J. Physiol. (1956) 132, 225–231

THE DIFFUSION OF WATER VAPOUR THROUGH HUMAN SKIN

By D. F. BREBNER, D. McK. KERSLAKE and J. L. WADDELL
From the R.A.F. Institute of Aviation Medicine, Farnborough, Hants

(*Received* 15 *November* 1955)

Observations on human subjects congenitally devoid of sweat glands (Loewy & Wechselmann, 1911; Richardson, 1926; Sunderman, 1941) and on the skins of normal subjects whose sweat glands have been inactivated (Trolle, 1937; Pinson, 1942; Burch & Winsor, 1944) have demonstrated that there is a loss of water from the skin which is not dependent on the secretion of sweat. It appears probable that this loss represents the passive diffusion of water through the epidermis, as was assumed by Taylor & Buettner (1953). This view is supported by Pinson's (1942) results, and by others involving the collection of water from small skin areas covered by capsules through which dry gas is passed (Trolle, 1937; Burch & Winsor, 1944). It is less precisely fitted by the findings of those investigators who have measured the loss of water from the whole body under various environmental conditions (Wiley & Newburgh, 1931; Gagge, 1937; Winslow, Herrington & Gagge, 1937*a*, *b*; Johnston & Newburgh, 1942; Peters, 1944).

The rate of water loss is stated to increase with rising skin temperature and to decrease with rising environmental humidity, as is to be expected on the basis of a simple diffusion: but in order to account for discrepancies in the quantitative relations additional factors have been directly or indirectly proposed. The difficulties can always be overcome by supposing that the impedance of the superficial tissues to diffusion can alter, either as a direct result of alterations in skin blood flow (Hardy & Soderstrom, 1938; Newburgh & Johnston, 1942; Wright, 1948), or as a result of changes in the effective level at which evaporation occurs (Taylor & Buettner, 1953). The active obstruction offered by some of the cells of the epidermis to the passage of water might also be expected to exert some effect, such as the operation of a constant or varying back pressure, which would have to be subtracted from the simple vapour pressure difference (Burch & Winsor, 1944).

The work described in this paper was performed in order to determine whether these complicating factors are responsible for the lack of agreement between the capsule experiments and those on the whole body, or whether the discrepancies can be ascribed to the secretions of the constantly acting sweat glands known to exist in some regions, and to possible errors in the estimates of pulmonary weight loss which have been used.

METHODS

The subject sat on a deck chair with a leg rest. The canvas of the chair and leg rest was replaced by a wide mesh nylon net in order to permit free passage of water vapour from the skin of the back. He wore no clothing except for a leather flying helmet, rubber gloves, close fitting thin rubber slippers and small sheets of polyvinylchloride arranged to cover and prevent evaporation from the axillae, pubic and perineal regions and the face. He breathed from a face mask, which was connected through valves to a closed circuit system consisting of a soda-lime container in the expiration line, an oxygen-filled bag of about 20 l. capacity and a return inspiratory line. The respiratory circuit could be switched from the bag to room air. Oxygen consumption over the period of the experiment was estimated by first emptying the bag and introducing a measured volume of oxygen. When the subject was ready for the experiment to begin he made a full expiration, at the end of which his respiratory circuit was switched from room air to the bag. At the end of the period of observation he made another full expiration and the mask was switched back to room air. The remaining oxygen was then pumped out of the bag through a gas meter, and the oxygen consumption found by difference. Repeated filling and emptying of the bag could be performed with an error of about 0·1 l., so that the chief inaccuracy of the method lies in the reproducibility of the subject's full expirations. Since posture was identical on both occasions this error is not likely to be great. The entire assembly was mounted on the platform of a continuously recording balance. Weight loss from the respiratory tract was eliminated by the use of the closed circuit system mounted on the balance, but allowance had to be made for the change in buoyancy of the system as oxygen was consumed. This accounts for an increase in apparent weight of about 20 g/hr, and it is considered that it could be estimated to within ± 1 g/hr. The record produced by the balance was usually slightly irregular, but the mean slope over a half-hour period of observation could be read to within ± 1 g/hr. Cases in which there appeared to be changes in the rate of weight loss throughout the period of the observation were rejected. The cutaneous water loss of the subject was expressed as the sum of the weight loss recorded on the balance (negative if there was a gain in recorded weight) and the weight of the air displaced by the oxygen consumed during the experiment. The whole was then expressed in g/hr.

