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THE EFFECT OF WATER INTAKE UPON HUMAN REACTIONS TO REDUCED COOLING POWERS.

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Lee and Mulder [1935*a*, *b*] investigated certain reactions experienced by unacclimatized human subjects when placed in certain atmospheres of reduced cooling power. In their investigations the subjects, in addition to taking no food or water for 12 hours prior to the experiment, received no water during the first 5 hours in the hot room. We wished to supplement their observations and check their conclusions by making parallel experiments upon subjects who drank known quantities of water at frequent stated intervals.

Procedure.

Six male junior medical students volunteered as subjects (Nos. 11–16). Their ages ranged from 19 to 30 years, and body weights from 52 to 83 kg., and their health was good. Each subject, having had nothing to eat or drink for at least 12 hours, arrived in the morning without hurrying and sat down in a "control" room (D.B. 70° F., W.B. 65° F., effective temp. 67° F.). After not less than 30 min., a complete set of observations was made in this room, in the course of which the subject stripped. He then entered the hot room (D.B. 110° F., W.B. 90° F., effective temp. 95° F.), where he remained for 6 hours. During this time he drank a stated quantity of tap water at body temperature every 15 min., and ate a standard lunch (two boiled eggs without salt, four cracker biscuits and 1 oz. butter) at the end of the third hour. The following observations were recorded and samples taken during his sojourn in the hot room, for comparison with those taken in the control room:

Hourly. Pulse rate; respiration rate; mouth and rectal temperatures; urinary volume and samples for titratable acidity, ammonia and chloride content; body weight and symptoms.

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Periodically. Respiratory volume per min. and venous blood from the median cubital vein for CO_2 content and "combining power" determinations.

Three of our subjects (Nos. 11, 12, 13) received 100 c.c. water every 15 min. while in the hot room; three (Nos. 14, 15, 16) 150 c.c. at similar intervals.

Methods and results.

All readings were made by the observer, none by the subject.

Since one of the purposes of this investigation is to compare the reactions of our water-fed subjects with those of the waterless subjects observed by Lee and Mulder [1935*a*, *b*], the results will be given in a form permitting of such comparison as well as setting out the individual variations in reaction and the differences brought about by the administration of different amounts of water. For convenience of reference, the subjects studied by Lee and Mulder in the hot dry room without water will be termed "waterless", those investigated here the "lesser" and "greater water-fed" respectively.

In all figures individual results are indicated. The one individual is indicated throughout by the same type of line, and by number. Subjects taking 100 c.c. water every 15 min. are represented by circles, those taking 150 c.c. by crosses. A thick black line (with triangles) indicates for reference the average results obtained upon waterless subjects under similar conditions.

The experimental atmospheric conditions employed were: D.B. 110° F., W.B. 90° F., R.H. 44 p.c., air movement 100 ft. per min., effective temp. 95° F. (The observations given as at zero time were made in a control room at D.B. 70° F., W.B. 65° F., effective temp. 67° F., immediately before entry.)

Pulse rate.

There is no essential difference (Fig. 1) between the two water-fed series. In both there is a mild rise in the 3 hours before food, followed, usually, by a greater rise after food, and terminating in a plateau in the region of 90 beats/min. Terminal rates are more constant than initial rates. Subject 15 is an exception in showing a rapid rise without plateau to 110 beats/min. after 5 hours.

After the first hour all the rates are definitely lower than the average for the waterless series; the terminal plateau is much more definite and of earlier development. The accelerating effect of food is seen in all three series.

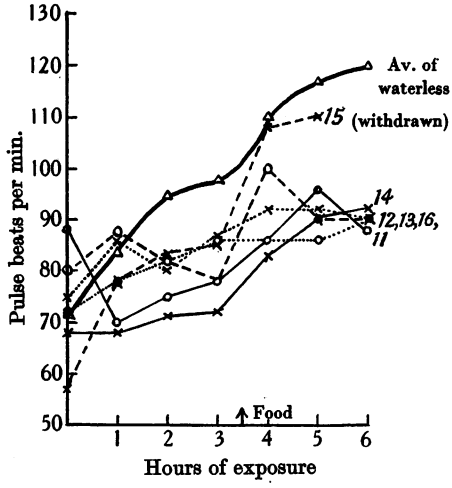

Fig. 1. Pulse rate.

