Precision feeding strategy for growing pigs under heat stress conditions¹

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ABSTRACT: This study evaluated the responses of individual daily precision (IPF) and conventional 2-phase (CON) feeding systems (FS) in terms of pig growth performance, nutrient balance, serum parameters, and meal patterns of growing pigs reared under thermoneutral (TN: 23 °C) and heat stress (high temperature [HT]: 30 °C) conditions. The animals in each treatment were assigned on the basis of equal BW to the experimental treatments (12 animals per treatment at 41.0 ± 4.87 kg of BW). The experiment lasted 55 d (phase 1 from days 0 to 27 and phase 2 from days 28 to 55). Pigs fed CON received within each phase a constant blend of diets with high and low nutrient density supplying the estimated nutrient requirements of the group, whereas the IPF pigs received daily a personalized blend providing the estimated amount of nutrients according to individual feed intake and body weight information. Body mineral content, and lean and fat masses were assessed through dual-energy X-ray absorptiometry at the beginning and end of each phase. Data were analyzed using a linear mixed-effect model, with fixed effects of the FS, temperature (AT), and the 2-way interaction between FS and AT and random effects of blocks. In relation to CON pigs, IPF pigs reduced ($P < 0.05$) Lys (19%),

protein (16%), and P (14%) intake without impairing ($P > 0.05$) body composition. Nitrogen excretion was 24% lower ($P < 0.05$) in IPF pigs than in CON pigs; however, both groups had similar N retention efficiency thoroughly the trial. Amount of time feeding, feed intake rate, and feed intake per meal were 15% lower ($P < 0.05$) in pigs raised under HT than under TN conditions. During the phase 2, only amount of time feeding, feed intake rate, and feed intake per meal were decreased ($P < 0.05$) in pigs under HT conditions during nocturnal (2000 to 0500 h) and diurnal (0501 to 1959 h) periods. Haptoglobin levels were affected by the AT, showing an increase of 70% and 43% in HT at 28 and 55 d of the experiment, respectively. Pigs raised under HT conditions had 10% lower ($P < 0.05$) serum albumin concentration at day 55 than those under TN conditions. For serum urea concentrations, IPF pigs had 28% lower ($P < 0.01$) levels than CON pigs. Even though HT conditions considerably reduced growth performance and activated inflammatory responses in growing pigs, IPF was not able to rescue performance during HT; however, it was equally effective at improving nutrient utilization and maintaining body composition in HT and TN conditions.

Key words: heat stress, nutrition, nutrient utilization, precision feeding, reduced protein, tropical conditions

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INTRODUCTION

Heat-stressed pigs reduce voluntary feed intake, body weight gain (Quiniou et al., 2000; Huynh et al., 2005), and nutrient use efficiency (Pearce et al., 2013). Many studies have been performed to understand the metabolism and identify the ideal environment and management practices (feeding and nutrition, housing, etc.) that will optimize the production of pigs in hot environments. Reducing ambient temperature is expensive and sometimes unprofitable in tropical areas. Nutritional studies have suggested changes to the conventional group phase-feeding program (CON), in which pigs' diets are formulated with low protein levels to reduce the heat increment, and increase and improve nutrient intake with adequate concentrations in terms of AA (Le Bellego et al., 2002a; Kerr et al., 2003). However, CON does not account for variation between individuals, and diets are usually formulated to optimize population performance, with most of the pigs receiving more nutrients than they actually need (Hauschild et al., 2010). Taking into consideration voluntary feed intake and growth, precision feeding has been proposed as an alternative, because it would enable managers to provide individual animals with diets that meet but do not exceed their requirements (Pomar et al., 2014). This approach has shown a reduced crude protein and P provision, resulting in a lower excretion of the aforementioned components in the environment (Andretta et al., 2014, 2016a; Pomar et al., 2014). Although this strategy seems to be a feasible way to cope with the consequences of heat stress in pigs, there are no studies on the subject in the current literature. This study was therefore conducted to evaluate the responses of individual daily precision (IPF) and CON feeding systems (FS) in terms of pig growth performance, nutrient balance, serum parameters, and meal patterns of growing pigs reared under thermoneutral (TN) and heat stress conditions.

MATERIALS AND METHODS

The protocol for this experiment was approved by the Institutional Animal Care and Use Committee at São Paulo State University, SP, Brazil (No. 16744/15).

Animals, Housing, and Experimental Design

This experiment was conducted at the Swine Research Facility of São Paulo State University,

