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Estimation of heat production from heart-rate measurements in cattle

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1. Heat production and heart rate of seven steers were measured simultaneously using either a calorimetric chamber or head-cage.

2. The relationship between heat production and heart rate for each animal was best described by linear regression.

3. Differences between individual animals made separate 'calibration equations' necessary for each animal.

4. Accuracy of prediction of heat production from heart rate was better than ±10% in all instances.

5. It is concluded that frequent measurement of heart rate appears to offer a practical method for estimation of heat production of free-range animals.

Practical estimates of the food energy requirements of farm animals are based largely on the results of trials on animals confined within metabolic chambers. Measurement of oxygen consumption of free-range animals has been achieved only at the expense of major interference with the animal's freedom or with the animal itself, such as tracheotomy (Blaxter & Joyce, 1963). Various workers have therefore sought some readily measurable quantity which is sufficiently well correlated with heat production to provide an alternative method for its estimation. Brockway (1978), reviewing such methods, has suggested that a minimum accuracy requirement for nutritional studies would be of the order of ±10%.

Heart-rate has been considered as a correlate of heat production by Webster (1967) who found a close relationship between heart rate and heat production in three of four sheep tested, the correlation constants being different for individual animals. Brockway & McEwan (1969), summarizing their own and Webster's (1967) work on sheep, describe the accuracy of predicting O_2 consumption from heart rate as only ±10% in three sheep, ±20–25% in two and none at all in the remaining four. They attributed the more consistent results in some individuals to prolonged training and handling, but concluded that a 6-month training period had not been long enough for their four 'worst' sheep. Holmes *et al.* (1976) working with calves; Yamamoto, Yamada *et al.* (1977) working with bull calves; and Yamamoto, Matsuoka *et al.* (1977) working with dairy steers all found prediction accuracies for heat production between approximately 2 and 10% for different individual animals. Yamamoto, Matsuoka *et al.* (1977) and Yamamoto, Yamada *et al.* (1977) removed the individual differences by expressing their results in terms of relative heart rate and relative heat production, that is the ratio, heart rate:corresponding 'basic' value and heat production:corresponding 'basic' value while the animals were resting before feeding in the morning. Relative heat production could then be predicted from relative heart rate with an accuracy of approximately 7% using a single prediction equation for all twelve animals tested. For practical purposes their method has the advantage that the 'calibration' of each animal is reduced to a determination of the 'basic' heat production and heart rate at a single (resting) condition, but the error of determining this 'basic' heat production would have to be included in the over-all prediction error of heat production.

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In all the reports cited heat production has been measured by the use of face masks, ventilated hoods or tracheotomized animals, and the danger exists that these methods may affect either heat production or heart-rate or the relationship between them; this may be one reason why training has sometimes been found important.

An opportunity to investigate the relationship between heat production and heart rate in relatively undisturbed animals was provided by a current series of calorimetric trials which are primarily designed to investigate heat storage by cattle. In these trials heat production is monitored at frequent regular intervals over a period of several days, whilst being subject to variations induced by the feeding regimen and by changes in posture. Heart-rate measurements were therefore included in four of the trials. In addition some comparisons were made between heart rate and heat production of four other animals using a ventilated head-cage.

METHODS

Determinations in the calorimeter

Three animals (Ayrshire steers) were each confined one at a time for 6 d in a gradient-layer calorimeter (McLean, 1971). One animal (no. 86) was subjected to the routine twice. Air temperature in the calorimeter was 12° for the first 24 h (day 1) and also for days 3, 5 and 6, but was abruptly changed to 25° for days 2 and 4. Food, consisting of (g/kg): 330 barley straw, 170 barley, 220 molasses, 280 'Nutrimax 34' (Scottish Agricultural Industries Limited) (10 g/kg body-weight), was given at 08.00 and 20.00 hours every day until day 6 when the ration was doubled. Water was available to the animal at 08.30 and 20.30 hours for 30 min.

