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WATER EVAPORATION FROM NORMAL SKIN UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

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Abstract. Water evaporation from human skin has been investigated in a climate chamber and was found to be between 0.9 and 1.7 mg $cm^{-2}h^{-1}$ at room temperatures of +15°C and +28°C. Skin evaporation increased slightly up to the temperature at which intense sweat secretion started. There was no difference in evaporation between men and women before sensible sweating began. Differences in air humidity did not significantly affect evaporation from the skin. This is discussed with regard to the evaporation conditions of the air and the hydrophilic properties of the skin. The permeability of excised skin to water was lower than the values obtained in vivo, and therefore part of the insensible perspiration is probably due to the weak activity of the sweat glands.

One of the most important functions of the skin is to prevent desiccation and thus to keep constant the interior of the body. If 30% of the skin area of a mammal is removed death ensues owing to desiccation and metabolic stress (18, 22). The first measurements of insensible perspiration were made by weighing subjects. During recent decades investigators have concentrated on making measurements over limited skin areas. The first methods were gravimetric, but now more accurate electro-hygrometric methods have been developed. Both ventilated and unventilated measuring capsules have been used. In 1944 Burch & Winsor (9) made measurements on living and dead human skin and in both cases they found that evaporation was about 6 mg $cm^{-2}h^{-1}$ when skin temperature was +33°C and air temperature +24°C with 50% RH. Shahidullah, Raffle & Frain-Bell (31) using an unventilated method obtained values between 1.4 and 4.4 mg $cm^{-2}h^{-1}$. Similar values were observed by Monash & Blank (21).

These rather high values may possibly be explained by the fact that a dry environment was used in the measuring capsule. If, when measurement is begun, the skin is humid compared with the air in the measuring capsule, evaporation will be more intense during the first period of measurement until equilibrium is established. If the measurement is made during this first period the results will be too high.

In his monograph on the perspiration of the skin, Yas Kuno (16) gives values between 0.7 and 1.7 mg $cm^{-2}h^{-1}$. Onken & Moyer (26) found that in vitro 0.3 mg $cm^{-2}h^{-1}$ passed through the skin at temperatures between +10° and +20°C. Cohen (10) measured on living skin an evaporation of 1.1 mg $cm^{-2}h^{-1}$ at a room temperature between +20°C and +24°C at 40–55% RH.

It should also be pointed out that many results are difficult to compare since they were obtained under different conditions. Table I shows the values obtained under comparable conditions by different authors.

Certain authors (6, 20) consider that cutaneous insensible perspiration is dependent upon two different factors: diffusion through the epithelium of the skin (transepidermal water loss) and slight water loss from the sweat glands. Others (9, 29) maintain that they have shown that no basal sweat-gland activity occurs. This view is supported by the fact that persons born without sweat glands have a transepidermal water loss of comparable size with those having normal sweat glands (29). Another phenomenon which denies basal sweating is that dry substances characteristic of sweating cannot be shown to be present on the skin after a period of insensible perspiration in persons who are normally equipped with sweat

Table I. *Evaporation from normal human skin in vivo according to different authors. Figures from comparable regions at similar conditions are taken*

Authors	Year	Skin water loss mg $cm^{-2}h^{-1}$
Felsher and Rothman (13)	1945	1.16–1.71
Kuno (16)	1956	0.7–1.7
Fallon and Moyer (12)	1963	0.43
Ohara and Ono (25)	1963	1.11–1.29
Bettley and Grice (6)	1965	0.25[a]
Cohen (10)	1966	1.1
Baker and Kligman (3)	1967	0.29–0.34[a]
Spruit (32)	1969	0.60

[a] Values with anticholinergic suppression of basal sweating

glands (16). For basal sweating speaks the fact that cutaneous evaporation can be lowered by anticholinergic drugs (16).

