Studies on diurnal variations of heat production and the effective lower critical temperature of early-weaned pigs under commercial conditions of feeding and management

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1. The heat production of groups of pigs, weaned at 10 d of age, was determined in an open-circuit respiration chamber at various ages between 10 and 33 d at temperatures above and below the lower critical temperature (T_{cl}).

2. The heat production was lowest on the second or third day post weaning when pigs were given feed increasing by 25 g/pig per d from day 2. There was a marked diurnal pattern in heat production, the lowest values being recorded between 24.00 and 08.00 h.

3. The mean thermal conductance ($H/\Delta T$, kJ/h per m^2 per °ΔT, where H is total heat production, m^2 is the surface area calculated as 0·097 W kg$^{0·633}$ (Brody, 1945) and °ΔT is the difference between rectal temperature, taken as 39°, and air temperature) below T_{cl} was calculated as 18·0, 16·9, 18·5 and 21·2 respectively at 10, 17, 24 and 31 d of age. Maximum values of $H/\Delta T$ obtained during feeding periods were, on average, 4·5 kJ/h per m^2 per °ΔT higher than the mean values.

4. The maximum value for T_{cl} during the immediate post-weaning period was 25·9°. The mean T_{cl} at 17, 24 and 31 d were respectively 21·7, 18·4 and 18·6° for pigs fed almost to appetite.

There are numerous reports on the development of the thermoregulatory mechanisms in the neonatal pig (Holub *et al.* 1958; McCance & Widdowson, 1959; Mount, 1959, 1962, 1968; Curtis & Rogler, 1970; Mount & Stephens, 1970) but relatively few which provide information on the thermoneutral zone of the pig during the first few weeks. Cairnie & Pullar (1957) reported measurements of heat loss from pigs between 4 and 12 kg, fed *ad lib.*, which indicated that the lower critical temperature of the singly-caged pig at 4 kg was above 30° and at 10 kg was approximately 20°. Short-term measurements by Ingram & Mount (1965) showed that the lower critical temperature of fed, singly-caged pigs weighing between 4 and 8 kg was above 20°. Mount (1960) found that pigs kept in groups could counteract the effects of environmental temperature by huddling together, thus reducing the rate of heat loss compared with that found with isolated pigs. The effect increased up to a group size of at least six pigs.

Recent developments in the use of controlled-environment, cage-rearing systems for early-weaned pigs and the high cost of providing supplemental heating have highlighted the lack of fundamental information on which to base practical recommendations of temperature. In designing experiments to obtain this information it was recognized that to obtain a response curve of heat production *v.* temperature at several ages with groups of pigs would incur considerable management problems and the use of a very large number of pigs.

An alternative means of estimating the lower critical temperature (T_{cl}) is to assume

Table 1. *Composition and analysis* (g/kg) of the diet given to pigs weaned at* 10 *d*

Ground flaked maize	317·5
Dried skim milk	280
Fatted skim milk (400 g fat/kg)	140
Fish meal	120
Sucrose	100
Groundnut oil	40
Trace minerals–vitamins†	2·5
Crude protein (nitrogen × 6·25)	242
Ether extract	121
Metabolizable energy (MJ/kg) (determined)	18·2

* Dry matter basis.

† The trace mineral–vitamin mixture provided (mg/kg): iron, 115; zinc, 65; copper, 35; manganese, 25; iodine, 2·0; cobalt, 1·0; selenium, 0·1; ascorbic acid, 200; choline chloride, 125; nicotinic acid, 10·0; calcium pantothenate, 8·5; riboflavin, 4·0; menadione, 4·0; pyridoxine hydrochloride, 3·0; thiamine hydrochloride, 1·0; cyanocobalamin, 0·001; retinol, 12·0; cholecalciferol, 0·035; α-tocopheryl acetate, 4·0.

that the rate of heat loss per unit surface area (thermal conductance) attains a constant minimal value at the T_{cl} (Kleiber, 1967). Holmes & Close (1977) have suggested that this is not the situation but calculations suggest that any decrease in the rate of heat loss below the T_{cl} is sufficiently small to permit the assumption to be made. It is then possible to compute T_{cl} from a knowledge of the heat production at two temperatures, one above and one below T_{cl}.

