J. Physiol. (1963), **167**, *pp.* 417–426
With 2 text-figures
Printed in Great Britain

MEASUREMENT OF CUTANEOUS MOISTURE VAPORIZATION FROM CATTLE BY VENTILATED CAPSULES

BY J. A. McLEAN

From the Physiology Department, The Hannah Dairy Research Institute, Ayr

(*Received* 14 *May* 1962)

Methods of measuring cutaneous moisture vaporization fall broadly into two categories, direct and indirect.

Direct methods are those in which the moisture loss from a small area is measured by placing an inverted cup or capsule over that area. The capsules may be ventilated or unventilated. In the ventilated capsule the rate of evaporation is usually determined by passing dry air into the capsule and measuring the gain in weight of a moisture absorber through which the outlet air is passed, for a period of 5–20 min. McDowell, Lee & Fohrman (1954) criticized the use of dry inlet air, because with this the skin under test is exposed to abnormal atmospheric conditions. To overcome this they recirculated air round a closed circuit incorporating a capsule and an absorption bottle, the latter containing a saturated salt solution. The factors influencing the choice of air flow through ventilated capsules do not appear to have received enough attention. Air-flow rates appear to have been chosen to suit the absorbers used, with little consideration of the effect this variable may have on the rate of evaporation within the capsule.

In the unventilated capsule air-flow rate is at least standardized, although at a level below that to which surrounding skin areas are exposed. Unventilated capsules normally contain a pad of desiccant material which is weighed at intervals. This method has been critically analysed by Randall, Peiss & Hertzman (1953), who showed that the quantity of desiccant used, and the distance between the desiccant and the skin surface, affected the observed rate of evaporation.

A disadvantage common to most capsule methods is that the measurement of evaporation, since it depends on the gain in weight of an absorber, can be made only over periods of several minutes.

Indirect methods are those in which cutaneous evaporation is calculated by difference from simultaneous measurements of total evaporation and respiratory evaporation. The hygrometric tent (Kibler & Yeck, 1959) is

effectively a ventilated capsule, but the entire animal is enclosed in a tent. Cutaneous evaporation from cattle has also been determined from measurements of insensible weight loss combined with simultaneous determination of both respiratory evaporation and metabolic weight loss due to oxygen-carbon dioxide exchange (Kibler & Brody, 1952). There is some confusion in the literature regarding the definition of the term 'insensible weight loss'. In this paper it refers to all gaseous exchange between the animal and the atmosphere, i.e. it includes any weight loss resulting from the evaporation of sweat but excludes the weight of faeces, urine and any saliva that may be lost.

Table 1 summarizes the results that have been previously reported for the rates of cutaneous moisture vaporization from cattle aged from 7 to 8 months and upwards, exposed to air temperatures of 38–42° C and relative humidities of 50–65 %. Measurements of the over-all mean rate of cutaneous evaporation made by indirect methods are, with one exception, all within the range 112–180 g/m^2.hr. Even those which include respiratory evaporation (and in some instances metabolic weight loss as well) are, again with the one exception, all below 228 g/m^2.hr. Measured rates of cutaneous evaporation obtained from capsules placed over individual skin areas are, however, all greater than 157 g/m^2.hr and extend to 650 g/m^2.hr. Even the measurements made on the paunch or belly area, which most observers agree to be a region of low evaporation (Volcani & Schindler, 1954; McDowell, McMullan, Wodzika, Lee & Fohrman, 1955; Berman, 1957; McLean, 1961), appear to be higher than the over-all mean rates obtained by indirect methods.

The object of the present work was to investigate the factors concerned with the technique of measurement that influence the rate of moisture vaporization within a ventilated capsule and to devise a technique that would provide continuous quantitative estimates of the rate of moisture vaporization from small areas of undisturbed skin.

The application of a capsule to the skin of an animal may alter the physical conditions at the site of measurement and so affect vaporization rate as follows: (1) by changing the rate of air movement near the skin, which would be expected to result in alteration to the heat losses by evaporation and convection; (2) by changing air temperature and humidity near the skin, which would also affect evaporation and convection; (3) by changing the radiant temperature of the local surroundings, which would affect heat loss by radiation; (4) by changing the local blood flow pattern if excessive pressure were used to hold the capsule in place; this might affect all forms of heat loss.