Many investigators consider that penetration of the skin by water is decreased by a special layer in the skin, the so-called "barrier" (8, 30, 35). The mechanism has not been elucidated beyond dispute. According to Szakall this layer consists of pars conjuncta of the stratum corneum, which is situated above the stratum granulosum. Other authors assert that there is no anatomically bounded barrier, but that this can be regarded rather as a name for a physical property (11, 28). This property is probably dependent upon a lipoprotein. Swanbeck & Thyresson (34) proposed (1965) that kerato-hyaline material comprises the structural basis for the barrier's function with respect to the diffusion of water.

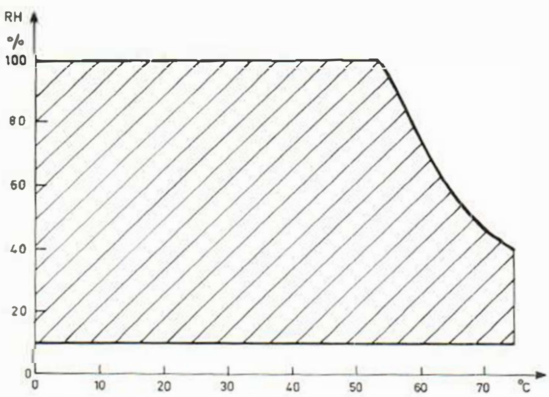

Fig. 1. Diagram showing the possibilities for the varying temperature and humidity in the climate chamber used. The range of conceivable climates lies within the shaded area (mod. after Lindgren (19)).

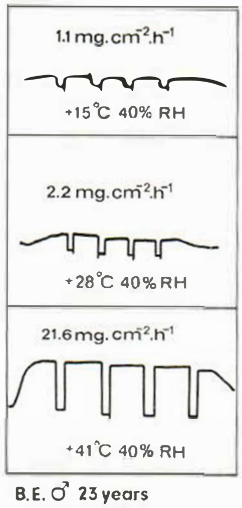

Fig. 2. Recordings from the same subject's thigh for different ambient temperatures.

The aim of the present investigation has been to study how the temperature and humidity of the surrounding air influence evaporation from normal skin. The results are intended to provide a basis for studies on burned skin and experiments for diminishing evaporation from burned patients.

MATERIAL AND METHODS

All the experiments were made in a climate chamber constructed as follows: the walls, whose λ-value was calculated to be 0.05 Kcal/m h °C, are lined on the inside with corrugated aluminium plate. The ceiling is of smooth aluminium plate and under this the air humidifiers and the cooling units are installed. The floor is of concrete with high thermal capacity. The climate area is shown in Fig. 1 [Lindgren (19)]. Accuracy, on adjustment within the relevant test area is, for temperature, $\pm 1/2$°C and for humidity, ± 4% RH.

To measure evaporation from the skin, an evaporometer was used (17). The instrument functions in such a way that a stream of air passes at 2.5 cm/sec over a 25 cm^2 test area. The increase in humidity is recorded after equilibrium has been established; and as the flow of air is known, the evaporation can be calculated. Fig. 2 shows typical recordings. The total weight loss of the subjects is measured with a weighing machine (Sauter VI SJ 25), the accuracy of which is ± 10 g. The skin temperature was determined with a thermocouple (Ellab TC 3) and recorded with an accuracy of ± 0.25°C. The method of measurement involves a small source of error inasmuch as the temperature values for the skin are influenced by the temperature of the surrounding air. To obtain more precise measurements, however, was not considered possible for practical reasons.

The investigation consisted of the following determinations:

(A) Quantitative determination of evaporation from subjects in air of varying temperature and humidity.

(B) Determination of temperature range in which a pronounced increase in sweating occurred in persons at rest.

(C) Quantitative determination of water diffusion through excised skin specimens.

(A) Determinations according to (A) were made on healthy subjects between the ages of 21 and 60 years. The investigations were divided into two series. At first, humidity was kept constant at 40% RH, whereas the temperature of the air was regulated to three different levels, +15°C, +28°C, and +41°C. Secondly, the air temperature was kept constant at +28°C and humidity was adjusted to 20%, 40%, and 80% RH respectively. Measurement was continued until skin temperature and evaporation were constant. At that time equilibrium was considered to be reached.