Brazil. Forty-eight barrows (Agrocères PIC, Rio Claro, Brazil) with an average initial BW of 34.0 ± 4.41 kg were assigned on the basis of equal BW to 2 experimental rooms (TN, 23 °C constant and high temperature [HT], 30 °C constant) in a single 24-m² pen with a fully slatted plastic floor. Thermostat-controlled heaters were used to raise the ambient temperature to 30 °C in the HT room. In the TN ambient-assigned room, temperature was controlled through air conditioning. Both rooms used an exhaust fan with air movement capacity of 115 m³/min to perform air renewal. Pigs were acclimated to room temperature for 9 d prior to the experimental period and received a highly concentrated commercial diet. This strategy was employed in order to reduce the variation caused by the physiological adaptations during the first week of exposure to HTs as demonstrated by Campos et al. (2014). Approximately 12 h of natural lighting were provided by glass windows. The animals in each treatment were assigned on the basis of similar BW to the experimental treatments (12 animals per treatment at 41.0 ± 4.87 kg of BW) in 2 complete blocks. Each block included 6 pigs per treatment also considering animals with similar BW, and blocks started 1 d apart. The experiment lasted 55 d (phase 1 from days 0 to 27 and phase 2 from days 28 to 55). In each room, water and pelleted feed were provided ad libitum by 4 nipple drinkers and 2 automatic feeders (Automatic and Intelligent Precision Feeder [AIPFs]; University of Lleida, Spain, Pomar et al., 2011). All animals were equipped with an exclusive transponder (a plastic button tag containing passive transponders of radio frequency identification; Allflex, Joinville, SC, Brazil) that was inserted in the right ear of each pig using the specific tagger pliers, and pigs were adapted to the automated feeders before the trial. Each AIPF consisted of a single-space feeder in which precision Archimedes screw conveyors delivered and simultaneously blended volumetric amounts of up to 4 feeds stored in independent containers located in the upper part of the AIPF (Pomar et al., 2011). The AIPF identifies each pig when its head is introduced into the feeder and then delivers feeds in response to each animal request according to the assigned experimental feeds (see Dietary Treatments). In this way, any pig in the pen could access any of the feeders and receive the feed prescribed for that animal. The pigs were weighed weekly and feed and water were provided ad libitum throughout the experiment.

Dietary Treatments

Two experimental diets were formulated on the basis of standard recommendations for NE, standardized ileal digestible (SID) AA, standard total tract digestible (STTD) of P, and total Ca (NRC, 2012; Table 1). Diet A (high nutrient density) was formulated to satisfy the requirements of one of the most demanding pigs (1.20% of SID Lys) at the beginning of the growing trial and diet B (low nutrient density) to satisfy the requirements of one of the least demanding pigs (0.40% of SID Lys) at the end of the growth trial. Through the use of the AIPF, pigs in the precision feeding (IPF) group received a personalized blend of feeds A and B on a daily basis to target sufficient SID Lys to meet their Lys requirement as estimated by the model proposed by Hauschild et al. (2012). This model has one main empirical and one main mechanistic model component. The empirical model component estimates the expected feed intake (FI), BW, and daily gain of the starting day based on historical individual FI and BW pig information collected before and during the trial. The estimates of FI, BW, and gain are used as inputs to the mechanistic model which uses factorial equations to estimate optimal Lys concentrations required to meet the pigs' requirements for maintenance and growth. The details of this model and its application have been previously described (Hauschild et al., 2012; Pomar et al., 2015). Also through the use of the AIPFs, pigs fed in the conventional (CON) group received a constant blend of diets A and B in each phase to meet the SID Lys requirements of the 80th-percentile pig in the group (Hauschild et al., 2010) determined during the first 3 d of the phase.

Performance and Body Composition

On the first day of the adaptation period and at the end of each feeding phase (days 9, 27, and 55), total body lean, body fat, bone mineral content, and bone mineral density were measured by dual-energy X-ray absorptiometry (DXA; Hologic Discovery, Hologic, Inc., Bedford, MA). Animals were fasted for 8 h before anesthetized by intramuscular injection of xylazine (1.5 mg/kg) and ketamine (15 mg/kg). Anesthetized pigs were scanned in prone position (from head to tail) and the experimental blocks were scanned 1 d apart. After each scan, backfat thickness and muscle depth were measured on the DXA scan table in the anesthetized animals in prone position using ALOKA equipment (500v series with a linear probe of 3.5

Table 1. Ingredient inclusion and nutritional values of the experimental diets

Item	A	B
Ingredient composition, as-fed basis, %		
Corn	64.91	92.59
Soybean meal	30.93	–
Dicalcium phosphate	1.35	0.39
Limestone	1.00	0.51
Dextrin	0.50	0.50
Vitamin premix ¹	0.25	0.25
Salt	0.17	0.18
L-Lysine sulfate (54.6%)	0.58	0.44
DL-Methionine	0.15	–
L-Threonine	0.10	0.05
L-Tryptophan	–	0.03
Kaolin	–	5.00
Choline chloride (60%)	0.06	0.06
Chemical composition, %		
DM	90.30	89.90
ME ² , kcal/kg	3318	3195
NE ² , kcal/kg	2478	2557
Crude protein	19.24	7.11
Lys	1.34	0.47
Met	0.34	0.12
Thr	0.77	0.34
SID ² Lys ³	1.20	0.40
SID Met ³	0.40	0.13
SID Met + Cys ³	0.67	0.25
SID Thr ³	0.71	0.24
STTD ⁴ phosphorus ³	0.33	0.12
Calcium ²	0.80	0.30

¹Supplied per kilogram of diet (as-fed basis): vitamin A, 8750 IU; vitamin D, 1250 IU; vitamin E, 12.5 mg; vitamin K3, 2.5 mg; vitamin B12, 27.5 µg; niacin, 35 mg; calcium pantothenate, 15 mg; pyridoxine (B6), 1.25 mg; thiamin (B1), 1 mg; copper, 22.5 mg; iodine, 0.31 mg; iron, 120 mg; manganese, 62.5 mg; selenium, 0.19 mg; and zinc, 120 mg.

²SID = standardized ileal digestible.

³Values estimated from the ingredients gross composition according to NRC (2012).

⁴STTD = standardized total tract digestible.

MHz, 13.5 cm) between the third and fourth last ribs at 4 to 5 cm from the midline. The scan on the first day of the adaptation period was also used as a test scan to determine problems with the procedure, to ensure adequate recovery of the animals, and to avoid problems with the forecast of feed intake.

