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Effects of short-term exposure to high ambient temperature and relative humidity on thermoregulatory responses of European (Large White) and Caribbean (Creole) restrictively-fed growing pigs

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Abstract – The effects of short-term exposure to high ambient temperature and relative humidity (RH) on thermoregulatory responses were studied in two consecutive experiments on a total of 12 Large White (LW) and 12 Creole (CR) growing pigs. The pigs were submitted to two or three consecutive thermal challenges over two (153 and 188 days of age; experiment 1) or three consecutive stages (97, 111, and 125 days of age; experiment 2). For each thermal challenge, the ambient temperature (T) varied daily from 22 to 34 °C between 0900 and 1500 and from 34 to 22 °C between 1500 and 2100 during five consecutive days. The RH was maintained constant at 70, 80, 90, 80, and 70%, on day 1, 2, 3, 4, and 5, respectively. The feeding level of each pig was adjusted on a BW basis to provide 1.3 of the maintenance metabolisable energy requirement. Cutaneous temperature (CT) was constant between 22 and 24 °C and increased linearly between 24 and 34 °C (+0.27 °C per °C; $P < 0.05$). The CT response was not affected by RH or breed ($P > 0.10$). Rectal temperature (RT) decrease ($P < 0.05$) between 22 and 26 °C (i.e. –0.3 °C), remained constant between 26 and 30 °C (i.e. 38.3 °C) and increased ($P < 0.05$) at higher temperatures (+0.6 °C between 30 and 34 °C). The temperature threshold at which RT began to increase (Upper Critical Temperature or UCT) was reduced ($P < 0.05$) when RH increased above 70%. Breed influenced the RT response; UCT decreased in LW pigs (between 30 and 32 °C vs. between 32 and 34 °C in CR pigs, $P < 0.01$) whereas the RT increment calculated between 28 and 34 °C was not affected by breed (i.e. +0.7 °C on average). Respiratory rate (RR) began to rise when the temperature exceeded 30 °C (= Evaporative critical temperature, ECT). A rise in RH from 70 or 80% to 90% increased ECT (between 28 and 30 °C vs. between 30 and 32 °C, $P < 0.01$) and the RR increment between 28 and 34 °C (+34.4 vs. 18.4 breaths per min, $P < 0.001$). The ECT was not affected ($P > 0.10$) by breed (between 30 and 32 °C) whereas the increase of RR from 28 to 34 °C was significantly lower for CR than for LW (19.0 vs. 27.6 bpm, $P < 0.01$). In both experiments, the thermoregulatory responses were reduced when the thermal challenge was repeated suggesting a long-term adaptation to heat stress. In conclusion, the present study suggested that breed can affect response to heat stress.

pigs / breed / heat stress / relative humidity / thermoregulation

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Résumé – Effets d’une exposition à court terme à une température et une hygrométrie élevée sur la thermorégulation de porc Européen (Large White) et Caribéen (Créole) rationnés au cours de la croissance. Les effets d’une exposition à court terme à une température et une hygrométrie ambiante (RH) élevées sur les réponses de thermorégulation ont été étudiés dans deux expériences consécutives portant sur un total de 12 porcs Large White (LW) et 12 porcs Créole (CR). Les porcs ont subi deux ou trois challenges thermiques à 153 et 188 jours d’âge et à 97, 111 et 125 jours d’âge respectivement dans l’expérience 1 et 2. Pour chaque challenge thermique, la température varie de 22 à 34 °C entre 09:00 et 15:00 h et de 34 à 22 °C entre 15:00 et 09:00 h pendant 5 jours consécutifs. Les porcs sont rationnés à 1,3 fois leur besoin d’entretien. L’hygrométrie ambiante est maintenue constante au cours du nyctémère à 70, 80, 90, 80, 70 % respectivement pour les jours 1, 2, 3, 4 et 5 du challenge thermique. La température cutanée (CT) est constante entre 22 et 24 °C et augmente significativement ($P < 0,05$) entre 24 et 34 °C (+0,28 °C par °C d’augmentation de la température). L’évolution de la CT n’est pas affectée par la RH ou le génotype ($P > 0,10$). La température rectale (RT) diminue entre 22 et 26 °C (–0,3 °C ; $P < 0,05$), reste constante entre 26 et 30 °C et augmente significativement entre 30 et 34 °C (+0,6 °C ; $P < 0,05$). La température à laquelle RT commence à augmenter (c’est-à-dire la température critique supérieure ou UCT) est réduite ($P < 0,05$) lorsque la RH dépasse 70 %. L’UCT est significativement plus faible chez les LW (entre 30 et 32 °C vs. entre 32 et 34 °C chez les CR ; $P < 0,01$) alors que l’augmentation de la RT entre 28 et 34 °C n’est pas affectée par la race (+0,7 °C en moyenne). L’augmentation du rythme respiratoire (RR) est significative lorsque la température dépasse 30 °C (= température critique d’évaporation ou ECT). Au-delà de 70 % de RH, l’ECT est significativement réduite (entre 28 et 30 °C à 80 ou 90 % vs. entre 30 et 32 °C à 70 % de RH ; $P < 0,01$) et l’augmentation du RR entre 28 et 34 °C est plus importante (+34,4 à 90–80 % vs. 18,4 ventilations par min à 70 % RH, $P < 0,001$). L’ECT n’est pas influencée par le type génétique ($P > 0,10$) alors que l’augmentation du RR entre 28 et 34 °C est significativement plus faible pour les CR comparativement aux LW (19,0 vs. 27,6 ventilations par min ; $P < 0,01$). Pour les deux expériences, les réponses à un stress thermique aigu sont modifiées par la répétition des challenges thermiques suggérant une acclimatation des porcs au stress thermique. En conclusion, cette étude montre que le type génétique peut influencer la réponse des porcs à un stress thermique.

