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COMPARISON OF THERMAL EXCHANGES IN MEN AND WOMEN UNDER NEUTRAL AND HOT CONDITIONS

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SUMMARY

1. The thermoregulatory responses in unacclimatized men and women were analysed and compared by means of standard heat exposure tests which allowed evaporative losses, body temperatures, heat storage and the complete thermal balance to be continuously recorded in all subjects.

2. The most pronounced differences were observed in delay before onset of sweating. Sweating always occurred faster with lower body temperatures in men than in women. The period immediately following ovulation was characterized by an increase in onset delay and a decrease in the sensitivity in sweating response compared with the pre-ovulation period.

3. The evaporative rate in the steady state did not change significantly in the post-ovulation period and was found to be higher in men who consequently had lower mean skin temperatures. Skin conductances, different under thermo-neutral conditions, were the same in men and women under hot conditions.

4. Women showed a more definite increase of body temperatures and heat storage than men due to delayed sweating and decreased sweating sensitivity. The body heat content in the steady state increased more markedly in women than in men. Furthermore, the highest heat storage values were found during the post-ovulation period. A high degree of correlation was found between body heat content and absolute onset delay.

5. The sweating kinetics and the transient phase just before the steady state of the thermal balance appeared to be decisive factors in the diffferentiation of the thermoregulatory behaviour in women before and after ovulation. Heat storage achieved during the transient phase and not made up by adequate evaporation seemed to be the cause of the large increase of body temperatures and heat content shown by women in hot environments.

INTRODUCTION

The fundamental work of Hardy & Du Bois (1940) has shown that the thermoregulatory responses in women are different from those in men. These sex differences have been analysed under various conditions, at rest (Du Bois, Ebaugh & Hardy, 1952), at work (Hertig & Sargent, 1963), high humidity (Weinman, Slabochova, Bernauer, Morimoto & Sargent, 1967), heat acclimatization (Wyndham, Morrison & Williams, 1965), during controlled hyperthermia (Fox & Löfstedt, 1968; Ferris, Fox & Woodward, 1968) and recently during hard work in desert heat (Dill, Yousef & Nelson, 1973). These studies all show that women have a less efficient sweating mechanism than men; as the onset threshold for sweating is high, body temperatures show far greater increase during heat exposure. Despite these clearly shown features there is some uncertainty about thermoregulatory patterns in women. Such processes become all the more difficult to determine as a result of the hormonal rhythms and the menstrual cycles which deeply alter the thermal exchanges and the salt and water metabolism (Senay, 1973) to an extent which has not yet been clearly defined. Comparison of male and female thermoregulatory responses during work in the heat is also complicated by sex differences in maximal aerobic capacity, lean body mass and body water content. Therefore, the work-in-the-heat technique is difficult to use in the differentiation of thermoregulatory patterns and physical work capacity.

The purpose of this study has been to examine the thermal responses in women at rest when exposed to an abrupt change from a neutral level to a hot environment. The thermal balance was evaluated by partitional calorimetry during the transient stage and the steady state. The test carried out allowed thermal exchanges to be measured during the pre- and post-ovulation period and compared with those obtained in male unacclimatized subjects.

METHODS

Subjects. The physiological characteristics of the nine men and the five women are set out in Table 1. The women were laboratory technicians and none of them was taking a contraceptive pill. The men were doctors, scientists, medical students and soldiers. None of the men or women had ever experienced hot climatic conditions and were therefore considered to be unacclimatized to heat. The experiments were carried out in the morning; the whole series spread over a 2 yr period.

Procedure for sweating tests. Sweating tests were carried out in the middle of pre- and post-ovulation periods, thus avoiding the time of ovulation and menstruation. The women took their rectal temperature each morning so as to define exactly the time of ovulation. Each woman was tested during four complete cycles with two sweating tests per cycle. The sweating tests were conducted in a temperature–humidity controlled chamber, previously described (Henane & Valatx, 1973). The

TABLE 1. Physical characteristics of the nine men and the five women; S/m is the surface to body mass ratio