Meal Pattern

For the assessment of meal patterns, the information of each feeder visit (initial, final time, and feed intake) was continuously registered. Visits of the same pig at intervals lower than 1 min were considered a single meal. The AIPF configuration allotted 15 g of feed per feed request throughout

the trial. A 40-s latency time decreasing progressively up to 20 s between solicitations was used from the beginning to the end of the experiment to avoid feed waste and ensure sufficient ingestion time. Feeding behavior data on days when the pigs were manipulated (i.e., submitted to scan and sample collections) were removed from the dataset. The diurnal (from 0501 to 1959 h) and nocturnal (2000 to 0500 h) meal pattern data obtained for each animal were summarized as follows: amount of time feeding (min), number of meals, feed intake rate (g/min), feed intake per meal (g), and feeding time per meal (min).

Serum Sampling, Chemical Analysis, and Calculations

On the morning of the last day of the phase (days 27 and 55), blood samples were collected (5 mL) via the jugular vein of all the pigs and the serum was separated from the whole blood by centrifugation at $1500 \times g$ for 10 min. The identified samples were stored at -20°C until analysis.

Thermographic images from the superior left side of each pig were taken at days 14, 18, 41, and 45 of experiment at 0800 and 1500 h using an infrared camera (Flir SC660, Portland, OR) and the whole body temperature values were assessed using an adequate software (Flir Tools 5.12 software).

Prior to formulating the diets, samples of ground soybean meal and corn were analyzed by near-infrared reflectance spectroscopy for composition of crude protein, ether extract, starch, crude fiber, and total AA and P. To assess the total AA of diets A and B, high-performance liquid chromatography was used (White et al., 1986). The feeds were assayed for dry matter (Method 930.15; AOAC, 2007), ether extract (Method 920.39, AOAC, 2007), ash (Method 942.05, AOAC, 2007), acid and neutral detergent fibers (Van Soest and Robertson, 1979), and total protein as $N \times 6.25$ (Method 990.03, AOAC, 2007) at the Animal Nutrition Laboratory ("LANA" São Paulo State University, Department of Animal Science, Brazil).

Total nutrient intake was obtained considering the daily feed concentration provided and the daily feed intake for each pig. Individual body protein, lipid, and P for each period were obtained by calculating the difference between the beginning and end of each phase. The DXA body lean and fat masses were converted to total body protein and lipid mass (kg) according to Pomar and Rivest (1996). Total body P value was estimated assuming 18% of P in DXA bone mineral content, 1.04% in lean

tissue, and 0.05% in the fat content (Létourneau-Montminy et al., 2015). The initial values for all DXA measurements were adjusted for day 0 of the experiment instead of -9 d. This adjustment consisted of the proportional percentage of BW for each DXA variable on the day of the scan and the BW from the first day of the experiment. Phosphorus efficiency was calculated by dividing P deposition by P intake, whereas N efficiency was calculated by dividing protein deposition by intake.

Total levels of ceruloplasmin, transferrin, albumin, and haptoglobin were accessed in sodium dodecyl sulfate-polyacrylamide gel electrophoresis (Weber and Osborn, 1969). The values of acute-phase proteins after electrophoresis were corrected by serum total protein analysis determined using the biuret method with a commercial reagent Labtest and performed by semiautomatic spectrophotometry (Labmax Plenno, Lagoa Santa, Brazil).

Statistical Analysis

Data were analyzed by experimental phase as a mixed model with the fixed effects of FS, ambient temperature (AT), and their interactions using the SAS MIXED procedure (version 9.3; SAS Institute Inc., Cary, NC). Differences among fixed effects were considered statistically significant with $P < 0.05$. The individual pig was considered the experimental unit in all instances and the initial BW was used as a covariate between AT when significant in the model. The model was as follows: $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$, where Y_{ijk} is the observed variable (observation for the k th animal from the (i,j) th cell), μ is the overall mean, α_i is the effect of the i th level of the FS factor, β_j is the effect of the j th level of the AT factor, $(\alpha\beta)_{ij}$ is the interaction of the i th level of FS with the j th level of AT, and e_{ijk} is the random error of k th observation from (i,j) th including the blocks as random effect. The GROUP statement was used to equalize the variance between means when convenient, based on the smaller Akaike information criterion.

RESULTS AND DISCUSSION

The temperature in the TN and HT rooms was $23 \pm 1.4^{\circ}\text{C}$ and $30 \pm 2.2^{\circ}\text{C}$, respectively. Relative humidity was $75 \pm 5.4\%$ and $62 \pm 6.3\%$, respectively. Pigs under TN conditions consumed feed and gained weight as expected. However, under HT conditions, 5 pigs had health disorders (2 foot infections, 1 sudden death, and 2 animals with weakness and anorexia, totaling 2 in the CON and

3 in the IPF treatments). These pigs were removed from the trial.

After the adaptation period, next day SID Lys requirements were estimated daily for each pig following the requirement for the pig that represented the 80th percentile of the population in each room. This concept of feeding pig populations according to the requirements of the 80th-percentile pig of the population was suggested by Hauschild et al. (2010) to maximize the population response in terms of ADG. These authors also reported that because CON feeding does not take into account individual pig variations, many pigs receive more nutrients than they require. In our study, the 80th-percentile strategy was applied in each room, because of the reduction in ADFI and ADG for pigs reared under HT conditions. The diet concentrations for the CON treatment showed values of TN 0.95% and HT 1.10% of SID Lys during the first phase, and TN 0.81% and HT 0.86% of SID Lys during the second phase (Figure 1).