For a recumbent naked person at rest the lower limit of the zone of physical temperature regulation is between +25° and +26°C. This applies provided the flow of the ambient air is not greater than the normal convectional flow around the body and the air is neither extremely dry nor humid. The upper limit has not been definitely established but is probably about +40 to +45°C. In a long series of climate chamber experiments at the Swedish Research Institute of National Defence, +28°C was found empirically to be the temperature at which the organism, according to both subjective and objective determinations, is in thermal balance (2, 14). Other temperatures caused a sensation of cold or sweating, respectively.

The first series, "the temperature series", consisted of 9 men and 10 women whose mean ages were 33.2 years and 36.5 years respectively. The second series, "the humidity series", consisted of 10 men and 6 women whose mean ages were 37.9 years and 40.8 years respectively.

Before the determination was made the subjects stayed for not less than half an hour in the relevant climate. The investigations were made with the subjects in a recumbent position. Evaporation was measured on the back, chest, forearm, and thigh (Fig. 3). Three determinations were made in each climate for each test area. The mean value was calculated for each test area.

(B) The determinations were made on 4 subjects at rest, 2 men and 2 women. The temperature was increased step by step at intervals of 2 hours, from +30°C to +38°C (+30°, +32°, +34°, +35°, +36°, and +38°). During the entire investigation the ambient air had a $40 \pm 4\%$ RH. By means of repeated measurements the point was observed when a pronounced increase in sweating occurred. It was assumed that at this temperature the body was no longer able, by radiation, conduction, convection, and insensible perspiration only, to maintain temperature balance, but had to resort to heavy cutaneous evaporation in order to ensure the necessary energy loss.

(C) In the investigation according to (C) the amount of water that penetrated excised specimens of human breast skin was determined. In connection with routine operations pieces of skin 5×5 cm were removed, corresponding to the measuring range of the evaporometer. Subcutaneous fat was removed from the skin, and the skin then fastened in the "diffusion chamber" of the measuring instrument (Fig. 4), so that its lower surface was in direct contact with the slowly flowing physiological saline solution. Special care was taken that the tension of the skin was the same as that in its natural state. The temperature of the circulating fluid was regulated so that the skin surface had the same temperature as under the corresponding in vivo conditions (+34°C). Evapora-

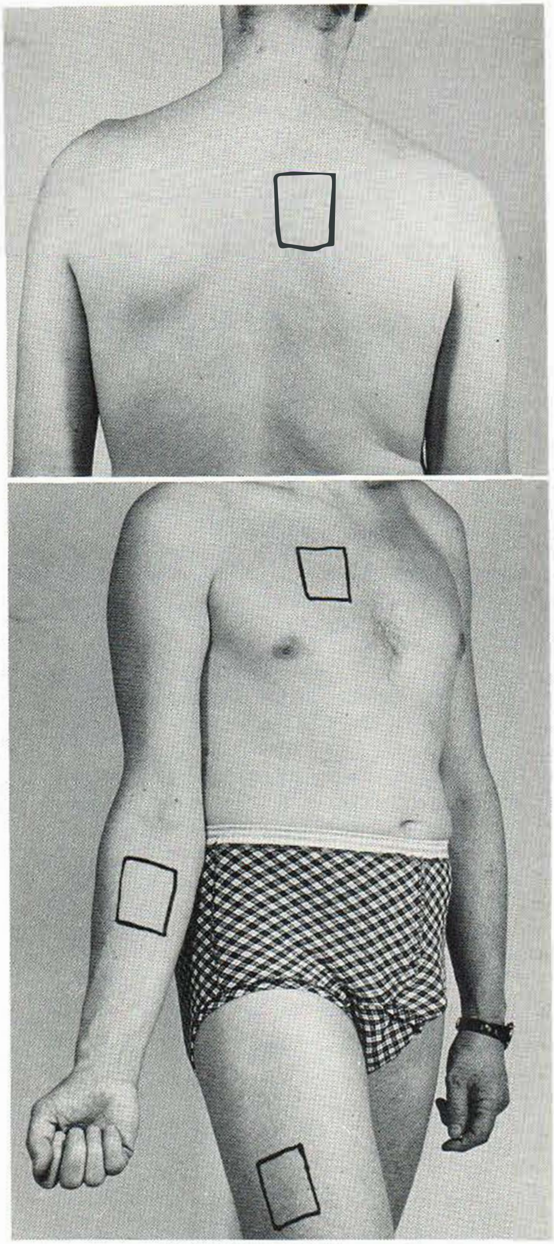

Fig. 3. The four test areas: back, chest, forearm and thigh.

