Effects of added dietary salt on pig growth performance[1,2]

Dwight J. Shawk,* Robert D. Goodband,*,[3] Mike D. Tokach,*
Steve S. Dritz,† Joel M. DeRouchey,* Jason C. Woodworth,*
Annie B. Lerner,* and Hayden E. Williams*

*Department of Animal Sciences and Industry, College of Agriculture, Kansas State University, Manhattan, KS 66506-0210; and †Department of Diagnostic Medicine/Pathobiology, College of Veterinary Medicine, Kansas State University, Manhattan, KS 66506-0210

ABSTRACT: Three studies evaluated the effects of added dietary salt on growth performance of pigs weighing 7 to 10, 11 to 30, and 27 to 65 kg. In experiment 1, 325 pigs were used with 5 pigs per pen and 13 pens per treatment. Pigs were fed a diet (0.39% Na and 0.78% Cl) for 7 d after weaning, then randomly assigned to diets with either 0, 0.20, 0.40, 0.60, or 0.80% added salt for 14 d. All diets were corn-soybean meal-based with 10% dried whey. Calculated Na concentrations were 0.11, 0.19, 0.27, 0.35, and 0.43% and calculated Cl concentrations were 0.23, 0.35, 0.47, 0.59, and 0.70%, respectively. Increasing salt increased (linear, $P < 0.05$) average daily gain (ADG) and gain to feed ratio (**G:F**). For ADG, the linear, quadratic polynomial (**QP**), and broken-line linear (**BLL**) models were competing with the breakpoint for the BLL at 0.59% salt. For G:F, the BLL reported a breakpoint at 0.33% while the QP indicated maximum G:F at 0.67% added salt. In experiment 2, 300 pigs were used in a 34-d trial with 5 pigs per pen and 12 pens per treatment. Pigs were weaned at 21 d of age and fed a phase 1 diet (0.50% Na and 0.67% Cl) for 11 d and then a phase 2 diet (0.35% Na and 0.59% Cl) for 14 d. Then pens of pigs were randomly assigned to corn-soybean meal-based diets containing 0.20, 0.35, 0.50, 0.65, or 0.80% added salt. Calculated dietary Na concentration were 0.10, 0.16, 0.22, 0.28, and 0.34% and calculated Cl concentrations were 0.23, 0.32, 0.41, 0.50, and 0.59%, respectively. Overall, ADG and G:F increased (quadratic, $P < 0.07$) with increasing added salt. For ADG, the QP and BLL had similar fit with the breakpoint for BLL at 0.51% added salt. For G:F, the BLL model predicted a break point at 0.35% added salt. In experiment 3, 1,188 pigs were used in a 44-d study with 27 pigs per pen and 11 pens per treatment. Pens of pigs were randomly assigned to corn-soybean meal-based diets containing 0.10, 0.33, 0.55, or 0.75% added salt. Calculated dietary Na concentrations were 0.10, 0.19, 0.28, and 0.36% and calculated Cl concentrations were 0.23, 0.36, 0.49, and 0.61%, respectively. Overall, there was no evidence to indicate that added salt above 0.10% of the diet affected growth. In conclusion, the BLL models suggested to maximize ADG for 7 to 10 and 11 to 30 kg pigs was 0.59% (0.34% Na and 0.58% Cl) and 0.51% added salt (0.22% Na and 0.42% Cl), respectively. There was no evidence that growth of 27 to 65 kg pigs was improved beyond 0.10% added salt (0.11% Na and 0.26% Cl).

Key words: chloride, growth, pig, salt, sodium

Transl. Anim. Sci. 2018.2:396–406
doi: 10.1093/tas/txy085

INTRODUCTION

[1]Contribution 18-388-J from the Kansas Agric. Exp. Sta., Manhattan 66506–0210.

[2]Appreciation is expressed to New Horizoin Farm (Pipestone, MN) for providing the animals and research facilities, and to H. Houslog, M. Heintz, and C. Stech for technical assistance.

[3]Corresponding author: goodband@ksu.edu

Received June 24, 2018.
Accepted July 8, 2018.