Performance, Body Composition, and Nutrient Balance

The effect of temperature. No interaction between FS and temperature was observed for performance, body composition, or nutrient balance. However, pigs under HT conditions increased ($P < 0.01$) their superficial body temperature compared with TN

Figure 1. Estimated requirement levels of standardized ileal digestible (SID) lysine provided daily for pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30 °C).

pigs (Figure 2). During the first feeding phase, pigs raised under HT conditions decreased ($P < 0.01$) ADFI and ADG by -31% (Table 2). During the second phase, however, the impact of HT on ADFI and ADG was lower than during the previous phase with reductions ($P < 0.01$) of -26% and -18% , respectively. The reduction in ADFI during the second feeding phase was around $100 \text{ g/}^\circ\text{C}$, with a 7°C difference between the HT and TN rooms. Consistent with our results, the ADFI reported by previous studies showed a decrease of $99 \text{ g/}^\circ\text{C}$ when temperatures rose above 25.5°C (Huynh et al., 2005), but decreases can vary depending on the breed, BW (Renaudeau et al., 2011), housing (Hyun and Ellis, 2001), and other factors. The lack of functional sweat glands forces pigs to increase their respiratory rate to increase heat loss during hot temperatures (Curtis, 1983). The upper critical temperature can be defined as the temperature at which pig heat production is equal to the maximum capacity of the pigs to lose heat (Holmes and Close, 1985). These authors also reported that one of the first strategies of heat-stressed pigs is to reduce physical activity and feed intake. These strategies are employed by pigs to balance heat production and dissipation in order to avoid body temperature increases.

The ADG of HT animals was 310 g/d lower than TN animals during the first phase and 175 g/d lower during the second phase. However, during previous studies done by Campos et al. (2014), 60-kg pigs were maintained for 14 d at 30°C , and they reduced ADG by 316 g/d , in comparison with pigs raised at thermoneutrality. It is expected that pigs with a higher BW would be more affected by HT. However, the ADG during the second phase was less affected, which may be due to the fact that the

Figure 2. Average of body temperature in pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30°C). Ambient temperature was significant ($P < 0.001$) during both experimental phases.

Table 2. Performance and body composition of pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30 °C)

	23 °C		30 °C			<i>P</i> value		
Item	IPF	CON	IPF	CON	SEM	T	FS	T*FS
Initial conditions								
BW, kg	42.2	43.1	38.6	40.2	1.37	0.02	0.36	0.81
Backfat thickness, cm	1.0	1.0	0.9	0.9	0.04	0.02	0.54	0.61
Loin muscle depth, cm	3.3	3.4	3.0	3.3	0.20	0.31	0.36	0.74
Body lipid ¹ , kg	10.1	9.4	9.5	9.4	0.42	0.52	0.35	0.52
Body protein ¹ , kg	6.0	5.8	5.8	5.5	2.25	0.32	0.31	0.89
Body bone mineral ¹ , kg	5.7	5.6	5.2	5.6	1.95	0.22	0.38	0.29
Phase 1 (0 to 27 d)—Performance and final conditions								
ADFI, kg/d	2.09	2.05	1.45	1.41	0.07	<0.01	0.59	0.99
ADG, kg/d	0.98	1.00	0.69	0.67	0.04	<0.01	0.98	0.60
G:F, kg/kg	0.47	0.49	0.48	0.47	0.01	0.63	0.86	0.36
Protein gain, g/d	165	176	138	139	12.9	0.01	0.62	0.65
Lipid gain, g/d	266	271	182	141	19.0	<0.01	0.40	0.29
BW, kg	68.5	68.6	60.4	58.8	1.23	<0.01	0.56	0.52
Backfat thickness, cm	1.4	1.3	1.0	1.0	0.04	<0.01	0.20	0.48
Loin muscle depth, cm	5.4	5.5	5.0	5.1	0.12	<0.01	0.70	0.90
Body protein ¹ , kg	10.4	10.5	9.5	9.3	0.21	<0.01	0.98	0.60
Body lipid ¹ , kg	17.2	16.7	13.7	12.8	0.41	<0.01	0.12	0.68
Body bone mineral ¹ , kg	8.5	8.9	7.7	8.1	0.21	<0.01	0.07	0.90
Phase 2 (28 to 55 d)—Performance and final conditions								
ADFI, kg/d	2.74	2.65	1.96	2.03	0.07	<0.01	0.92	0.47
ADG, kg/d	0.94	0.96	0.75	0.80	0.04	<0.01	0.49	0.75
G:F, kg/kg	0.34	0.37	0.38	0.39	0.01	0.10	0.30	0.77
Protein gain, g/d	115	125	106	117	7.8	0.31	0.20	0.91
Lipid gain, g/d	346	311	198	192	20.4	<0.01	0.35	0.51
BW, kg	94.7	95.3	81.4	81.3	2.2	<0.01	0.93	0.87
Backfat thickness, cm	1.7	1.7	1.3	1.4	0.07	<0.01	0.83	0.38
Loin muscle depth, cm	6.0	6.4	6.0	6.1	0.17	0.43	0.24	0.52
Body protein ¹ , kg	13.6	14.0	12.4	12.6	0.35	<0.01	0.42	0.81
Body lipid ¹ , kg	26.9	25.4	19.2	18.2	0.62	<0.01	0.19	0.81
Body bone mineral ¹ , kg	11.5	12.5	10.3	10.7	0.22	<0.01	0.10	0.47
Overall performance (0 to 55 d)								
ADFI, kg/d	2.42	2.35	1.71	1.72	0.07	<0.01	0.70	0.58
ADG, kg/d	0.96	0.98	0.72	0.74	0.03	<0.01	0.94	0.86
G:F, kg/kg	0.41	0.43	0.43	0.42	0.01	0.11	0.67	0.21
Protein gain, g/d	140	150	122	128	7.8	0.02	0.31	0.79
Lipid gain, g/d	305	288	184	163	17.7	<0.01	0.31	0.90

T = temperature; FS = feeding system; T*FS = temperature vs. feeding system interaction. Least-square means of 12 pigs per treatment, except for IPF at 30 °C and CON at 30 °C for which the data are means of 9 and 10 pigs, respectively.