porcs / race / stress thermique / hygrométrie / thermorégulation

1. INTRODUCTION

Like other homeothermic animals, the pig maintains a constant body temperature under varying environmental conditions by balancing heat loss and heat production. The principles and physiological mechanisms involved in maintaining the thermal balance under heat stress are well described in the literature [20]. When temperature rises above the lower critical temperature (LCT), homeothermy is maintained by mechanisms that require little effort including changes in posture and in blood flow to the skin in order to increase non evaporative heat loss (conduction, convection and radiation). With a further increase in temperature, the body temperature is maintained constant by an increase in evaporative heat loss, particularly from the lungs through an increased

respiration rate or by a reduction in voluntary feed intake. The temperature at which the evaporative heat loss begins to increase is termed evaporative critical temperature (ECT); the thermal zone of comfort is defined as the range in ambient temperatures between LCT and ECT. These critical temperatures are both affected by environmental factors such as feeding level, floor type, group size, space allocation [15, 30, 31] and climatic factors other than ambient temperature (relative humidity, air speed, ...) [7, 18]. In addition, LCT and ECT are also influenced by animal related factors such as BW, physiological status, body condition, and genotype [6]. The reports on the effect of breed on the lower or upper limits of the thermal comfort zone in the pig and therefore, on its tolerance to heat stress, are scarce, in contrast to ruminant or poultry species. In pigs,

Table I. Pig characteristics for both experiments^a.

	Experiment 1			Experiment 2		
	Breed	Challenge 1	Challenge 2	Challenge 1	Challenge 2	Challenge 3
Mean age (d)						
	CR	153 (1)	188 (1)	97 (1)	111 (1)	125 (1)
	LW	153 (1)	188 (1)	97 (1)	111 (1)	125 (1)
Mean BW (kg)						
	CR	61.4 (0.8)	83.4 (3.1)	28.0 (3.0)	34.3 (2.7)	39.3 (2.8)
	LW	82.7 (2.3)	110.8 (3.0)	37.8 (1.3)	45.4 (2.8)	52.7 (2.5)
Feed intake as a multiple of MEm ^b						
	CR	1.25 (0.10)	1.25 (0.08)	1.29 (0.09)	1.37 (0.10)	1.35 (0.06)
	LW	1.29 (0.06)	1.29 (0.03)	1.27 (0.03)	1.31 (0.05)	1.31 (0.04)

^a Values are means (SD).

^b Metabolisable energy for maintenance (MEm = 1 MJ ME per kg^{0.60} according to [22]).

the existence of a different heat tolerance among breeds is reported between halothane positive and negative boars [1, 9, 27] and between high and low producing genotypes [14, 21]. In both of the latter studies, heat tolerance of low producing lines is attributed to their lower heat production as a consequence of their low productivity and maintenance requirements suggesting that low production is itself an adaptive attribute [2]. In the French West Indies, the local Caribbean breed (i.e. Creole pig) is known for its hardiness and adaptation to harsh tropical environments, which would partly be due to their lower growth potential. However, because of its low susceptibility to tropical conditions, the Creole pig can be used as a model to study the genetic variability of heat tolerance in pigs by comparing it with the Large White.

The objective of this study was to evaluate the effects of short-term exposure to high ambient temperature and relative humidity in Creole (CR) and Large White (LW) growing pigs to evaluate the possible breed differences. The results reported are part of a larger project aimed at understanding the mechanisms implicated in pig breed differences in heat tolerance.

2. MATERIALS AND METHODS

2.1. Experimental design

Thermoregulatory responses were measured on 2 experiments with 12 castrated pigs (6 Large White and 6 Creole) over two (153 and 188 days of age; experiment 1) or three consecutive stages (97, 111, and 125 days of age; experiment 2) (Tab. I). For each thermal challenge, ambient temperature (T) varied daily from 22 to 34 °C between 0900 and 1500 and from 34 to 22 °C between 1500 and 2100 during five consecutive days. Between midnight and 0900 and 2100 and 2300, T was maintained at 22 °C (Fig. 1). The relative humidity (RH) was kept constant at 70, 80, 90, 80, and 70%, on days 1, 2, 3, 4, and 5, respectively. Between two days, RH was changed at 00:00 over 4 h. The feeding level of each pig was adjusted on a BW basis for each thermal challenge in order to provide about 1.3 of the maintenance metabolisable energy requirement (1 MJ ME per kg^{0.60}, Noblet et al. [22]). The pigs were fed ad libitum and T and RH were fixed at 22 °C and 75%, respectively, except during thermal challenge.