Sodium and chloride are ions that serve several key roles in the body. Both ions are involved in acid-base balance. Sodium is a cation that is involved in the sodium potassium pump, nerve impulse, and muscle contraction. Chloride is anion that regulates osmotic pressure and is a component of HCl, which is critical in digestion. The NRC (1998) requirement estimate for Na and Cl were 0.20% and 0.20% for 5 to 10 kg pigs, 0.15% and 0.15% for 10 to 20 kg pigs, and 0.10% and 0.08% for 20 to 80 kg pigs. Mahan et al. (1996) evaluated Na and Cl requirements independently in corn-soybean meal diets with 20% dried whey and observed that average daily gain (ADG) increased up to a dietary Na concentration of 0.34% in 7 to 8 kg pigs and a dietary Cl concentration of 0.50% in 6 to 9 kg pigs. In two separate studies, Mahan et al. (1999) evaluated Cl concentrations by adding HCl to the diet. ADG improved up to a dietary Cl concentration of 0.32%. Mahan et al. (1999) also noted improvements in ADG of 7 to 15 kg pigs up to a dietary addition of 0.40% salt (0.36% Na and 0.49% Cl) in corn-soybean meal diets containing lactose and spray-dried animal plasma.

Based on the observations of Mahan et al. (1996, 1999) and others, the NRC (2012) increased the Na and Cl requirement estimates to 0.35 and 0.45% for 7 to 11 kg pigs, 0.28 and 0.32% for 11 to 25 kg pigs, and 0.10 and 0.08% for 25 to 75 kg pigs. Sodium bicarbonate, sodium tripolyphosphate, ammonium chloride, and HCl are sources of Na and Cl that have been used to establish the Na and Cl requirement; however, in commercial diets the most common source of Na and Cl is added salt. Currently there is limited research to confirm the Na and Cl requirement estimates of modern genotype pigs and effects of added salt. Therefore, the objective of these experiments was to evaluate added salt on the growth performance of nursery pigs weighing 7 to 10 and 11 to 30 kg and grower pigs weighing 27 to 65 kg.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments.

Experiment 1

A total of 325 barrows (Line 200 × 400; DNA, Columbus, NE, initially 6.6 ± 0.15 kg body weight [BW]) were used in a 21-d growth trial with 5 pigs per pen and 13 pens per treatment. Pigs were weaned at 21 d of age and were randomly allotted to pens of 5 based on their initial BW. Pigs were fed a common diet (0.39% Na and 0.78% Cl) for 7 d after weaning. On day 7 after weaning, considered day 0 in the trial, pens of pigs were blocked by BW and then randomly assigned one of five dietary treatments fed for 14 d. The dietary treatments were corn-soybean meal-based with 10% dried whey. They included a diet with no added salt, or diets with either 0.20, 0.40, 0.60, or 0.80% added salt; resulting in calculated Na concentration of 0.11, 0.19, 0.27, 0.35, and 0.43% and calculated Cl concentrations of 0.23, 0.35, 0.47, 0.59, and 0.70%, respectively (Table 1). Nutrient profiles, amino acid standardized ileal digestibility values as well as Na and Cl concentrations were derived from NRC (2012). Pigs were then fed a common diet from day 14 to 21 (0.16% Na and 0.34% Cl). Pens of pigs were weighed and feed disappearance was recorded weekly to determine ADG, average daily feed intake (ADFI), and gain to feed ratio (G:F).

The study was conducted at the Kansas-State University Segregated Early Weaning Facility in Manhattan, KS. Each pen (1.22 × 1.22 m) was equipped with a 4-hole, dry self-feeder and a nipple waterer to provide ad libitum access to feed and water. The source of drinking water was from a municipal water system. It was not analyzed for Na or Cl content. Diets were manufactured at the K-State O.H. Kruse Feed Technology Innovation Center, Manhattan, KS. Soybean meal, salt, and L-Lysine–HCl samples were collected at the mill at the time of feed manufacturing, pooled, and subsampled for chemical analysis. The 0 and 0.80% added salt diets were manufactured then blended to create the intermediate diets. Feed samples were collected from eight feeders per treatment, pooled, and subsampled for chemical analysis.

