# EVAPORATIVE HEAT LOSS FROM THE HUMAN BODY IN DIFFERENT THERMAL ENVIRONMENTS *

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This paper studies the relation of tne evaporative heat loss to theraal stress in naturally acclimatized subjects under Indian conditions. The environmental conditions under which the subjects were made to perform light exercise ranged from 18·9°C E.T. to 30°C E.T. The evaporative heat was found to be significantly correlated to the 1% level with the air and effective temperatures, with correlation constants of 0·79 & 0·80 respectively. The average rate of change of the evaporative heatloss with air temperature was 15·4 K cal/Hr/°C and with the effetivet emperature 9·1 K cal/Hr/°C.

The human body maintains thermal equilibrium in its core through the dynamical adjustment of the heat generation in the body and heat dissipation from the surface. The heat generation is entirely from metabolism, and the heat dissipation takes place through the mechanisms of radiation, convection, conduction and evaporation of water from the skin. The dissipated heat from the body is absorbed by the environment but environmental conditions may sometimes be such that the body receives heat from the hotter surroundings. The rate and manner of the heat exchange between the body and the environment is governed by the ambient thermal conditions particularly the air temperature, humidity, air velocity and the radiant temperature of the surrounding objects. In cooler environments, the channel of dry heat exchange, i.e., through radiation and convection, plays an important part. In hotter environments, evaporation of water from the skin assumes greater responsibility for keeping the body cool.

As a result of this need for enhanced evaporation for adequate heat regulation, the water output through the skin is increased in proportion to the stress of the environment. Robinson[1] and McCutchan[2] have found that the rate of sweating is augmented as the thermal stress becomes more severe. Their data indicates the relation between effective temperature and sweat loss under effective temperatures ranging from 20°C to 30°C.

As a part of the investigations conducted in this laboratory on the responses of Indian subjects to heat, the heat loss through evaporation has been studied. This paper reports the relation of the evaporative heat loss to thermal stress in naturally acclimatized subjects under Indian conditions. These experiments were undertaken with a view to ascertain the extent and pattern of adjustments of Indian subjects to rising environmental temperatures.

## EXPERIMENTAL PROCEDURE

The experiments were conducted in a closed room (10′ × 10′ × 16′) where the thermal environment was assessed at ten-minute intervals according to standard procedures of Ramanathan et al[3]. The thermal conditions, i.e., the dry and wet bulb temperatures taken with a sling psychrometer remained within ±0·5°C during the experimental period. The air velocity given by a kata thermometer was less than 20 fpm (10·2 cm/sec.) indicating that still air conditions prevailed in the room. Radiant heat was negligible since the black globe thermometer reading and the air temperature were not detectably different in any case.

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TABLE 1

ANTHROPOMETRIC DATA FOR THE FOUR SUBJECTS

| Subject | Age (years) | Weight (kg.) | Height (cm.) | Body surface area (m²) |
|---|---|---|---|---|
| MB | 30 | 55·1 | 161·3 | 1·56 |
| BBS | 48 | 65·3 | 177·1 | 1·81 |
| KKG | 32 | 66·2 | 166·4 | 1·73 |
| KG | 36 | 50·3 | 169·9 | 1·57 |

