficiency depends on the level of the sweat rate itself. In fact, for a given subject at a given state of acclimation, the relationship between η and w is confirmed. Nevertheless, inter-subject differences will introduce a wide dispersion of results observed at high levels of skin wettedness (w > 90%).

Hidromeiosis

1. Onset of Sweat Decline (t_o). In our conditions, hidromeiosis is considered to have begun as soon as the sweat rate decreased from its maximum value. As shown in Fig. 1, sweat decline always developed during the second hour of heat exposure; and it only decreased the unevaporated dripping sweat rate without modifying the rate of evaporation of sweat. When considering the results of the first experimental series, where the entire skin surface was exposed to humid conditions, the average onset time for sweat decline varied from 61 min before acclimation to 76 min after acclimation. Due to wide interindividual variability, these two mean values were not statistically different. However, when analyzed with a *t*-test for two-tailed variables, the difference between sweat decline onset time before and after acclimation was highly significant. The present results, coupled with those from the experiments cited in Candas et al. 1979b, show that acclimation delays the occurence of sweat decline by 17 min ($p < 0.001$). This result agrees with our previous results that showed an average increase of 18 min in the period before the onset of sweat decline after acclimation (Candas et al. 1980).

2. Intensity of the Sweating Decline. After one hour of heat exposure the sweat rate and the drippage rate decreased in a similar manner. The intensity of the sweating depression was studied by comparing the drippage rate at hidromeiosis onset to the drippage rate that was observed one hour after this value. Figure 3 shows all data of dripping rates that we obtained in our laboratory. The relation was fitted by inspection. This figure shows that for an initial drippage rate of 600 $g \cdot h^{-1}$ the drippage rate will be 290 $g \cdot h^{-1}$ one hour later (indicating that the drippage is reduced by 310 $g \cdot h^{-1}$) but if the initial drippage rate is 200 $g \cdot h^{-1}$, it will reach 60 $g \cdot h^{-1}$ one hour later, being reduced only by 140 $g \cdot h^{-1}$. Thus, the greater the sweat lost by drippage, the greater the consecutive drippage rate decline. In our results however, when the drippage rates were very intense ($> 750\ g \cdot h^{-1}$) the value of the drippage decrement remained constant, indicating that hidromeiosis may have reached its maximum intensity.

Since the decrease in sweating was more prevalent after acclimation due to a higher dripping sweat rate, the skin wettedness, which also increased with acclimation, seems to be a variable of great importance in sweat decline. To verify the effects of local skin wettedness on hidromeiosis development, we carried out the second series of experiments in hot humid conditions.

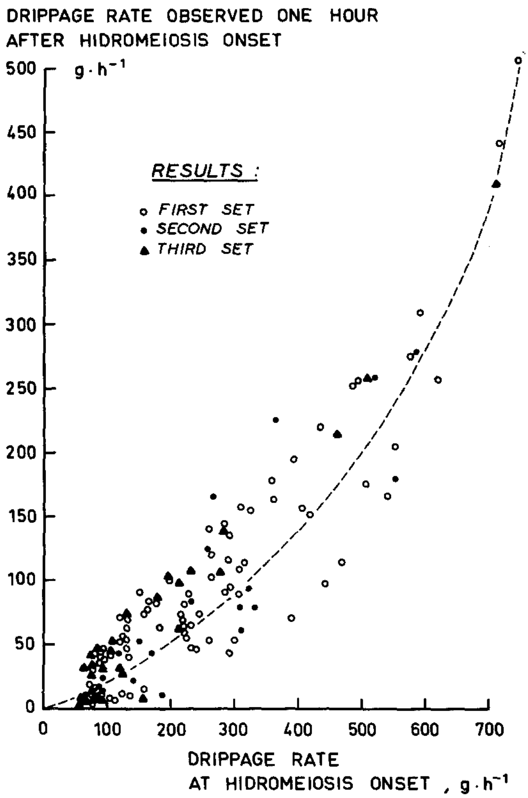

Fig. 3. Relation between the drippage rates observed one hour after hidromeiosis onset and the drippage rates at hidromeiosis onset. The first set of results corresponds to already published results in this journal (1980) 44: 123–133. The second set corresponds to unpublished data from the experiments described in J Appl Physiol (1979b) 47: 1194–1200. The third set corresponds to data found in the present study (first series of experiments)