The work reported includes studies on the diurnal variations in heat production of pigs subjected to continuous light and fed at 8 h intervals and estimates of the T_{cl} of 10 d weaned pigs immediately post weaning and at 17, 24 and 31 d.

EXPERIMENTAL

Feeding and management of experimental animals

The pigs were obtained from a hysterectomy-derived, Large White × Landrace herd and were weaned at 10 d. No creep feed was available before weaning. They were removed from the sow at approximately 10.00 hours and transferred to the experimental unit within 1 h. Normally six pigs were selected from a litter to give the least range of live weight within the group. Water, which was medicated (Terramycin; Pfizer Ltd) for the first 72 h was continuously available from nipple drinkers. Feed was withheld for the first 24 h. Except where the experimental routine required otherwise or the appetite of the pigs was inadequate the feeding scale employed subsequently was 25 g/pig per d on the second day and increasing by 25 g/pig per d thereafter. The composition and analysis of the diet, which was pelleted, are given in Table 1. The metabolizable energy content of the diet was determined using individually-caged pigs.

Environment

Normally the pigs were transferred immediately post weaning to a respiration chamber for 3 d for the measurement of heat production. The initial temperature was 29 ± 0·5°. The metabolism cage in the respiration chamber measured approximately 1·5 m × 0·6 m and the floor was expanded metal. The cage was positioned over a galvanized metal sump so that quantitative collection of excreta and split feed could be effected. Between periods in the respiration chamber the pigs were transferred to a room in which the temperature could be controlled in the range 20–30° with an accuracy of ± 2°. The temperature was adjusted linearly from an initial temperature of 27° at 13 d to 22° at 35 d. The cages were in a

Table 2. *Expt 2. Summary of experimental conditions*

Age (d)	Temperature (°) Warm	Cold	Feeding pattern
10	29	20	Fasted
17	27	16	8 h
24	25	16	8 h
31	25	16	8 h

commercial three-tier block but otherwise of similar size and structure to that used in the respiration chamber. Continuous low-intensity light was provided.

Measurement of heat production

The respiration chamber was an open-circuit system as described by Gray & McCracken (1976). Due to constraints on the response time of the gas sampling system, the composition of the exhaust air was recorded at 5 min intervals. Incoming air was analysed after every ten scans of exhaust air. Oxygen consumption and carbon dioxide production were calculated using the modified Brouwer (1965) equation:

Heat production (kJ) = $16{\cdot}175\ O_2\,(l) + 5{\cdot}021\ CO_2\,(l) - 5{\cdot}987 \times N\,(g)$, where N is the daily urinary nitrogen output. The daily N output was estimated from values obtained by J. W. Jordan (personal communication) with individually-caged pigs.

Experimental design

Expt 1. Two groups of pigs weaned at 10 d were placed in the respiration chamber for 3 d and 4 d respectively and given feed, according to the scale described previously, at 08.00, 16.00 and 21.00 hours, to simulate commercial conditions.

Expt. 2. Pigs weaned at 10 d were placed in the respiration chamber without food for 48 h and heat production was measured continuously. After 24 h at 29°, the temperature was reduced to 20° for 10 h and then returned to 29° for the last 14 h (Table 2). The pigs were each given 50 g feed on the first day after removal from the chamber and then were continued on the feeding scale described previously, the feed being offered at 08.00, 16.00 and 24.00 hours. During subsequent 48 h periods in the chamber (Table 3) feed was offered in six equal quantities. In order to minimize weight differences above and below T_{cl}, whilst maintaining the strict 8 h regimen, heat production was measured for the first 8 h at the higher temperature, then for 24 h at the lower temperature and finally for 16 h at the higher temperature. Four litters of pigs were used giving four replicates of the measurements at each age.

Calculation of T_{cl}

The thermal conductance (H/m² per h per °ΔT, $H/\Delta T$) at the T_{cl} was calculated from the heat production at a temperature chosen to be below T_{cl} (H is the total heat production (kJ), m² is the surface area calculated as $0{\cdot}097\ W\ kg^{0{\cdot}633}$ (Brody, 1945); °ΔT is the difference between rectal temperature, taken as 39°, and air temperature). The total heat production at a temperature chosen to be above $T_{cl} \div H/\Delta T$ and subtracted from 39° (Mount, 1959 1960; Holmes & Close, 1977) then gave an estimate of T_{cl}.