TABLE 2

EVAPORATIVE HEAT LOSS DURING EXERCISE IN DIFFERENT THERMAL ENVIRONMENTS

| Subject | Air Temperature | | Relative Humidity | Effective Temperature | | Latent Heat of Evaporation | Water loss | Rate of water loss | Evaporative Heat loss |
|---|---|---|---|---|---|---|---|---|---|
| | °C | °F | % | °C | °F | Kcal/gm | kg/hr | g/kg hr | Kcal/hr |
| | 32·3 | 90·2 | 68 | 29·6 | 85·3 | 0·5911 | 0·47 | 8·5 | 278 |
| | 31·0 | 87·8 | 90 | 30·0 | 86·0 | 0·5814 | 0·44 | 8·0 | 256 |
| MB | 29·8 | 85·6 | 56 | 26·1 | 79·0 | 0·5974 | 0·36 | 6·5 | 215 |
| | 27·9 | 82·2 | 58 | 25·3 | 77·5 | 0·5959 | 0·35 | 6·4 | 209 |
| | 23·9 | 75·0 | 56 | 21·4 | 70·5 | 0·5970 | 0·21 | 3·8 | 125 |
| | 22·2 | 72·0 | 58 | 20·0 | 68·0 | 0·5814 | 0·23 | 4·2 | 134 |
| | 31·7 | 89·1 | 64 | 28·2 | 82·8 | 0·5931 | 0·37 | 5·7 | 219 |
| | 28·4 | 83·1 | 50 | 24·4 | 76·0 | 0·6010 | 0·29 | 4·4 | 174 |
| BBS | 27·4 | 81·7 | 58 | 23·6 | 74·5 | 0·5959 | 0·20 | 3·1 | 119 |
| | 22·6 | 72·7 | 61 | 20·8 | 69·5 | 0·5943 | 0·08 | 1·2 | 48 |
| | 21·4 | 70·3 | 48 | 19·2 | 66·5 | 0·6017 | 0·19 | 2·9 | 114 |
| | 29·5 | 85·1 | 75 | 26·4 | 79·5 | 0·5877 | 0·38 | 5·7 | 223 |
| | 26·7 | 80·1 | 75 | 24·6 | 76·3 | 0·5876 | 0·27 | 4·1 | 159 |
| KKG | 26·1 | 79·0 | 64 | 22·5 | 72·5 | 0·5929 | 0·31 | 4·7 | 184 |
| | 25·6 | 78·1 | 44 | 22·2 | 72·0 | 0·6050 | 0·28 | 4·2 | 169 |
| | 23·4 | 74·1 | 55 | 20·8 | 59·5 | 0·5976 | 0·26 | 3·9 | 155 |
| | 21·1 | 70·0 | 60 | 19·2 | 66·5 | 0·5946 | 0·28 | 4·2 | 166 |
| | 27·8 | 82·0 | 59 | 24·7 | 76·5 | 0·5956 | 0·32 | 6·4 | 191 |
| KG | 26·4 | 79·5 | 49 | 23·1 | 73·5 | 0·6018 | 0·19 | 3·8 | 114 |
| | 23·4 | 74·1 | 54 | 20·8 | 69·5 | 0·5983 | 0·07 | 1·4 | 42 |
| | 23·1 | 73·6 | 73 | 21·7 | 71·0 | 0·5885 | 0·11 | 2·2 | 65 |
| | 22·8 | 73·0 | 40 | 19·7 | 67·5 | 0·6080 | 0·08 | 1·6 | 49 |

Thus the thermal conditions as indicated by the Effective Temperature (Basic Scale computed from the thermal observations in the experiment room could be considered invariant during any single experiment. The variation of the climate from experiment to experiment was due to natural seasonal changes.

Sweating was induced in the subjects by exercise on a bicycle ergometer at a fixed rate of 60 pedals/min. against a fixed friction load of 2 lbs. This exercise was of a moderate level requiring energy expenditure of 150 Kcal/Hr on the average. Four fit and healthy subjects whose anthropometric data is given in Table 1, were made to perform the exercise for one hour every time. The subjects wore only cotton underwears (weighing about 60 gm) duringthese experiments. Before commencing the exercise, the subjects were made to rest in the closed room for 20 minutes. Sweat loss was determined by weighing the subject nude on an accurate $\pm$(12·5 gm) plat-form balance immediately before and after the exercise after wiping the skin dry each time. The environmental conditions used were such that no significant dripping of unevaporated sweat from the body occurred during the exercise. The experiments on each subject were performed at long intervals of time in the eorder to avoid the effects of training.

In all, 22 experiments on the four subjects were carried out in environments ranging from 66°F ET(B) to 86°F ET (B) [18·9°C ET (B) to 30°C ET (B)]. The evaporative heat loss in each case was determined by multiplying the total water loss by the latent heat of evaporation of water for the corresponding air temperature and humidity. The latent heat of evaporation for each experiment was computed by the method given by Hardy[4] viz.

$$\text{Latent heat of evaporation} = 0{\cdot}578 + 0{\cdot}1104\,(273+t_a)\; ln\; 1/\text{RH Kcal/gm.}$$

where $t_a$ is the air temperature, RH the relative humidity and 0·578 is the latent heat of evaporation of water at 91·4°F (33°C), which is assumed to be the skin temperature. In the computation of the latent heat, a small nearly constant term (0·008 Kcal/gm) due to the cooling of water vapour from skin temperature to room temperature is omitted. For calculating the evaporative heat loss the total weight loss is taken and not the rate of sweating only. The total weight loss includes the relatively small loss of water vapour by evaporation from the lung surfaces, a negligible quantity of unevaporated sweat wiped off before the final weighing and the negligible weight change due to metabolism. Loss of weight due to dripping of sweat from the body was negligible during these experiments.

