THE REGULATION OF BODY TEMPERATURE IN EXTREMES OF DRY HEAT.

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SINCE 1903 the writer has been in the Deccan, India, where during the hot weather (*March, April, May*) the maximum temperature is daily seldom under 100° F. (38° C.) and in some parts rises to over 110° F. (43° C.) for long periods. The "wet bulb" remains usually between 65° and 70° F. (18°–21° C.), showing a very low percentage of moisture. Wet heat is not usual, since with the rains the weather becomes cool.

During extremes of dry heat no great discomfort is felt by healthy persons, and fairly hard physical work is possible in the sun, even with a "shade" temperature of 110° F. or more. These conditions present physiological and hygienic conditions of much interest.

It is, firstly, essential to arrive at a clear understanding as to what the organism is called upon to do, in order to prevent any marked rise in internal temperature. Radiation and conduction are only available as cooling agents when the outside temperature is below that of the body. Further, it is clear that if the outside temperature be above that of the body, heat is actually added instead of lost: and this additional heat is greatly increased by exposure to a very hot sun or wind.

The organism must therefore depend solely on evaporation as a cooling agent: and evaporation must be sufficient to neutralise all the heat added from external sources, and also the whole heat which is due to internal metabolism. This latter can be approximately determined by taking the net heat value of the average diet and calculating the amount of water, the evaporation of which will absorb this heat. With diets liberating 3,500 Calories, 6 litres of water will be required (*vide* following calculation):

I. Latent heat of steam at 37° C. (98·6° F.) = 582.

II. Heat liberated in the body by metabolism 3,500 Cal. (for abled-bodied Europeans leading an active out-door life this estimate is a moderate one).

Each litre of water evaporated neutralises 582 Calories.

The total amount of water required to neutralise the heat produced by metabolism is therefore

$$\frac{3500}{582} = 6 \text{ litres } (13{\cdot}2 \text{ lbs., } 10{\cdot}5 \text{ pints or } 1\tfrac{1}{4} \text{ gallons}).$$

Water must therefore be taken into the system in food and drink in sufficient quantities to satisfy the following:

1. Urine and faeces, up to 1,500 c.c.
2. To neutralise by evaporation the heat added by metabolism, up to 6,000 c.c.

[Cool nights may considerably lower this figure.]

3. To neutralise, by evaporation, the heat added to the body by radiation and conduction, ?amount.

[The time spent in the sun is an important factor.]

4. To allow for inefficient or wasted perspiration, local or general, ?amount.

[A very variable amount, but probably never negligible.]

A closer study of (2) is interesting. Presuming for the sake of argument that the air temperature remains constant at 98·6° F. dry bulb and 68·6° F. wet bulb (37° C. and 20° C.), radiation and conduction are neutral, and evaporation the sole cooling agent. The water evaporated, however, will absorb heat not only from the body but also from the air in contact with the body; *e.g.* presuming that in a given time 582 Calories were liberated by metabolism, and 1 litre of water evaporated, equilibrium would not be obtained, for of these 582 Calories some would not be body heat but air heat.

Equilibrium would occur at some lower temperature than *98·6°*: or if at 98·6° then an increase in the amount of water evaporated would be required.

Again, one may refer to work done recently by Douglas and Haldane (*Journal of Physiology*, XLV. p. 236, 1912). They determined the oxygen absorption under varying conditions of work, and an average of results gave the following:

On waking, in bed	237 c.c. O_2 per minute
At rest, standing	330 ,, ,, ,,
Walking 2 miles per hour	780 ,, ,, ,,
,, 3 ,, ,,	1065 ,, ,, ,,
,, 4 ,, ,,	1595 ,, ,, ,,
,, 4½ ,, ,,	2005 ,, ,, ,,
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https://doi.org/10.1017/S002217240000512X Published online by Cambridge University Press

With an ordinary proportion of fat, proteid, and carbohydrate in food, one litre of oxygen produces, in oxidation, 4·8 Cals. Walking without a load at 4½ miles per hour may be taken as moderately severe exercise, and during such exertion the hourly energy production is

$$2{\cdot}005 \times 60 \times 4{\cdot}8 \text{ Cals.} = 577{\cdot}4 \text{ Cals.}$$

Taking, as an extreme figure, 10 % of this amount as being given off in the form of outside mechanical work done, there remains an hourly 520 Calories to be neutralised. In terms of evaporation this entails 900 c.c. of water, or 1·98 lbs. Even at three miles an hour, over one pound of water would be required, while for really severe exertion a very high figure would be reached.