Subjects	Age	Height (cm)	Weight (kg)	Surface (m^2)	S/m	Remarks
			Men			
J.B.	33	165	60·8	1·65	0·027	Short, muscular
P.B.	27	168	66·5	1·74	0·026	Short, muscular
G.G.	21	183	69·0	1·89	0·027	Tall, slightly underweight
R.H.	41	170	61·7	1·70	0·028	—
F.L.	26	170	63·5	1·73	0·027	—
J.P.M.	26	188	74·8	1·98	0·026	Tall, underweight
G.P.	27	170	60·7	1·69	0·028	—
A.P.	27	170	62·1	1·75	0·028	—
J.P.V.	25	179	65·3	1·79	0·027	Tall, underweight
			Women			
A.M.H.	32	162	60·5	1·63	0·027	Slightly overweight
A.M.I.	22	162	60·4	1·62	0·027	Slightly overweight
S.M.	42	158	54·2	1·53	0·028	—
P.S.	27	163	52·2	1·53	0·029	—
G.P.	30	163	58·4	1·62	0·028	—

procedure followed in the sweating tests comprised three phases (Fig. 1): pre-heating period (neutral stage). The subjects, having had a light meal and clad only in shorts (men) or 'Bikini' (women), were placed recumbent on a wire-mesh bed suspended from one end of a beam balance. The beam projected through the chamber wall to an electric differential balance located outside. The subject was maintained for 90 min in a thermally neutral environment: T_{db} = 30° C, T_{wb} = 23° C, wind speed = 0·4 m.sec^{-1}, water vapour pressure = 2·3 kPa (16·9 mmHg), mean radiant temperature = 30° C.

Dry heating period. The temperature of the chamber was rapidly raised (6° C. min^{-1}); this period lasted for 90–120 min until the thermal balance was reached: T_{db} = 45° C, T_{wb} = 30° C, wind speed = 0·8–1 m.sec^{-1}, water vapour pressure = 3·2 kPa (24·6 mmHg), mean radiant temperature: 45° C, E_{max} = 430 W.m^{-2}.

Rapid cooling period. The climate was rapidly adjusted to initial conditions of the pre-heating period; observations made during the rapid cooling phase are out of the scope of the present work. The experiment came to an end when body temperatures had returned to their initial level.

Skin temperatures. The skin temperatures were measured at ten sites with copper–constantan thermocouples: foot (mid-point dorsal surface), leg (mid-point lateral surface), thigh (mid-point lateral surface), abdomen (McBurney's point), chest (below the nipple for men and lower costal margin for women), back (lower costal margin), arm (mid-point lateral surface), forearm (mid-point lateral surface), hand (dorsal surface), forehead (centre). In addition, skin temperatures were checked every 5 min with a radiometer (Heimann KT 40) so as to continuously correct the errors introduced by the thermocouples. The skin temperatures averaged in terms of area weighting were accurate to 0·1° C.

Deep body temperatures. Rectal temperature (T_{re}), tympanic temperature (T_{ty}) were recorded as previously described. All the body temperatures, T_{re}, T_{ty}, and T_{sk}

were continuously recorded with a 16-channel recorder (Leeds & Northup, Speedomax) connected in series with a data acquisition system, a desk-top computer, a digital plotter and a printer (Hewlett–Packard system) allowing on-line and real time computation of changes of heat storage.

