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THE INFLUENCE OF BODY CORE TEMPERATURE AND PERIPHERAL TEMPERATURES ON OXYGEN CONSUMPTION IN THE PIG

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SUMMARY

1. The rate of oxygen consumption was measured in young pigs exposed to different ambient temperatures and the effect on metabolic rate of changing the temperature of thermodes implanted in the hypothalamus and over the spinal cord was determined. In some experiments the temperature of the skin over the trunk was changed by means of a water-perfused coat.

2. Cooling the hypothalamus or the spinal cord in a warm ambient did not change the rate of oxygen consumption. At a thermoneutral ambient temperature, cooling either thermode increased oxygen consumption. In a cold environment, cooling either thermode increased the rate of oxygen consumption more than at a thermoneutral temperature. The increase in the rate of oxygen consumption was greatest during cooling of the spinal cord and it appeared that the pigs also shivered more violently. Heating either thermode tended to decrease oxygen consumption in a cold environment.

3. In pigs with thermodes both in the hypothalamus and over the spinal cord, cooling both thermodes was accompanied by a greater increase in oxygen consumption than cooling either thermode alone. The increase in oxygen consumption on cooling one thermode could be reduced by heating the other.

4. The skin temperature (fixed by the water perfused coat, or the ambient temperature) at which the rate of oxygen consumption increased, was lowered during heating of the thermodes, but the rate of increase in oxygen consumption appeared not to change as a function of falling skin or ambient temperature.

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INTRODUCTION

The mechanisms by which an animal's heat loss and heat conservation are controlled are known to involve thermosensitive regions both in the skin and deep in the tissues of the body. Amongst the thermosensitive regions in the body core, the preoptic region of the hypothalamus (Hammel 1968) and the spinal cord (Thauer, 1970; Klussmann & Pierau, 1972) are known to be of particular importance, although in some species (Rawson & Quick, 1970; Ingram & Legge, 1972) other regions are also involved. In the pig, heating or cooling the spinal cord produces changes in peripheral blood flow and evaporative heat loss (Ingram & Legge, 1971, 1972) of a similar nature to heating or cooling the hypothalamus, and on the basis of these results and studies on other species (Jessen & Mayer, 1971; Jessen & Ludwig, 1971; Jessen & Simon, 1971) it appears that thermal signals from the two regions are regarded by the control system as being more or less equivalent. Behavioural thermoregulation, as studied by the technique of operant conditioning can also be influenced by changes in the temperature of the hypothalamus in the pig (Baldwin & Ingram, 1967), but in a recent study, Carlisle & Ingram (1973) have demonstrated that heating or cooling of the spinal cord of the pig is accompanied by behavioural responses which differ from those observed when the hypothalamic temperature is changed.

The relative importance of signals from the various thermosensitive regions of the body, even within the same species, cannot therefore be assumed to be the same for each channel of heat loss and heat conservation, but must be separately investigated. In the present experiments the role of thermal stimulation of the hypothalamus, the spinal cord, and the skin in the control of oxygen consumption has been investigated and some of the interactions between those stimuli have been studied.

METHODS

Animals

The results presented are derived from experiments on ten young pigs weighing between 11 and 16 kg. The animals were taken from the farm and housed separately during the course of the investigation. They were fed at least 2 hr before the beginning of an experiment and again at the end of the day.

Thermodes

The thermodes implanted into the preoptic region of the hypothalamus were similar to those used in previous studies (Baldwin & Ingram, 1967; Carlisle & Ingram, 1973) and consisted of a small tank with an inlet and outlet tube. The temperature of the thermode was measured with the aid of a thermistor attached to the tank. The thermode over the spinal cord consisted of a loop of polyethylene tube inserted in the thoracic region at T10 and extending up to C1 (Ingram & Legge, 1971; Carlisle & Ingram, 1973). The temperature of this thermode was assessed by threading a thermojunction down a blind-ended catheter inserted along with the thermode. All operative procedures were carried out under general anaesthesia using aseptic precautions, and the position of the thermodes checked by means of radiographs. Four pigs received thermodes over the spinal cord, two into the hypothalamus and four had thermodes in both positions. The position of the thermode over the spinal cord was checked again by means of a radiograph at the end of the experiment to ensure that it had not moved caudally beyond C2.