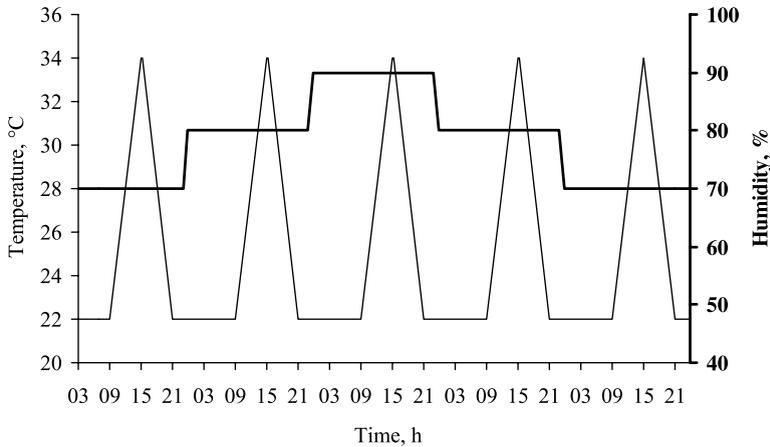


Figure 1. Ambient temperature (normal line) and relative humidity (bold line) variations during a thermal challenge.

2.2. Animal management and housing

Ten days before the beginning of the experiment, the pigs were moved to a climatic room (10.0×15.0 m) and kept at 22°C and 75% RH with a photoperiod of 12 h of artificial light (0600 to 1800). In the experimental room, both T and RH were controlled within $\pm 0.2^\circ\text{C}$ and 3%, respectively. The ventilation rate was set at 50 m^3 per h and air speed was not controlled but it did not exceed 0.15 m per s. The experimental room contained twelve individual pens (0.85×1.50 m) with metal slatted floors equipped with feed dispensers and nipple water drinkers designed and adjusted so that animals could not spray themselves. During the thermal challenge, the pigs had no access to water between 0900 and 1500 to prevent the wetting of the skin surface and to feed between 0700 and 1800 to limit the thermal effect of meal on thermoregulatory responses. The diet contained 10.4 MJ ME per kg, 16.7% crude protein, and 0.90% crude lysine.

2.3. Measurements

The pigs were weighed at the beginning and at the end of each thermal challenge. Except during the thermal challenge, daily

feed intake was determined as the difference between feed allowance and refusals. Rectal (RT) and cutaneous (CT) body temperatures and respiratory rate (RR) were measured every hour only from 0900 to 1500. During this period, the T was raised by two degrees per hour, so measurements were done at 22, 24, 26, 28, 30, 32, and 34°C for a total of seven temperature measurements. The RR rate was determined visually by counting the flank movements over a period of one minute but only on resting animals. After RR measurements in all pigs were completed, RT was measured using a digital thermometer. For technical reasons, CT was measured only in the second experiment on the back at the last rib level and on an intermediate point between the back and the belly (i.e. flank) using a digital thermometer (HH-21 model; Omega, Stamford, CT, USA) with a K probe. For each trial, the pigs were accustomed to the presence of the observers and the measurements during the adaptation period.

2.4. Statistical analysis

The gradient between RT and CT temperature was calculated only for the 2nd

experiment. Since the RR data were not normally distributed, they were submitted to a logarithmic transformation before analysis. To involve comparisons of treatment (breed, relative humidity, challenge) at a specific ambient temperature or of ambient temperatures within a treatment, the data were analysed using a general linear mixed procedure of SAS [26] including the effects of breed ($n = 2$), temperature ($n = 7$), relative humidity ($n = 3$), and challenge within experiment ($n = 2$ or 3) and their interaction as fixed effects. Repeated measures data were analysed using an unstructured covariance structure with pigs within day as subjects in order to consider the correlation between two successive ambient temperatures within each day. The effects of location of measurement (back or flank) were also taken into account in the preceding model only for CT and gradient between RT and CT. Contrasts were generated to test the effect of breed on the thermoregulatory responses measured at a constant BW (i.e. 1st challenge for LW pigs vs. 2nd challenge for CR pigs and 1st challenge for LW pigs vs. 3rd challenge for CR pigs, in 1st and 2nd experiments, respectively).

3. RESULTS

In the first experiment, average BW over the two challenges were 61.4 and 83.4 kg, and 82.7 and 110.8 kg for CR and LW pigs, respectively (Tab. I). The corresponding values for the three consecutive challenges of the second experiment were 28.0, 34.3, and 39.3 kg and 37.8, 45.4, and 52.7 kg for CR and LW pigs, respectively. The feed consumption was in agreement with the objective of the experiment (i.e. about $1.3 \times$ maintenance requirement).