The effects of many of these factors may be eliminated in the special instance where an animal is exposed in a climatic chamber to an environ-

mental temperature equal to skin temperature and where the capsule is ventilated with room air. If ambient air, walls and skin temperature are all the same, the capsule will attain the same temperature and there will be no net radiation exchange. Under these circumstances any difference (ΔT) between the skin temperature measured inside the capsule and that measured outside will therefore be due to differences in ventilation. It is possible to determine the air-flow rate at which $\Delta T = 0$; this 'critical flow rate' gives ventilation inside the capsule equivalent to that outside it. The critical flow rate determined at this air temperature may be still valid at other air temperatures; but the condition $\Delta T = 0$ is no longer applicable,

TABLE 1. Summary of previously reported measurements of the rate of cutaneous evaporation (g/m².hr) from cattle exposed to air temperatures between 38 and 42° C and relative humidities between 50 and 65 %

Reference	Animals	Mean rate of cutaneous evaporation	Total evaporative weight loss	Method
a	Jerseys (lactating)	142	179	Insensible weight loss measurements corrected for metabolic weight loss
a	Holsteins (lactating)	161	203	
a	Brown Swiss (lactating)	162	228	
a	Brahmans (lactating)	148	176	
a	Brahmans (dry)	112	141	
a	Brown Swiss (heifers)	156	209	
a	Brahmans (heifers)	122	151	
b	A.I.S.* (lactating)	—	179	Insensible weight loss measurements not corrected for metabolic weight loss
c	Jerseys (lactating)	170	196	
d	A.I.S.* (1 year)	—	178	
d	Zebu–Hereford (1 year)	—	191	
e	Zebu–A.I.S.* (1 year)	180	194	
e	Shorthorn (1 year)	271	294	
f	Brahmans (heifers)	170	186	Hygrometric tent

Reference	Animals	Rates of cutaneous evaporation from different regions: Withers	Paunch	Neck	Loin	Forechest	Method
g	Cow	646	401	363	296	—	Ventilated capsules
g	Jersey (cow)	—	591	—	—	583	
g	Sindhi–Jersey (cow)	—	582	—	—	650	

Reference	Animals	Ventral surface	Dewlap	Neck	Legs	Trunk	Method
h	Sindhi–Jersey (cow)	160	367	446	157	418	Ventilated capsules

Reference	Animals	Shoulder	Belly	Method
j	Zebu–A.I.S.* (7–8 months)	336	229	Ventilated capsules
j	Shorthorn (7–8 months)	229	222	
j	Brahman (7–8 months)	381	—	
k	Zebu–Jersey (heifers)	320	—	Desiccated capsules room R.H. 28 %
k	Ayrshire (heifer)	160	—	

* Australian Illawarra Shorthorn.

References: *a* Kibler & Brody, 1952; *b* Robinson & Klemm, 1953; *c* Knapp & Robinson, 1954; *d* Klemm & Robinson, 1955; *e* Taneja, 1958; *f* Kibler & Yeck, 1959; *g* McDowell, Lee & Fohrman, 1954; *h*, McDowell, McDaniel, Barrada & Lee, 1961; *j*, Taneja, 1959; *k*, Ferguson & Dowling, 1955.

since radiative loss is now altered by the application of the capsule. It remains to be proved that alteration of the radiative loss within the capsule does not affect evaporation from this area. This may be shown by heating or cooling the capsule. If no change in evaporation rate results, it is probable that the alteration to the radiative loss, when a capsule is applied under conditions when air temperature is not equal to skin temperature, is also without influence on evaporation rate.

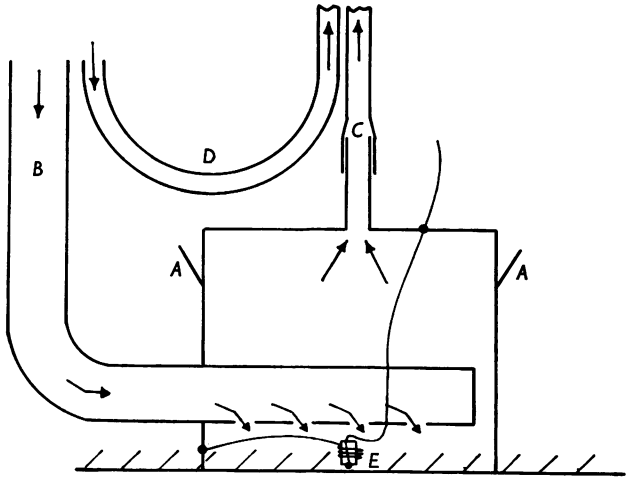

Fig. 1. The form of ventilated capsule used. *AA* fixing lugs, *B* inlet tube, *C* outlet tube, *D* inlet sampling tube, *E* thermojunction.