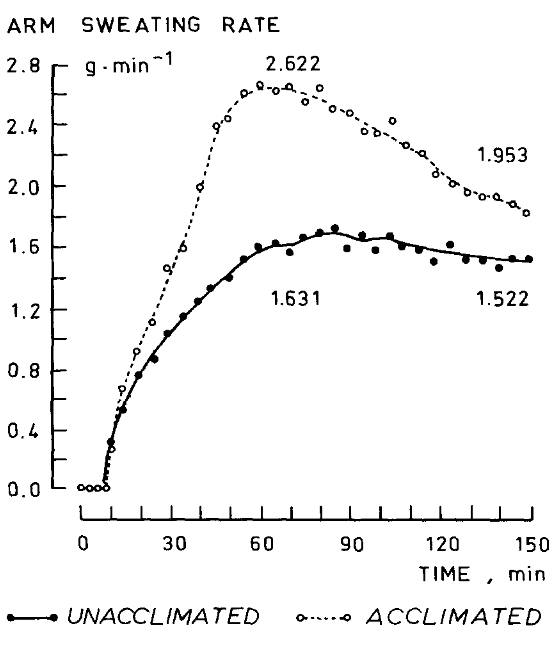

Fig. 4. Right arm sweat rate plotted against time. Numbers indicate the average of 20 min of maximal sweating and of final sweating. This example corresponds to arm sweating of subject S_2 exposed to condition A2 of Table 3

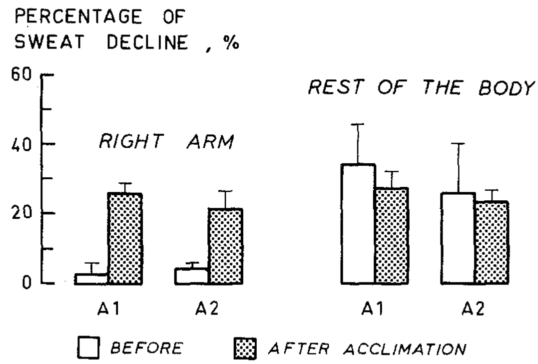

Fig. 5. Mean percentage of decrease in sweat rate of the arm and of the rest of the body. Vertical bars represent the standard deviation (four subjects). These percentages were calculated as the ratio between the sweat decline (maximal minus final sweating) and maximal sweating. Parameters of conditions A1 and A2 are given in Table 3

Typical examples of the local arm sweat rate, which was continuously measured from the outflow of the arm chamber with a dew-point technique, are given in Fig. 4. Before acclimation, arm sweat rate remained constant or slightly decreased. After acclimation, the arm sweat rate, which was more intense, always decreased after the first hour of humid heat exposure.

Figure 5 gives the average results of these experiments. This illustration shows the mean percentage of sweat decline on the arm and on the rest of the body, when compared to their maximum levels reached at the end of the first hour of exposure. The body always exhibited a great sweat decline (right half of the figure) in the two ambient conditions. Before acclimation (left half of the figure) arm sweat decline was very small (3–4%), but when the subject was acclimated, arm sweating showed a considerable percentage of decrease, the observed differences being highly significant (twotailed t-test, $p < 0.001$).

Discussion

As depicted in Fig. 1, the sweating response can be described in two phases and the main objective of the discussion concerns these two sweating phases with special focus on the sweating decline.

The level of maximal sweating reached at the end of the first hour is linked to skin wettedness values. The observed sweat rate which is necessary for the realization of the required evaporation is, in humid heat, always higher than the required evaporative rate (Clifford et al. 1959; Kerslake 1972). In the present work, the values of the evaporation-sweat rate ratio for high levels of skin wettedness are smaller than those observed in our previous studies (Candas et al. 1979a, 1979b) and this could be related to the individual maximal sweating capacity which can be influenced by the acclimation procedure.

During this first phase of increasing sweat rate, the skin appears to become more and more hydrated, that is to say, the skin swells and this is accompanied by a progressive disapearance of the sweat which covers the skin.