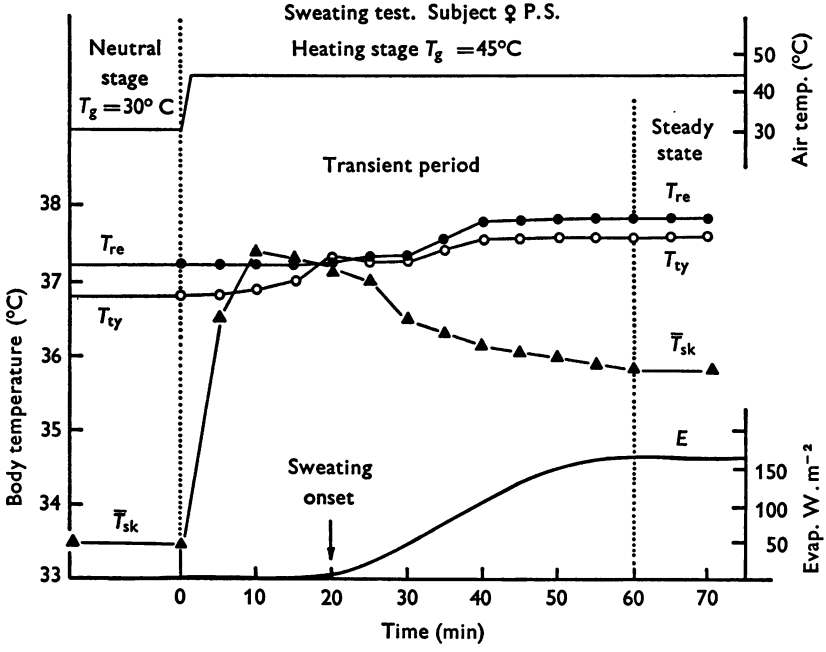

Fig. 1. Sweating test in the female subject P.S. Note the transient phase characterized by a change of body temperatures and evaporative rate which are stabilized during the steady state. Zero time: starting of heating stage.

Sweat rate. Sweat output was monitored by continuously weighing the subject throughout the experiment (electric differential balance Testut-Aequitas, Paris). The weight changes were given to an accuracy of ± 3 g and 0·3 g.min^{-1} by differentiation. No correction has been made for respiratory vapour loss, insensible and metabolic weight changes. The delay before the onset of sweating was the most important measurement in our experiments. This was accurately determined using three procedures: (1) clear change of the slope of recorded weight loss; (2) resistance hygrometer cell applied to the skin of the anterior chest wall; (3) start of the skin cooling, mean skin temperatures being continuously monitored. Previous experiments (Timbal, Boutelier & Colin, 1968) during which changes of skin impedance were observed showed that local changes of skin impedance are well correlated with the onset of sweating. Changes of skin impedance were monitored using a Beckman Dynograph coupler 9892A. A good agreement was found between estimates by the three methods, allowing thus, the delay before onset of sweating to be measured to within ± 30 sec.

Metabolism. Metabolic measurements were carried out during the steady state

of neutral stage using Douglas bag technique; expired gases samples were analysed for O_2 and CO_2 content with respectively Beckman OM 11 and LB 2 fast response gas analysers, calibrated with gas mixtures which had been analysed by the Lloyd–Haldane method. Heart rate and digital plethysmography (photocell technique Beckman type 9874 photoelectric plethysmograph coupler) were continuously monitored.

Calculations. The evaporative weight loss was directly displayed on the chart paper recording (Figs. 2 and 3). The evaporative rate E was computed according to the formula

$$E = \lambda \dot{m}/3{\cdot}6\, A_D \quad (\mathrm{W.m^{-2}}),$$

λ = latent heat of sweat (2·42 $\mathrm{kJ.g^{-1}}$), $\dot{m}$ = rate of weight loss ($\mathrm{g.h^{-1}}$), A_D = body area, $\mathrm{m^2}$.

Dry exchanges $(R+C)$ were calculated using combined heat transfer coefficient h, measured during steady state of the heating period:

$$h = (E-M)/(T_g - \bar{T}_{sk}) \quad (\mathrm{W.m^{-2}.^\circ C^{-1}}).$$

T_g: globe temperature; $\bar{T}_{sk}$: mean skin temperature. Mean value for h was found to be: $12{\cdot}7 \pm 0{\cdot}4$, $\mathrm{W.m^{-2}.^\circ C^{-1}}$.

The rate of heat storage S was computed each 5 min from the equation

$$S = [M + h(T_g - \bar{T}_{sk}) - E] \quad (\mathrm{W.m^{-2}}).$$

The change of body heat content ΔS, related to body mass, was obtained by integration of S:

$$\Delta S = \int_0^t [M + h(T_g - \bar{T}_{sk}) - E]\, dt \quad (\mathrm{kJ.kg^{-1}}).$$

The change of body temperature $\Delta \bar{T}_b$ was computed from the equation

$$\Delta \bar{T}_b = \Delta S/3{\cdot}48 \ (^\circ \mathrm{C}).$$

ΔS: change of body heat content in $\mathrm{kJ.kg^{-1}}$; 3·48: body specific heat, $\mathrm{kJ.kg^{-1}.^\circ C^{-1}}$.