It may be presumed that the organism is capable of secreting from air passages and skin enough water to neutralise by evaporation any heat which is produced in the body. No figure can however yet be given or quoted as to the maximum secretion of water. It will be shown later that a rate of about 2 lbs. an hour is readily obtained in healthy men even at rest, and this may be far from the maximum.

Douglas and Haldane's figures for oxygen absorption "on waking" are important, and indicate that during sleep as low a rate as 68·29 Calories per hour are produced. In terms of evaporation this implies 0·118 litres, or 0·259 lbs. of water per hour. A cool night (*e.g.* at 85° F.) might thus allow of an almost total cessation of sweating; radiation, conduction, and evaporation from lungs, etc., being sufficient. Such relief during a few hours of the night is of great importance in admitting of sound sleep.

During the day-time, however, metabolism is raised in proportion to activity. The water required by different individuals will thus vary enormously, the main factors being variation in activity, air temperature, and exposure to sun.

It is unfortunately impossible as yet to give or quote figures for (3) (the heat added to the body by radiation or conduction), but it should not be impossible to secure fairly accurate data.

It seems probable that in high air temperatures no heat would actually pass from the air to the body, but rather that increased evaporation would occur and then prevent such entrance of heat. Even at 98·6° F. some of the cooling effect of evaporation is applied to air, and as the outside temperature rose this amount would proportionately increase. Many factors would influence this: *e.g.* hot winds, clothing, etc.

https://doi.org/10.1017/S002217240000512X Published online by Cambridge University Press

The value *582* for the latent heat of steam would also vary, but such variation would be slight and can be neglected. Thus, at 98·6° F. it is 582, and at 68·6° F. 592; while if evaporation took place at a higher temperature than 98·6° F., the value would tend to diminish.

It is interesting to compare these hypothetical estimates with an actual though rather rough observation, taken during the greatest heat the writer has yet experienced.

In May 1910 the writer had the opportunity of studying fairly accurately three healthy Europeans during an exceedingly hot and very dry spell of weather.

For some hours at midday, the lowest temperature which could be secured in tents under trees was 109° F. (45° C.). All dry objects were as hot as this or hotter; and were uncomfortable to handle. The thermometer fell at once when a hand was placed near it, or if it were breathed upon. No "standard" reading of "shade" temperature could be taken, since a fairly complicated apparatus is needed; but it would have been at least 6° F. above the air in the tent. It is, however, the temperature inside the tents, etc., which counts. Up till about midday the party remained in the sun with no shade whatever, walking, etc., and a considerable amount of physical exercise was taken until the next camping ground was reached. Such a life is led by hundreds of Europeans, and usually with a gain rather than a loss to health. When health suffers it is through such side issues as malaria.

As regards the amount of liquid consumed, none of the party, using strict moderation, consumed less than three gallons per day; and one exceeded this considerably. The writer is convinced that a less amount would have been inadvisable, for even with three gallons (or 13·6 litres) the flow of urine is by no means free. Unfortunately no exact figures can yet be given for the urine.

The conditions under which this party were placed probably represent a combination of heat and exposure which nearly approach the limit as far as comfort is concerned.

The three gallons of liquid consumed is not far removed from the amount suggested by the hypothetical estimate.

It must be clearly understood that this amount is only needed where there is considerable exposure and activity in extremes of heat; and the same weather conditions could be endured inside a good bungalow with about a third of three gallons. It may further be observed that as a rule persons have no conception of the amount of liquid they consume in the twenty-four hours, unless they carefully record it.