Skin temperature was measured at thirteen points not covered by the clothing. These were chosen so that the mean of the readings was approximately correctly weighted for the different areas. An end to end copper-constantan thermocouple, lightly tensed bow-string fashion on a plastic holder, was applied to each point in turn, with sufficient pressure to produce slight deformation of the skin. The temperatures were read on a galvanometer calibrated at the end of each experiment.

Experiments were performed in a room in which air temperature was controlled to better than $\pm 0{\cdot}25^\circ$ C and relative humidity to better than $\pm 0{\cdot}5\%$. The air movement was a complex circulation from ceiling distributors to extraction orifices at the four lower corners of the room. Katathermometer readings in the region occupied by the subject gave air movement values between 45 and 55 ft./min.

The room conditions were set up at least 12 hr before the experiment began, and it was found that after this time there was no further change in weight of the chair. The nude subject entered the room half an hour before the beginning of the experiment and rested until the preparations were complete. He then put on the clothing and took his place on the balance. The skin temperatures were measured and the balance adjusted. The subject then made an expiration, the respiratory circuit was switched over and the balance started. After about half an hour the recording was stopped, the respiratory circuit switched back to room air, after another full expiration had been made, and the skin temperatures measured again. The mean of both sets of skin temperatures was taken as the mean skin temperature. Ambient temperature and humidity were measured at intervals during the experiment.

Table 1. Observations of cutaneous water loss of resting subjects under various ambient conditions. Results are calculated from a half-hour period of observation. The column headings refer to the following quantities: Dry, ambient dry-bulb temperature (° C) which was equal to the wall surface temperature; Wet, ambient wet-bulb temperature (° C); p_a, ambient water vapour pressure (mm Hg); R, air displaced by oxygen consumption (g/hr); W, recorded rate of weight loss (g/hr); $R+W$, sum of the previous two columns, representing the rate of cutaneous water loss; T_s mean temperature of exposed skin (° C); p_s^* saturated water vapour pressure at skin temperature (mm Hg).

Dry	Wet	p_a	R	W	$R+W$	T_s	p_s^*	$p_s^*-p_a$
		Subject D.B.	Total surface area 1·8 m² (Dubois)					
29·1	21·6	16	25	41	66	34·25	41	25
28·1	21·2	15	26	−3	23	34·3	41	26
27·7	20·9	15	28	−5	23	34·3	41	26
27·4	25·7	24	27	−3	24	33·95	40	16
26·9	14·8	6	30	−2	28	33·7	39	33
21·8	17·9	14	28	−10	18	31·65	35	21
23·5	15·4	9	25	−1	24	32·4	36	27
24·3	22·3	19	22	−4	18	33·05	38	19
28·0	23·5	19	24	−4	20	34·5	41	22
27·5	16·0	8	27	3	30	34·45	41	33
		Subject J.W.	Total surface area 1·84 m² (Dubois)					
23·4	14·4	8	25	−4	21	32·9	38	30
27·6	22·1	17	24	−8	16	34·0	40	23
24·0	21·5	18	24	−7	17	32·75	37	19
27·2	16·9	9	23	−1	22	34·0	40	31
28·2	17·3	9	21	0	21	34·1	40	31
28·8	25·0	22	23	−8	15	34·6	41	19
29·7	20·9	14	23	−2	21	35·15	42	28
29·1	20·5	14	26	−4	22	34·5	41	27
27·8	20·4	14	23	−2	21	34·6	41	27
22·1	17·8	13	24	−7	17	32·7	37	24
26·8	16·1	8	24	−2	22	33·7	39	31
28·0	22·4	18	23	−6	17	33·85	39	21