Heat production (y) (watts) was estimated using a modified form of the equation given by McLean & Watts (1976):

$$y = (F+V\frac{d}{dt})\,(-204{\cdot}7\ \Delta O_2+7{\cdot}3\ \Delta CO_2-64{\cdot}6\ \Delta CH_4)-5{\cdot}99\ N \qquad (1)$$

where ΔO_2, ΔCO_2 and ΔCH_4 represent the differences in percentage concentrations of oxygen, carbon dioxide and methane between stale air leaving and fresh air entering the calorimeter; F is the stale-air flow rate (l/s at normal temperature and pressure), V is the volume of the calorimeter (l) and N is the rate of urinary nitrogen excretion (mg/s). N which makes only a small contribution to y was in fact not measured but assumed to be 0·032 g/l O_2 consumed (McLean, 1972). Also the term involving ($d\Delta CH_4/dt$) was ignored; this is because methane tends to be eructed by the animal in an irregular series of bursts which can bear little relationship to its actual rate of production in the rumen. O_2, CO_2 and CH_4 concentrations were measured by paramagnetic and infrared gas analysers and flow rate by a Rotameter fitted with an analogue output device (McLean & Davidson, 1978). All quantities were recorded and calculated every 10 min using a computer-controlled data logger.

Heart rate was recorded using two surface or needle electrodes placed on the right shoulder and left anterior thorax. The amplified signals were recorded on a paper chart for 30 s every 5 min and later counted. For comparison with 10 min readings of heat production (y), mean heart rate (x) was calculated from a weighted average of three successive measurements, $x = (x_{-1}+2x_0+x_{+1})/4$, where x_{-1} and x_{+1} correspond in time to two successive gas concentration determinations and x_0 is the intermediate measurement of heart rate.

Corresponding measurements of x and y were thus available for every 10 min period throughout the 6 d except for a few interruptions (usually three daily) when the chamber door was briefly opened for changing excreta collectors and other routine maintenance, or when the calorimeter temperature was being altered.

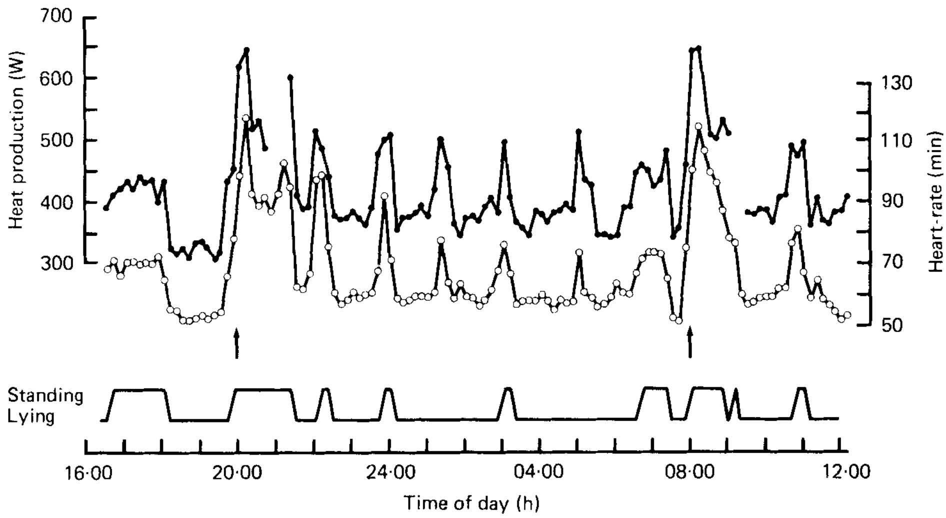

Fig. 1. Typical plot over 20 h of heat production (●——●), heart rate (○——○) and posture (——) for steer no. 65. ↑, Feeding times.