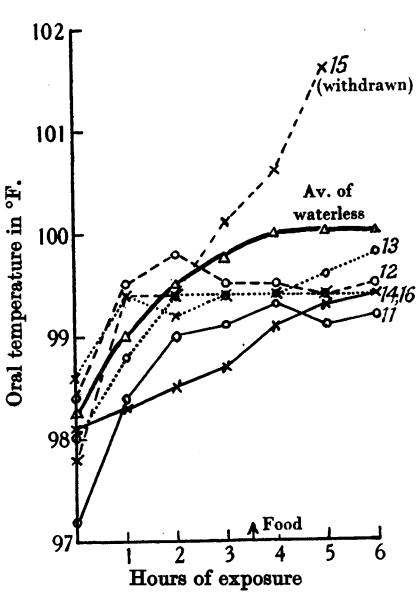

Fig. 2 *a*.

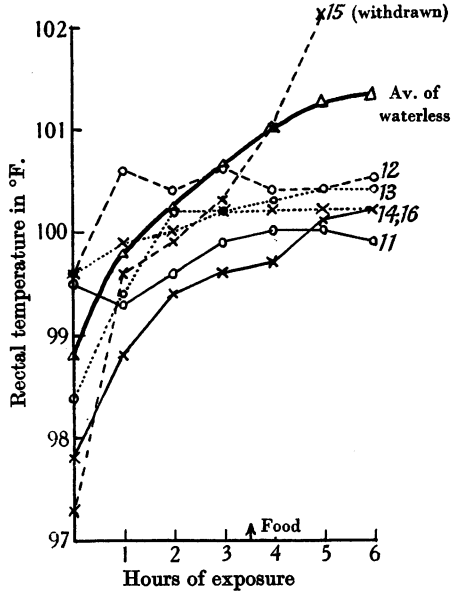

Fig. 2 *b*.

Fig. 2. Body temperature. *a*, oral; *b*, rectal.

Body temperature.

This was measured by clinical thermometers in both mouth and rectum. There is little essential difference (Fig. 2*a*, *b*) between the two water-fed series. An early rise is followed by a plateau, which is at a

higher level (99·9–100·5) in the rectum than in the mouth (99·2–99·8). Food has no effect upon the curves. Final temperatures are more constant than initial. Subject 15 is again exceptional in maintaining a continuous rapid rise of temperature.

After the second hour, the water-fed subjects maintain a lower temperature than the waterless, especially in the rectum, and attain a much more definite plateau.

Body weight.

The subject was weighed upon a platform scale indicating half-ounces. The results, corrected for food intake, are given in Fig. 3. In the lesser water series the weight at first rises a little, but later tends to fall progressively. In the greater water series the initial rise is much more marked, but its subsequent behaviour varies with that of its determinant factors—sweat loss and urine output. Waterless subjects, of course, suffer a progressive weight loss.

Sweat loss.

This was determined by computation from weight loss, urine output, and water intake, by neglecting loss of weight due to respiratory evaporation and respiratory and cutaneous gas exchange.

There is little essential difference between the two water series (Fig. 4), except perhaps an earlier onset in the greater water-fed. The rate fluctuates about a steady level; there is a reduction in the hour succeeding food. Subject 15 is again exceptional in maintaining a definitely lower level of sweating than the remaining subjects.

There was nothing in the nature of bursts of sweating observable after the periodical taking of water, such as is seen when larger quantities are taken [Lee and Mulder, 1935*b*].

The average level of sweating in the waterless series is a little lower than that occurring in the water-fed (56·3 oz. in 5 hours, as compared with 67·6 oz.).

Urine loss.

The subject emptied his bladder as required into a graduated measure. Subject 16 alone experienced some inhibition.