Skin conductance k_b was measured at steady state, in thermo-neutral (T_g = 30° C) and hot environments (T_g = 45° C) from the formula

$$k_b = E - (R+C)/(T_{re} - \bar{T}_{sk}) \quad (\mathrm{W.m^{-2}.^\circ C^{-1}}).$$

RESULTS

Metabolism, body temperatures, sweating functions and heat storage were measured at steady state of both neutral stage and heat exposure. Three comparisons were made: (1) women in the pre-ovulation period; (2) women in the post-ovulation period; (3) men. The results are summarized in Table 2.

(1) *Basal conditions (neutral stage)*

Metabolism. Basal heat production in women in the pre-ovulation period was significantly lower than in men. No significant differences were found at other times.

Body temperatures. Rectal temperatures, as expected, where higher after ovulation. No other significant differences were found.

TABLE 2. Metabolism ($W.m^{-2}$), rectal, tympanic and mean skin temperatures (° C) body conductance k_b ($W.m^{-2}.°C^{-1}$), increment of body temperature $\Delta\bar{T}_b$ (° C), rectal temperature, threshold for sweat onset (T_{re}, thr.), during neutral stage and heating period.

	Neutral stage T_g = 30° C					Heating stage T_g = 45° C					
	M	T_{re}	T_{ty}	$\bar{T}_{sk}$	k_b	T_{re}	T_{ty}	$\bar{T}_{sk}$	$\Delta\bar{T}_b$	T_{re} thr.	k_b
(1) Women Pre.	43·2	36·9	36·5	34·3	12·7	37·8	37·5	35·6	1·0	37·0	19·5
	± 5·5	± 0·1	± 0·3	± 0·1	± 3·2	± 0·1	± 0·2	± 0·6	± 0·07	± 0·02	± 7·8
(2) Women Post.	44·7	37·4	36·7	33·6	11·7	37·9	37·9	36·0	1·6	37·4	23·3
	± 5·0	± 0·2	± 0·4	± 0·5	± 2·9	± 0·2	± 0·1	± 0·3	± 0·2	± 0·1	± 3·1
(3) Men	51·8	36·9	36·3	34·3	19·9	37·4	37·2	35·3	1·1	37·1	24·7
	± 6·9	± 0·3	± 0·3	± 0·4	± 1·9	± 0·1	± 0·2	± 0·5	± 0·09	± 0·1	± 6·8
P (1) – (2)	N.S.	< 0·01	N.S.	< 0·01	N.S.	N.S.	< 0·01	N.S.	< 0·01	< 0·01	N.S.
P (1) – (3)	< 0·05	N.S.	N.S.	N.S.	< 0·01	< 0·001	< 0·01	N.S.	N.S.	N.S.	N.S.
P (2) – (3)	N.S.	N.S.	< 0·02	< 0·02	< 0·01	< 0·001	< 0·001	< 0·02	< 0·01	< 0·01	N.S.

(1) Women: pre-ovulation period. (2) Women post-ovulation period. (3) Men (means ± S.D.; n.s. = non-significant).

Mean skin temperatures appeared significantly lowered during the post-ovulation phase.

Skin conductance. k_b appeared to be significantly higher in women than in men both during pre- and post-ovulation periods.