The mean thermoregulatory responses to T are presented in Table II. For both experiments, RT was significantly reduced between 22 and 26 °C (i.e. -0.3 °C on average, $P < 0.05$) whereas it remained constant between 26 and 30 °C (i.e. 38.3 on average). At higher temperatures, RT significantly increased from 38.4 to 38.9 °C and from 38.2 to 38.9 °C

between 30 and 34 °C in experiments 1 and 2, respectively. For both trials, the critical threshold temperature, which marked the beginning of the rise of RT (i.e. upper critical temperature or UCT), was between 30 and 32 °C. For both experiments, RR was reduced between 22 and 26 °C (i.e. -3.5 breaths per min on average, $P < 0.01$) and was constant between 26 and 30 °C. Since pigs could not wet their skin surface, the evaporative heat loss increased only from the lungs through increased RR. The temperature at which RR increased markedly was termed the evaporative critical temperature (ECT). According to RR data, ECT was between 30 and 32 °C for both trials. Above 30 °C, the RR increment was not linear since $+3.1$ and 19.3 breaths per min (bpm) were obtained between 30 and 32 °C, and 32 and 34 °C, respectively. As far as CT is concerned, the values obtained at the back and flank locations were significantly different (35.7 vs. 36.2 °C, $P < 0.01$). The effects of T, RH, or breed on CT response were rather similar whatever the site of measurement. To simplify, CT calculated as the mean of the back and flank temperatures was used as a single criterion in this paper. CT was constant from 22 to 24 °C (i.e. 35 °C) and increased linearly at higher temperatures ($+2.7$ °C between 24 and 34 °C, $P < 0.01$). When ambient temperature increased, the gradient between RT and CT decreased to reach 1.3 °C at 34 °C.

Within each experiment, the thermoregulatory responses were affected by thermal challenge (Fig. 2). RT was significantly higher during the first thermal challenge at 22 °C, and above 26 °C in experiment 1 and at 22 °C and above 30 °C in experiment 2. However, UCT was not affected by the challenge (i.e. between 30 and 32 °C). Whatever the ambient temperature, the RR values were higher in the first thermal challenge for both experiments; the RR difference between challenges averaged 6 bpm. ECT was significantly ($P < 0.001$) lower during the first thermal challenges for both trials (between 30 and 32 vs. between 32–34 °C). In the second experiment, the interaction between

Table II. Physiological responses to ambient temperature.

Items	Exp.	N ^a	Temperature, °C							RSD ^b	Statistical analysis ^c
			22	24	26	28	30	32	34		
Rectal temperature, °C (RT)											
	1	777	38.6 ^d	38.5 ^d	38.4 ^e	38.4 ^e	38.4 ^e	38.6 ^d	38.9 ^f	0.3	T ^{**} , HR [†] , C ^{**} , B×T [*] , C×T [*]
	2	1200	38.5 ^d	38.4 ^e	38.1 ^f	38.1 ^f	38.2 ^f	38.5 ^d	38.9 ^g	0.3	T ^{**} , C ^{**} , B×T [*] , C×T ^{**} , T×RH ^{**}
Respiratory rate, breaths per min (RR)											
	1	744	19.8 ^d	16.2 ^e	14.9 ^f	14.0 ^f	15.3 ^f	19.4 ^d	40.3 ^g	10.3	T ^{**} , RH ^{**} , C ^{**} , B×T ^{**} , T×RH ^{**} , C×T ^{**} , R×B×T ^{**}
	2	1121	17.5 ^d	17.5 ^d	15.5 ^e	14.1 ^e	14.0 ^e	16.2 ^d	34.0 ^g	9.6	B [*] , T ^{**} , RH ^{**} , C ^{**} , B×T [†] , T×RH ^{**} , C×T [*]
Cutaneous temperature, °C (CT)											
Back	2	1239	34.9 ^k	35.1 ^k	35.2 ^k	35.4 ^k	35.7 ^k	36.6 ^k	37.5 ^k		
Flank	2	1239	35.0 ^l	35.0 ^l	35.4 ^l	36.0 ^l	36.7 ^l	37.2 ^l	37.8 ^l	0.7	T ^{**} , S ^{**} , T×RH ^{**} , B×S [*] , T×S ^{**}
Mean	2	1239	35.0 ^d	35.1 ^d	35.3 ^e	35.7 ^f	36.2 ^g	36.9 ^h	37.7 ⁱ		
RT-CT gradient, °C	2	1239	3.6 ^d	3.3 ^e	2.8 ^f	2.4 ^g	2.0 ^h	1.6 ⁱ	1.3 ^j	0.7	T ^{**} , S ^{**} , T×RH ^{**} , B×S [*] , T×S ^{**} , C×T [*]

^a Total number of observations.

^b Residual Standard Deviation.

^c Respiratory rate data were log transformed before the analysis. From an analysis of variance with a general linear mixed model including the effects of breed (B), ambient temperature (T), relative humidity (RH), challenge (C) and their interactions as fixed effects. Repeated measures data were analysed using an unstructured covariance structure with pigs within day as subjects. The effect of the site of measurement (S: back or flank) was considered in the preceding model for skin temperature data. Statistical significance: [†] $P < 0.10$, * $P < 0.05$, ** $P < 0.01$.