The "basal" level attained by subjects kept in a normal temperature without water lies about 15–30 c.c./hour [Lee and Mulder, 1935*b*]. The output of the lesser water series (Fig. 5*a*) never falls below this, and frequently lies above it, particularly during the sixth hour. The output of the greater water series (Fig. 5*b*) is usually greatly in excess of the "basal", and represents with some lag roughly the excess of water intake

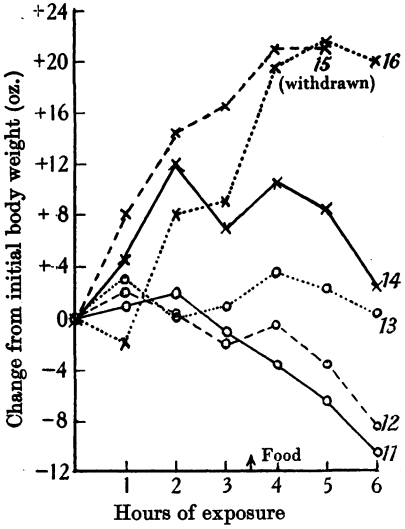

Fig. 3. Change in net body weight.

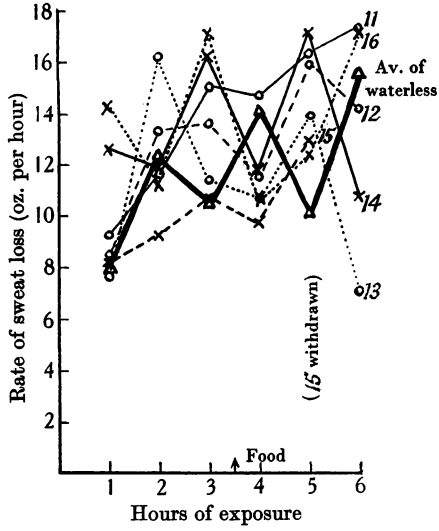

Fig. 4. Rate of sweat loss.

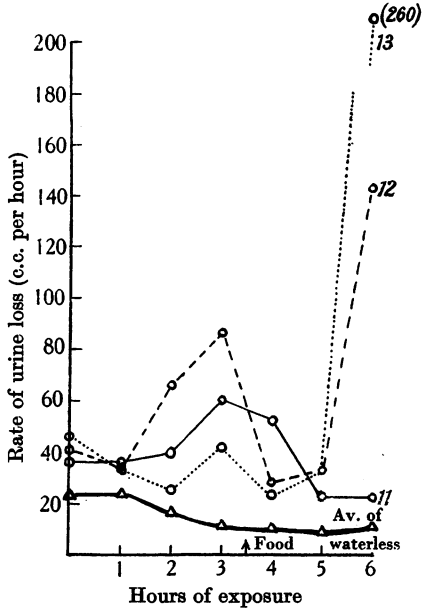

Fig. 5 *a*.

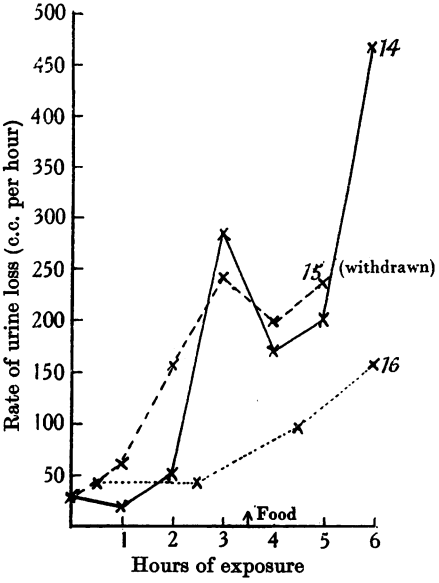

Fig. 5 *b*.

Fig. 5. Rate of urine excretion. *a*, subjects receiving 100 c.c. water every 15 min.; *b*, subjects receiving 150 c.c. water every 15 min.

over sweat loss. The output of the waterless, on the other hand, is lower than the "basal".

Subject 15 presents no abnormalities, but No. 16 shows a comparative reduction of output.