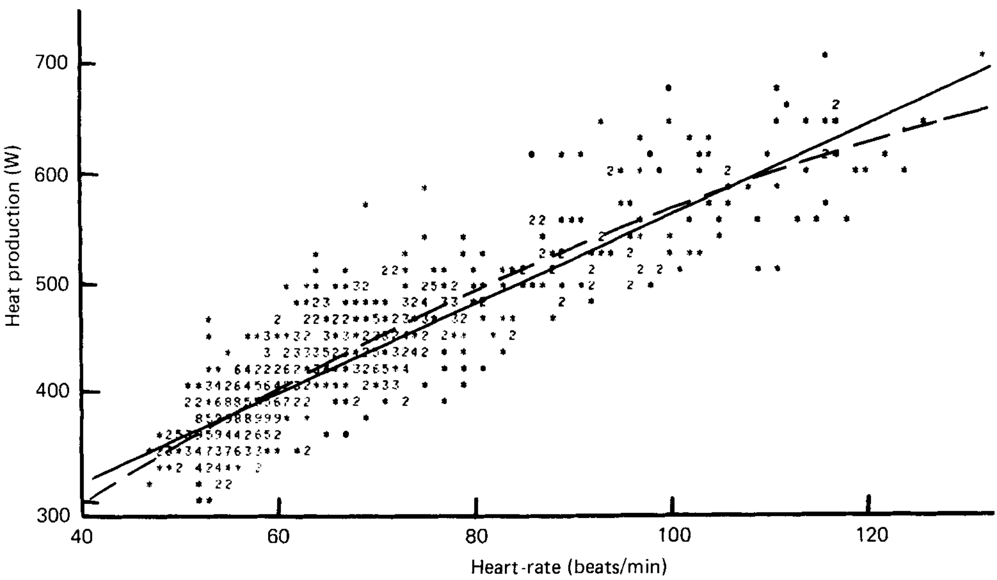

Fig. 2. Computer plot of all measurements of heat production *v.* heart rate for steer no. 65. Numerals 2, 3, 4, 5, 6, 7, 8, 9, coincident points. ——, Linear regression line; – –, quadratic regression line.

Determinations using a head-cage

These experiments on four different steers took place in a climatic chamber controlled at 19°. The animals had not been fed for 18 h when they entered the climatic chamber, but were offered food at intervals, until they declined any more, in an attempt to raise heat production gradually throughout the day. Meanwhile heat production was measured at intervals by placing a ventilated cage over the head for 10–15 min; heart rate was measured continuously over the same period by the method described previously.

Table 1. *Values of the regression constants in the equation relating heat production* (y) *to heart rate* (x) (*regression equation:* $y = a+b(x-60)$, *where* b *is regression coefficient and* a *is the intercept*) *for eight steers*

	Calorimeter				Head-cage			
Animal no.	65	86(a)	86(b)	85	95	96	99	100
Body-wt (kg)	285	224	243	242	167	177	198	191
No. of measurements	698	649	711	701	26	25	21	21
b: watt/min: Mean	4·10	4·57	4·25	4·92	2·66	2·39	3·63	3·53
SE	0·08	0·11	0·11	0·11	0·43	0·17	0·39	0·34
watt/min per kg body-wt$^{0.75}$	0·059	0·079	0·069	0·080	0·057	0·049	0·069	0·069
a: watt	399	312	332	294	295	314	301	322
watt/kg body-wt$^{0.75}$	5·75	5·40	5·39	4·78	6·32	6·44	5·71	6·28
PE*	7·8	8·7	9·7	9·6	7·4	4·1	8·5	8·1

* PE, residual variation of *y* from the regression line expressed as a percentage of the mean of *y*.

Heat production (watts) was calculated over the measurement period from a simplified equation (McLean, 1972):

$$y = -204{\cdot}7\, F_O\, \Delta O_2, \tag{2}$$

where F_O is the mean ventilation rate of the cage (l/s at normal temperature and pressure).

RESULTS

Fig. 1 shows a plot of heart rate (x), heat production (y) and posture *v*. time for a typical 20 h period extracted from one calorimeter experiment (animal no. 65). Both x and y vary with time according to the same general pattern. The fluctuations are associated with postural changes and with feeding routines.