Control of skin temperature

Skin temperature over the skin of the trunk was controlled independently by means of a temperature-controlled coat (Ingram & Legge, 1971).

Measurement of oxygen consumption

The animals were equipped with a harness and lightly restrained in a stall inside a respiration chamber 60 cm × 60 cm × 125 cm long, which was ventilated at the rate of 50 l./min. The chamber was housed inside a temperature-controlled room although the animal's activity could be observed through a system of windows and a mirror. A sample of the exhaust air from the respiration chamber was taken continuously and passed through a paramagnetic oxygen analyser (Beckman model F3). The output of the analyser was displayed on a chart recorder as the percentage of oxygen in the sample and from this information, the ventilation rate of the chamber, and the pig's weight, oxygen consumption could be calculated as ml. $O_2/kg^{2/3}$ min. The two-thirds power has been used in order to reduce the differences between pigs which are related to differences in body weight (Mount, 1968).

Experimental procedure

The calibration of the oxygen analyser was first checked against room air, and then against a sample of a standard gas mixture. The animal's oxygen consumption was then recorded until a steady state had been established. Once a base line had been achieved the thermode temperature was changed and the new rate of oxygen consumption was established over the next 20–30 min. Subsequently, the thermode was returned to normal for 20 min before being either heated or cooled to a different level. When all the required thermode temperatures had been investigated the calibration of the oxygen analyser was again checked against room air and the standard gas and the animal was returned to the animal house until the next session when a different ambient temperature was used.

In one pig with a thermode over its spinal cord, the temperature of the thermode was first raised in steps to 43° C and then decreased in steps to 10° C without returning to the control value between each change of temperature.

Effect of animal movement

Any excessive movement on the part of the animal affected the oxygen consumption and for this reason only those values obtained while the animal was lying down, or standing still were used. Because of this restriction a number of observations could not be used and two animals had to be rejected completely, leaving only ten pigs on which to base the final analysis.

Effects of changing thermode temperatures on tissue temperature

In two studies reported elsewhere the effect of changing thermode temperature on the surrounding tissue was examined. In the hypothalamus, a thermode temperature of 10° C lowered the temperature of the brain tissue 5 mm away by 2·8° C (Baldwin & Ingram, 1967). Cooling the thermode over the spinal cord was accompanied by considerable temperature gradients across the cord which could be as great as 16° C (Carlisle & Ingram, 1973).

RESULTS

Effect of heating or cooling the thermode in the hypothalamus

During this study and another on behavioural thermoregulation (Carlisle & Ingram, 1973) it was noted that the behavioural responses to cooling the hypothalamus and the spinal cord were different. Cooling the hypothalamus in the present study tended to make the pigs restless,

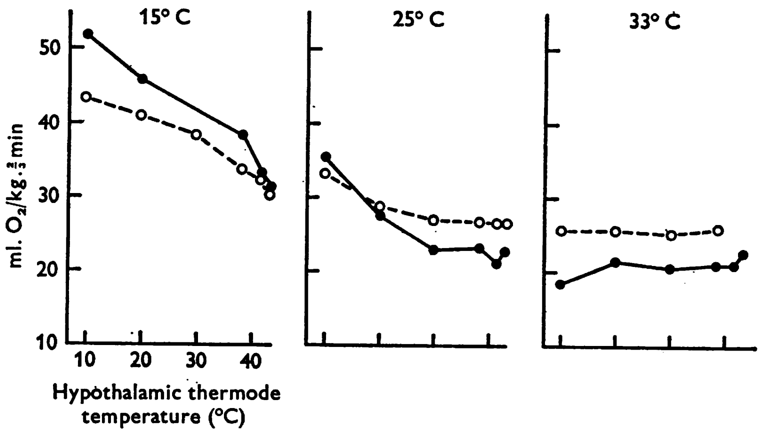

Fig. 1. The effect on the rate of oxygen consumption of changing the temperature of a thermode in the hypothalamus at ambient temperatures of 15, 25 and 33° C. The results obtained from two pigs are presented.

particularly at low ambient temperatures, and since activity affected oxygen consumption, it was possible to obtain useful information on only two animals with thermodes in the hypothalamic region.