Percentage of serum protein.

This was determined with the Abbé refractometer, with the use of Neuhausen and Rioch's data [1923]. Fig. 6 shows that the lesser water-fed series experienced a definite concentration of serum protein after 2–3 hours, while the greater water-fed subjects suffered no essential variation. (The detailed protocol for Subject 15 has been mislaid, but it, too, showed no essential change.)

The initial percentage of serum protein in the water-fed subjects is apparently lower than in the waterless; this is probably due to a change in the zero setting of the refractometer between the two occasions.

The concentration in the lesser water series is of smaller extent and of later onset than that in the waterless.

Percentage of hæmoglobin.

This was determined by the Stadie-Wu cyanhæmoglobin method [Peters and van Slyke, 1932] upon finger-blood samples of 0·2 c.c. The sample obtained in the "control" room was in each case taken as the standard, and all succeeding samples expressed as a percentage of this. The results appear in Fig. 7.

The curves exhibit the general form of an initial fall followed by a recovery. The depth of the initial trough is variable. The subsequent rise is generally more marked in the lesser water-fed series than in the greater. The average depth of trough and extent of subsequent recovery is less in the water-fed than in the two waterless subjects previously studied.

Chloride content of whole blood.

The micro-method of Rehberg [1925] was used, in which samples of finger-blood of 0·1 c.c. were employed. The final back titrations were made with a modification of Rehberg's apparatus [Lee, 1935*a*] (and a little nitro-benzene used to sharpen the end point). Control estimations made by this method agreed to within outside limits of 5 p.c. Fig. 8 sets out the results.

The subjects in the lesser water-fed series show a slight tendency to a rise in blood chloride, while two of the greater water-fed series maintain a steady level. Subject 14 exhibits a much lower initial level, and suffers a progressive reduction.

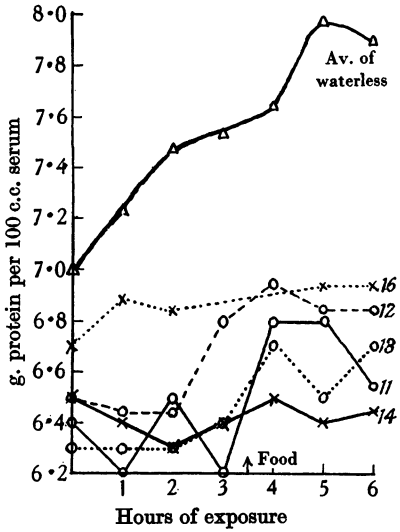

Fig. 6. Percentage of protein in serum.

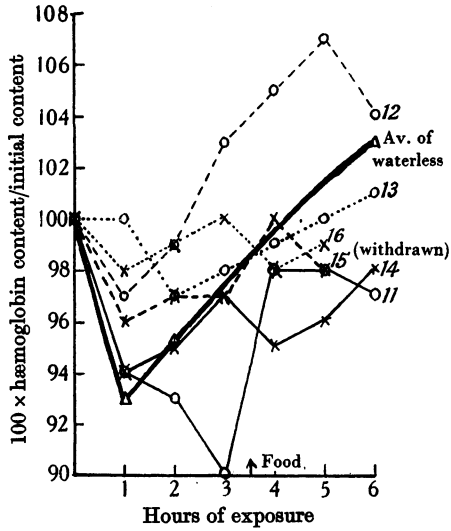

Fig. 7. Variation in hæmoglobin content of blood (in terms of initial content = 100).

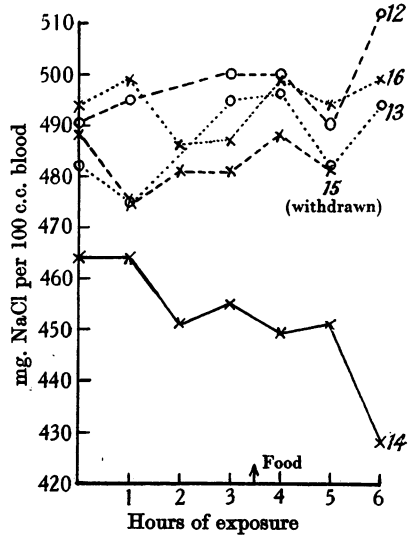

Fig. 8. Concentration of sodium chloride in whole blood.