## RESULTS

The results obtained from these experiments are presented in Table 2, which gives the environmental conditions, the total water loss, the rate of water loss and the heat loss due to evaporation for every experiment.

The relation of the evaporative heat loss to the air and effective temperatures for each subject was analysed statistically and linear relations were established by the least square method. These are presented in Table 3. The correlation was significant in every case and the correlation constant ranged from 0·72 to 0·97 for air temperature and 0·67 to 0·98 for effective temperature. For the four subjects together the correlation constant

TABLE 3

CORRELATION OF EVAPORATIVE HEAT LOSS WITH AIR AND EFFECTIVE TEMPERATURE

| Abscissa | Subject | No. of observations (n) | Y-intercept (a) | Slops (b) Kcal/hr/°C | Correlation constant (r) |
|---|---|---|---|---|---|
| Air Temperature | MB | 6 | —217·2 | 15·1 | 0·97 |
| | BBS | 5 | —207·3 | 13·0 | 0·86 |
| | KKG | 6 | 17·1 | 6·3 | 0·72 |
| | KG | 5 | —555·9 | 26·2 | 0·97 |
| | All | 22 | —246·5 | 15·4 | 0·79 |
| Effective Temperature | MB | 6 | —436·1 | 8·2 | 0·98 |
| | BBS | 5 | —499·7 | 8·6 | 0·83 |
| | KKG | 6 | —86·2 | 3·6 | 0·67 |
| | KG | 5 | —1107·5 | 16·8 | 0·95 |
| | All | 22 | —522·1 | 9·1 | 0·80 |

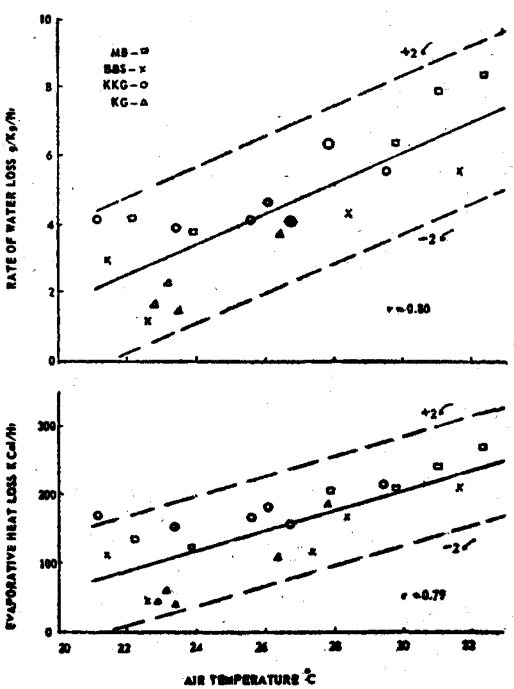


Fig. 1—Relation of evaporative heat loss and rate of water loss with air temperature.

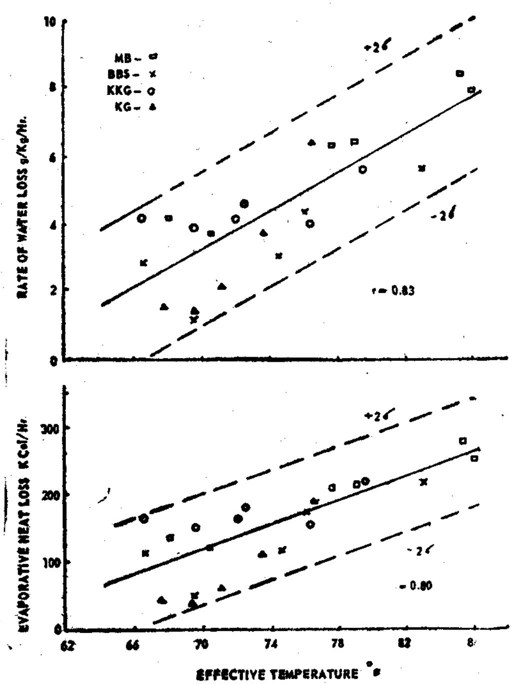


Fig. 2—Relation of evaporative heat loss and rate of water loss with effective temperature.

was 0·79 for air temperature and 0·80 for effective temperature. These correlations were significant to the 1% level as depicted in Fig 1 and 2.

