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Heat transfer between animal and environment

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Calorimetric measurements are usually made in standardized environments, in which the mean radiant and air temperatures are equal to each other in a regimen of natural (free) convection, and where there is an insulated floor and the animal is unwetted. In such an environment, the air temperature by itself provides an adequate assessment of the thermal characteristics. When there are differences between mean radiant and air temperatures, or if the animal is exposed to solar radiation or wind, or the floor is uninsulated or the animal is wetted, the thermal environment becomes complex and cannot be represented by air temperature alone. Instead, the heat transfers through evaporation, radiation, convection and conduction need to be estimated separately, and the combined heat transfer can be used as an index of the thermal environment. This has been done in a number of ways: operative temperature for combined radiant and convective effects (Gagge, 1940); effective temperature for man (Bedford, 1946); solar radiation has been equated to increments in air temperature (Burton & Edholm, 1955; Lee & Vaughan, 1964); equivalent standardized environments have been described (Burton & Edholm, 1955; Mount, 1975). Apart from effective temperature, these various assessments have taken the form of calorimetrically derived temperatures, which are equivalent environmental temperatures that would lead to the same total heat loss from the animal as the actual conditions to which it is exposed. Monteith (1973, 1974) considers heat and mass transfer in terms of diffusion resistance and postulates a unitary temperature scale for the thermal environment in terms of the apparent equivalent temperature.

The extent to which variation in the several components of the thermal environment influences an animal's heat loss is illustrated by measurements that have been made of the critical temperature, defined as the air temperature at the lower end of the zone of thermal neutrality, for cattle exposed to different sets of conditions. A well-fed beef cow in dry calm weather with sunshine has a critical temperature of −21°, whereas when it is exposed to overcast conditions, rain and a wind of 4·5 m/s, the critical temperature is +2° (Webster, 1974). For sheep with 100 mm fleece depth, Alexander (1974) has calculated that the critical temperature is about 0° in still air, rising to about 23° in a wind of 7 m/s. The critical temperature is affected by the type of floor and bedding; in a group of 40 kg pigs it is 11·5° to 13° on straw, 14° to 15° on asphalt and 19° to 20° on concrete slats (Verstegen & van der Hel, 1974). These figures give some measure of the increase in air temperature that is required to compensate for increased heat loss through evaporation, convection and conduction.

Estimates of heat transfer

In a thermally neutral environment, the rate of heat production (Q) depends on the plane of nutrition and determines the rate of heat loss (H). In a cold environment, which demands extra heat production, it is H that determines Q (Mount, 1974, 1976). In each case, the evaporative loss and the effective area, characteristics and temperature of the animal's surface are so related to the humidity, mean radiant temperature, incident solar radiation, air temperature and wind speed of the environment that $Q=H$, provided that there is no storage of heat in the organism. The resulting thermal balance leads to the sum of heat transfers through evaporation, radiation, convection and conduction being equal to Q.

Together with measurements of oxygen consumption to give Q, the relative importance of the variables of the thermal environment as they affect the energy exchanges of animals was assessed by Winslow, Herrington & Gagge (1936, 1938) in their extensive series of measurements using partitional calorimetry with human subjects. Mount (1964) used a tent of polyethylene to produce environments of different combinations of mean radiant and air temperatures to estimate radiant and convective heat losses in young pigs. Joyce, Blaxter & Park (1966) used different emissivities of the walls of a metabolic chamber to estimate radiant heat exchange in sheep, and formulated a prediction equation to provide estimates of the animal's external insulation both indoors and out-of-doors.

The question now arises: to what degree is it possible to estimate an animal's sensible heat loss, and consequently its heat production, from its surface area and surface temperature taken together with the prevailing air temperature, wind speed and radiant environment, without recourse to other calorimetric measurements?

Heat transfer coefficients

For estimating heat exchange, it is convenient to use coefficients to link the animal's surface parameters with those of the environment. Such a coefficient for sensible heat transfer has the units of W/m^2 per deg C, which implies that if the coefficient, the animal's effective surface area for the particular mode of heat exchange, and the surface-environment temperature difference are known, the heat exchange can be calculated as the product of the three quantities. The term 'sensible heat transfer' implies dependence of heat transfer on temperature differences; this type of transfer includes radiation, convection and conduction, as distinct from evaporative transfer, which depends on differences in water vapour pressure.

For evaporative heat transfer, the coefficient is in terms of W/m^2 per mbar, referring to the vapour pressure difference between the skin surface and the environment. The vapour pressure at the skin surface is determined by the rate of sweating and the ambient humidity, and can be obtained by assuming a 'per cent wetted area' of the skin (Burton & Edholm, 1955; Ingram & Mount, 1975*a*). Evaporative loss from the respiratory tract can be estimated from the respiratory minute volume by assuming the expired air to be saturated at the temperature at which it leaves the body (McLean, 1974).