METHODS

Measurements were made of moisture vaporization from the skin of Ayrshire bull calves aged between 5 and 10 months. Evaporation was stimulated by exposing the animals to air temperatures between 15 and 40° C in a climatic laboratory (Findlay, McLean & Bennet, 1959). Temperatures were measured by means of copper-constantan thermocouples. The ventilated capsules used had the form shown in Fig. 1. The capsule is a metal can of 7·3 cm diameter and 6 cm depth, held in place on the skin by an elastic belt connected to the wire lugs *AA*. Ambient air is drawn into the inlet tube *B* by applying suction to tube *C*. The end of tube *B* that projects inside the capsule has holes drilled in its wall to distribute the air over the test area. A separate tube *D*, mounted beside the inlet, is used for sampling inlet air. Tubes *C* and *D* are each connected through wet- and dry-bulb apparatuses and rotameter flowmeters to a common air pump. If skin temperature measurements are required, a thermocouple *E*, on a short length of plastic rod, is spring-mounted on to the wall of the capsule by a length of piano wire, the thermocouple lead passing through a sealed hole in the top of the capsule.

The humidity of inlet and outlet air is measured with specially constructed wet- and dry-bulb thermocouple apparatuses (Fig. 2). Air passes from right to left along a polished brass tube *A* of 1·2 cm internal diameter and 9 cm long. This tube is connected to vinyl tubes, which are slipped over the ends of it. A smaller brass tube *B* is soldered to the lower side of *A* near one end to form a T-piece. The lower end of the smaller tube is fixed into a glass reservoir *C*. A length of polythene cannula of 1 mm external diameter containing

lead wires to a 40 s.w.g. copper-constantan thermocouple, is threaded through punctures in the vinyl tubing, through holes in the insulating supports *DD* and along the axis of tube *A*. The wick *E* is a hollow cotton sleeve of the type used in petrol lighters. The wick rises from the reservoir as far as the axis of tube *A*, where a hole in the side of the wick allows the polythene cannula to enter its bore. The wick surrounds the cannula for a distance of 4 cm. The wet-bulb thermojunction *F* is situated midway along the portion of cannula which is surrounded by the wick. Another thermojunction *G*, for dry-bulb temperature measurements, made from varnished 40 s.w.g. wire, is fixed at the upstream end of tube *A* by being lightly twisted a few times round the polythene cannula. A glass tube *H* also enters the reservoir, and to the other end of this tube is fitted a short length of pressure tubing whose bore is closed by a solid glass rod. The reservoir is filled with distilled water by piercing the pressure tubing with a hypodermic needle; this procedure avoids disturbing the position of the wick. After assembly all joints are sealed with plastic vapour-proof paint.

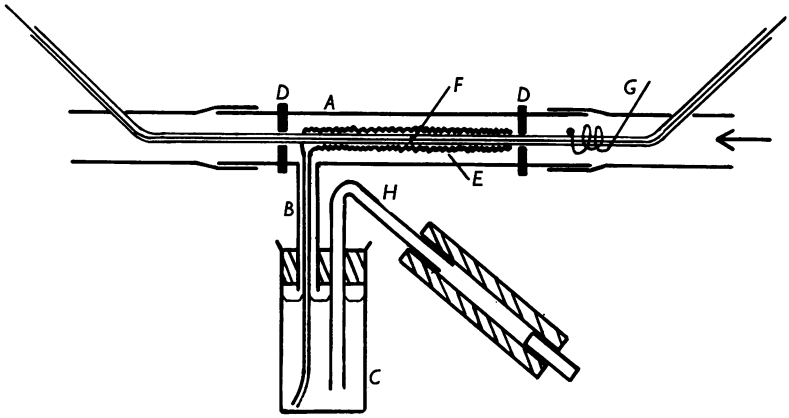

Fig. 2. Wet- and dry-bulb thermocouple apparatus. *A*, *B* brass tubes, *C* reservoir, *DD* insulating supports, *E* wick, *F*, *G* thermojunction, *H* glass tube. The arrow indicates the direction of air flow.