Experiment 2

A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE; initially 11.3 ± 0.21 kg BW) were used in a 34-d trial with 5 pigs per pen and 12 pens per treatment. Pigs were weaned at 21 d of age and were allotted to pens based on their initial BW. All pigs were fed a common phase 1 diet (0.50% Na and 0.67% Cl) for 11 d and then a common phase 2 diet (0.35% Na and 0.59% Cl) for 14 d. At day 25 after weaning, considered day 0 of the trial, pens of pigs were blocked by BW and then randomly assigned to one of five diets which were fed for 27 d. Dietary treatments were corn-soybean meal-based and contained either 0.20, 0.35, 0.50, 0.65, or 0.80% added

Table 1. Diet composition, experiment 1 (as-fed basis)

Ingredient[3], %	Experimental[1]	Common phase 3[2]
Corn	51.00	63.77
Soybean meal (48% crude protein)	29.60	32.86
Dried whey	10.00	---
HP 300 (Hamlet Protein)[4]	5.00	---
Choice white grease	1.00	---
Monocalcium P (21% P)	1.05	1.10
Limestone	1.05	0.98
Salt	---	0.35
L-Lysine HCl	0.30	0.30
DL-Methionine	0.18	0.12
L-Threonine	0.15	0.12
Trace mineral premix[5]	0.15	0.15
Vitamin premix[6]	0.25	0.25
Phytase[7]	0.02	0.02
Zinc oxide	0.25	---
Total	100	100
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lysine	1.35	1.35
Isoleucine:lysine	63	57
Leucine:lysine	124	117
Methionine:lysine	35	30
Methionine and cystine:lysine	59	51
Threonine:lysine	66	57
Tryptophan:lysine	19	17
Valine:lysine	67	62
Total lysine, %	1.49	1.37
Net energy, kcal/kg	2,321	2,363
Crude protein, %	22.8	21.4
Calcium, %	0.78	0.70
Phosphorus, %	0.68	0.64
Available Phosphorus, %	0.48	0.41
Sodium, %	0.11	0.16
Chloride, %	0.23	0.34
Potassium, %	1.15	0.96
Dietary electrolyte balance, mEq/kg[8]	276	218

[1]Experimental diets were fed approximately from 7 to 12 kg. Corn was removed and replaced with salt to create the treatment diets. Treatment diets containing 0% and 0.80% salt were manufactured and blended at the feed mill to create the intermediate diets of 0.20%, 0.40%, and 0.60% salt.

[2]Common phase 3 diet fed to all pigs from day 21 to 28 after weaning.

[3]All nutrient profiles for ingredients were derived from NRC (2012).

[4]Hamlet Protein, Findlay, OH.

[5]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[6]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.

[7]Ronozyme HiPhos 2700 (DSM Nutritional Products, Inc., Parsippany, NJ), providing 406.3 phytase units (FTU)/kg and an estimated release of 0.10% available P.

[8]Calculated as = (Na*434.98) + (K*255.74) – (Cl*282.06).

salt (Table 2). This resulted in calculated dietary Na concentrations of 0.10, 0.16, 0.22, 0.28, and 0.34% and calculated Cl concentrations of 0.23, 0.32, 0.41, 0.50, and 0.59%, respectively. Pigs were then fed a common diet from day 27 to 34 (0.16% Na and 0.29% Cl). Pens of pigs were weighed and feed disappearance was recorded weekly to determine ADG, ADFI, and G:F.

This study was conducted at the Kansas-State University Swine Teaching and Research Center in Manhattan, KS. Each pen (1.2 × 1.5 m) was equipped with a 4-hole, dry self-feeder and a nipple waterer to provide ad libitum access to feed and water. The source of drinking was the same as in experiment 1. Diets were manufactured at the K-State O.H. Kruse Feed Technology Innovation Center. Sodium and Cl values for ingredients that were determined in experiment 1 were used in diet formulation. Feed samples were collected from eight feeders per treatment, pooled, and subsampled for analysis.

Experiment 3

A total of 1,188 pigs (PIC 359 × 1050; initial BW 27.1 ± 0.95 kg) were used in a 44-d trial with 27 pigs per pen and 11 pens per treatment. Pigs were blocked by BW and then randomly assigned to one of four dietary treatments that were fed for 44 d. Dietary treatments were corn-soybean meal-based and contained either 0.10, 0.33, 0.55, or 0.75% added salt (Table 3). This resulted in calculated dietary Na concentrations of 0.10, 0.19, 0.28, and 0.36% and calculated Cl concentrations of 0.23, 0.36, 0.49, and 0.61%, respectively. Pens of pigs were weighed and feed disappearance was recorded on day 0, 16, 31, and 44 to determine ADG, ADFI, and G:F.