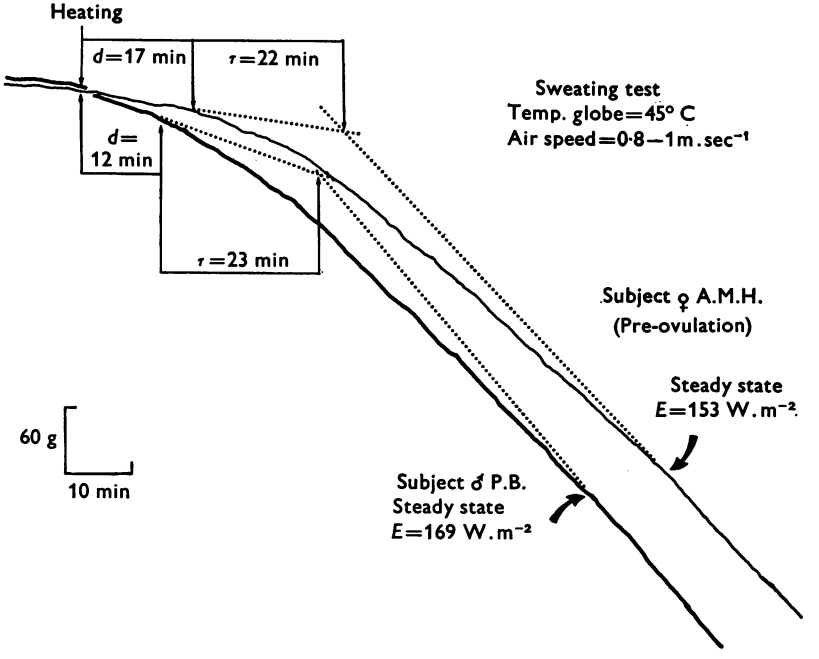

Fig. 2. Comparison of the evaporative weight loss in the female subject A.M.H. during pre-ovulation phase and in male subject P.B. Note the short onset delay (12 min) observed in the male subject as compared to that of the female (17 min). Time constants as defined by Timbal *et al.* (1969) are nearly the same but the male exhibits a slightly higher steady state of the sweat rate. Black arrows: steady state of the thermal balance. Note the increase of the perspiration preceding true sweating onset observed in the male subject.

(2) *Heating stage*

Body temperatures. Tympanic and rectal temperatures increased to higher levels in women than in men: no differences between pre- and post-ovulation periods.

Mean skin temperatures remained significantly lower in men than in women. Changes of body temperatures, $\Delta\overline{T}_b$, appeared to be higher after ovulation. Moreover, women after ovulation exhibited a significant increase of $\overline{T}_b$ as compared to men.

Skin conductance k_D increased during heat exposure but no significant differences appeared between the three conditions.

Sweating functions. Absolute delay before onset of sweating. The absolute delay d showed marked changes in the three conditions. Men exhibited the shortest delays (Fig. 2). The post-ovulation period was characterized by a significant increase of the absolute delay as compared to the pre-ovulation phase (Fig. 3). Mean values for the three conditions are shown in Fig. 4.

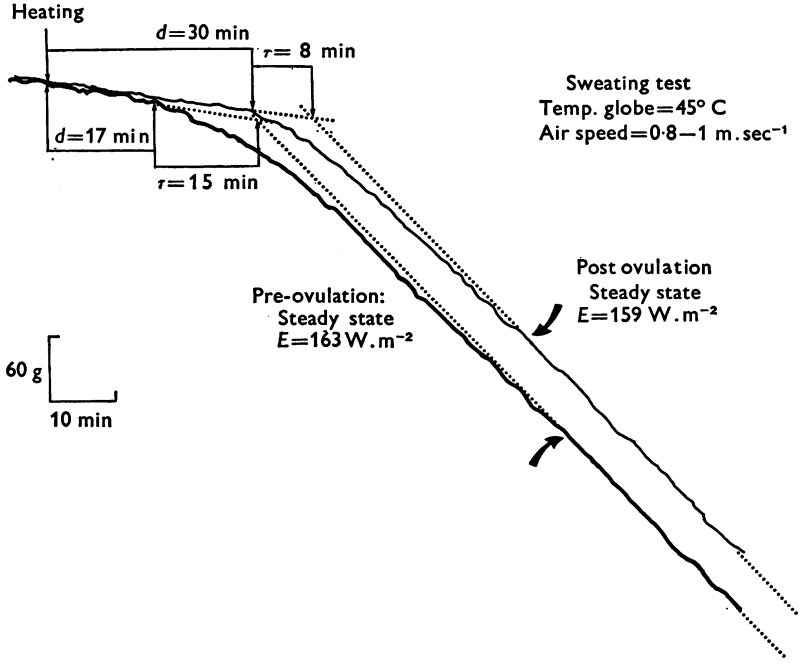

Fig. 3. Recording of the evaporative weight loss (g) in the female subject S.M. during the pre- (thick line) and post-ovulation (thin line) periods. Note the increase of onset delay d (expressed in min) in post-ovulation phase. No change of evaporative rate at the steady state is clearly apparent. Black arrows indicate the steady state of thermal balance. τ: time constant for sweating (min).