Measurements of wet-bulb temperature given by individual apparatuses made to this pattern at flow rates of 1 l./min or greater differ from those given by an Assman hygrometer by $\pm 0{\cdot}3°$ C. The error of a given apparatus is, however, consistent and is believed to be related to the exact positioning of the wick and thermojunction. For capsule measurements the apparatuses were always used in pairs, one for inlet and the other for outlet air, and the zero error due to differences between the two apparatuses was determined experimentally by passing room air through both. At flow rates below 1 l./min the performance of the wet-bulb apparatus falls off. Some capsule measurements were made at flow rates down to 0·5 l./min by applying a correction to allow for the reduced depression of the wet-bulb temperature.

The gain in absolute humidity, x, of the air as it passes through the capsule, is approximately proportional to the difference between the two wet-bulb temperatures, a quantity that may readily be recorded continuously as the output from a single thermocouple. For quantitative determinations the value of x was obtained from psychrometric tables (Hellman, 1955). It was estimated that the over-all error of any experimental determination of x was $\pm 0{\cdot}2$ mg/l. The rate of moisture vaporization, E, per unit area was then obtained from

$$E = \frac{xF}{A},$$

where F is the volumetric flow rate and A the cross-sectional area of the capsule.

RESULTS

A capsule was fitted with seven thermojunctions for measuring skin temperature. Four of these measured skin temperature at different points inside the capsule, while the other three measured skin temperature outside it. The capsule was applied to the skin of a calf exposed to an air temperature of approximately 38° C. Measurements of the skin temperatures at all seven positions were made at frequent intervals.

The variation of temperature over the surface of the skin within the capsule was estimated from the range of the skin temperature measurements made inside the capsule and found to be $\pm 0{\cdot}13°$ C (S.D.). Similarly the variation of temperature over the skin surface outside the capsule was found to be $\pm 0{\cdot}11°$ C (S.D.). Neither variation was affected by altering air flow through the capsule up to rates of 4 l./min. Thus ventilation of the capsule did not appear to set up any appreciable gradients in skin temperature within it. It was therefore concluded that for the purpose of measuring the difference, ΔT, between mean skin temperature inside and outside the capsule, no appreciable improvement in precision would be obtained by increasing the number of thermocouples employed.

The pressure applied to the capsule

In order to provide adequate sealing between the rim of the capsule and the skin, a pressure of approximately 1 lb, applied to the capsule as a whole, was necessary for most regions, although less pressure was required on regions where the surface was smooth. Prolonged application of a capsule caused an annular depression in the skin surface which persisted for several minutes following removal of the capsule. The cutaneous blood flow under the rim of the capsule was thus probably restricted to some extent, but there was no visual evidence of any abnormality in the skin at a distance further than 1 mm from the rim. When the pressure of application of the capsule was deliberately altered, no effect on the rate of moisture vaporization was observed until the seal between capsule and skin was obviously broken at very low pressures.

Cooling and heating the capsule

On a number of occasions, at an air temperature equal to skin temperature, the local radiative conditions under the capsule were suddenly altered by applying a water-filled polythene bag to the outer surface of the capsule. In this way capsule temperatures were raised or lowered by up to 10° C above or below skin temperature. It was found that this resulted in no observable change in the continuous record of rate of moisture vaporization, except that cooling occasionally caused a transient

decrease of up to 10 % lasting approximately 5 min, after which the original level was re-established.

From these experiments it was concluded that alteration of the radiative heat loss, from the small area covered by the capsule, did not result in any permanent physiological adjustment which re-established the heat balance in that particular area, by adjusting the amount of water available for evaporation. The use of capsules for measuring moisture vaporization when ambient temperature is not equal to skin temperature is therefore justified. The transient drop observed when the capsule was cooled may have been due to condensation of moisture on the walls of the capsule.

Variation of air-flow rate

Four calves were each exposed three times to an air temperature equal to skin temperature (approximately 38° C). A capsule, fitted with eight thermojunctions, connected in series opposition as four thermocouples, for measuring $4 \times \Delta T$, was applied to the left mid flank, and another capsule to the right sacral back region. Flow rates through both capsules were varied between 0·5 and 3·9 l./min.