As can be seen from Fig. 1, at an ambient temperature of 33° C, which is well above the critical temperature for a pig of this age, changing the temperature of the thermode did not change oxygen consumption. Within the thermoneutral zone, at 25° C, cooling the thermode in the hypothalamus to 20 or 10° C was accompanied by an increase in oxygen consumption, but not when the thermode was cooled to only 30° C. There was some suggestion of a decrease in oxygen consumption in one animal when the hypothalamus was warmed, but since metabolic rate was already low at 25° C, no large decrease would be expected. In an ambient temperature of 15° C, oxygen consumption increased even at a thermode temperature of 30° C, and at thermode temperatures of 20 and 10° C metabolic rate was even higher than at corresponding thermode temperatures in an ambient of 25° C. At 15° C ambient when the thermode temperature was at normal body temperature, metabolic rate was elevated above the basal level, and when the thermode was then heated oxygen consumption decreased although it did not fall to the basal value.

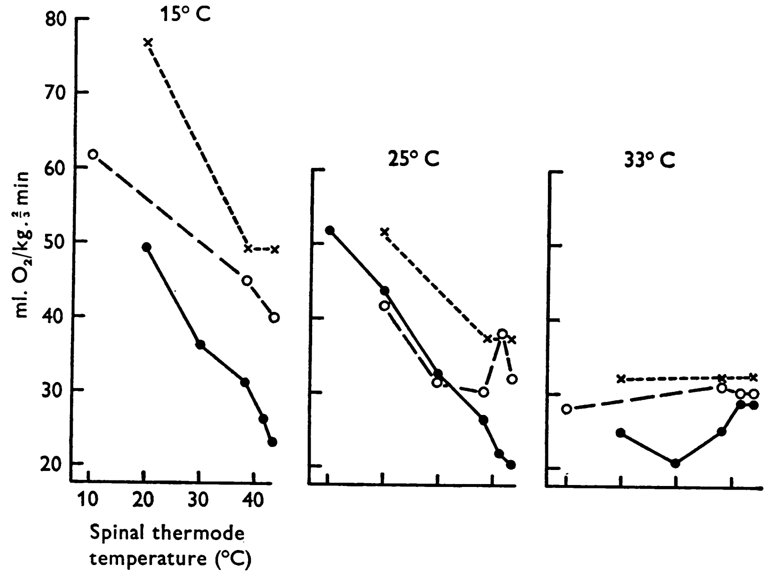

Fig. 2. The effect on the rate of oxygen consumption of changing the temperature of a thermode over the spinal cord at ambient temperatures of 15, 25 and 33° C. The results were obtained from three pigs different from those in Fig. 1.

Effect of heating or cooling the thermode over the spinal cord

In three animals, the effect of changing the temperature of the spinal cord was investigated at the same three ambient temperatures used in the study of the hypothalamus. At 33° C there was no consistent effect of changing the thermode temperature (Fig. 2). At 25° C there was some indication that cooling the thermode to 30° C was accompanied by an increase in oxygen consumption, and at 20 or 10° C the effect was very marked. Heating the thermode appeared to decrease oxygen consumption although the effect was not always observed. At 15° C ambient temperature the effect of cooling the thermode over the spine was even more marked than at an ambient of 25° C and heating the thermode was accompanied by a decrease in metabolism in two out of the three pigs. Although no quantitative measurements were made, it appeared that the pigs shivered more violently during cooling of the spinal cord as compared with cooling the hypothalamus and this is in keeping with the greater increase in oxygen consumption.

A fourth particularly placid animal which lay down quietly in the respiration chamber at all ambient temperatures, even as low as 7° C, was also available in this experiment. Such pigs are not common and the opportunity was taken to carry out a slightly different type of experiment