3. *Relationships between evaporative rate and central temperatures*

Fig. 6 shows the individual values obtained during the heating stage. The great inter-individual variability and the non-linearity of the relations did not allow a reliable linear regression analysis. Passing from pre- to post-ovulation periods elicited a shift up the rectal temperature scale, without a clear change of slope. The temperature threshold for the

onset of sweating in all the women was clearly shifted to the right, indicating a decreased sensitivity of the sweating control system to increase in core temperature.

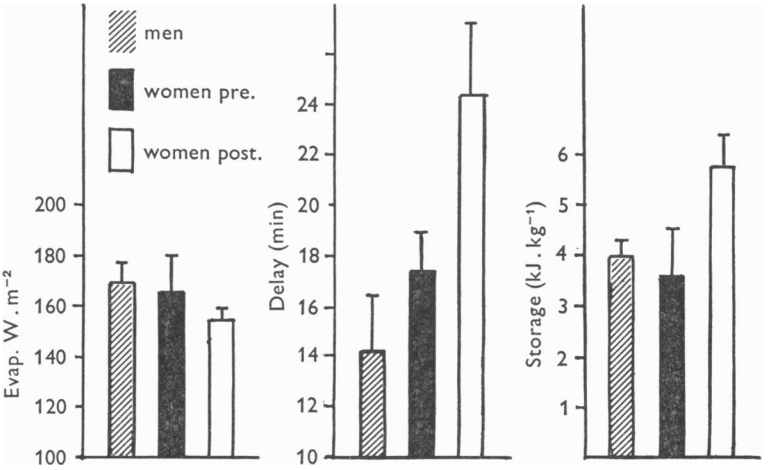

Fig. 4. Steady-state evaporative rates, absolute delays and changes of storage measured at steady state for men and women during heat exposure. Means ± S.D.

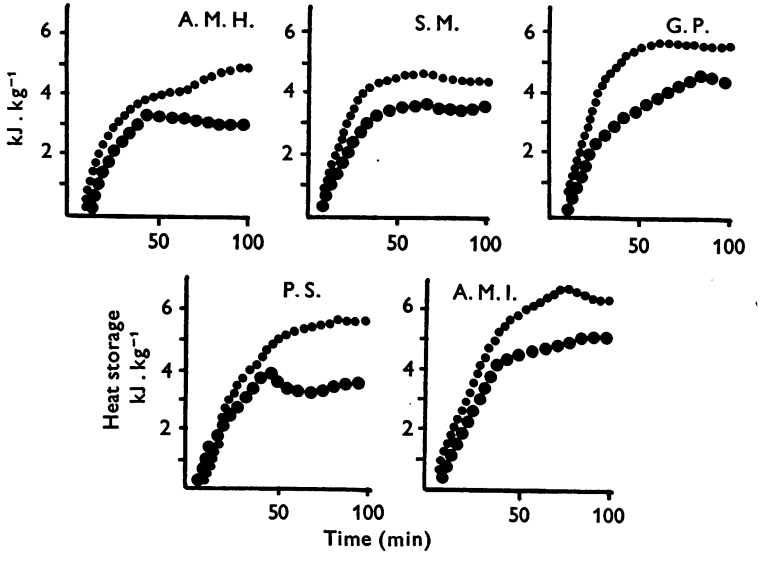

Fig. 5. Individual values of body storage, continuously measured during the heating period starting at zero time. Large filled circles: pre-ovulation phase. Small filled circles: post-ovulation phase.

4. *Relationships between storage and absolute delay for sweating in men and women*

Fig. 7 shows the regression lines relating storages to absolute onset delays. These relations appeared to be highly significant both in men and women. The correlation of 0·80 and 0·90 accounted for 64 and 81 %