During a second phase, the sweat rate decreased with time and in our conditions, this sweat decrease reduced the dripping sweat rate. In a given environment, when evaporation is kept constant, decreases in sweat rate are equal to the decreases in drippage rate. But this does not imply that hidromeiosis is the consequence of a given sweat rate: the extent of the sweat decrease is dependent on evaporation conditions. In other words, hidromeiosis will be greater if E_{max} is low, due to high ambient water vapor pressure, while hidromeiosis will be non-existent if all excreted sweat is evaporated. Thus at the same level of sweating command, hidromeiosis will be different in unequal conditions of maximum evaporative power, and for this reason, it cannot be hypothetized from our results that the sweat drippage rate and thus the sweat rate itself decreased because of body dehydration. It is obvious that in hot humid conditions, well-acclimated subjects, who sweat profusely, will show hidromeiosis at high levels of water deficit. But, our data in Fig. 1 show for example, that subjects had lost only 320 g when hidromeiosis occurred in unacclimated subjects and 680 g in acclimated ones. Thus it can be concluded, and this is also confirmed in Fig. 3, that hidromeiosis exists at a low level of water loss. Moreover, if body dehydration were the cause of the sweat decline, it would also induce a decrease in local arm sweating rate whatever the state of acclimation, and this has not been observed in our experiments on local sweat rate.

The fact that the decline in sweating occured before acclimation on the majority of the body surface while the sweat rate of the dry arm remained constant, confirms that:

1. hidromeiosis is not the reflection of a dysfunction of the thermoregulatory system (such as sweat gland fatigue, body dehydration, neuroglandular blockage, negative effect of high level of body temperature);
2. hidromeiosis is not solely dependent on a single central factor which acts on the whole-body surface.

After acclimation, local arm sweating and evaporation were transiently more intense (at constant heat evaporative coefficient and at constant local skin temperature). This increase in sweating rate was always followed by the occurence of hidromeiosis. Thus, it can be concluded that the arm skin wettedness was increased and this factor might be responsible for skin hydration and consecutive hidromeiosis.

Many reports (Gerking and Robinson 1946; Randall and Peiss 1957; Hertig et al. 1961; Brebner and Kerslake 1964; Gonzalez et al. 1974) demonstrate that skin wettedness is the factor necessary for the occurrence of sweat decline. Our results confirm this conclusion but do not support the hypothesis that hidromeiosis only originates from mechanical obstruction of the sweat ducts (Peiss et al. 1956; Collins and Weiner 1962) due to superficial skin hydration since, after acclimation, the arm sweat rate decreased even when efficient local evaporation occurred. Therefore, the coexistence of another factor acting on salt and water reabsorption cannot be ruled out; this factor, which could be non-existent or ineffective before acclimation, could be operating after acclimation. This latter observation however does not allow us to conclude that excessive skin hydration is the only factor to induce hidromeiosis unless it could be supposed that, at a high level of arm sweat rate, the skin becomes locally hydrated without any sweat drippage.

The present work cannot directly prove which phenomenon is involved, but some hypothesis could be put forward on the basis of the results found in the literature. There is no reason to rule out the possibility of some control for Na and water reabsorption in the sweat duct (Ohara 1966). A local factor could be dependent on skin hydration and on its consequences, such as ionic or osmotic change. A general control could depend on a humoral factor (Hénane 1972) or on blood ionic composition (Nielsen 1974), and this factor could act on the secretion-reabsorption processes. However, as we have previously stated, this general control may not be operating to a significant extent before acclimation, but it would be operating after acclimation, depending on the absence or presence of the local factor. The above hypothesis could explain why hidromeiosis may reduce general or only local sweat rates. However, our results do not permit us to draw any definite conclusion concerning the mechanism involved in hidromeiosis.

From the various data in the literature (Gerking and Robinson 1946; Hertig et al. 1961; Collins and Weiner 1962; Brown and Sargent 1965) and from the present results, the typical pattern of the sweat rate in severely humid atmospheres allows us to make some comments about sweating mechanisms. Sweating starts at the beginning of heat exposure and is increased by surface and core temperatures and regulated by central control (Hammel et al. 1963). During the first phase of increasing sweat rate, the degree of wettedness acts as a determinant factor (Nadel and Stolwijk 1973) since sweating rate appears to be dependent on wettedness requirements. At the same time, skin hydration begins, causes swelling of the superficial layers of the skin and thus induces hidromeiosis: this sweat decline will be more intense in acclimated subjects, due to the higher sweat drippage rate, in contrast with the findings of Fox et al. 1967.

Our results confirm that hidromeiosis does not involve general physiological disturbances, and therefore the term sweat suppression is inadequate since it implicates a definitive sweating blockage. In unsaturated atmospheres it is likely that the sweat rate will reach E_{max}, and unlikely that it will reach zero.

It seems that this second phase of sweating due to hidromeiosis, corresponds to an active, local, adaptative sweating mechanism, because the evaporative rate remained remarkably constant. The negative feedback from hydrated skin which reduces local sweat output is clearly demonstrated. However, an associative effect of wettedness and of some humoral factor(s) is not to be ruled out.

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