¹Body protein and lipid estimated according to Pomar and Rivest (1996) from dual-energy X-ray absorptiometry measurements (DXA). Body mineral content estimated by DXA.

animals adapted after being exposed to HTs during the adaptation (7 d) and first experimental phase (27 d). These results offer compelling evidence of a biphasic profile of physiological responses (i.e., respiratory rate, skin temperature, and rectal temperature), previously characterized by Renaudeau et al. (2010), where the physiological responses increase faster in the primary phase (short-term heat acclimation) than in the subsequent phase (long-term acclimation). This subsequent phase of acclimation

is characterized by these same authors as a gradual decrease in physiological responses.

In terms of body composition, the pigs reared under HT conditions had reduced ($P < 0.05$) lipid deposition (−40%) compared with the pigs reared under TN conditions during the overall growth period. The reduction in lipid deposition, and protein to a lesser degree, has been observed in pigs raised at HTs (Christon, 1988; Rinaldo and Le Dividich 1991; Le Bellego et al., 2002b). That

reduction in lipids and protein deposition is associated with the poor performance of the pigs reared under HT conditions, which had a lower BW than those reared under TN conditions at the end of the experiment. When lipid deposition is reported per unit of ADG, the pigs reared under HT conditions showed, in relation to those reared under TN conditions, a reduction of 13% and 27% during the first and second experimental phases, respectively. [Le Bellego et al. \(2002b\)](#) indicated that feeding pigs at HTs with diets formulated for pigs raised under TN conditions can result in an inadequate provision of nutrients as a result of the lower feed intake, which further contributes to the reduction of protein and lipid deposition. [Kellner et al. \(2016\)](#) demonstrated that the lower energy intake of heat-stressed pigs resulted in a higher lipid catabolism than in underfed pigs reared under HT conditions. Normally, the reduction of fatty acids in the tissue is dependent on albumin ([Vernon and Clegg, 1985](#)), which is an acute-phase protein that decreased in the pigs reared under HT conditions during the second phase ([Table 3](#)).

In our experiment, the pigs reared under HT conditions reduced ($P < 0.05$) P retention during all feeding phases; however, P retention efficiency was not affected at any time during the experimental period. It has been previously observed that high water consumption and evaporation for cooling under HT conditions increase P losses and therefore, mineral retention ([Holmes and Grace, 1975](#); [Christon, 1988](#)). Moreover, increased water consumption is necessary to enhance the pigs' ability to dissipate excess body heat ([Patience et al., 2005](#)). The observed reduction in P retention under HT

in our study may also be related to the lower P intake in addition to the physiological adaptations to thermal environment. This is supported by the fact that P retention efficiency was similar in pigs reared under HT and TN conditions.

The effect of feeding technique. When compared with CON pigs, IPF pigs had a similar ADFI but reduced ($P < 0.05$) nutrient intake in both feeding phases (i.e., 19% for Lys, 16% for CP, and 14% for P) ([Table 4](#)). This reduction in nutrient intake did not impair lipid and protein deposition and thus, the pigs' final body composition. Feed intake is expected to be reduced in heat-stressed pigs because digestion and nutrient metabolic utilization generate heat, this heat being defined as the thermic effect of feed ([West, 2003](#)). The impact of feed composition on heat production was highlighted by [Noblet et al. \(1999\)](#), who estimated that in growing pigs, each gram of dietary protein contributes to 1.7 kcal of heat production. Furthermore, excess and imbalanced protein needs to be deaminated and excreted, generating 1171 kcal/kg in heat loss ([Whittemore, 1983](#)). As expected, the IPF pigs reduced protein intake by 49 and 35 g/d, during the first and second experimental phases, respectively. Feeding pigs without excess nutrients, especially protein, is therefore recommended for pigs reared under HT conditions to reduce heat production. In this study, it was expected that the reduced nutrient provision to the IPF pigs would allow ADFI to be maintained under HT. Indeed, previous studies have shown decreased heat production in pigs reared under HT conditions receiving reduced CP diets ([Kerr et al., 2003](#)). However, despite the

Table 3. Serum concentration of urea, total protein, and acute-phase protein of pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30 °C)

Item	23 °C		30 °C		SEM	P value		
	IPF	CON	IPF	CON		T	FS	T*FS
27 d								
Urea (mg/dL)	29.0	28.8	20.3	24.4	2.33	<0.01	0.39	0.35
Total protein (g/dL)	6.178	6.21	6.29	6.76	0.175	0.05	0.14	0.19
Haptoglobin (mg/mL)	0.298	0.229	0.371	0.524	0.0739	0.01	0.56	0.13
Albumin (mg/mL)	40.06	39.56	36.86	40.5	1.678	0.46	0.31	0.18
55 d								
Urea (mg/dL)	22.8	28.9	18.9	24.6	1.90	0.02	<0.01	0.91
Total protein (g/dL) ¹	6.562	6.556	7.100	6.383	0.179	0.29	0.04	0.04
Haptoglobin (mg/mL)	0.260	0.244	0.404	0.317	0.0612	0.04	0.32	0.49
Albumin (mg/mL)	45.33	43.67	39.97	40.17	2.041	0.02	0.70	0.62

T = temperature; FS = feeding system; T*FS = temperature vs feeding system interaction. Least square means of 12 pigs per treatment, except for IPF at 30 °C and CON at 30 °C for which the data are means of 9 and 10 pigs, respectively.