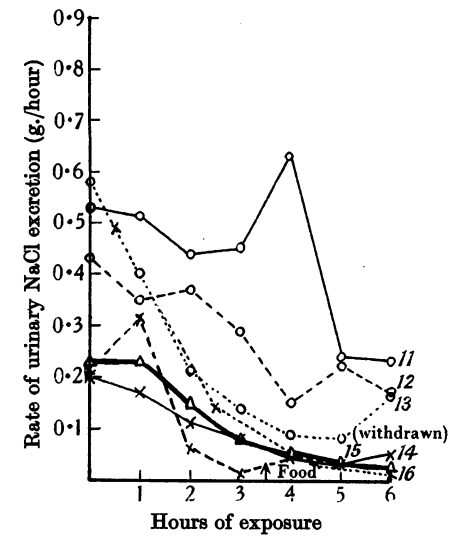

Fig. 9. Rate of sodium chloride excretion in urine.

Urinary chloride excretion.

The concentration was determined by the modified Volhard-Harvey method [Peters and van Slyke, 1932]. The hourly rates of excretion appear in Fig. 9.

All subjects show a progressive fall in chloride excretion, as did the waterless subjects. Those in the lesser water-fed series, however, do not reach such low levels as those in either the greater water-fed or the waterless series. (The initial level in these cases, on the other hand, is also somewhat higher.)

Acid-base equilibrium.

Blood was withdrawn from the median cubital vein of each subject three times: in the control room, 3 hours after, and 5 hours after entering the hot room respectively. That from Subjects 11, 12 and 13 was expelled under paraffin and stirred with a little powdered oxalate and fluoride, and subsequently analysed by the manometric technique of van Slyke to determine its CO_2 content. That from the remaining three subjects was withdrawn without paraffin, mixed with the oxalate-fluoride powder, placed in a tonometer containing 5 p.c. CO_2 in O_2, equilibrated at room temperature for 15 min., and then analysed for its CO_2 content.

In addition, in four subjects, some of the venous blood was allowed to clot and the separated serum analysed for its CO_2 content after equilibration in the same way. The results may be termed respectively the CO_2 content, the CO_2 combining power of whole blood, and the CO_2 combining power of serum.

The CO_2 content (Fig. 10*a*) at the third hour is lower than its initial value, but has risen again by the fifth. The initial fall, but not the subsequent rise, was seen also in the waterless subjects.

The CO_2 combining power of whole blood usually follows the same trends (Fig. 10*a*) as does also the combining power of separated serum (Fig. 10*b*).

The concentration of acidic factors in the urine was estimated by adding together the titratable acidity (to a *p*H of 7·4) and the ammonia content. The former was determined by Henderson and Palmer's method [Peters and van Slyke, 1932], and the latter by the alkaline aeration method. The results, expressed as c.c. of *N*/10 acid per hour are given in Fig. 11.

There is little essential difference in urinary acid excretion between the two water-fed series. There is an early rise in nearly all cases, but the subsequent behaviour varies. The average output is much greater than that achieved by the waterless subjects, and approximates to that of normal subjects [Lee and Mulder, 1935*a*]. In general, titratable acid and ammonia contents behave in parallel fashion. Subject 15 exhibits a very low acid output, conforming to the waterless type.

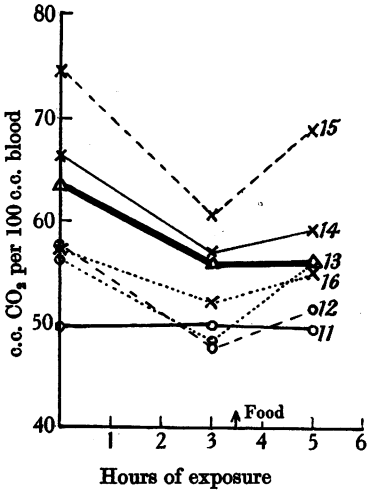

Fig. 10 *a*.