It was found that for any calf on any day ΔT fell as flow rate (F) was increased. The fall in ΔT was approximately linear with log F. The general level of ΔT, however, varied greatly from day to day, and so therefore did the estimate of critical flow rate F_0 (i.e. the air flow rate corresponding to $\Delta T = 0$). ΔT is a small quantity, being the difference between two nearly equal temperatures and having a magnitude of 0·2° C or less. Any local variation of skin temperature due to large blood vessels near the skin surface, or any form of poor contact of any of the eight thermojunctions with the skin would be likely to cause large errors in the measurement of ΔT. Large day-to-day variations in the measured values of ΔT were therefore to be expected. However, with the capsule fixed in any one place on the skin relative values of ΔT on any one day were likely to be more consistent, as was indeed found. The day-to-day variations in the mean level of ΔT showed no relation to day-to-day variations in moisture vaporization rate, rectal, skin or air temperature or any other measured quantity; this strengthens the belief that such variations were in fact purely error from the causes mentioned above.

The regression equation of log F on ΔT was calculated from the mean values of ΔT averaged over all exposures for each flow rate. Hence the critical flow rate corresponding to $\Delta T = 0$ was evaluated as $F_0 = 1{\cdot}93$ l./min. Individual values of log F_0 were also determined for each of the twelve exposures and the standard deviation calculated. The 95 % confidence limits for F_0 so determined may be expressed as $1{\cdot}11 < F_0 < 2{\cdot}70$ l./min.

The measured rate of evaporation, E, rose as flow rate was increased.

When log E was plotted against log F the relation was approximately linear. The linear regression coefficient $k = \mathrm{d}(\log E)/\mathrm{d}(\log F)$ was calculated from the results of each exposure. The mean of twenty-three determinations of k was $0{\cdot}202 \pm 0{\cdot}014$ (S.E.).

DISCUSSION

The rate of moisture vaporization from the skin under a ventilated capsule may be assumed to be the same as that which would occur from undisturbed skin, provided that the critical air-flow rate (F_0) is used for ventilation. If any other air-flow rate, F, is employed then the observed rate of moisture vaporization may be expected to be altered by a factor of $(F/F_0)^k$. In the experiments described here the estimate of F_0 (1·93 l./min) for the particular capsule design used and under the conditions of air movement pertaining in the climatic chamber (approximately 15 m/min) may have been in error by as much as 75 % of the true value. This could have resulted in a 12 % error in the estimate of the normal rate of cutaneous moisture vaporization. For any alternative design of capsule the values of both F_0 and k would have been different. An earlier series of experiments, in which capsules without baffled inlet ports had been used on clipped skin areas, had suggested a value of approximately 0·4 for k. Under such conditions a 75 % error in F_0 would affect the observed rate of evaporation by approximately 24 %. Kibler & Yeck (1959) used ventilated capsules similar in size to those used in the present experiments. They also found increasing rates of evaporation as ventilation rate rose, and their results suggest a value for k of approximately 0·5. Taneja (1959), who used hemispherical capsules of area 19·6 cm², stated that on increasing flow rate from 0·5 to 2 l./min evaporation rose from 75 to 200 g/m².hr at the same air temperature; this corresponds to $k = 0{\cdot}71$. The quantity k, which represents the degree to which moisture vaporization is affected by ventilation rate, appears to be kept small if the area and depth of the capsule are large and the design ensures an even distribution of air over the skin area under examination. It seems probable that choice of capsule designs and flow rates may account for some of the exceptionally high rates of cutaneous moisture vaporization previously reported for cattle.

When the relation between moisture vaporization rate and flow rate through the capsule is known it is not essential that experimental determination of evaporation rate should be carried out at the critical flow rate. For subsequent measurements with the capsules described here the nominal flow rate $F = 1{\cdot}2$ l./min has been chosen for experimental convenience, and the observed rates of evaporation corrected by use of the multiplying factor $(F_0/F)^k$. In later experiments (McLean, 1963) cutaneous

evaporative weight loss from the animal as a whole has been estimated from capsule measurements and found to be in agreement with simultaneous independent measurements of insensible weight loss corrected for respiratory weight losses.

The main disadvantage of the capsule design described is that the detection of leaks is difficult, since the fitting of any air-flow measuring device to the inlet tube defeats the object of leaving the flow of inlet air unimpeded. Small leaks under the rim, if they do occur, do not result in gross errors, since ambient air is still drawn into the capsule, but some moisture is liable to be collected from outside the test area.