Fig. 2 shows a computer plot of y *v*. x for all measurements on animal no. 65. Calculated linear and quadratic regressions have been superimposed on the plot. The constants of the linear regression ($y = a+b\,(x-60)$) are listed in Table 1 for all four calorimeter experiments and also for the four head-cage experiments. In both series y and x varied over a 2- to 3-fold range. It is clear that the regression constants differ between animals, that is each animal has its own 'calibration'. When the regression constants are expressed per unit metabolic body size (body-weight $^{0.75}$), the between-animal variation in regression coefficients is reduced, but individual differences persist. The percentage error (PE) of predicting y from a single measurement of x, that is the standard deviation of y from the fitted regression line expressed as a percentage of the mean level of y, is within the range 7·4 to 9·7 for all animals except one, for which PE was 4·1.

In order to examine possible sources of variation in the relationship between y and x, regressions were calculated individually from the results of each day of each calorimeter experiment. Values for a, b and PE were each subjected to analysis of variance, the results of which are summarized in Table 2. The differences in values for b between experiments were not statistically significant, but differences in values for a were highly significant ($P < 0{\cdot}001$). Values for both a and b showed significant variation between different days of the experimental routine. The value for b was significantly higher than the mean on day 1 and lower on day 6 (double feeding). On days 2 and 4 when ambient temperature was 25°, values for a were significantly lower than on the other days, at 12°. PE showed no significant variation either between days or between experiments, and was always within the range 7·7–9·9.

Table 2. *Mean values for intercept* (a) *and regression coefficient* (b) *in the regression equation relating heat production* (y) *to heart rate* (x) *and percentage error* (*PE**) *for four steers on* 6 *d and when standing and lying* (*regression equation:* $y = a+b(x-60)$)

	a		*b*		PE*	
	Mean	Statistical significance†	Mean	Statistical significance†	Mean	Statistical significance†
Animal no.						
65	401	$P < 0.001$	4.43	NS	7.7	NS
86(*a*)	310	±13	4.75		8.7	
86(*b*)	326		4.98		9.9	
85	292		5.14		9.9	
Day no.						
1	344	$P < 0.01$	5.48	$P < 0.05$	8.0	NS
2	314	±16	4.90	±0.32	8.2	
3	343		5.02		8.5	
4	319		4.65		8.8	
5	340		4.63		7.9	
6	333		4.27		7.5	
Standing	379	NS	3.29	$P < 0.05$	8.5	NS
Lying	318		4.48		8.3	

NS, not significant.

* PE, residual variation of y expressed as a percentage of the mean of y.

† Significance levels for there being differences amongst the means, and the smallest significant differences ($P < 0.05$) for comparing two individual means.

The full results of each calorimeter experiment were also subdivided into standing and lying, and the differences in regression constants between these two categories were subjected to statistical t tests. The results of these analyses are also included in Table 2. Values for b but not a differed significantly between standing and lying ($P < 0.05$); PE was virtually the same for both.

DISCUSSION

For each animal under trial accuracy of PE values, predicting heat production (y) from heart rate (x) by linear regression of the full set of results, was better than ± 10 (usually 7–10 but in one instance 4). PE was similar for both calorimeter and head-cage measurements. The calorimeter method of measuring heat production achieves a high speed of response without encumbering the animal with a mask or head-cage, and allows measurement to continue whilst the animal is feeding and free to stand or lie at will. The fast response is the result of including the rate-of-change terms for O_2 and CO_2 concentration (equation no. 1, p. 508). Unfortunately this introduces additional error (but not any systematic bias) to each individual determination of y, due to the difficulty of measuring rate of change of gas concentration accurately over a short period (an error of only 0.01% in O_2 concentration difference over 10 min results in an error of approximately 8% in heat production). This type of error, however, decreases in inverse proportion to the time interval between measurements. Consequently, the full sets of results from the calorimeter experiments were averaged over 30 min periods and the linear regressions re-calculated. This procedure also reduced the effects of any possible errors that may have arisen if the individual measurements of x and y were imperfectly synchronized. The 30 min values gave similar regression constants to those obtained from the full set of results, but PE was lowered to within the range 5·5–7·2 compared with 7·8–9·6. A further improvement in prediction accuracy could be achieved by extending the averaging period.