Activity measurements

It was not possible to obtain a complete record of activity but it was noted from direct observation that any movement during periods of minimum activity produced an almost

Table 3. *Expt 2*. Heat production (kJ per h per m²) of 10 d pigs during the first 24 h post weaning and during the period 38–46 h post weaning at 29° and during the period 26–36 h post weaning at 20° and the calculated values of $H/\Delta T$ (kJ/h per m² per °) and T_{cl} (°)*

Litter no.	Mean wt (kg)	Heat production at 29° 0–24 h	Heat production at 29° 38–46 h	Heat production at 20° 26–36 h	$H/\Delta T$	T_{cl} 0–24 h	T_{cl} 38–46 h
1	3·90	317	263	388	20·3	23·3	26·0
2	2·81	300	239	351	18·5	22·8	26·1
3	3·27	302	223	319	16·8	21·0	25·7
4	3·04	282	220	311	16·4	21·8	25·6
Mean	—	300	236	341	18·0	22·2	25·9
SEM	—	7·2	9·8	16·4	0·87	0·51	0·12

$H/\Delta T$, thermal conductance (H/m² per h per °ΔT, where H is total heat production (kJ), m² is the surface area calculated as 0·097 W kg$^{0·633}$ (Brody, 1945) and °ΔT is the difference between rectal temperature, taken as 39°, and air temperature).

* For details of experimental conditions, see Table 2.

immediate response in the CO_2 and O_2 readings. On a number of occasions, activity was monitored intermittently, using a video-tape recorder and this was correlated with changes in the exhaust-air analyses.

Correction for body-weight change

Pigs were weighed individually before entering, and on being removed from, the respiration chamber. The mean weights during 8 h or 24 h sub-periods were interpolated assuming a linear gain or loss of weight while in the respiration chamber.

Statistical analysis

Heat production on consecutive days and $H/\Delta T$ and T_{cl} at different ages were statistically analysed using the paired t test.

RESULTS

Expt 1. The mean initial weights (kg) of the two groups were 3·59 (group 1) and 3·00 (group 2) respectively. The mean heat productions (kJ/pig per d) on consecutive days during the immediate post-weaning period were 1672, 1491, 1502 for group 1 and 1213, 1175, 1120, 1163 for group 2. There was a marked diurnal pattern (Fig. 1), the lowest values of heat production occurring between 24.00 and 08.00 hours. For this period, the mean values on successive days were 285, 253, 255 for group 1 and 258, 240, 238, 235 kg/h per m² for group 2.

Expt 2. The typical pattern of heat production and the mean values of heat production for fasted pigs at 29 or 20° during the immediate post-weaning period are summarized in Fig. 2 and Table 3. Taken in conjunction with the pattern shown in Fig. 1, it is clear that the period for low temperature coincided with the normal period of highest activity and heat production. The mean heat production during the first 24 h at 29° averaged 300 kJ/h per m². The mean for the 24.00–08.00 hours period on day 1 was 269 ± 10·5 and was significantly different ($P < 0·01$) from the value of 236 ± 9·3 on day 2. Heat production during the 10 h at 20° averaged 341 kJ/h per m² and was significantly higher ($P < 0·05$) than that at 29°. The mean value of $H/\Delta T$ was 18·0 kJ/h per m² per ° and the mean value of T_{cl} for the first day was 22·2°. Assuming that the period between 38–46 h fasting corresponds to the period of lowest heat production then the mean maximum T_{cl} was 25·9°.