RESULTS

Satisfactory weight records were obtained in a total of twenty-two experiments on two subjects. The results are set out in Table 1, which shows the observed temperatures and the components from which the total water loss was calculated. The columns of importance in the subsequent examination of the data are those showing the total skin water loss, the saturated water vapour pressure at skin temperature, the ambient water vapour pressure and the difference between the last two pressures. If a simple diffusion mechanism is assumed, the rate of water loss should be given by

$$W=k(p_s^*-p_a)+c$$

where W is the rate of cutaneous water-loss, p_s^* the pressure of saturated water vapour at skin temperature, p_a the ambient water vapour pressure, k the permeability of the skin and air layers to water vapour, and c a constant representing possible systematic errors. With two exceptions, the data plotted in Fig. 1 fit such an equation. For subject D.B. the regression equation is

$$W = (0{\cdot}831 \pm 0{\cdot}055)\ (p_s^* - p_a) + 1{\cdot}49 \pm 1{\cdot}46 \quad (\pm \text{S.E.}).$$

For subject J.W.

$$W = (0{\cdot}525 \pm 0{\cdot}079)\ (p_s^* - p_a) + 5{\cdot}72 \pm 2{\cdot}21 \quad (\pm \text{S.E.}).$$

The intercepts are not significant in either case, and the data can be represented by regression lines constrained to pass through the origin, with the following equations:

$$\text{D.B.} \quad W = 0{\cdot}89(p_s^* - p_a),$$

$$\text{J.W.} \quad W = 0{\cdot}74(p_s^* - p_a).$$

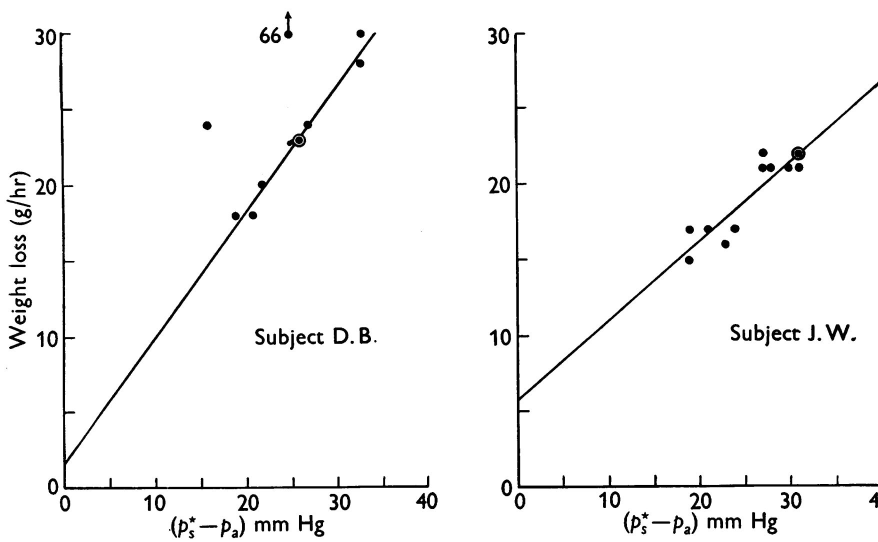

Fig. 1. The relation between the rate of cutaneous water loss and the vapour pressure gradient from saturation at skin temperature to ambient. Rings indicate two coincident markings.

It will be seen that the first and fourth experiments on D.B. give points considerably above the regression line, which has been drawn through the remainder of the results. Such cases would be expected to arise when some activity of the sweat glands in the exposed skin areas was taking place, and this has been assumed to be the reason for these discrepancies. The first result was obtained at the highest ambient dry-bulb temperature and the second at the highest humidity and wet-bulb temperature. These results have been omitted from the calculations.