^{d, e, f, g, h, i, j} Effect of temperature; within a row, means not followed by the same superscript differ ($P < 0.05$).

^{k, l} Effect of site of measurement (back vs. flank skin temperature); within a column, means not followed by the same superscript differ ($P < 0.05$).

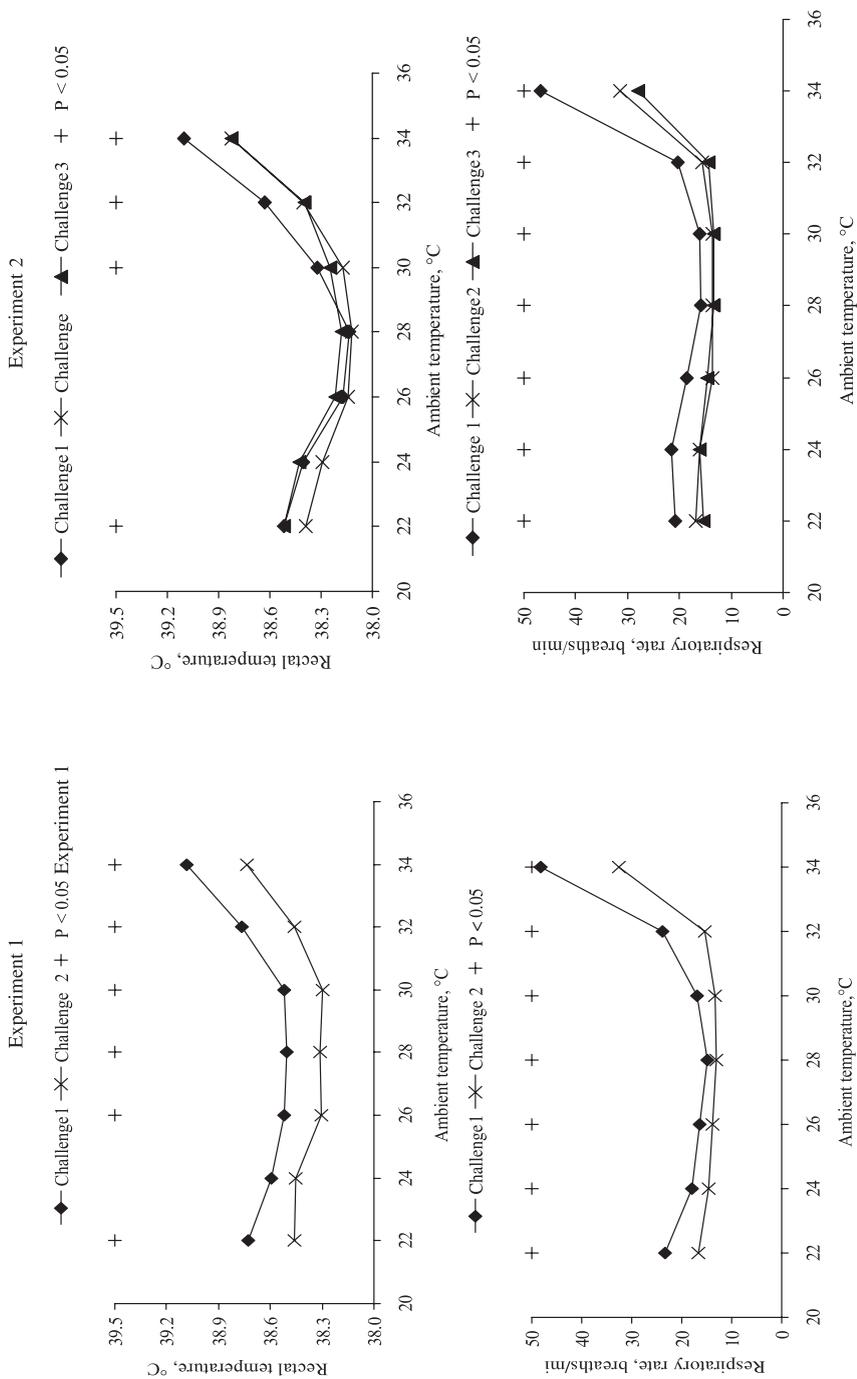


Figure 2. Effect of thermal challenge and ambient temperature on respiratory rate and rectal temperature in growing pigs for each experiment. + mean thermoregulatory response was significantly ($P < 0.05$) affected by thermal challenge.

thermal challenge and ambient temperature was significant for the RT-CT gradient ($P < 0.05$).

Mean variations of RR, CT and RT for each breed determined from data obtained in both experiments are presented in Figure 3. Except for CT and the gradient between RT and CT, the thermoregulatory responses were influenced by breed. RT was lower ($P < 0.01$) in CR pigs than in LW pigs when the ambient temperature was above 30 °C (-0.2 °C on average). UCT was significantly lower for LW pigs than in CR pigs (between 28 and 30 °C vs. between 30 and 32 °C, $P < 0.01$) but the RT increment calculated from 28 to 34 °C was not different between breeds (0.7 °C on average). RR was lower in CR pigs at 34 °C (32.7 vs. 41.9 bpm for LW pigs, $P < 0.01$). ECT was not affected ($P > 0.10$) by breed (between 30 and 32 °C) whereas the increase of RR from 28 to 34 °C was significantly lower for CR than for LW (19.0 vs. 27.6 bpm, $P < 0.01$). In both experiments, the heat acclimatisation measured during successive challenges did not allow for comparisons of thermoregulatory responses between breeds at a constant BW.