¹Temperature × feeding system interactions ($P < 0.05$) were found for total protein IPF ($P = 0.032$), 30 °C ($P = 0.006$).

Table 4. Net energy, protein and phosphorus intake, nitrogen and phosphorus balance, and efficiency of pigs fed according to individual daily precision (IPF) or conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30 °C)

Item	23 °C		30 °C		SEM	P value		
	IPF	CON	IPF	CON		T	FS	T*FS
Phase 1 (0 to 27 d)								
NE intake MJ/d	23.2	22.3	14.9	14.6	0.81	<0.01	0.46	0.73
SID ¹ Lys intake, g/d	19.0	21.6	12.2	16.0	0.69	<0.01	<0.01	0.44
CP intake, g/d	303	334	194	243	11.9	<0.01	<0.01	0.48
N retention, g/d	26.4	28.2	22.1	22.2	1.80	0.01	0.62	0.64
N excretion, g/d	22.1	25.1	10.3	16.8	1.86	<0.01	0.02	0.39
P intake, g/d	9.7	10.5	6.2	7.6	0.37	<0.01	<0.01	0.50
P retention, g/d	2.4	2.8	1.8	2.1	0.21	<0.01	0.09	0.80
P excretion, g/d	7.3	7.7	4.4	5.5	0.32	<0.01	0.03	0.35
N retention efficiency, %	53.1	51.5	66.9	57.5	5.19	0.04	0.22	0.38
P retention efficiency, %	24.7	26.3	28.7	26.8	2.81	0.35	0.93	0.45
Phase 2 (28 to 55 d)								
NE intake MJ/d	29.1	28.0	20.8	21.5	0.79	<0.01	0.85	0.45
SID ¹ Lys intake, g/d	16.7	20.1	13.5	16.1	0.47	<0.01	<0.01	0.61
CP intake, g/d	280	322	221	256	7.5	<0.01	<0.01	0.79
N retention, g/d	18.5	20.1	16.9	18.8	1.25	0.31	0.20	0.91
N excretion, g/d	26.3	31.5	18.4	22.2	0.81	<0.01	0.01	0.66
P intake, g/d	9.3	10.5	7.2	8.3	0.24	<0.01	0.02	0.89
P retention, g/d	2.4	2.9	2.1	2.1	0.12	0.02	0.38	0.33
P excretion, g/d	6.9	7.5	5.2	6.2	0.26	<0.01	0.03	0.64
N retention efficiency, %	41.1	39.8	47.3	46.1	2.43	0.02	0.62	0.98
P retention efficiency, %	26.5	27.5	28.6	24.2	2.44	0.82	0.50	0.29
Overall (0 to 55 d)								
NE intake MJ/d	26.2	25.2	18.0	18.1	0.71	<0.01	0.63	0.53
SID ¹ Lys intake, g/d	18.0	20.9	13.1	16.2	0.65	<0.01	<0.01	0.92
CP intake, g/d	291	328	208	249	7.5	<0.01	<0.01	0.83
N retention, g/d	22.3	24.1	19.5	20.5	1.25	0.02	0.31	0.79
N excretion, g/d	24.2	28.3	14.4	19.5	1.11	<0.01	<0.01	0.75
P intake, g/d	9.5	10.5	6.7	7.9	0.24	<0.01	<0.01	0.79
P retention, g/d	2.4	2.9	1.9	2.1	0.10	<0.01	0.10	0.37
P excretion, g/d	6.9	7.6	5.3	6.2	0.23	<0.01	0.03	0.80
N retention efficiency, %	47.4	45.7	56.4	51.7	2.55	0.02	0.26	0.62
P retention efficiency, %	26.2	27.1	26.2	24.6	1.22	0.43	0.81	0.39

T = temperature; FS = feeding system; T*FS = temperature vs feeding system interaction. Least-square means of 12 pigs per treatment, except for IPF at 30 °C and CON at 30 °C for which the data are means of 9 and 10 pigs, respectively.

¹SID = standardized ileal digestible.

decreased heat production, reduced CP diets did not affect ADFI or ADG (Le Bellego et al., 2002a; Kerr et al., 2003; Morales et al., 2018), which is consistent with our results.

An optimal nutrient allowance in heat-stressed animals is a challenge because pigs reduce feed intake and, consequently, ADG. To maintain an adequate supply of nutrients in the pigs reared under HT conditions, it is necessary to reduce nutrient excesses and adapt the nutrient concentration of the feeds to the reduced feed intake. Adapting the feed to the HT reduced feed intake is difficult. White et al. (2015) found an overpredicted FI for the pigs reared under HT conditions, which led to

an underestimation of nutritional requirements when the NRC (2012) model was used. An over-predicted estimation of FI may result in inadequate diets, which may compromise the pigs' growth even further. In our study, most of the pigs received the amount of nutrients required for maintenance and growth, given that these pigs' nutrient requirements were estimated using the actual ADFI and ADG, using the 80th-percentile in the CON pigs, as suggested by Hauschild et al. (2010), or estimated in real time in the IPF pigs, as suggested by Hauschild et al. (2012). The adequate supply of nutrients can be confirmed by the fact that the pigs in both FS had similar body composition. In a previous study