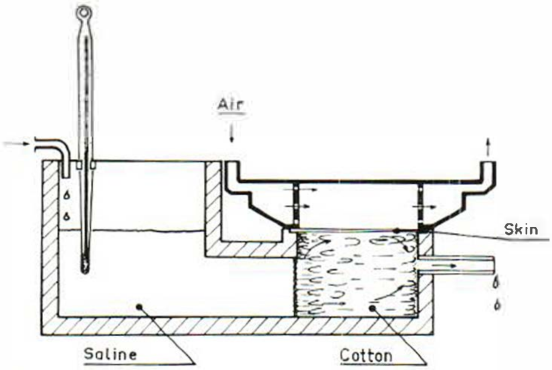

Fig. 4. Diffusion chamber for determining water penetration through excised skin.

tion was measured with the evaporometer as stated above. For each piece of skin three determinations were made on the first day at intervals of two or three hours, after which the mean value was calculated. In all, 10 skin specimens were investigated at +28°C and 40% RH.

The accuracy for practical use of the evaporometer method was tested by comparing the values obtained with the evaporometer with the losses recorded when weighing the subjects. A total of 9 determinations was made for 6 subjects both at +28°C, 40% RH, and at +15°C, 40% RH. Immediately before the subjects were weighed, evaporation from the skin of the four above mentioned areas was measured, after which total evaporation was calculated for the whole body surface area. The subjects were weighed again after 7 hours. The weight was then corrected for drink and urine. The losses through the respiratory system were calculated after the volume of the exhaled air, the humidity and the temperature had been determined. The corrected values are shown in Table II. On comparing the values obtained when using the evaporometer with those obtained by weighing, no significant difference was found. The mean difference between the values of the two methods was for the higher temperature (+28°C) 5.4±5.0 g/h and for the lower temperature (+15°C) 3.7±1.7 g/h. Thus, there was good agreement between the measurements made according to this method and those obtained by the method of weighing the subjects which previously had been usually employed.

RESULTS

A. *Quantitative determination of evaporation in subjects in air at different temperatures and with varying humidity content*

During the determination of evaporation from the skin at different temperatures and degrees of humidity all the subjects felt well during and after the experiments. At +28°C all of them experienced a sense of well-being. During the time they were subjected to a temperature of +41°C moderate sweating occurred after 15–20 min. At +15°C all the subjects experienced a troublesome sense of cold after 15–30 min. In all of them at this temperature peripheral vasoconstriction began to appear with white fingers and toes.

In the series with constant temperature (+28°C) and varying humidity (20%, 40%, and 80% RH) the subjects felt no discomfort.

The mean values of the whole material for the different climates are shown in Fig. 5.

The effect of different room temperatures on

Table II. *Comparison between water loss according to evaporometer and weighing at +28°C and +15°C respectively*

Subject	Temp. +28°C, humidity 40% RH			Temp. +15°C, humidity 40% RH		
	Skin evaporation (g/h)	Total loss according to evaporometer and calculated respiratory loss (g/h)	Total loss according to weight (g/h)	Skin evaporation (g/h)	Total loss according to evaporometer and calculated respiratory loss (g/h)	Total loss according to weight (g/h)
A 1	44.0	59.0	57.1	16.1	30.7	27.1
B 1	30.0	45.0	47.1	16.3	30.9	30.0
C 1	31.7	46.7	45.7	18.6	33.1	35.7
D 1	54.7	69.7	71.4	17.6	32.1	41.4
E 1	32.4	47.4	55.7	18.0	32.6	37.1
F 1	43.4	58.4	100.0	16.0	30.6	33.1
A 2	26.9	41.9	50.0	13.6	28.1	40.0
C 2	40.6	55.6	42.9	13.7	28.3	35.7
F 2	32.3	47.3	50.0	14.0	28.6	28.6
Mean±S.E.	37.3±3.0	52.3±3.0	57.8±6.0	16.0±0.6	30.6±0.6	34.3±1.7