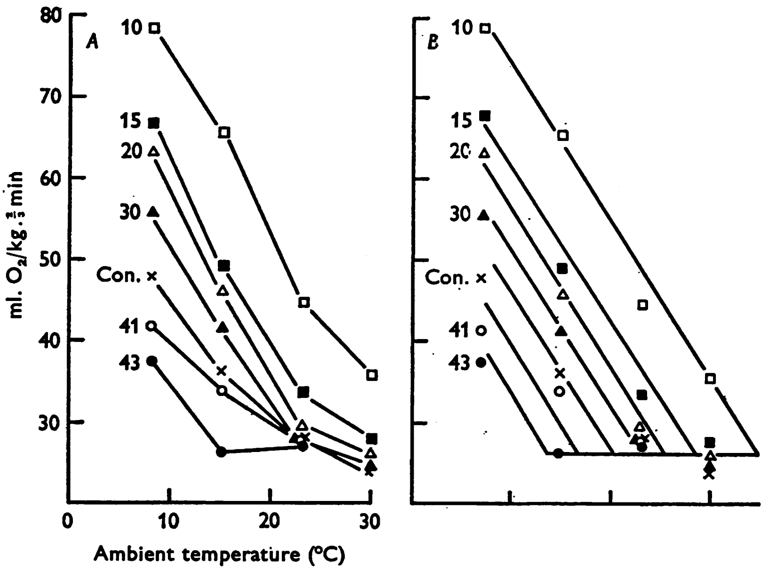

Fig. 3. The effect on the rate of oxygen consumption of changing the temperature of the thermode over the spinal cord at various ambient temperatures which are indicated on the abscissa. The temperature of the thermode over the cord is indicated in the Figure (Con = normal body temperature) and the data relating to different thermode temperatures are represented by points of a different shape. In *A* the points are simply joined together. In *B* lines have been drawn parallel to each other and close to each set of points. See text for discussion.

over a greater range of ambient temperatures. In this study the thermode temperature was changed in successive 5° C steps at ambient temperatures of 7, 15, 23 and 30° C. In Fig. 3*A* the rate of oxygen consumption obtained at various thermode temperatures has been plotted against ambient temperature, and as can be seen metabolism was again affected both by central and peripheral stimulation.

Effect of changing both spinal and hypothalamic temperature

Experiments involving two thermodes were carried out on two pigs and the thermodes were heated or cooled independently. A record of this type of experiment at an ambient temperature of 20° C is shown in Fig. 4. As will be seen, cooling the thermode in the hypothalamus to 30° C was followed by an increase in oxygen consumption and when the thermode over the spine was also cooled oxygen consumption increased even further. After 10 min of cooling both thermodes, the one in the hypothalamus was returned to a normal temperature and oxygen consumption fell after about 4 min. Fifteen minutes later, when the thermode over the

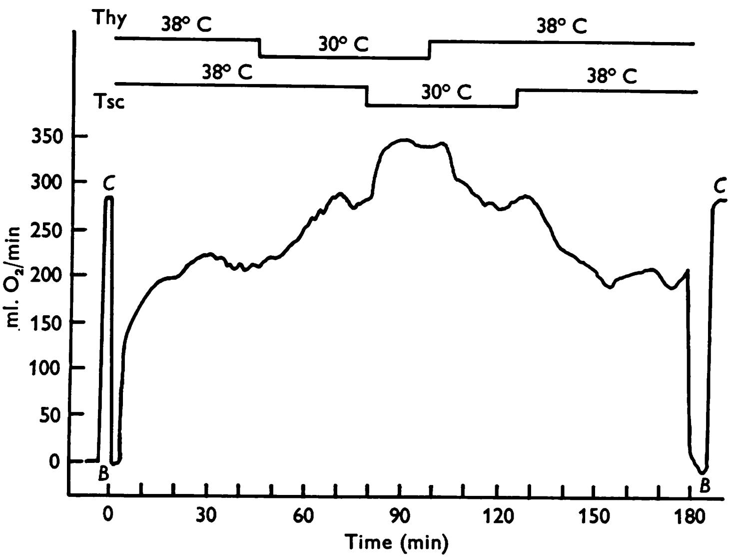

Fig. 4. A record taken from the chart recorder indicating the rate of oxygen consumption while the temperature of thermodes in the hypothalamus (Thy) and over the spinal cord (Tsc) were changed independently at an ambient temperature of 20° C. *B* indicates the base line when the analyser sampled room air and *C* indicates the reading when the analyser sampled the standard calibration gas at the beginning and end of the observation period.

spine was allowed to warm to normal body temperature, the rate of oxygen consumption returned to the control value. In other experiments it was demonstrated that heating one thermode could reduce the effect of cooling the other.