(Kerr et al., 2003), the use of low-protein diets supplemented with industrial AA was not sufficient to improve the lean and fat deposition in growing pigs under HT. This confirms that many other strategies, such as reduced physical activity, thermal regulation, and other adaptations, are used by pigs reared under HT conditions in an attempt to reduce heat production, minimize the feed intake reduction (NRC, 1981). However, under such HT conditions, feed intake was not improved in the IPF pigs. Because the CON pigs had a similar FI to that of the IPF pigs but they ate higher levels of protein, they received a higher dietary heat load than the IPF pigs. On the other hand, the feeding behavior alterations may presumably be the major strategy used for ad libitum pigs reared under HT conditions to avoid reductions in FI, which is discussed later in this paper.

Feeding pigs with daily-tailored diets reduced ($P < 0.05$) N excretion by 24% and P excretion by 13%. Similar results for reduced excretion of nutrients in precision fed pigs were observed in pigs raised under TN conditions (Andretta et al., 2014, 2016a; Pomar et al., 2014), which corroborates that, as observed under TN conditions, feeding pigs with daily-tailored diets in hot environments can reduce lysine intake by 19% and nitrogen excretion by 26% without compromising pigs' performance.

Feeding Behavior

Two daily periods were used for the feeding behavior analysis based on natural daily light (Figures 3 and 4). Natural light and dark periods (provided through the glass windows in each room) were the same in both experimental rooms and temperatures were kept constant during the day to allow proper feeding behavior comparisons between treatments. Diurnal activity was measured between 0501 and 1959 h and nocturnal activity between 2000 and 0500 h. The thresholds between diurnal and nocturnal periods were established considering that light appeared at sunrise and disappeared 1 h after sunset (i.e., sunrise was around 0520 h and sunset around 1858 h during the trial). It was also assumed that pigs needed 1 h per day to eat their feed and considering that 2 feeders were available in each room (12 pigs/feeder), 15 h of diurnal activity time was sufficient to allow pigs to eat during daylight hours.

During the first feeding phase, nocturnal amount of time feeding (min) for the IPF pigs was 40% lower under TN than HT conditions, whereas this reduction was 8% in the CON pigs

Figure 3. Average feed intake during the hours of the day in pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under thermoneutral (23 °C) and heat stress (30 °C) conditions (days 0 to 27). Light period from 0520 to 1858 h.

($P < 0.10$ for the interaction between temperature and FS). During the second feeding phase, in the IPF pigs, the diurnal and nocturnal feed intake rate (g/min) was 9% lower under HT than TN conditions, whereas this reduction was 20% and 17% in the CON pigs for diurnal and nocturnal periods, respectively ($P < 0.05$ for the interaction between temperature and FS). These interactions suggest that the IPF pigs raised under HT conditions eat less at night than the CON pigs. Andretta et al. (2016b) did not find any differences in the feeding behavior between the IPF and CON pigs raised under TN conditions. It is plausible and consistent with our findings that the feeding behavior of pigs reared under TN conditions and receiving adequate diets is not affected by FS. However, apart from the physiological adaptations to HTs, pigs also modify their feeding behavior in order to attenuate the thermic effect of feeding over the day. Reducing the size of meals (Quiniou et al. 2000) and nocturnal eating can help pigs to maintain homeothermy at high ambient temperatures (Table 5).

HTs reduced ($P < 0.05$) diurnal amount of time feeding, diurnal feed intake, diurnal and nocturnal feed intake rates, and feed intake per meal during the first growing phase. The diurnal period was also

Figure 4. Average feed intake during the hours of the day in pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under thermoneutral (23 °C) and heat stress (30 °C) conditions (days 28 to 55). Light period from 0520 to 1858 h.

preferred for pig feeding activities in previous studies (Quiniou et al., 2000; Andretta et al., 2016b). Despite the fact that heavier pigs have more difficulty dissipating heat than lighter ones, the number of nocturnal and diurnal meals and the diurnal amount of time feeding were not affected by ambient temperature during the second phase. It seems that the pigs reared under HT may have adapted to that condition during the second phase, and despite the pigs still being affected by the temperature, they returned to a normal number of meals, managing only their amount of time feeding and volume of feed ingested. Waltz et al. (2014) noted that pigs raised in HTs reduce their physical activity in order to avoid heat production even if this adaptation can have negative consequences on feeding activities.

Serum Urea, Protein, and Acute-Phase Protein Responses

HTs reduced ($P < 0.05$) serum urea concentrations by 23% and increased total protein concentrations by 5%, whereas the IPF strategy reduced ($P < 0.01$) serum urea concentrations by 28%. These reductions in serum urea concentrations result from the reduction of protein intake at HTs or in IPF in relation to the control treatments, given that urea is

an end-product of AA catabolism (Eggum, 1970; Whang et al., 2000). Andretta et al. (2016a) also found that in relation to conventionally fed pigs, pigs fed a daily-tailored diet reduced protein intake and, concomitantly, plasma urea concentration.

The inflammatory responses of pigs were studied because high ambient temperature may affect the immune function (Lacetera, 2012), and serum haptoglobin concentration was chosen as an indicator of the intensity of immune activation (Murata et al., 2004). Indeed, serum haptoglobin increased in the pigs reared under HT conditions ($P < 0.05$) at 28 and 55 d of the experiment in relation to those reared under TN conditions by 70% and 43%, respectively (Table 3). These results confirm the activation of the immune system caused by the chronic exposure to HT. Besides these results, we expected that lowering protein deamination in the IPF pigs could contribute to reducing heat stress in HT, but no differences in haptoglobin concentrations were observed between FS.