Radiant heat exchange. This may be considered in two parts: longwave and solar (shortwave) radiation. For longwave radiation, the reflectivity for most surfaces approaches zero, that is the emissivity is close to unity, so that the surface temperatures correspond closely to black-body temperatures. The coefficient for longwave exchange, K_R, is given by $4\sigma T^3$, where σ is the Stefan-Boltzmann constant ($5{\cdot}67\times10^{-8}$ W/m^2 per K^4) and T is the absolute temperature (Ingram & Mount, 1975*a*). When T=295 K (22°), $K_R=5{\cdot}8$ W/m^2 per deg C; at 305 K, $K_R=6{\cdot}4$. For a mean radiant environmental temperature of 15–20°, and a surface (skin or coat) temperature of 30–35°, K_R is close to 6 W/m^2 per deg C.

Solar radiation is a source of external heat that is absorbed and reflected by, and penetrates, skin, coat and clothing to varying degrees (Hutchinson & Brown, 1969; Monteith, 1973; Cena, 1974; Ingram & Mount, 1975*b*). Burton & Edholm (1955) point out that the efficiency of absorbed solar radiation in heating the organism is given by the ratio of the air-ambient insulation (external to the coat surface) to the combined air-ambient and coat insulation, so that only a part of the incident solar heat energy is added to the animal's heat load. The effect of solar radiation can be expressed as a rise in environmental temperature by an amount equal to the product of the absorbed radiation and the air-ambient insulation.

The reflectivity of coats is an important factor in determining the animal's heat load from solar radiation, but radiation is scattered forwards from the hairs towards the skin as well as being reflected back to the environment (Cena, 1974). Although a light coat is more reflective than a dark coat, more radiation reaches the skin through a light coat than through a dark coat, and the depth of penetration depends on wind speed as well as on coat colour (Monteith, 1973). With a dark coat, incident radiation is more likely to be absorbed in the outer layers, with the heat being dissipated by convection and longwave radiation, than would be the case with a light coat.

The radiation profile of the body determines the total incident radiation, and it depends on the orientation of the animal and the altitude of the sun (Clapperton, Joyce & Blaxter, 1965; Underwood & Ward, 1966; Ingram & Mount, 1975*a*). The profiles and consequently the effective surface areas are different for longwave radiation from the ground and surrounding objects, and for solar radiation (direct, scattered and reflected). The animal's mean effective surface area for radiant exchange is usually close to 0·7 to 0·75 of the total body surface area.

Convective heat exchange. This may take place primarily either through forced convection or through natural convection. Forced convective heat transfer is due to wind impinging on the surface; natural convective transfer occurs in still air or at low wind speeds, and is due to warmed air rising from the skin surface as a result of its decreased density. The heat transfer coefficients can be derived from empirical relations between dimensionless numbers: Nusselt and Reynolds numbers for forced convection, and Nusselt and Grashof numbers for natural convection (Monteith, 1973; Mount, 1977). Kerslake (1972) remarks that for man forced convective heat transfer predominates at wind speeds above 0·2 m/s, and natural convection at lower wind speeds.

Conductive heat exchange. Heat transfer by conduction (Bruce, 1977) is important in animals that lie on the ground or on concrete. Heat loss from the pig to an insulated floor is often about equivalent per unit area to that lost from the free surface by radiation and convection (Mount, 1968). A sheep living on cold, poorly-insulated ground may dissipate up to 30% of its minimum heat production by conduction (Gatenby, 1977), which is comparable with heat loss per unit area from the free surface even under these conditions.

Estimates of sensible heat loss from coefficients

For radiant exchange, the coefficient $4\sigma T^3$ can be used. For convective exchange, it is necessary to select the appropriate forced or natural convection coefficient on the basis of wind speed and surface-air temperature difference. Conductive loss per unit area can be assumed to be equal to the combined radiant-convective loss per unit area.

Convective heat loss is commonly a large part of total heat loss. In recent calculations based on measurements of skin temperature on the backs of pigs of 4, 20 and 60 kg body-weight (Mount, 1977), the forced (K_{CF}) and natural (K_{CN}) convection coefficients were found to be

$$K_{CF}=3\cdot 96\,(V/d)^{0\cdot 5}$$

and

$$K_{CN}=1\cdot 4\,((T_s-T_a)/d)^{0\cdot 25},$$

where V=air velocity (m/s), d=diameter of pig's trunk (m) (characteristic dimension), T_s=skin temperature on the back (°C), and T_a=air temperature (°C).