The pattern of heat production in fed pigs at 17, 24 and 31 d was affected by their appetite in relation to the feed allowance. However, there did not appear to be any major change in

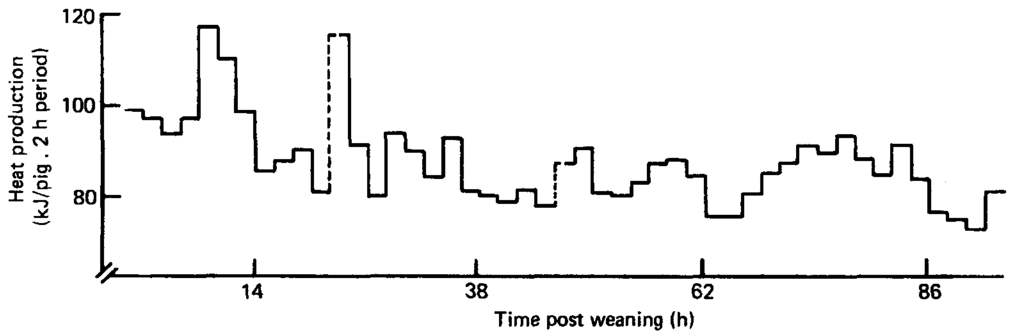

Fig. 1. Variations in heat production (kJ/pig per 2 h period) of a group of six pigs, mean initial weight 3·0 kg, during the 4 d period immediately post weaning. (Pigs were weaned at 10.00 hours and given 0, 25, 50, 75 g food/pig per d on days 1–4 respectively.)

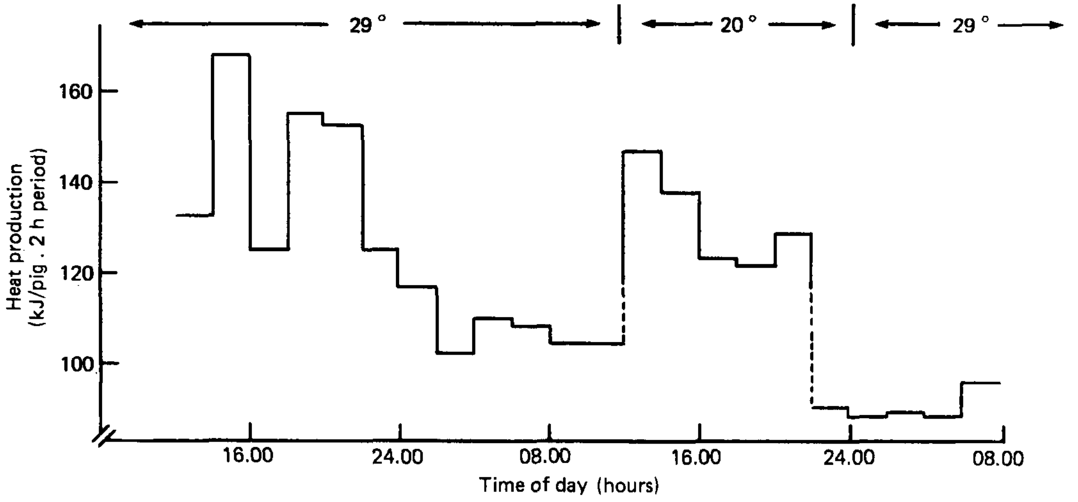

Fig. 2. Pattern of heat production (kJ/pig per 2 h period) at 29° or 20° of a group of six pigs weaned at 10 d during the 48 h period immediately post weaning. (Pigs, initial weight 3·42 kg, were weaned at 10.00 hours and food was withheld during the period of measurement of heat production).

pattern resulting from the sudden change in temperature (Fig. 3). Studies of activity by direct observation and intermittent photography confirmed that periods of high heat production above and below the critical temperature were associated with high activity mainly in relation to feeding.

The heat productions of the fed pigs at 17, 24 and 31 d are summarized in Table 4. The litter differences observed at 10 d were apparent at all ages and accentuated by variations in food intake. The mean values of $H/\Delta T$ (kJ/h per m² per °) at 17, 24 and 31 d were respectively 16·9, 18·5 and 21·2 for the complete 24 h period. The difference between the values at 17 and 31 d was significant ($P < 0·05$). Despite the variations in feed intake, heat production and $H/\Delta T$ the estimates of T_{ct} showed little litter variation at each age. The mean T_{ct} at 17, 24 and 31 d were respectively 21·7, 18·4 and 18·6°. The differences between the values for 17 and 24 d and 17 and 31 d were significant ($P < 0·05$ and $P < 0·001$).