Serum albumin is a negative acute-phase protein and its concentration in serum decreases in mammalian species under stress (Mackiewicz, 1997). Moreover, heat-stressed animals show increased renal buffering capabilities via H^+ excretion and urine acidification (Patience et al., 2005), whereas the blood flow is redistributed away from the gastrointestinal tract (Bell, 1993; Hall et al., 2001). Renal and gastrointestinal changes can result in decreased hepatic synthesis and compromise albumin synthesis (Kaneko, 1997). Serum albumin in the CON pigs was decreased ($P < 0.05$) by 10% under HT at day 55 of the experiment. With the decrease in serum albumin, their unused pool of amino acids may be directed to generate positive acute-phase proteins and other important mediators of inflammation (Paltrinieri, 2008). These responses can support the fact that even after 55 d in HTs, pigs use different adaptive mechanisms to cope with the constant heat stress, which may explain why these pigs had higher levels of haptoglobin under these conditions compared with the pigs under TN conditions.

The results of this study indicate that pigs exposed to constant HTs reduce feed intake and growth performance and that these responses are similar in conventional and precision FS. Feeding individual pigs with daily-tailored diets, however, improves N and P efficiency and reduces their excretion without compromising the pigs' body composition. Nonetheless, the CON fed pigs reared under HT ate more feed at night than the IPF pigs, probably in an attempt to dissipate the extra heat resulting from the excess dietary protein. Precision

Table 5. Meal patterns of pigs fed according to individual daily precision (IPF) and conventional 2-phase (CON) feeding systems under 2 thermal conditions (23 and 30 °C)

	23 °C		30 °C			P value		
Item	IPF	CON	IPF	CON	SEM	T	FS	T*FS
Phase 1 (0 to 27 d)								
Diurnal								
Amount of time feeding, min	66	69	50	50	4.95	0.01	0.77	0.78
Feed intake, g	1650	1721	1085	1037	115.01	<0.01	0.90	0.54
Meals	9.5	8.6	7.1	6.6	0.84	<0.01	0.31	0.79
Feed intake rate, g/min	24.9	25.3	22.5	20.7	0.81	<0.01	0.34	0.13
Feed intake meal, g	183	208	154	164	14.78	0.01	0.20	0.58
Nocturnal								
Amount of time feeding, min	22.0	18.3	13.2	16.9	2.34	0.02	0.98	0.07
Feed intake, g	524.7	424.4	282.6	341.5	55.69	<0.01	0.67	0.10
Meals	3.4	2.7	2.3	2.8	0.56	0.24	0.80	0.22
Feed intake rate, g/min	23.5	23.9	21.6	20.1	0.89	<0.01	0.47	0.25
Feed intake meal, g	191	180	122	126	16.86	<0.01	0.92	0.86
Phase 2 (28 to 55 d)								
Diurnal								
Amount of time feeding, min	68.6	68	61	65	5.23	0.29	0.70	0.61
Feed intake, g	2049	2094	1640	1626	163.8	<0.01	0.91	0.83
Meals	8.5	7.3	7.9	7.9	0.88	0.98	0.46	0.48
Feed intake rate, g/min	29.8	30.1	27	24.9	0.77	<0.01	0.48	0.03
Feed intake meal, g	254	304	213	227	31.1	0.02	0.20	0.47
Nocturnal								
Amount of time feeding, min	22	22	12.8	17.8	3.26	0.02	0.37	0.37
Feed intake, g	621.3	562.8	324.1	426.4	74.98	<0.01	0.74	0.23
Meals	2.7	2.2	2.2	2.6	0.53	0.97	0.87	0.31
Feed intake rate, g/min	27.8	30	25.3	23.9	0.79	<0.01	0.56	0.02
Feed intake meal, g	296	384	152	171	39.2	<0.01	0.14	0.35
Overall (0 to 55 d)								
Diurnal								
Amount of time feeding, min	68	68.4	55.9	59.2	4.96	0.02	0.72	0.86
Feed intake, g	1859	1917	1376	1346	86.71	<0.01	0.91	0.70
Meals	9	7.9	7.5	7.3	0.79	0.15	0.38	0.58
Feed intake rate, g/min	28	28.2	24.7	23.2	0.8	<0.01	0.35	0.26
Feed intake meal, g	217	252	185	197	21.45	0.02	0.19	0.51
Nocturnal								
Amount of time feeding, min	22	19.1	13	17.4	2.49	0.02	0.72	0.09
Feed intake, g	575.4	497.1	304.4	386.1	61.75	<0.01	0.97	0.14
Meals	3	2.5	2.3	2.7	0.54	0.58	0.86	0.25
Feed intake rate, g/min	25.6	26.9	23.3	22.1	0.66	<0.01	0.96	0.07
Feed intake meal, g	239	261	138	148	22.43	<0.01	0.38	0.76

Diurnal period from 0501 to 1959 h; Nocturnal period with low luminosity and less activity from 2000 to 0500 h. Least-square means of 12 pigs per treatment, except for IPF at 30 °C and CON at 30 °C for which the data are means of 9 and 10 pigs, respectively.

feeding is an effective approach to reduce nutrient intake and excretion, but its effectiveness in mitigating the negative impact of HTs on feed intake and growth performance may appear when pigs are unable to dissipate the extra heat by modifying their feeding behavior.

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