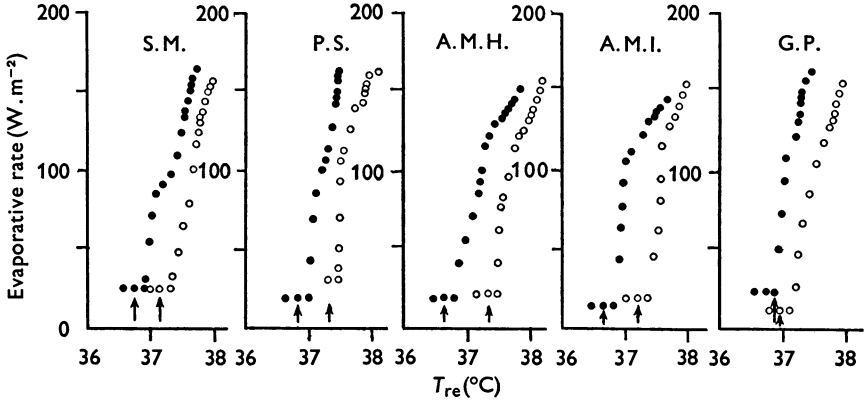

Fig. 6. Individual values of evaporative rate as related to rectal temperature during heat exposure. Filled circles: pre-ovulation phase. Open circles: post-ovulation phase. Arrows indicate the starting of heating stage. Measurements are made every 5 min, last value corresponding to steady-state completion.

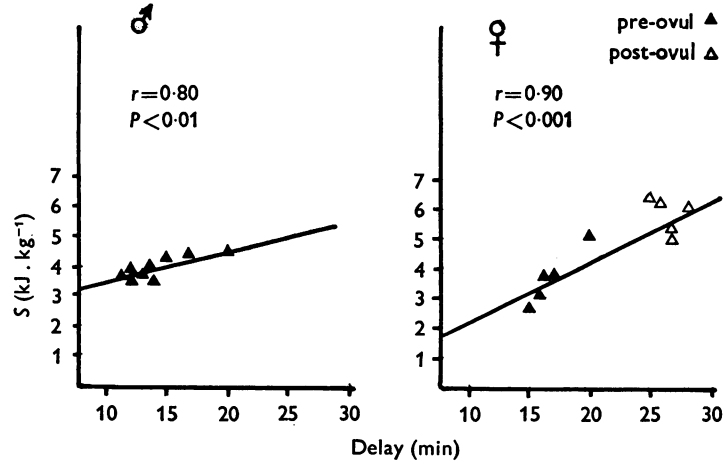

Fig. 7. Regression lines relating body heat storage to absolute delays for men and women. The slopes are 0·10 kJ.kg^{-1} per min for men and 0·22 kJ.kg^{-1} per min for women.

(dependence degree r^2) of the variability between storage and absolute delay values. An increase of 1 min for absolute delay elicited a storage of 0·22 kJ.kg^{-1} in women and 0·10 kJ.kg^{-1} in men.

DISCUSSION

Our results confirmed the results of previous studies showing that women have a lower heat dissipation in a hot environment (Hardy *et al.* 1940). The lower heat dissipation appeared to be related to later and less extensive sweating than in men under the same climatic conditions, leading to an increase of the body heat content with a rise in body temperatures. The analysis of these thermoregulatory responses seemed to us to be of interest and importance. Weight loss due to evaporative sweating (sweat output) must be considered separately from evaporative rate (rate of change or first derivative curve). Fig. 2 and 3 clearly show that at a given moment, the same subject being considered during different experiments, different weight losses corresponded to an identical evaporative rate (same slope of the weight loss curve). This fact allowed for example, the steady state to be characterized by a lower total weight loss in women, whilst its rate of change was almost identical to that observed in men.

Analysis of the delay before onset of sweating

Evaporative sweating does not appear instantaneously. It is a delayed phenomenon, and in men at rest there is always a time lag between the moment when the thermal change is applied and the moment when sweating starts. This time lag is referred to as the absolute onset delay. What is more, when skin evaporation takes place, its steady state is not immediately reached. Fig. 1 shows that in the female subject P.S., the steady state was reached only after 60 min of heat exposure. During this transient phase the heat gains were greater than the evaporative losses, leading to a positive storage. Body temperature stabilization was achieved when the rate of storage had fallen to zero. At that moment, heat gains were exactly compensated by the heat losses. Of all the values measured in our experiments, the absolute delay appeared to be the most significantly changed. The post-ovulation period had a much longer onset delay than the pre-ovulation period had. Male subjects showed considerably shorter delays than female subjects did. Logically, it might be inferred than those subjects which exhibited the shorter delays were those which least stored heat. Our results confirmed this statement. Fig. 5 shows that the heat content was increased to a greater extent in women than in men. Further, in the sample of women tested, the most extensive heat storage occurred

immediately after ovulation and was characterized by an increase in the onset delay. The heat contents were found to be 4·0 kJ.kg^{-1} in men, 3·6 kJ.kg^{-1} in women before ovulation and 5·8 kJ.kg^{-1} in women after ovulation. The respective mean onset delays were 14·2, 17·4 and 24·4 min. The significant heat content increase in the post-ovulation period could not be explained by the steady-state evaporative rate which did not change. These differences could not also be explained by changes of skin conductance. As a matter of fact k_b measured under thermo-neutral condition appeared to be significantly lower in women (see Table 2) and was attributable to the higher body insulation. During heat exposure, however, no significant sex differences in k_b could be detected. The only differences observed between the pre- and post-ovulation periods were in the sweat onset delay, leading to differences in the body heat content.