K_{CF} increases as air velocity increases, and both K_{CF} and K_{CN} fall as body size increases. In general, the calculations showed that K_{CF} exceeded K_{CN} at wind speeds of 0·2 m/s and above, and was less than K_{CN} at wind speeds of 0·1 m/s and below, corresponding to Kerslake's (1972) estimate for man.

The convection coefficients ranged from 3 to 11 W/m^2 per deg C, so that the combined radiation-convection coefficient lay between 9 and 17 W/m per deg C, the convection component constituting 33 to 65% of this depending on conditions. K_{CF} equalled K_{CN} at wind speeds of 0·17, 0·20 and 0·21 m/s for 4, 20 and 60 kg pigs at T_a=20°, and at 0·11, 0·15 and 0·18 m/s at T_a=30°.

Comparison of calculated sensible heat losses with calorimetric measurements

To compare sensible heat loss estimated from coefficients with measurements in whole-animal calorimeters, values for K_{CN} at a low air velocity, V=0·1 m/s, were used since conditions in calorimeters are usually arranged to be close to those of still air, unless the effect of wind is being investigated. The values given in Table 1 suggest that the use of coefficients can lead to fairly good approximations under conditions of low air movement. A temperature of 20° is cool for the 4-kg pig and is below the expected critical temperature; 20° is close to the critical temperature

Table 1. *The values of K_{CN} when V=0·1 m/s, the effective surface areas, the air (environmental) and skin temperatures, and the sensible (radiant and convective) heat losses from the pig calculated from* 0·75 A $(T_S—T_a)$ $(4\sigma T^3+K_{CN})$*, compared with sensible heat losses derived from calorimetric measurements made by a number of authors.*

Body-wt (kg)	Air temperature, T_a(°C)	Skin temperature, T_s(°C)	Convection coefficient K_{CN} W/m^2 per deg C V=0·1 m/s	Effective surface area (m^2) 0·75A	Calculated sensible heat loss (W)	Sensible heat loss from calorimetric measurement* (W)	Reference
4	20	35·5	4·7	0·18	29	19	a
						22	b
						28	c
	30	36·5	3·9		12	13	a
						13	b
						14	d
						15	c
20	20	32·5	3·9	0·49	61	53	d
						53	e
						53	f
						56	g
						57	h
						58	j
	30	37·0	3·3		31	33	g
						34	k
						35	l
60	20	30·5	3·4	0·98	90	90	d
						93	f
						94	m
						97	e
						104	l
	30	36·5	3·0		59	56	l
						58	m

A, surface area from body-weight (m^2), and the factor 0·75 was derived statistically (Mount, 1977).

*To obtain sensible heat losses from the calorimetric results, estimated evaporative losses were subtracted; the proportions of heat loss due to evaporation in 4, 20 and 60 kg pigs were taken as 10, 25 and 40% at T_a=20°, and 20, 55 and 60% at T_a=30°.

(a) Cairnie & Pullar (1959); (b) Mount (1963); (c) Stombaugh, Roller, Adams & Teague (1973); (d) Holmes & Close (1977); (e) Verstegen, van der Hel & Cöp (1974); (f) Fuller & Boyne (1972); (g) Gray & McCracken (1974); (h) Close & Mount (1975); (j) Verstegen, Close, Start & Mount (1973); (k) Close, Mount & Start (1971); (l) Close & Mount (1976); (m) Holmes & Mount (1967).

for the 20-kg pig, and probably above the critical temperature for the 60-kg pig. Due to postural variation the area factor 0·75 may therefore be high for the 4-kg pig and low for the 60-kg pig, at 20°. 30° is in the zone of thermal neutrality for all three pigs, and perhaps in the warm zone for the 60-kg pig. The animal's behaviour tends to diminish its thermal responses to environment (Baldwin, 1974), particularly by changing effective surface area (Mount, 1968).

Conclusions

The assessment of sensible heat loss from calculated coefficients gives reasonable approximations in the pig both within and below the zone of thermal neutrality under conditions of low air movement. From its nature this type of assessment is probably more useful for estimating changes in sensible heat loss than in providing absolute values. The method lends itself to estimations on animals either indoors or out-of-doors, in standardized or complex thermal environments. An advantage is that no immediate restraint of the animal is required, only observation of its shape, size and surface temperatures (possibly by thermography: Cena, 1974; Clark, Mullan & Pugh, 1977). Extension of the assessment to the total heat loss requires a corresponding observational method for obtaining an estimate of evaporative loss. This is particularly important in those animals (and man) where evaporative loss is a larger part of total heat loss than it is in the pig.

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