Breed difference recorded for RT and RR responses were not significantly emphasised when RH increased ($P > 0.05$). Thermoregulatory responses to heat stress were affected by RH irrespective of the experiment and of the breed (Fig. 4). Above 30 °C, the average RT was higher at 90% RH compared to 70 and 80% RH (+0.20 °C on average). However, the increase of RT between 28 and 34 °C was not affected by RH (+0.6 °C on average). The UCT was lower ($P < 0.01$) at 80 or 90% RH than at 70% RH (between 28 and 30 °C vs. between 30 and 32 °C, respectively). ECT was significantly lower at 90% RH than at 80 or 70% RH (between 28 and 30 °C and 30 and 32 °C respectively, $P < 0.05$). Between 28 and 34 °C, the RR increment was two times higher at 90% than at 70 and 80% RH (+34.4 vs. 18.4 bpm, $P < 0.01$). Cutaneous temperature response to ambient temperature was affected by RH

at 34 °C (37.8 vs. 37.5 °C at 90% and 70–80% RH, respectively).

4. DISCUSSION

An unexpected result of this work is the decrease of RT and RR between 22 and 26 °C. Even if physical activity was not recorded in this present study, the animals were frequently lying down and standing up at 0900, which may be explained by the presence of staff between 0700 and 0800 in the experimental room for collection of orts and for cleaning. Moreover, according to Van Milgen et al. [29], the duration of the thermic effect of feed averages 5 h in growing pigs. This result suggests that the elevated RT and RR values measured at 22 °C may also be related to digestion or metabolism of a meal intake before 0700.

One of the effects of increased ambient temperature is a linear increase of CT; our results (+0.23 °C per extra degree of temperature) are in agreement with those of Quiniou and Noblet [23] in lactating sows (+0.27 °C per °C between 18 and 29 °C) and Giles and Black [12] in growing pigs (+0.23 °C per °C between 23 and 31 °C). This elevation of peripheral temperature is explained by an increase in blood flow in skin vessels to promote heat loss [8]. In contrast to CT, the gradient between RT and CT was linearly reduced as ambient temperature increased. Moreover, according to Quiniou and Noblet [23], this gradient could be viewed as a useful index to estimate the rate of non-evaporative thermolysis. In agreement with the review by Holmes and Close [15], non-evaporative heat loss declines as temperature rises above LCT making the animal more dependent on water evaporation from the lungs to prevent a rise in body temperature. The ECT obtained in the present study on LW pigs (i.e. between 30 and 32 °C) is critically higher than the values reported by Giles and Black [12] in 89 kg pigs (i.e. between 22 and 25 °C) and Brown-Brandl et al. [4] in 67 kg pigs (i.e. between 24 and 28 °C) where ECT was determined from RR measurements. Moreover, below ECT, our