In such extremes of dry heat, any failure of perspiration must lead to instant and grave risk. Such failure may result from an insufficiency of drinking water being available. It may equally result from pathological processes incidental to slight malaria, early typhoid, or any other process by which heat-regulation is upset. An individual might suffer from but slight fever while indoors: he might in fact be unaware that he was ill: yet his whole regulation might completely fail if he were at work in the sun under conditions which involve, even for the healthiest, an extreme effort. The writer has come in contact with cases which suggest that this may readily occur, but has come across no case as yet of pure "heat stroke" or sunstroke in a proved healthy individual.

Observations were commenced on June 22, 1912, in the Physiological Laboratory at Oxford with a view to determining as far as possible the amount of sweat which can be secreted without great bodily disturbance or discomfort; and, secondly, to determine whether any marked alteration occurred in the percentage of sodium chloride in the sweat.

It was thought possible that as the water in the body was reduced, the NaCl in the sweat would increase, and that this increase would disappear on a resumption of drinking. The experiments however were not carried to any extreme, and no marked change was found.

Dr Haldane kindly lent the room and respiration chamber which he had used in 1905 to determine body temperature alterations under extremes of wet heat. Sweat was collected while the subject was in the chamber, the air being saturated at 93° to 94° F. (34°–35° C.). At this temperature neither condensation on the skin nor evaporation can occur to any appreciable extent; and the subject can remain inside a sufficient time for ample sweat to be collected. A balance was fitted up in the room for estimating body weight.

The NaCl in the sweat was estimated by Volhard's method, and the solutions standardised against each other and against known weights of NaCl.

It may be noted that the percentages found on the subject quoted are lower than those usually given. This may be due to the fact that he has been accustomed to prolonged heating exertion (such as cycling), and has spent some time in hot climates. Very free and habitual secretion of sweat would perhaps tend to a low NaCl content, as otherwise chlorides would be unduly removed from the system. During the period of observation here quoted the NaCl in the urine remained about 0·8 %.

It was however found that unless great care was taken in cleansing the skin, the NaCl percentage rose and estimates of 0·26, 0·32 and 0·37 were found due to this cause. Thus a ·20 % sample was taken in the chamber at 94° F. saturated: and after two or three minutes' exposure to the drier air of the room itself (94° dry bulb, 85° wet bulb) a second chamber sample showed 0·26 %. The readings 0·32 and 0·37 were obtained after prolonged stays in the room, with exercise, the subsequent sponging of the skin and rub down being insufficient to remove sweat residues.

This factor may possibly apply to some of the published analyses. It may however be added that high readings were found on other subjects, the skin being undoubtedly free of sweat residue, *e.g.* 0·43 % from a case of granular kidney.

The percentage of NaCl in sweat was first determined on five days, some few hours after breakfast, when the body weight was at its normal of 164 lbs. (74·5 kilos). It varied between 0·18 and 0·2 %, the lowest figure being obtained on a cold day when the urine was very free.

On the 27th June, in order to procure a maximum withdrawal of water with a minimum of discomfort, the subject was treated to a Turkish bath. No liquid was taken after 8.30 a.m. but a light lunch of cold meat and bread at 12.45 p.m. At 2.10 p.m. the "bath" was commenced, firstly at 140° F. (60° C.) and then at 180° F. (84° C.), returning at intervals to the 140° F. room.

At 4.40 p.m. the cooling room was entered and the usual thorough scrub carried out, which would necessarily remove all traces of dried sweat. By the bath weighing machine, exactly 5 lbs. were lost, the rate of loss being 2 lbs. per hour.

After leaving the bath, the laboratory hot room was re-entered and at 5.30 p.m. a sample of sweat was taken in the chamber, and the flow was as free as usual. The weight was then again taken on the balance and since 8.30 a.m. the drop was 6 lbs. 12 ozs. To this loss must be added at least 8 ozs. for food taken at 12.45 p.m.

At 6.30 p.m. after four pints of liquid had been drunk and the body weight had been proportionately raised, the chamber was again entered and a further sample of sweat obtained.

Analysis of the 5.30 p.m. sample showed *0·21* % and the 6.30 sample showed *0·213*, the slight increase in the latter being fully accounted for by the residue of the previous sweat not having been completely removed.