The appearance of Fig. 2 suggests that a better fit might have been obtained with a quadratic equation of the form $y = a+bx+cx^2$. This was tried with the full sets of values from all four calorimeter experiments and yielded PE values in the range 7·7–9·6. These were practically the same as those obtained from linear regression and provide no justification for regular use of the more complex formula. A non-linear relationship between heat production and heart rate would result if the O_2 pulse, that is the O_2 consumption per heart beat (Webster, 1967), decreased with increasing heart rate.

The form of regression equation used ($y = a+b(x-60)$) expresses the intercept a as the heat production when heart rate is 60 beats/min. The value 60 was chosen as representing an approximate mean resting heart rate for all the animals. The conventional intercept, at zero heart rate, would have been physiologically meaningless. Significantly different regression equations were found when the results were classified according to posture or to day of experiment. For measurements taken when the animals were standing, values of b were lower than for lying. Also on day 6, when the animal was given a double food ration, values for b were low. Both of these effects may result from the over-all regression being slightly curvilinear. Thus standing and double feeding, which tend to be associated with above average levels of x and y, are represented by points on the upper end of the curve where slope is reduced, whereas lying is represented by values at the lower end of the curve. On days 2 and 4 when air temperature was 25°, values for b were not significantly different from the over-all mean but values for a were low. The reason for this is not known but to some extent it may be a fortuitous consequence of selecting the value 60 for the heart-rate intercept. Close examination of the regression lines reveals that, had almost any value other than 60 been chosen, the differences in values for a on days 2 and 4 would have been less striking. Despite the differences in regression equations between standing and lying and between different days, PE was no better for any of the individual categories than for the full results on each animal. There is, therefore, no advantage to be gained from subclassifying results from a single animal for prediction purposes.

The significantly higher values of b on day 1 may have been connected with the animals being relatively unaccustomed to the calorimeter routine, though all had received prior training in a dummy chamber. Apart from the results of day 1 there is no evidence of training or acclimatization causing changes either in the regression constants or in prediction accuracy over the period of the experiment. Brockway & McEwan (1969) have suggested that even 6 months' training of sheep was not always enough to make prediction of heat production from heart rate sufficiently accurate to be useful. The training period involved in the present experiments is very much less than 6 months, but it would be expected that changes due to training would be most marked in the initial phase. Nevertheless, prediction accuracies are considerably better than those reported by Brockway & McEwan (1969) for sheep. The prediction accuracies are, however, similar to those reported for cattle by Holmes *et al.* (1976) and Yamamoto, Matsuoka *et al.* (1977) and Yamamoto, Yamada *et al.* (1977). It may be that prediction of heat production from heart rate is more accurate in cattle than in sheep.

Since heat production increases during growth, comparisons of regression equations between animals are best made if the results are expressed per unit metabolic body size. However, even after making this adjustment the variation in regression coefficients is still ±16%. Nor does comparison of relative heart rate with relative heat production (Yamamoto, Yamada *et al.* 1977) remove the individual variation from the present results. However, the results do suggest that if each animal is 'calibrated' individually, either by means of a calorimeter or a head-cage, subsequent estimation of heat production from heart-rate measurements is possible with an accuracy of $\pm 10\%$. If several heart-rate measurements are averaged over, for example, a 30 min period, accuracy of estimated heat production is improved to $\pm 7\%$.

The calorimeter method of calibration is much preferable to the head-cage method as it provides very many calibration points with minimum disturbance of the animal.

It appears that frequent measurement of heart rate, possibly by means of a simple telemetry system, could offer a practical method for measuring heat production of cattle on free range. Each animal would first have to be 'calibrated' and the calibrations would have to be repeated at intervals on growing animals. Further work is required to determine how repeatable the calibration becomes for adult animals.

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