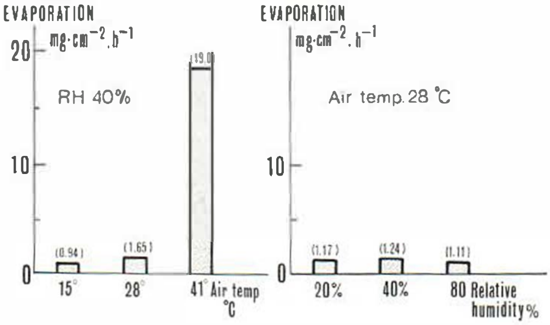

Fig. 5. Mean values for evaporation from the skin measured at varying temperatures and humidity.

evaporation from the skin. A comparison between evaporation at +15°C and at +28°C showed a mean difference of about 0.70±0.15 mg $cm^{-2}h^{-1}$. This difference is highly significant (Tables III *a* and III *b*).

At +41°C moderate sweating occurred, and the difference between evaporation here and that at the other two temperatures was, as expected, highly significant.

A comparison between the values for the common climate of the two series (+28°C and 40% RH) did not show any significant difference.

At both of the lower temperature ranges (+15°C and +28°C) no difference was observed between men and women. On the other hand, at +41°C there was a significant difference between these two groups. The difference between the mean values was 7.9 mg $cm^{-2}h^{-1}$. According to these measurements the evaporation in women in mg of water per cm^2 and hour was 30% less than that of men.

Statistical analysis with the *t*-test for paired observations for evaporation from the different parts of the body showed only at +15°C and +41°C statistically significant differences between the trunk and the extremities. At +41°C no significant difference between various parts of the body could be demonstrated for certain. No difference was observed between back and chest or between arms and legs. At +15°C the skin temperature was, as expected, higher for the trunk than for the extremities, but no difference was found at +28°C and +41°C. This is especially noteworthy with regard to the above-mentioned difference between trunk and extremities in different climates.

The effect of differences in air humidity on evaporation. In this series no difference was observed for certain between the various climate areas (Tables IV *a* and IV *b*). Here, perhaps more

Table III *a*. *Skin evaporation in mg water per cm² and hour ±S.E. at 40% RH and different ambient air temperature. Results from 9 male subjects at three different temperatures. Actual skin temperature within parentheses*

Air temp.	Back	Chest	Arm	Leg	Mean
15°	1.10±0.11 (31.7°)	1.23±0.17 (31.5°)	0.87±0.09 (30.9°)	0.83±0.09 (29.4°)	1.01±0.10 (30.9°)
28°	1.73±0.19 (35.0°)	2.14±0.24 (34.9°)	1.55±0.18 (34.9°)	1.65±0.21 (34.3°)	1.75±0.17 (34.8°)
41°	24.23±1.90 (36.0°)	26.05±1.82 (36.0°)	21.00±1.50 (36.3°)	20.23±0.90 (35.9°)	22.92±1.35 (36.1°)

Table III *b*. *Skin evaporation in mg water per cm² and hour ±S.E. at 40% RH and different ambient air temperatures. Ten females measured three times in each climate. Actual skin temperature within parentheses*

Air temp.	Back	Chest	Arm	Leg	Mean
15°	0.89±0.06 (31.6°)	0.90±0.05 (31.0°)	0.87±0.04 (30.1°)	0.81±0.04 (28.1°)	0.86±0.05 (30.2°)
28°	1.51±0.20 (35.1°)	1.63±0.21 (35.1°)	1.53±0.19 (34.6°)	1.49±0.23 (33.8°)	1.54±0.21 (34.7°)
41°	17.60±2.20 (36.3°)	14.37±2.09 (36.6°)	12.81±1.83 (36.4°)	15.44±1.58 (36.3°)	14.99±1.69 (36.4°)