The effect of changing the temperature of the skin on the trunk while the hypothalamus and spine were heated or cooled

In these studies on two pigs, the room temperature was fixed at 25° C. In the control experiments, the thermodes over the spine and in the hypothalamus were kept at 39° C and oxygen consumption was measured while the temperature of the trunk skin was changed by means of the special coat worn by the animal. As seen in Fig. 5, changes in trunk skin temperature between 35 and 41° C had no effect on oxygen consumption, but at a skin temperature of below 35° C the rate of oxygen consumption increased. When the experiment was repeated while both the thermodes were held at 43° C, cooling the skin below 35° C had less effect on oxygen consumption than in the control experiment, and there was some indication that the oxygen consumption did not increase unless the skin temperature was below 33° C. At skin temperature above 35° C the rate of

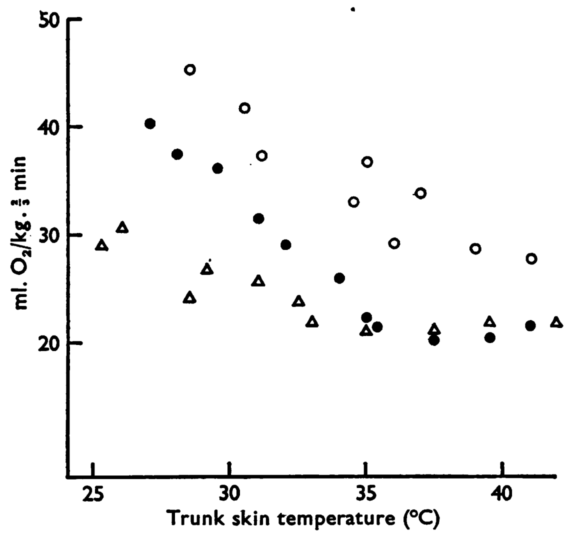

Fig. 5. The effect on the rate of oxygen consumption of changing the skin temperature on the trunk at an ambient temperature of 25° C. ●, Results obtained when the thermodes in the hypothalamus and over the spine were at normal body temperatures. ○, Results obtained when the thermodes were both cooled to 20° C. △, Results obtained when both thermodes were warmed to 43° C.

oxygen consumption was the same in both control experiments and when the thermodes were heated. In another set of experiments the thermodes were both cooled to 20° C and it was found that even at a skin temperature on the trunk of 41° C the rate of oxygen consumption was above the control level. At skin temperatures below 36° C, oxygen consumption increased at about the same rate as in the control studies but the absolute level was higher.

DISCUSSION

The results of the present study demonstrate that the rate of oxygen consumption in the pig is influenced both by the temperature of the environment stimulating peripheral tissue, and by temperature changes deep in the body core. At a warm ambient temperature, i.e. above thermoneutrality, cooling either the hypothalamus or the spinal cord had no effect on the rate of oxygen consumption. But, at thermoneutrality, cooling either thermode increased the rate of oxygen consumption, and at a cold ambient temperature the increase in the rate of oxygen consumption for a given degree of cooling was even greater. These findings are in accordance with those obtained by Baldwin, Ingram & Le Blanc (1969) who found that the excretion of noradrenaline in the urine was increased after cooling the hypothalamus of pigs exposed to cold, or thermoneutral ambients, but not when the ambient temperature was high.

The effects of changing body temperatures of pigs at various ambient temperatures have now been investigated in relation to metabolism, peripheral blood flow (Ingram & Legge, 1971), respiratory evaporative heat loss (Ingram & Legge, 1972), and behavioural thermoregulation (Baldwin & Ingram, 1967; Carlisle & Ingram, 1973). From a consideration of the results of those studies it appears that thermal stimuli of the same sign applied to different regions always reinforce each other. Thus the vasoconstriction associated with a given degree of cooling in the hypothalamus or spine increases at lower ambient temperatures, and the vasodilatation which accompanies a warm stimulus to the hypothalamus or spine is greater at higher ambient temperatures. The interaction between peripheral and central stimuli in relation to the control of respiratory frequency is even more marked, since warming the hypothalamus or spine increases the frequency of breathing only when the ambient temperature is warm. Studies of behavioural thermoregulation using operant conditioning techniques also indicate that thermal stimuli of the same sign reinforce each other.