Analysis of body temperatures, evaporative rate and heat storage

Rectal temperatures measured in steady states during heat exposures were higher in women in a pre- and post-ovulation phase than in men. The highest T_{re} levels were found in post-ovulation women. The $\bar{T}_b$ increment ($\Delta\bar{T}_b$) was more marked in women than in men, which corresponds to the results of Weinman *et al.* (1967). The pre- and post-ovulation periods, which were very different with respect to onset delay, showed no significant differences of evaporative rate and consequently $\bar{T}_{sk}$ values in pre- and post-ovulation phases were unchanged. The differences of about 10–16 W.m^{-2} of evaporative rates observed between men and women could be explained by the differences of sex in metabolic heat production (see Table 2 and Fig. 4) and by the sensible heat exchange ($R+C$) due to differences in skin temperatures. Our results confirmed those found by Hardy *et al.* (1940), and Du Bois *et al.* (1952) by showing that male subjects started sweating at lower body temperatures than women. But the difference appeared to be only significant when comparing men and post-ovulation women. In addition, men exhibited a greater evaporative rate, for an identical central drive, than did women (Fig. 2). If the statement of Nadel & Stolwijk (1973) is accepted, the parallel shift to the left, down the temperature scale, indicates a reduction of set point of the central drive in the following order: post-ovulation women, pre-ovulation women, men. Displacement of the set-point was observed by Kenshalo (1966) and by Cunningham & Cabanac (1971) with a behavioural approach in both pre- and post-ovulation women. A significant correlation appeared when the relationships between body heat content measured at steady state and the absolute delay were compared both in men and women.

Importance of sweating kinetics in heat dissipating processes

Sweating kinetics and the transient phase preceding thermal equilibrium appeared to be the prominent factors in the differentiation of the thermoregulatory responses between pre- and post-ovulation women and men. The sweat onset delay is poorly understood but regularly observed when evaporation is recorded by continuous weight measurements in a subject under basal conditions (rest at thermal neutrality for at least 90 min as pointed out by Colin & Houdas, 1965). This delay seems to be linked to the thermal history of the subject and is shortened with increased body-heat content. The sweating time constant defined by Timbal, Colin, Guieu & Boutelier (1969) is not fully understood. Its relationships to body temperatures and heat storage are not clearly explained. The slowness with which the heat dissipating processes were put into play in women could explain the long duration of the transient period characterized by a positive storage. The reason for this slowness of the sweating responses, above all in the post-ovulation period, has not been clearly explained. Hormonal mechanisms are almost certainly involved (Sargent & Weinmann, 1966; Morimoto, Slabochova, Naman & Sargent, 1967; Wells & Horvath 1973, 1974), occurring through modifications of either the central drive or the sensitivity of the peripheral receptors. Kawahata's experiments (1960) support this view. This author showed that women who were treated with testosterone had a decreased onset delay. On the other hand, men treated with oestradiol had an increased onset delay, hence reacting in a female manner. Sexual differences could also be related to differences of body water content. Senay's work (1973) has recently emphasized this point. Body water content in women is lower than in men and water movements are more restricted. The work of Wyndham *et al.* (1965) showed that men displayed 'prolific' sweating whilst women adjusted their sweating rate better according to requirements. Other factors could be involved, social, behavioural, resulting in women being less acclimatized than men, as pointed out by Ferris *et al.* (1968). The thermoregulatory behaviour of women in a hot climate, characterized by an economic sweating rate, heat storage and increased body temperatures, could be considered as a perfect adaptation to heat. This statement, however, remains purely speculative until the metabolic and hormonal factors which determine the female thermal balance are better defined.

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