It is important to estimate as closely as possible the amount of water which the body had lost between 8.30 a.m. and 5.30 p.m. Urine and faeces had not been voided, and can thus be left out of the calculation for the time being. To the total loss of 6 lbs. 12 ozs. must be added about 8 ozs. for the food taken at lunch. In all 7 lbs. 4 ozs. Of this loss, 5 lbs. occurred between 2.10 and 4.40 p.m. and the remainder during the other hours, especially in the morning while in the hot room and during the 5.30 p.m. sweat.

Of the total loss, some was due to Respiratory Exchange, but this amount can be neglected[1].

Meanwhile water was being produced by oxidation in the tissues, but this amount is more than off-set by the amount secreted by the kidneys and locked up in the bladder (410 c.c.).

The total loss of water by evaporation must have therefore been more than 7 lbs. in weight. Yet at 5.30 p.m. in the chamber sweating was as free as ever.

The source of this water must be some tissue or tissues from which it can be readily spared, since no great discomfort was complained of, nor were the general appearance and condition worse than is daily seen in individuals after hard exercise in great heat.

Since the volume lost is not far short of that of the blood, it is clear that the blood cannot be the ultimate source of this water. In order to further decide on this point, the percentage of haemoglobin was estimated with a Gowers-Haldane haemoglobinometer on three other subjects, before and after sweating. No change could however be detected[2].

[1] The subject was at rest, or standing, for the greater part of the eight hours, and as average figures the oxygen absorption and CO_2 output may be taken as:—

320 c.c. oxygen absorbed per minute :

270 c.c. CO_2 output per minute.

Loss of weight can be thus represented:—

270 c.c. CO_2 − 320 c.c. O_2 per minute.

Actual weight can be obtained, calculating 1 litre of CO_2 as weighing 1·97 grammes and estimating the oxygen in proportionate molecular weight.

$$\left(\frac{270 \times 1{\cdot}97}{1000}\right) - \left(\frac{320 \times 1{\cdot}97}{1000} \times \frac{32}{44}\right) \text{ grammes per minute}$$

$$= \frac{531{\cdot}9}{1000} - \frac{458{\cdot}5}{1000} \text{ grammes per minute}$$

$$= {\cdot}0734 \text{ grammes per minute}$$

$$= 35{\cdot}2 \text{ grammes in 8 hours.}$$

This is 1·1 ozs. and is thus a negligible amount.

Subject B: 2½ hours in Turkish bath. Weight fell from 202 to 197 lbs. Haemoglobin constant at 103 %.

Subject C: 2½ hours in Turkish bath. Weight fell from 143 to 138 lbs. Haemoglobin constant at 105 %.

Subject D: Less than one hour in bath, and obviously could not stand heat. Yet the

The low percentage of NaCl in the sweat (0·21 %) indicates that the lymph is almost equally innocent. Yet the source must be very abundant, and the small amount of discomfort shown and the continued freedom with which the sweat was produced show that the 7 lbs. had by no means exhausted the supply which could be spared.

Muscle and skin seem to be the only tissues capable of supplying this large quantity. It has been shown by Engels[1] that muscular tissue in dogs varies widely in the amount of water it can contain, and analyses of muscle show that its percentage of NaCl is but a quarter that in plasma (Bunge). Next in importance to muscle comes skin, which in conjunction with muscle accounted for 85 % of the total range of water variation, from maximum to minimum (skin 17·1 %, muscle 67·9 %) (*vide* table in footnote[1]).

There seems to be no *a priori* reason why tissues such as muscle and skin in the human being should not be used by the organism as storehouses for water, thus securing a reserve for emergency.

The danger period is reached when the reserve is nearing depletion.

haemoglobin remained constant at 94 %. The sweating chamber was available for this case, and the sweat showed an NaCl percentage of 0·38 at the commencement and 0·43 at the end of sweating. Simultaneously there was a marked fall in the NaCl percentage in urine (0·13 % to 0·06 %). The urine contained albumen and this case has a pathological rather than a physiological interest.