Since the pattern of heat production appeared to be similar at temperatures above and below T_{ct}, it was deemed appropriate to calculate T_{ct} for periods of high activity using the

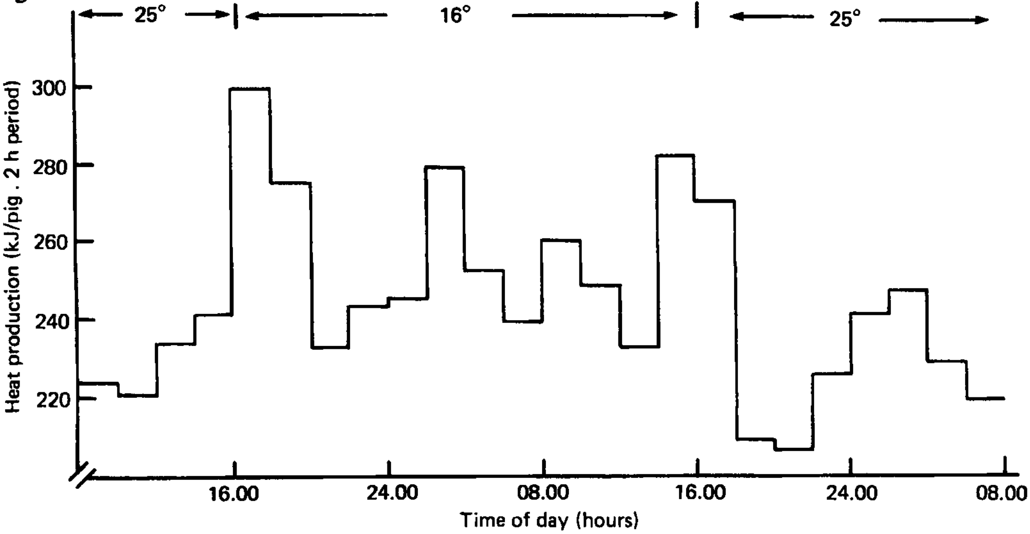

Fig. 3. Pattern of heat production (kJ/pig per 2 h period) at 25° or 16° of a group of six pigs aged 24 d fed three times daily at 08.00, 16.00 and 24.00 hours since 12 d of age. (The mean weight of the pigs was 6·1 kg and feed intake, 285 g/pig per d).

maximum hourly values of heat production recorded above T_{cl}. The resulting estimates of T_{cl} were similar to those obtained from the mean 24 h values of heat production.

DISCUSSION

The results of Expt 1 indicate that heat production is lowest on the second or third day post weaning. Even on day 4, heat production had not returned to the level of the first day although the energy intake was slightly above that required for zero energy balance. The mean heat production between 38–46 h fasting of the four groups in Expt 2 was identical to the lowest values obtained in Expt 1. Furthermore, the ratio, mean value for 24.00–08.00 hours on day 1: corresponding value on day 2 was 1·14 in Expt 2 compared with 1·11 for the fed pigs in Expt 1 indicating that the 38–46 h values would tend to underestimate minimum heat production under fed conditions. It would seem that the value of 25·9° (Table 3) may be regarded as the upper limit of T_{cl} for groups of cage-reared pigs weaned at 10 d.

Strictly speaking the use of total heat production in the calculation of $H/\Delta T$ is incorrect since the evaporative loss is not directly related to the temperature gradient. However, results of Mount (1962) indicate that the evaporative component is less than 10% of the total heat production below T_{cl} and is relatively constant. Therefore the error in the estimate of T_{cl} arising from the use of total heat production should be minimal. The calculations of Holmes & Close (1977) indicated that a further source of error would be that due to the continued decrease of $H/\Delta T$ below T_{cl}. At each age the low temperatures were chosen to be as near T_{cl} as possible in order to minimize the possibility of underestimating $H/\Delta T$. In some instances, due to problems with the refrigeration unit, the chamber temperature was higher than intended. There is no evidence of any relationship between $H/\Delta T$ and the difference between T_{cl} and the chamber temperature. The higher values of $H/\Delta T$ for litter nos 1 and 2 at 31 d may have resulted from the chamber temperature being above T_{cl} during periods of high activity or high post-prandial heat production. The over-all mean value for $H/\Delta T$ at T_{cl} was 18·6 kJ/h per m^2 per ° which is mid-way between the