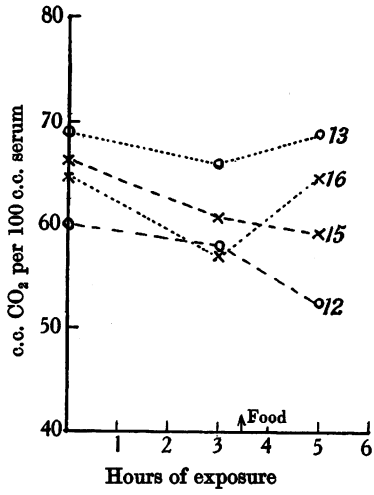

Fig. 10 *b*.

Fig. 10. *a*, CO_2 content (circles) and CO_2 combining power (crosses) of whole vein blood; *b*, CO_2 combining power of separated serum.

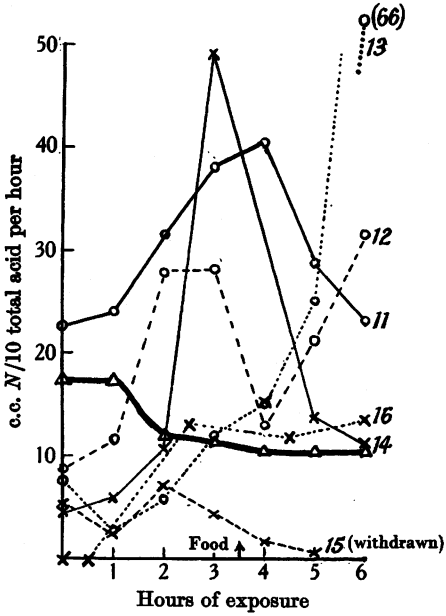

Fig. 11. Rate of excretion of titratable acid plus ammonia in urine.

Respiratory minute volumes, measured by having the subjects expire through a calibrated dry meter, showed no essential alterations. Respiratory rates, likewise, showed no constant variation.

Symptoms.

Five of the subjects experienced nothing more than a slight fullness of the head, some lassitude and a disinclination to study. There was no thirst, irritability or vertigo. This is in contrast to the experience of the dehydrated subjects, and is in agreement with clinical experience in the use of pyreto-therapy [Perkins, 1931].

Subject 15, on the other hand, developed a headache before lunch. Although some temporary relief followed food, the symptoms soon grew worse, with restlessness, irritability and a sense of confusion. Later the respirations became irregular, drowsiness increased and the complexion took on a congested and almost cyanotic appearance. At this point the subject was withdrawn and made to take a warm bath, which allayed most of his symptoms.

Discussion.

Body temperature.

It is clear that, with the amounts of water here supplied, thermal equilibrium was maintained in five subjects, merely suffering a shift of its equilibrium point to the higher level of 99·9–100·5° F. This is in marked contrast to the precarious hold upon stability maintained by the waterless subjects in an equivalent environment.

If the final excess body temperature reached by the waterless over the water-fed be taken as 1·5° C., the body weight as 65 kg., and the specific heat of the body as 1, then the excess heat accumulated by the waterless subject is 97·5 calories. This is equivalent to the latent heat of vaporization of 170 c.c. of water. In this time the water-fed subject secreted, on an average, 340 c.c. more sweat than the waterless. If the efficiency of utilization of this sweat can be regarded as reaching 50 p.c., then the question of the mechanism of thermal adjustment in relation to hydration can be regarded as answered. Nevertheless, it would be interesting to know whether any qualitative or quantitative changes in metabolism result from dehydration, and so affect the heat balance also.

Circulatory system.

Only a few aspects of this complex and highly integrated system are touched upon in these experiments. The pulse rate exhibits the same lessening of reaction and increase of stability in the water-fed subjects

as does the thermal equilibrium. The susceptibility of this mechanism to food intake, however, does not seem to be affected by the degree of hydration, or body temperature.