The range of skin temperatures examined was limited by the need to prevent thermal sweating or shivering, and is equivalent to a range of about 6 mm Hg in the saturated vapour pressure at skin temperature. The range of ambient vapour pressure was limited by the need to keep the dry-bulb temperature below 29° C in order to prevent sweating and by the minimum ambient humidity available of about 6 mm Hg. These ranges are sufficient, however, to demonstrate that the cutaneous water loss is dependent on both the ambient water vapour pressure and on the saturated water-vapour pressure at skin temperature. This has been shown by a dual regression of cutaneous water loss on skin vapour pressure and ambient vapour pressure. The coefficients were found to be significant in each case and did not differ significantly in magnitude, although of opposite sign, as is to be expected. The values are set out in Table 2.

Table 2. Partial regression coefficients of rate of skin water loss on saturated vapour pressure at skin temperature and on ambient vapour pressure

	Coefficient ± S.E.	
Subject	p_s^*	p_a
D.B.	$+0{\cdot}946 \pm 0{\cdot}116$	$-0{\cdot}810 \pm 0{\cdot}058$
J.W.	$+0{\cdot}674 \pm 0{\cdot}231$	$-0{\cdot}513 \pm 0{\cdot}083$

DISCUSSION

The results show that when the secretion of the constantly acting sweat glands is not permitted to evaporate, loss of water vapour from the remainder of the skin takes place in a manner consistent with a simple diffusion process from an interface near the skin surface. Although the observations on both subjects were fitted by regression lines having insignificant intercepts, small intercepts might be expected to be present on account of the slightly higher temperature at the interface, the depression of vapour pressure caused by the dissolved substances in tissue fluid and the errors in measurement of skin temperature. No evidence was found of a change in the permeability of the epidermis under different temperature conditions, and since the subject's physiological state varied from nearly sweating to nearly shivering it is improbable that cutaneous vasodilation significantly affects this function.

It seemed possible that the permeability might be affected by variations in epidermal hydration resulting from the different skin relative humidities (Mole, 1948), but this was not sustained by the findings. Under the conditions of air movement used in these studies, a vapour pressure gradient of about 1 mm Hg is required in order to evaporate 20 g/hr from a wet surface of 1·5 m^2. The actual vapour pressure at the skin surface was thus about 1 mm Hg higher than ambient in all cases, and so varied from 7 to 25 mm Hg. This represents a range of about 17–62 % in skin relative humidity. Over this range there was no detectable change in the permeability of the epidermis. It will be appreciated that as the bulk of the diffusional resistance in these circumstances is deep to the skin surface, this wide range of relative humidity was not associated with any change in wetted area (Gagge, 1937), which remained constant at about 4%.

The findings agree with those cited in the introduction which favour a simple diffusion hypothesis. The results obtained from studies on the loss of water from the whole body, which were found not to be in quantitative agreement with this view, may be explained in terms of the constantly acting sweat glands and of possible errors in the assumption of the weight loss from the respiratory tract. However, Buettner (1953), in capsule studies at high vapour pressures found that skin water loss was zero when the ambient vapour pressure (in the capsule) was about 20 mm Hg, although the skin temperature was about 35° C ($p_s^* = 42$ mm Hg). Raising the vapour pressure further resulted in the passage of water into the skin at substantial rates (e.g. about 20 g/m^2/hr at 34 mm Hg). These experiments were performed chiefly on the hairless inner side of the forearm. They lead to the expectation that at an ambient vapour pressure of 20 mm Hg there should have been no measurable loss of water from the skin surface. There is clearly a disagreement with the findings described in the present paper, which is not easy to reconcile. It seems improbable that activity of the thermal sweat glands can be made to account for the observed water loss at this ambient water vapour pressure, since the amount is small and thermal sweating is not usually so accurately reproducible. Alternatively, it may be supposed that the absence of hair from the area studied by Buettner (1953) and its prevalence over most of the exposed surfaces of the subjects used in the present study may explain the difference. It must then be assumed that hairless epidermis behaves as Buettner describes, but that water vapour can diffuse along hair stems or follicles with greater freedom. It would be impossible to demonstrate this by shaving the subjects, since the resistance to diffusion of water is relatively very small in the air layer, being located mainly in the epidermis, beyond effective reach of the razor.