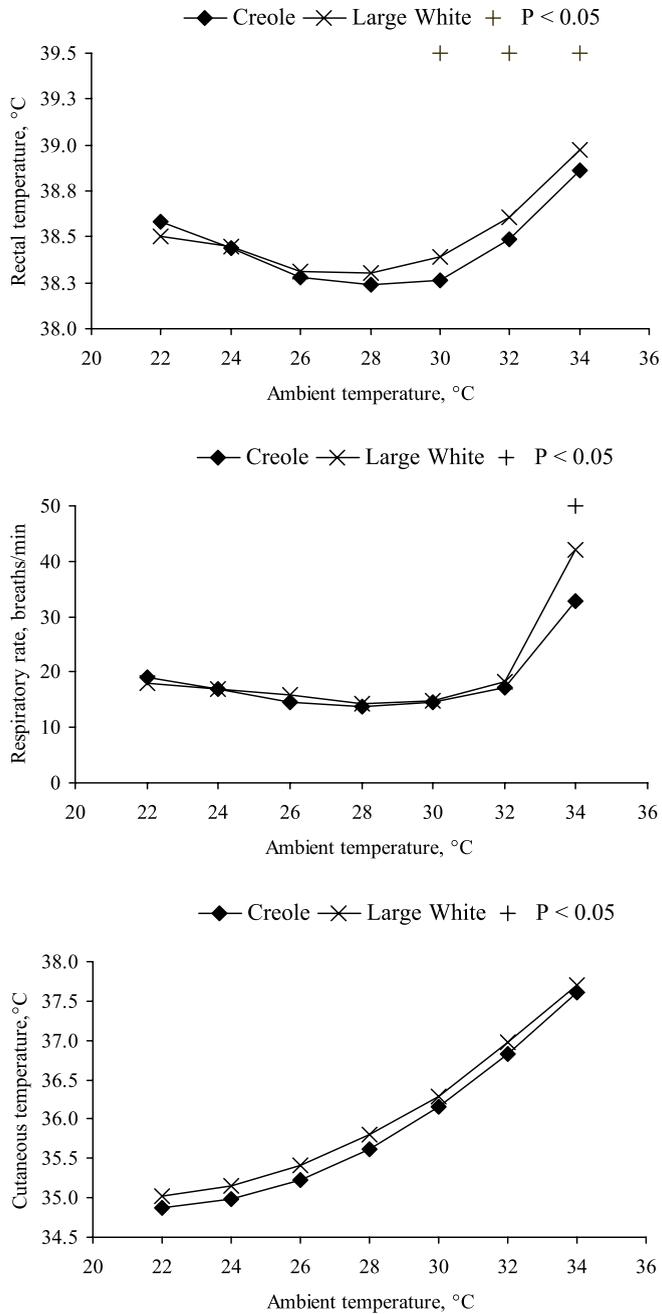


Figure 3. Effect of ambient temperature and breed on respiratory rate, rectal and cutaneous temperature in growing pigs. + mean thermoregulatory response was significantly ($P < 0.05$) affected by breed.

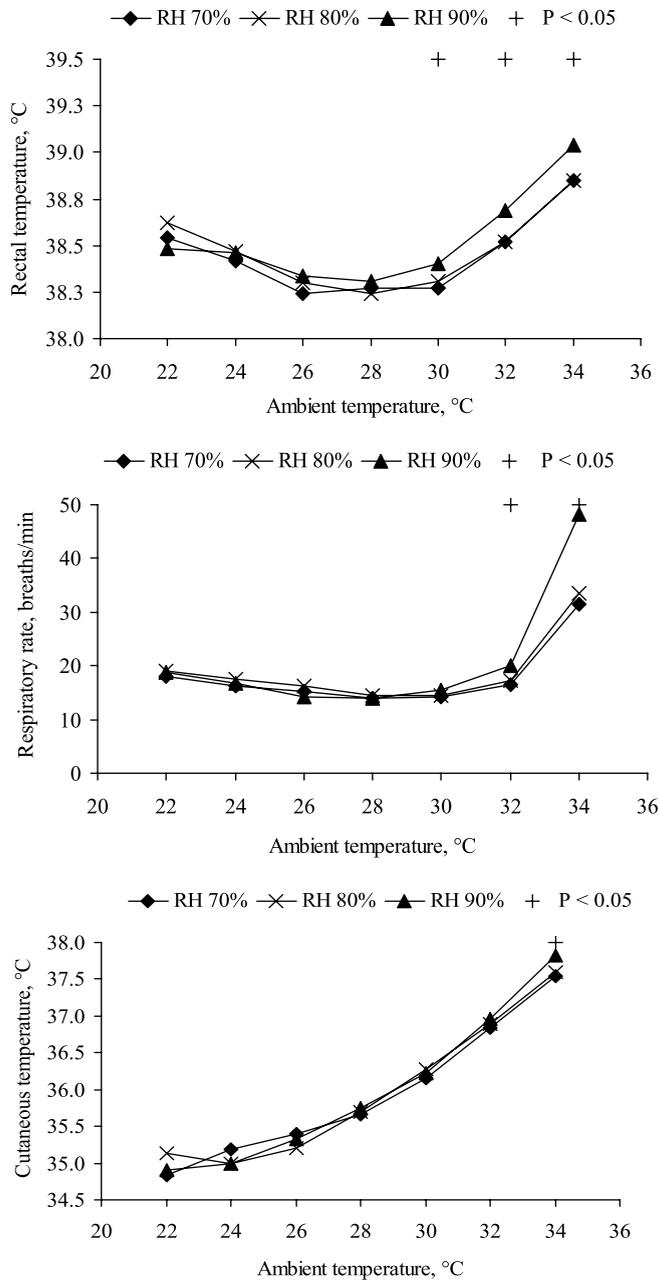


Figure 4. Effects of ambient temperature and relative humidity (RH) on respiratory rate, rectal and cutaneous temperature in growing pigs. + mean thermoregulatory response was significantly ($P < 0.05$) affected by relative humidity (RH).

average value of RR (17 bpm) was lower than the corresponding values reported by Giles and Black [12] and Brown-Brandl et al. [4] (39 and 46 bpm, respectively). The discrepancy between both sets of data is probably related to differences in animal characteristics (e.g. BW, genotype) or in experimental conditions (e.g. housing, diet composition, or feeding level). In the present study, pigs were fed close to the maintenance requirements and they had no access to feed during the thermal challenge whereas in both Giles and Black [12] and Brown-Brandl et al. [4] studies, the pigs were allowed ad libitum access to feed. These results would suggest that lower values of RR measured in our pigs are related to their lower feeding level. Moreover, as shown for LCT [15], a negative relationship between the feeding level and ECT can be assumed, suggesting that lower sensitivity to heat stress recorded in the present work could also be explained by the restrictive feeding level.