The circulatory volume is almost certainly better maintained in the water-fed than in the waterless, as is suggested by the reduction or absence of active concentration of blood constituents in these subjects. That circulatory efficiency is much better is also indicated by the comparative mildness of the symptoms experienced by the water-fed.

Chloride balance.

The restriction upon urinary chloride output which was observed to develop in the waterless is apparent also in the water-fed subject, in spite of the increased urine flow. This conforms with the observations of numerous workers in tropical [Young, 1919; Morton, 1932; Marsh, 1933; Dill *et al.* 1933], industrial [Moss, 1923] and therapeutic [Stecher, 1935] fields.

In three subjects the original chloride level of the blood was well maintained, even though the water content of the body was kept up. In these cases the chloride reserves were apparently sufficient to effect replacement of blood chloride lost in sweat. Transfer of water from the blood to the cells (see below) may also assist in maintaining the concentration of chloride. In Subject 14, however, the blood chloride was low at the commencement, and fell progressively, indicating that there must have been here practically no chloride reserve. This subject subsequently volunteered the statement that, while normally disliking salt, experienced a marked desire for it in his food that evening.

Water balance and distribution.

The percentage of serum protein is the best single index of "blood concentration", though by no means infallible [Lee and Mulder, 1935*b*]. Its behaviour when the body is exposed to heat is interesting.

TABLE I.

Subjects and conditions	Loss of weight in 5 hours	Average conc. p.c. in blood		Ratio Observed / Calculated	Reference
		Calc.	Obs.		
Waterless, hot dry	66·2	4·64	11·28	2·46	Lee and Mulder, 1935*b*
Waterless, hot wet	29·6	2·22	7·66	3·56	,, ,,
Lesser water-fed, 11 and 12	4·5	0·29	5·50	21·35	This series
Lesser water-fed, 13	Nil	Nil	6·30	Inf.	,,
Greater water-fed	Minus	Minus	Nil	—	,,

We can calculate the average concentration to be expected in the watery tissues of the body, if we assume that 65 p.c. of the body weight is water, and we know the loss of body weight. We can compare this with the "concentration" observed in the circulating blood. The results given in Table I emerge from this and previous studies.

Two explanations are suggested: (1) That continued exposure to heat induces a loss of water from the blood stream in addition to that due to any dehydration of the body as a whole, and that this is inhibited or compensated only when a definite excess of water is presented to the body. (2) That addition of serum protein to the blood stream occurs during exposure to heat. The fact that the hæmoglobin percentage, once the initial fall has been established, behaves in a parallel fashion to serum protein percentage suggests that the former explanation is the more likely. Darrow and Yannet [1935] have shown that a removal of electrolyte from the extracellular fluid may induce a transfer of water from the extra- to the intracellular phase. The present observation would conform with theirs. Such a removal of water from the blood would help to maintain the chloride concentration but would adversely affect circulatory efficiency.

It is interesting to note that, in spite of a falling body weight, Subjects 11 and 12 did not establish a reduction of urinary volume below the normal "basal" level. Apparently dehydration must be well marked before the urinary secretion can be reduced to the lower levels encountered in the waterless subjects when in the hot room. The failure of the body to maintain weight under these circumstances is usually ascribed to a protective device for the maintenance of a normal blood chloride level [Marschak and Klaus, 1929; Zuntz and Schumburg, 1901]. There is no evidence to suggest a failure of chloride reserves in these two subjects, however. On the other hand, the operation of such a mechanism would not be inconsistent with the reactions of Subject 14.

The increase of the sweating loss here observed agrees with the findings of Kuno [1934] and of Haldane [1935] and his co-workers; rather than with those of Laschtschenko [1898].

Acid-base balance.

It was suggested by Lee and Mulder [1935*a*] that the fall they observed in the CO_2 content of cutaneous venous blood during exposure to heat was due partly to loss of CO_2 through the skin and partly to increased cutaneous blood flow. The parallel behaviour found in the present studies between the CO_2 content and combining power of whole

blood and of serum suggest that the variations in the first of these are due to a change in the fundamental acid-base factors of the blood as well as to a simple local acapnia. This question is the subject of further study. It is doubtful whether there is much variation in the *p*H of the blood, since the CO_2 content and the CO_2 combining power behave in parallel fashion.