Whether the transfer of water takes place in several ways, or whether it is indeed a simple diffusion and an alternative explanation must be sought for Buettner's findings, it may be empirically expressed, over the range of conditions studied in the present investigation, as a simple function of the vapour pressure gradient from saturation at skin temperature to ambient.

SUMMARY

1. Past observations of total skin water loss from non-sweating subjects have failed to agree quantitatively with the hypothesis that such water loss is due to a passive diffusion of water through the epidermis.

2. The discrepancies may have been caused by including in the weight loss the sweat produced by constantly sweating areas and by possible inaccuracies in the estimation of weight loss from the respiratory tract.

3. When these factors are controlled it is shown that the rate of water loss is a simple function of the vapour pressure gradient from saturation at approximately skin temperature to ambient water vapour pressure.

We are grateful to the Director-General of Medical Services, R.A.F., for permission to publish this work.

REFERENCES

BUETTNER, K. (1953). Diffusion of water and water vapour through human skin. *J. appl. Physiol.* **6**, 229–242.

BURCH, G. E. & WINSOR, T. (1944). Rate of insensible perspiration (diffusion of water) locally through living and through dead human skin. *Arch. intern. Med.* **74**, 437–444.

GAGGE, A. P. (1937). A new physiological variable associated with sensible and insensible perspiration. *Amer. J. Physiol.* **120**, 277–287.

HARDY, J. D. & SODERSTROM, G. F. (1938). Heat loss from the nude body and peripheral blood flow at temperatures of 22° C to 35° C. *J. Nutr.* **16**, 493–510.

JOHNSTON, M. W. & NEWBURGH, L. H. (1942). Calculations of heat production from insensible loss of weight. *J. clin. Invest.* **21**, 357–363.

LOEWY, A. & WECHSELMANN, W. (1911). Zur Physiologie und Pathologie des Wasserwechsels und der Wärmeregulation seitens des Hautorganes. *Virchows Arch.* **206**, 79–121.

MOLE, R. H. (1948). The relative humidity of the skin. *J. Physiol.* **107**, 399–411.

NEWBURGH, L. H. & JOHNSTON, M. W. (1942). The insensible loss of water. *Physiol. Rev.* **22**, 1–18.

PETERS, J. P. (1944). Water exchange. *Physiol. Rev.* **24**, 491–531.

PINSON, E. A. (1942). Evaporation from human skin with sweat glands inactivated. *Amer. J. Physiol.* **137**, 492–503.

RICHARDSON, H. B. (1926). Clinical calorimetry. XL. The effect of the absence of sweat glands on the elimination of water from the skin and lungs. *J. biol. Chem.* **67**, 397–411.

SUNDERMAN, F. W. (1941). Persons lacking sweat glands; hereditary ectodermal dysplasia of the anhidrotic type. *Arch. intern. Med.* **67**, 846–854.

TAYLOR, C. L. & BUETTNER, K. (1953). Influence of evaporating forces upon skin temperature dependency of human perspiration. *J. appl. Physiol.* **6**, 113–123.

TROLLE, C. (1937). A study of the insensible perspiration in man and its nature. *Skand. Arch. Physiol.* **76**, 225–246.

WILEY, F. H. & NEWBURGH, L. H. (1931). The relationship between the environment and the basal insensible loss of weight. *J. clin. Invest.* **10**, 689–701.

WINSLOW, C.-E. A., HERRINGTON, L. P. & GAGGE, A. P. (1937*a*). Physiological reactions of the human body to varying environmental temperatures. *Amer. J. Physiol.* **120**, 1–22.

WINSLOW, C.-E. A., HERRINGTON, L. P. & GAGGE, A. P. (1937*b*). Physiological reactions of the human body to various atmospheric humidities. *Amer. J. Physiol.* **120**, 288–299.

WRIGHT, S. (1948). *Applied Physiology*, 8th ed. p. 694. Oxford University Press.