The significance of the extraordinary diminution in NaCl excretion in the urine may however be referred to, for Subject B showed a tendency in the same direction, although in perfect health, *e.g.* during the three hours which included the Turkish bath the urine excreted was 93 c.c. in amount and the NaCl percentage was 0·52. With a similar diet, and during the same time of day on another occasion without sweating, in 2¾ hours 270 c.c. of urine showed 0·89 % NaCl. This clearly needs further investigation, the chief point being the lowered percentage of NaCl.

[1] Engels, *Arch. f. Exp. Pathol.* 1904.

Dogs were taken in pairs, each individual of a pair being as far as possible identical with the other.

One of each pair was given the maximum and the other the minimum of water. Dogs then killed.

Mean weight of dog 6·6 kilo.

Mean weight of water taken up 0·81 kilo.

	Of the water taken up the following percentages were found in the various tissues	Percentage increase in the weight of each organ or tissue
Muscle	67·89	17·1
Skin	17·75	11·9
Blood	1·55	2·4
Liver	2·96	8·9
Intestines	2·25	3·0
Kidneys	1·41	17·9

Apart from all considerations such as kidney excretion, and commencing concentration of blood, lymph, etc., there would be the restriction of sweat, and consequent danger, in dry heat, of a rise in body temperature. The body, in fact, would be deprived of evaporation as a means of heat regulation, and a dry heat of even 94° F. would be as fatal as a saturated atmosphere of that temperature in a normal individual. The limit of safety in wet heat has been investigated by Haldane, *Journal of Hygiene*, Oct. 1905, and H. Sutton, *Journal of Pathology*, XIII. 1908.

When the body temperature rises much above normal, general excitability is evinced, and the general metabolism is increased so that a vicious circle is indicated. There is thus no real compensation by lessened heat production or by increased heat loss with rise of body temperature, and temperature regulation fails abruptly and completely.

Further observations suggest that when water is once extensively withdrawn from the storehouse, its return is not very rapidly accomplished. A free intake of water by the mouth is at once followed by a corresponding rise in body weight, and often by wasteful perspiration. Free micturition may in part be but a clearing up of old accumulations. Thirst rapidly recurs in spite of copious drinking, and if this is excessively indulged in much water is, as above mentioned, wasted in needless profusion of sweat, while in a short time the thirst recurs again. After the experiment quoted, 16 hours passed before a normal condition was reached and thirst ceased to recur unduly, although the surroundings of the subject were ideal. This seeming delay in the re-accumulation of borrowed water may have an important bearing in prolonged and arduous work in dry heat: for under such circumstances the difficulties of replacement are increased and may be impossible except where a full amount of drinking water is obtainable. This may perhaps explain that the ill effects of prolonged work in great heat are unquestionably minimised by free drinking of water during work; and this applies as obviously to horses as it does to man.

Stress may perhaps be laid on the suggestion that great temporary dehydration may be very false economy; since while the depleted reserves are being restored, water may be run to waste in the form of unnecessary perspiration.

Finally a word may perhaps be said on the subject of "wet heat." Here the air is already more or less saturated with moisture, and this is indicated by high "wet bulb" thermometer readings. Evaporation is slow and so inefficient that, according to Haldane, with a still atmosphere, 89° F. (31·6° C.) (wet bulb) represents the limit of safety, even during rest, and about 78° F. (25·5° C.) during work. The amount of sweat evaporated is small, and the excess which is secreted merely increases the soddenness of skin and clothing. Any increase in the amount of water consumed merely spells increased discomfort.

Short summary and conclusions.

(1) Comfort and health can readily be maintained in dry heat where for long periods the air temperature is above that of the body.

(2) The amount of water absolutely required, and actually consumed, is very large; and this is accounted for by the necessity for neutralising, in some circumstances, the whole heat of metabolism (requiring up to 6,000 c.c.) and in addition a variable but sometimes very large amount of heat added to the body by radiation and conduction.

(3) A healthy man carries in his body a large reserve of water, this reserve being mainly stored in muscle and being so readily available that the percentage of water in the blood is not appreciably diminished even when several litres of water have been lost by sweating. If, however, it be extensively drawn on, replacement seems to occupy many hours, and this delay is an important factor, forming a strong argument against any undue or needless use of the stored water owing to restriction of drinking.