Failure of adaptation.

When the human body is exposed to hot environments, numerous adaptations are essential. Acute failure of adaptation, and breakdown of the equilibrium between the body and its environment may result from one or more of four physiological crises [Lee, 1935*b*]—thermal (heat stroke), circulatory (heat exhaustion), electrolytic (heat cramps), or hydrating (thirst). Cases 14 and 15 present some features indicative of incipient failure.

Case 14. Had the experiment been continued, this subject would almost certainly have developed the condition of "heat cramps" which has been clearly shown to be associated with a hypochloræmia [Talbott and Michelsen, 1933].

Case 15. This subject presents five outstanding differences in reaction from the remaining subjects: (i) he shows no attempt at a stabilization of thermal equilibrium; (ii) his cardiac rate fails to attain a steady state, but the discrepancy is not so marked; (iii) his sweat loss is definitely subnormal; (iv) the urinary acid excretion is very low; (v) the symptoms are out of proportion to the circumstances.

It might be thought that the primary failure here lies in the sweating response, thermal and circulatory failures being natural consequences from this, but subsequent observations have cast doubt upon the validity of this simple conception. There is no doubt, however, that circulatory failure is the factor which was rapidly bringing about a dissolution of his equilibrium with his environment when he was withdrawn. (That his more urgent symptoms are due to circulatory failure is indicated by their removal by bathing and is in conformity with clinical experience [van Zwalenburg, 1933].) We have here an example of what must frequently happen in hot climates—the avoidance by the body of the major issue of thermal failure by the previous forcing to a crisis of the relatively minor issue of circulatory adjustment. It is often the robust well-trained man who by avoiding heat exhaustion lays himself open to the onslaught of heat stroke.

Summary and conclusions.

Experiments are described in which unacclimatized male subjects were exposed to an atmosphere of 95° F. "effective temperature" (D.B. 110° F., W.B. 90° F.) for 6 hours and given 100 or 150 c.c. of water to drink at 15-min. intervals. Observations were made upon certain factors entering into the balances of body temperature, circulatory function, chloride metabolism, water metabolism and acid-base regulation. The variations in individual reactions are noted, and the general reactions compared with those found in subjects deprived of water but otherwise subjected to the same conditions, the accounts of which have previously appeared from this laboratory. Incipient breakdown of equilibrium between two subjects and their environment is discussed. The following conclusions are reached:

1. Maintenace of bodily hydration markedly increases the stability of the thermal equilibrium and reduces the degree of shift of the equilibrium point.

2. The rate of sweating is somewhat increased in the water-fed as compared with the waterless subject; this may be sufficient to account for the differences in thermal behaviour.

3. The circulatory functions are rendered more efficient by hydration, as shown by the increased stability of cardiac rate, its lowered deviation from normal and the reduction of symptoms referable to inefficient circulation.

4. There is a definite reduction of urinary chloride excretion during exposure to heat, no matter what the urinary volume.

5. Apart from the concentration of blood consequent upon dehydration, there tends to be a decrease during exposure to heat of the ratio between water and protein in the serum.

6. Reduction of urine output below the normal "basal" level found in temperate atmospheres will not occur before a certain level of body dehydration is achieved.

7. Certain disturbances in the acid-base equilibrium of venous blood reduction of CO_2 combining power and CO_2 content—tend to occur during exposure to moderate heat.

We wish to acknowledge our indebtedness to Prof. C. Lovatt Evans and to Dr G. P Crowden for their continued interest and valuable criticism, to the London School of Hygiene and Tropical Medicine for the use of the Air-Conditioning Room and to the subjects who cheerfully submitted to the many discomforts of the experiments. We have also to acknowledge the Grant made to one of us (D. H. K. L.) by the Medical Research Council from which the expenses of the investigation were met.

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