Table IV*a*. *Skin evaporation in mg water per cm² and hour ±S.E. at +28°C air temperature and at different relative humidities in ambient air. Results from 10 male subjects. Actual skin temperature within parentheses*

Air humidity	Back	Chest	Arm	Leg	Mean
20%	1.37±0.13 (35.0)	1.65±0.31 (34.7)	1.12±0.07 (34.6)	1.18±0.08 (34.1)	1.32±0.12 (34.6)
40%	1.33±0.10 (34.9)	1.69±0.25 (34.8)	1.24±0.12 (34.7)	1.17±0.13 (34.2)	1.37±0.12 (34.7)
80%	1.30±0.12 (35.0)	1.37±0.18 (34.9)	1.05±0.04 (34.8)	0.93±0.06 (33.9)	1.16±0.08 (34.7)

Table IV*b*. *Skin evaporation in mg water per cm² and hour ±S.E. at +28°C air temperature and at different relative humidities in ambient air. Results from 6 females. Actual skin temperature within parentheses*

Air humidity	Back	Chest	Arm	Leg	Mean
20%	1.16±0.15 (34.9)	1.07±0.05 (34.8)	0.92±0.06 (34.4)	0.94±0.09 (33.6)	1.02±0.07 (34.4)
40%	1.18±0.17 (35.0)	1.29±0.18 (35.0)	1.22±0.16 (34.3)	1.09±0.17 (33.9)	1.19±0.16 (34.6)
80%	1.14±0.07 (35.1)	1.16±0.09 (35.2)	1.07±0.08 (34.7)	0.86±0.04 (34.0)	1.07±0.06 (34.8)

substantial evaporation might have been expected in the drier climate, but no such increase was recorded.

No statistically significant difference between men and women was observed in this climate with varying humidity. On the other hand, the previously noted difference between various parts of

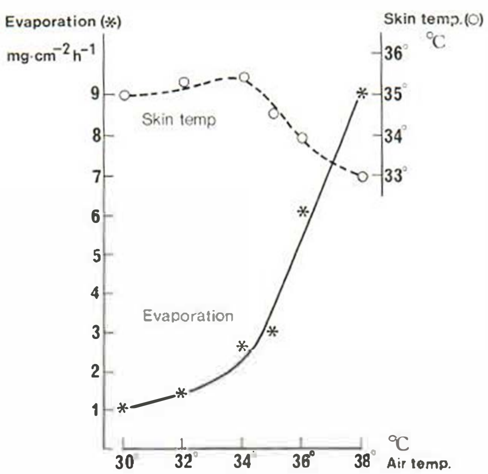

Fig. 6. Curves showing the increase in evaporation from the skin and the fall in skin temperature when the ambient temperature is increased beyond the sweating point.

the body was again found. Thus, in all the cases, with the exception of two, there was at least an almost significant difference between the trunk and the extremities. The two exceptions referred to the comparison between chest and arms and back and arms in a climate of 40% humidity.

No significant difference between men and women could be demonstrated, although the mean value for the men appeared to be somewhat higher.

Skin temperature showed only slight variations in the climates with different humidity. The temperature of the outer side of the thigh was slightly lower than that of the other parts of the body. Tables IV *a* and IV *b* show the values obtained.

B. *Determination of the temperature range in which pronounced increase in sweating occurs in persons at rest*

In this investigation the subjects did not feel any discomfort from the warmth at +30°C. At +32°C this caused slight discomfort, and at +34°C slight sweating on the thigh began. At +35°C the subjects sweated on their foreheads and on certain parts of the back. Visible sweating over large parts of the body was observed at +36°C. At the onset of sweating there was a pronounced decrease in skin temperature (Fig. 6). There was no appreciable difference between the onset of sweating in men and in women.