## DISCUSSION

The rate of increase of evaporative heat loss was different for the four subjects (see Table 3, column 5). This difference in the slope of the regressions is only due to individual differences in the sweating pattern of the subjects. On the average, the rate of increase of evaporative heat loss with rise of air temperature was 15·4 Kcal/hr/°C; with the effective temperature the increase was at the rate of 9·1 Kcal/hr/°F ET (B). Robinson[1] has obtained an increase of about 75 kcal/m$^2$/hr at a metabolic rate of 125 Kcal/hr for an air temperature rise of 12°C or 6·25 Kcal/m$^2$/hr/°C; assuming an average body surface area of 1·8 m$^2$ for his western subjects, the rate of increase of evaporative heat loss is 11·25 Kcal/hr/°C. Hardy's[4] figures, adapted from the results of Winslow *et al*, yield slightly lower values. The Indian subjects respond to a relatively greater extent to temperature rise. This may be attributed to their state of acclimatization.

From a similar analysis of the rate of water loss in g/kg body wt/hr with the environmental temperature, it was found that the rate of water loss was also significantly correlated to the air and effective temperatures; the correlation constants were 0·80 and 0·83 with air and effective temperatures respectively. These correlations are also presented in Fig. 1 and 2; the relative scatter of the points in this case in comparison to the regression of the evaporative heat loss may be noted. The rate of water loss for the subjects ranges from 1·2 to 8·5 g/kg/hr when the effective temperature rises from 66·5 to 85·30° F ET (B) [19·2°C to 29·6°C ET (B]; or it rises by 0·39 g/kg/hr for every °F rise in effective temperature (0·71 g/kg/hr/°C ET). Lind[5] obtained an increase of sweat loss from 3 to 15 g/kg/hr when the effective temperature varied from about 60 to 90°F ET (15·6°C to 32·1°C ET). This works out to 0·40 g/kg/hr/°F ET indicating close agreement with the present value.

The present experiment shows the linear response of the evaporative heat loss in the '*Zone of Vasomotor Control*' (19—31°C). The rise of evaporative heat loss would be more pronounced in the '*Zone of Evaporative Cooling*' (above 31°C) and the increase would continue till maximum evaporative loss is achieved. On the cooler side, the evaporative water loss falls till the rate of insensible prespiration is reached; beyond this point no further diminution is possible. Lind[5] has presented a figure where this patern can be discerned.

These results are quite in keeping with theoretical premises and with the observations of previous worker[1,5] Robinson[1] has observed that the evaporative heat loss rises from 25 to 100 Kcal/m$^2$/hr at a metabolic rate of 125 Kcal/hr and to about 140 Kcal/m$^2$/hr for a metabolic rate of 175 Kcal/hr for an air temperature increase from 18—32°C. In the present investigation, the average evaporative heat loss increases from 56 to 138/ Kcal/m$^2$/hr for an air temperature change from 21—32°C. The slightly higher value of the lower limit, *i.e.*, 56 Kcal/m$^2$/hr in the present case may be due to the fact that (*i*) the metabolic work performed by the subjects is different (*ii*) the evaporative heat loss is computed from total water loss and not sweat loss alone as in Robinson's case (*iii*) the lower temperature limit is 3°C more in the present case and (*iv*) the state of acclimatization, fitness etc. of Indian subjects are different. Hardy[4] has presented a figure adapted from Winslow *et al* where the variation of the evaporative heat loss is of the same order namely 20 to 120 Kcal/m$^2$/hr for a similar temperature change.

The present experimental confirmation of the linear response of evaporation to ambient temperature conditions in Indian subjects has been obtained during short period exposures (1 hour) and in naturally occuring climatic conditions in contrast to the climatic chamber findings of Robinson and other previous workers. This clearly shows how readily the heat regulatory mechanism adjusts itself to the vagaries of the environment. The range of air temperatures in which the present study was conducted lies in the Zone of *Vasomotor Regulation* in which the blood flow to the skin is increased to enhance the skin temperature for greater radiative, convective and evaporative cooling of the human body.

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