Table 4. *Expt 2*. Mean 24 h heat production and maximum hourly heat production (kJ/h per m²), above and below the minimum critical temperature (T_{cl}), of groups of fed pigs aged 17, 24 or 31 d, and the calculated values of $H/\Delta T$ (kJ/h per m² per °) and T_{cl} (°)*

Age (d)	Litter no.	Mean wt (kg)	Apparent feed intake (g/pig per d)	Heat production above T_{cl}		Heat production below T_{cl}			$H/\Delta T$		T_{cl}	
				24 h mean	1 h maximum	24 h mean	1 h maximum		24 h mean	Maximum	24 h mean	Maximum
17	1	4·58	153	310	354	381	456		17·3	20·7	21·0	21·9
	2	3·66	175	330	406	427	513		19·4	23·3	21·8	21·6
	3	3·54	150	273	334	296†	391†		15·2	20·0	21·3	22·3
	4	3·29	130	248	294	306†	379†		15·3	19·4	22·8	23·8
								Mean	16·9	20·9	21·7	22·4
								SEM	0·99	0·85	0·39	0·49
24	1	6·11	284	377	447	418	496		18·2	21·6	18·3	18·3
	2	5·25	340	416	505	404††	480††		18·4	22·9	< 18	< 18
	3	5·20	300	366	474	443	545		18·4	22·7	19·1	18·1
	4	4·99	300	403	509	456	584		19·0	24·3	17·7	18·1
								Mean	18·5	22·9	18·4	18·2
								SEM	0·17	0·55	0·41	0·07
31	1	8·99	475	499	559	506††	623††		24·1	29·7	18·3	20·2
	2	8·08	475	449	594	485†††	581†††		22·0	26·4	18·6	< 17
	3	7·20	425	425	530	499	605		20·8	25·2	18·5	18·0
	4	6·54	302	360	451	433	533		18·0	23·0	19·0	19·4
								Mean	21·2	26·1	18·6	19·2
								SEM	1·27	1·46	0·14	0·64

$H/\Delta T$, thermal conductance (H/m² per h per °ΔT, where H is total heat production (kJ), m² is the surface area calculated as 0·097 W $kg^{0.633}$ (Brody, 1945) and °ΔT is the difference between rectal temperature, taken as 39°, and air temperature).

* For details of experimental conditions, see Table 2.

† 19·5°, †† 18°, ††† 17°.

estimates made by Holmes & Close (1977) for newborn pigs and pigs over 20 kg kept in groups (20·0 and 17·4 respectively).

Since huddling in a group reduces the rate of heat loss below T_{cl} (Mount, 1960) the mean daily values of $H/\Delta T$ obviously underestimate the rate of heat loss for a pig separated from the group during feeding periods or standing to drink, defecate or urinate. Except where the amount of food offered was surplus to appetite there was a clear pattern of high activity immediately post feeding and this tended to be associated with the highest hourly heat production (e.g. Fig. 3). It was also noted that when chamber temperature was reduced at around the time of the 16.00 hours feed, the pigs were initially very active. It was common for the highest value of heat production to be recorded during the hour after the reduction of chamber temperature. Although this value does not necessarily correspond to the maximum $H/\Delta T$ for individual pigs it is considered that it does provide a reasonable estimate of the maximum $H/\Delta T$ under a group situation. The over-all mean of 23·3 kJ/h per m^2 per ° falls between the estimates of Holmes & Close (1977) for singly-caged newborn and 20 kg pigs (31·4 and 19·2 respectively). Since the pattern of activity did not seem to differ above and below T_{cl}, it is concluded that the best estimate of T_{cl} for the animals during periods of activity is obtained from the maximum value of $H/\Delta T$ and the maximum rates of heat production above T_{cl}. The calculated values for T_{cl} under these conditions are almost the same as those determined from the 24 h values.

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