When contrary thermal stimuli are applied to periphery and core, however, differences between thermoregulatory mechanisms become evident. Heating the hypothalamus or spine even in a thermoneutral zone will not cause panting and in a cold ambient heating central thermosensitive regions will not cause vasodilatation; cooling the hypothalamus or spine will not cause an increase in metabolism if the ambient is warm. Such findings suggest that peripheral signals override those from the core; but by contrast cooling either the spine or the hypothalamus inhibits panting in a warm environment, and heating the spine or hypothalamus has an inhibitory effect on the rate at which pigs obtain thermal reinforcement during exposure to cold. In so far as generalizations are possible it appears that when contradictory stimuli are received from core and periphery, then the stimulus from the core may inhibit a mechanism, but is unlikely to activate a heat loss or heat conservation process. Even this generalization, however, has limitations, for although cooling the hypothalamus does not always initiate operant responses for heat in a warm ambient, it does do so on occasion (Baldwin & Ingram, 1967).

A detailed comparison of the effects of changing the temperature of the hypothalamus and spinal cord is not possible because of the thermal gradients which are set up in tissues, as discussed by Jessen & Mayer (1971), Jessen & Ludwig (1971) and Jessen & Simon (1971). One difficulty is that because of the thermal gradients not all the thermosensitive units in a particular region are stimulated to the same extent. A second difficulty is that the distribution of the thermosensitive units, particularly in the cord, is not yet properly understood and simply because the thermodes in the two regions are held at the same temperature it therefore does not follow that the thermosensitive units in the two regions are equally stimulated. As judged by the metabolic response, the effects of the temperature changes in the spinal cord and hypothalamus appear to be similar, although cooling the cord is accompanied by the greater increase in oxygen consumption. It is, however, quite possible that an equal thermal stimulation of the units in the two regions is achieved only when the thermode over the spine is cooled to 20° C and that in the hypothalamus to 10° C.

What is clear is that the nature of the metabolic response to changing the temperature of the two regions is similar, while behavioural responses to cooling the two regions (Carlisle & Ingram, 1973) display some differences inasmuch as cooling the cord led to postural changes associated with heat conservation which were seen less frequently when the hypothalamus was cooled. There is an additional possibility concerning the apparent hypersensitivity of the spinal cord in response to cooling which relates to the work of Suda, Koizumi & Brooks (1957). They demonstrated that at local temperatures between 25 and 35° C in the cord (although the motoneurones decreased their sensitivity) the duration of the action potential in motoneurones and interneurones was considerably prolonged. Moreover, the longer the duration of the signal the greater the degree of desynchronization of the multiple elements involved. Thus once an afferent impulse had initiated shivering it would be expected that it would be prolonged and quite violent.

The results obtained from the particularly placid pig in this study provided the opportunity to test two general ideas about the interaction between peripheral and central temperatures. One possibility, out of many, is that changes in the temperatures of one region cause a change in the 'set point' temperature of the other region at which a response occurs. This idea is supported by the work of Hammel, Jackson, Stolwijk, Hardy & Strømme (1963) and Hellstrøm & Hammel (1967). The second hypothesis is that the 'set point' temperature remains the same, but the 'gain' of the system, that is the magnitude of the response for a given temperature change in one region, depends on the temperature of other regions, and this view is supported by the findings of Nadel, Horvath, Dawson & Tucker (1970). In Fig. 3 oxygen consumption has been plotted against ambient temperature for a pig in which the temperature of the cord was held at a series of values. In Fig. 3*A* the points have been simply joined together, but in *B*, lines have been deliberately drawn parallel to each other so as to fit the given set of points. The fact that the agreement between the parallel lines and the observed points is good suggests that a large part of the variance can be explained by the hypothesis that changing the temperature of the thermosensitive region in the cord alters the 'set point' with respect to the skin, an observation which fits a model suggested by Hammel *et al.* (1963). In the original model it was proposed that changes in ambient temperature were accompanied by changes in the 'set point' temperature of the hypothalamus, and it was later demonstrated that deep body temperature itself also affected the 'set point' (Hellstrøm & Hammel, 1967). Thus a low ambient temperature would raise the 'set point' of the hypothalamus for the onset of increased oxygen consumption, and low spinal temperature could be expected to raise the 'set point' even further. It appears from the present results in the pig that if there is any contribution made by changes in the 'gain' of the system, i.e. the rate of increase of oxygen consumption with temperature, it is relatively small, although it cannot be excluded and there is no reason why components of both systems should not be present.

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