The present results indicate that pathways implicated in body temperature regulation are all saturated or insufficient to prevent an RT increase when the temperature exceeded 30 °C. This value for UCT was comparable with previous values measured by Giles and Black [12] (between 26 and 29 °C), Brown-Brandl et al. [4] (between 28 and 31 °C), and Tauson et al. [27] (between 30 and 32 °C) or calculated by Holmes and Close [15] (between 30 and 32 °C).

During heat stress, an increase in RH reduces the efficiency of evaporative cooling since the vapour pressure gradient between the animal and the environment declines [25]. In our study, the reduction of ECT and the increase of RR values above 32 °C when thermal challenges were performed at 90% RH could be interpreted as an adaptation to compensate for the reduction of evaporative loss efficiency from the respiratory tract. However, the decrease of UCT and the increase of the RT value at 34 °C implied a faster saturation of pathways implicated in heat loss at 90% RH than at 80 or 70% RH. Similarly, Morrison et al. [18] exposed 85-

kg pigs to various combinations of RH and ambient temperatures and they showed an increase of RT when RH increased from 30 to 90% at 35 °C. Moreover, even if evaporative heat loss from the skin is limited in pigs, Ingram [16] reported a significant decrease of skin water loss in piglets under hot conditions with high RH. Overall, because pigs rely to a greater extent on evaporative heat loss from the respiratory tract during heat stress, RH becomes an important factor to be considered under these conditions.

All the processes described above correspond to a short-term adaptation to warm exposure. Moreover, our results show a long-term adaptation, i.e. changes in physiological function by which tolerance of heat stress is improved when thermal challenges are repeated. To our knowledge, there is little information about the mechanisms underlying this long-term adaptation in pigs. When growing pigs were exposed over a long term to high ambient temperature (i.e. > 10 days), Morrison and Mount [19] and Giles [11] reported a significant decrease of RT, RR, and oxygen consumption over the time of exposure whereas feed intake remained unchanged throughout the duration of the experiment. They suggest that acclimatisation to heat stress can be explained by an increase in evaporative heat loss efficiency rather than a decrease of heat production. Similarly, according to our results, it can be suggested that the heat acclimatisation is related to an increase of evaporative heat loss efficiency from the lungs. However, according to the significant effect of the repetition of challenges on the gradient between RT and CT, it can be hypothesised that an increase of non evaporative heat loss, via an increase of tissue conductance, could also be implicated in acclimatisation to high temperature. In poultry, early age thermal conditioning by exposure of chicks during 24 h to 36–40 °C durably increases the resistance to heat stress and decreases mortality in the finishing period without any effect on growth performance; this adaptation is related to an increase in both evaporation and non evaporative heat loss pathways and a reduction

of thermogenesis (thyroid metabolism and mitochondrial uncoupling proteins) under warm conditions [5].

In contrast to other species like ruminants [17] or poultry [13], the existence of genetic variation in heat stress responsiveness within or between breeds is poorly documented in pigs. Tauson et al. [27] have evaluated thermoregulatory responses (RR and RT) to short term exposure to high temperature (i.e. 40 °C) in 100-kg boars of different breeds. They showed that stress susceptible Danish Landrace halothane positive and Hampshire boars were more severely heat stressed than Yorkshire, Danish Landrace halothane negative or Duroc boars. Our results show that CR responded differently to heat challenge than LW pigs with an increase in UCT and a reduced response for RT and RR above 30 °C. From this, it has been hypothesised that an increase in heat dissipation capacity and/or reduction of total heat production could explain the greater ability to resist to a short term exposure to heat stress. In an experiment that involved 4 piglets, Berbigier [3] showed that the non-evaporative heat loss capacity is lower in LW pigs than in CR × LW crossbred pigs. In accordance with the results obtained in cattle [10], this suggests that CR pigs have a higher ability to lose heat by a non-evaporative method than LW pigs. As hypothesised in tropical ruminant species [2], the greater ability to dissipate heat from skin in CR pigs would allow to a lesser to use perspiration capacity, which is an energy costly process due to respiratory muscle activity. This assumption is reinforced by the lower RR value at 34 °C in CR than in LW pigs. According to Henken et al. [14], the lower LCT measured in LW than in Landrace pigs was connected to an increase of backfat thickness. This increase of thermal insulation resulted in a decrease in the thermal heat transfer coefficient and the ability to lose heat [15]. In our intensive conditions, it should be noticed that CR pigs had greater backfat thickness than LW pigs from 90 days of age (i.e. 11.0 vs. 8.3 mm; Renaudeau et al. [24]) which suggests that

heat tolerance of CR would be artificially underestimated. Nienaber et al. [21] indicated that pigs from a high lean growth potential line are more sensitive to heat stress than those from a moderate growth line in connection with the lower energetic efficiency for protein deposition than for lipid deposition. According to Van Milgen et al. [28], fasting heat production increases linearly with muscle percentage suggesting that additional fasting heat produced by LW increases their susceptibility to high ambient temperature. These results suggest that the heat tolerance in CR pigs could be attributed to a greater ability to lose heat and their low heat production. However, the molecular mechanisms underlying this breed difference in heat tolerance remain to be investigated.

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