C. Quantitative determination of the diffusion of water through the excised skin specimens

The mean evaporation from 10 excised specimens was 0.80 ± 0.09 mg $cm^{-2}h^{-1}$ at +28°C and 40% RH. Evaporation from the same surface of water and at the same temperature and humidity conditions was, according to the evaporometer 52.6 mg $cm^{-2}h^{-1}$. The skin thus reduced the evaporation by 98.5%. The corresponding evaporation from living subjects was 1.46 mg $cm^{-2}h^{-1}$. Hence evaporation from the excised skin was 45% less than that from normal skin.

DISCUSSION

In the series with constant humidity and varying ambient temperature a highly significant difference was observed between skin perspiration at +15°C and +28°C. Apparently, the amount of water given off is decreased at lower temperatures which is favourable to the heat balance. This was established also by Grice & Bettley (15). Ohara, Kondo & Ogino (24) found that it was primarily the lowered circulation that influenced evaporation from the skin.

More water was given off from the trunk than from the extremities at +15°C and +41°C. At +28°C no difference could be measured for certain. Nor did Baker et al. (3), who studied the corresponding parts of the body, observe any difference within this temperature range. That the difference in evaporation from various parts of the body is smallest at +28°C may be due to the fact that the skin temperature is then very similar in different parts of the body. This indicates that skin circulation, and hence surface temperature, stands in a definite relation to basal insensible perspiration. At +41°C, when sweating was moderate, the difference is probably due to numerical variation of functioning sweat glands (16).

It has been shown (27) that if the sweat glands are inactivated, evaporation increases only slightly with rising temperature. In our measurements, which were made without inhibition of sweat gland activity, a slight increase in sweating from the skin with rising ambient temperature was observed. This increase could be due to the fact that the activity of the sweat glands was augmented and constituted an increasing part of the insensible perspiration.

At 41°C and 40% RH, when sweating was moderate, a significant difference was found between men and women. The value for women was about 30% less than that for men. This condition can be explained partly by the fact that men have a higher metabolism, and that at this temperature range the body energy produced can only be disposed of by sweating.

In the series with varying air humidity it was found that evaporation from the skin remained unchanged in the different atmospheres. Here, lower evaporation had been expected in a more humid environment, on account of the reduced capacity of the ambient air to take up more water. The explanation for this is probably that the water supply to the surface at +28°C is insignificant compared with the evaporation and transport capacity of the passing air, thus the water that reaches the surface will easily be evaporated and transported away whether the air is dry or moist.

Another contributory factor is that the skin is hydrophilic (20) and contains more water when the humidity is higher. This will cause a higher degree of water penetration through the moist skin according to Spruit & Malten (33). Adachi & Ito (1) considered that this was dependent upon the fact that, when air humidity was higher, the respiratory water loss was lower, which led to a rise in cutaneous sweating. Some investigators have also found a slight decrease in evaporation from the skin when the humidity of the ambient air is increased (7, 10).

The measurements showed that subjects at rest began to sweat at a room temperature between +34° and +35°C. This agrees with earlier observations (5, 23). When treating burns with warm dry air (4) the temperature of the air should be kept just below this temperature so as to ensure that water loss is not increased by sweating from the unaffected parts.

On testing the permeability of the excised skin to water vapour it was found that this, compared with a surface of water, reduced evaporation by 98.5%. The same reduction was found by Onken et al. (26). Compared with in vivo determinations these values were 45% lower. This indicates that part of the insensible perspiration is made up of transepidermal water loss.

To sum up, we found that at rest and at room temperature, evaporation from the skin slightly exceeded 1 mg $cm^{-2}h^{-1}$ corresponding to an insensible perspiration from the skin of 400–500 g/day for a body surface of 1.7 m^2. A rise in the ambient temperature only slightly increases skin perspiration up to the onset of sweating. Evaporation from the skin at normal room temperature is affected very little by changes in air humidity. For persons at rest, sweating starts when the ambient temperature is between +34°C and +35°C. Consequently, when treating burns with warm air, until further investigations have been made, the temperature of the air should be kept just below this value in order to prevent sweating in the unaffected parts.

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