SUMMARY

1. Previous measurements of the rate of cutaneous moisture vaporization from cattle are discussed and an apparent discrepancy found between the results of capsule methods and of indirect determinations by weighing of the whole animal.

2. The factors influencing observed rates of cutaneous evaporation under ventilated capsules have been investigated.

3. It has been found that the geometry of the capsule and the ventilation rate affect the rate of evaporation.

4. A capsule technique has been developed by which allowance may be made for the effects, due to the presence of the capsule, on the rate of cutaneous evaporation.

I wish to thank Dr J. D. Findlay for his advice and criticism. This work was done in a climatic laboratory built with the aid of a grant from the Colonial Development and Welfare Fund.

REFERENCES

BERMAN, A. (1957). Influence of some factors on the relative evaporation rate from the skin of cattle. *Nature, Lond.*, **179**, 1256.

FERGUSON, K. A. & DOWLING, D. F. (1955). The function of cattle sweat glands. *Aust. J. agric. Res.* **6**, 640–644.

FINDLAY, J. D., MCLEAN, J. A. & BENNET, R. D. (1959). A climatic laboratory for farm animals. *Heat Vent. Engr*, **33**, 95–100.

HELLMAN, G. (1955). *Aspirations–Psychrometer–Tafeln*, 3rd edn. Braunschweig: Friedr. Vieweg und Sohn.

KIBLER, H. H. & BRODY, S. (1952). Relative efficiency of surface evaporative, respiratory evaporative and non-evaporative cooling in relation to heat production in Jersey, Holstein, Brown Swiss and Brahman cattle, 5° to 105° F. *Res. Bull. Mo. agric. Exp. Sta.* no. 497.

KIBLER, H. H. & YECK, R. G. (1959). Vaporization rates and heat tolerance in growing Shorthorn, Brahman and Santa Gertrudis calves raised at constant 50° and 80° F temperatures. *Res. Bull. Mo. agric. Exp. Sta.* no. 701.

KLEMM, G. H. & ROBINSON, K. W. (1955). The heat tolerance of two breeds of calves from 1 to 12 months of age. *Aust. J. agric. Res.* **6**, 350–364.

KNAPP, B. J. & ROBINSON, K. W. (1954). The role of water for heat dissipation by a Jersey cow and a Corriedale ewe. *Aust. J. agric. Res.* **5**, 568–577.

MCDOWELL, R. E., LEE, D. H. K. & FOHRMAN, M. H. (1954). The measurement of water evaporation from limited areas of a normal body surface. *J. Anim. Sci.* **13**, 405–416.

McDOWELL, R. E., McDANIEL, B. T., BARRADA, M. S. & LEE, D. H. K. (1961). Rate of surface evaporation from the normal body surface and with sweat glands inactivated under hot conditions. *J. Anim. Sci.* **20**, 380–385.

McDOWELL, R. E., McMULLAN, H. F., WODZIKA, M., LEE, D. H. K. & FOHRMAN, M. H. (1955). Rate of water evaporation from various areas of a normal body surface and with sweat glands inactivated under hot conditions. *J. Anim. Sci.* **14**, 1250.

McLEAN, J. A. (1961). *Studies in Thermal Transport and Loss in the Bovine*, Ph.D. Thesis, University of Glasgow.

McLEAN, J. A. (1963). The partition of insensible losses of body weight and heat from cattle under various climatic conditions. *J. Physiol.* **167**, 427–447.

RANDALL, W. C., PEISS, C. N. & HERTZMAN, A. B. (1953). An analysis of the desiccating capsule technique in the measurement of regional water losses from the skin. *U.S.A.F. Tech. Rep.* 6680, Part 14.

ROBINSON, K. W. & KLEMM, G. H. (1953). A study of heat tolerance of grade Australian Illawarra Shorthorn cows during early lactation. *Aust. J. agric. Res.* **4**, 224–234.

TANEJA, G. C. (1958). Cutaneous evaporative losses in calves and its relationship with respiratory evaporative loss and skin and rectal temperatures. *J. agric. Sci.* **50**, 73–81.

TANEJA, G. C. (1959). Cutaneous evaporative loss measured from limited areas and its relationship with skin, rectal, and air temperatures. *J. agric. Sci.* **52**, 50–61.

VOLCANI, R. & SCHINDLER, H. (1954). Physiological reactions of dairy cows in various seasons and in different regions of Israel. *Refuah. vet.* **11**, 174–177.