This study was conducted at a commercial research-finishing site located in southwest Minnesota (New Horizon Farm, LLC, Pipestone, MN). Pigs were housed in a naturally ventilated and double-curtain-sided barn. Each pen (3 × 5.5 m) contained a 4-hole stainless steel feeder and cup waterer for ad libitum access to feed and water. Source of drinking water was from well water and not analyzed for Na or Cl. Feed additions to each individual pen were made and recorded by a robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN). Experimental diets for experiment 3 were manufactured at New Horizon Feed LLC. Dried distillers grain with solubles samples were collected at the mill, pooled, and subsampled for analysis prior to manufacturing the dietary treatments.

Table 2. Diet composition, experiment 2 (as-fed basis)

Ingredient[3], %	Experimental[1]	Common grower[2]
Corn	60.12	71.50
Soybean meal (48% crude protein)	34.66	25.71
Choice white grease	1.30	---
Monocalcium P (21% P)	1.15	0.55
Limestone	0.88	1.13
L-Lysine HCl	0.35	0.31
DL-Methionine	0.16	0.06
L-Threonine	0.14	0.09
L-Tryptophan	0.004	---
L-Valine	0.04	---
Trace mineral premix[4]	0.15	0.15
Vitamin premix[5]	0.25	0.15
Phytase[6]	0.02	0.02
Sand	0.60	---
Salt	0.20	0.35
Total	100	100
Calculated analysis		
Standardized ileal digestible (SID) AA, %		
Lysine	1.30	1.05
Isoleucine:lysine	61	62
Leucine:lysine	124	135
Methionine:lysine	35	30
Methionine and cystine:lysine	58	55
Threonine:lysine	62	61
Tryptopahn:lysine	18.5	18.0
Valine:lysine	69	69
Total lysine, %	1.45	1.18
Net energy, kcal/kg	2,447	2,463
Crude protein, %	22.0	18.5
Calcium, %	0.70	0.62
Phosphorus, %	0.65	0.49
Available phosphorus, %	0.43	0.29
Sodium, %	0.10	0.17
Chloride, %	0.23	0.46
Potassium, %	0.97	0.81
Dietary electrolyte balance, mEq/kg[7]	226	154

[1]Experimental diets were fed from approximately 11 to 30 kg. Sand was removed and replaced with salt to create the additional experimental treatment diets.

[2]Common grower diet was fed to all pigs from approximately 30 to 37 kg.

[3]Analyzed Na and Cl values from experiment 1 were used in diet formulation. Nutrient profiles for all other ingredients are from NRC (2012).

[4]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[5]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.

[6]Ronozyme HiPhos 2700 (DSM Nutritional Products, Inc., Parsippany, NJ), providing 406.3 phytase units (FTU)/kg and an estimated release of 0.10% available P.

[7]Calculated as = (Na*434.98) + (K*255.74) – (Cl*282.06).

Like experiment 2, Na and Cl concentrations from ingredients determined in experiment 1 were used in formulation. Feed samples from six feeders per treatment were collected at the beginning and the end of the trial, pooled, and subsampled for analysis.

Chemical Analysis

Feed samples for experiment 1 and dried distillers grain with solubles samples and feed samples for experiment 3 were submitted for analysis of Na and Cl (Ward Laboratories, Kearney, NE). Sodium samples were prepared by removing organic matter and lipids with HNO_3, HCl, and H_2O_2 (Campbell and Plank 1991; Wolf et al., 2003) and samples were then analyzed for Na via inductively coupled plasma spectroscopy (Kovar, 2003). Dietary Cl concentrations were determined by titrating sliver nitrate until all Cl ions are precipitated and then detecting the concentration of free sliver ions using a Metrohm 855 Robitic Titrosampler and a Metrohm 6.0430.100 Ag Titrode (Metrohm USA Inc, Riverview, FL, AOAC 969.10, 2000; Kalra et al., 1991; Mills et al., 1991). Soybean meal, L-Lys-HCl, salt, and feed samples for experiment 2 were submitted to Cumberland Valley Analytical Service (Maugansville, MD) for analysis of Na and Cl. Sodium within each sample was analyzed following procedures outlined by AOAC (2000). To analyze samples for Cl samples were prepared with nitric acid and then analyzed using a Metrohm 848 Titrono Plus (Metrohm USA Inc, Riverview, FL). Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01), and crude protein (Method 990.03; K-State Analytical Laboratory, Manhattan, KS).

Statistical Analysis

Data for all experiments were analyzed as a randomized complete block design with body weight as the blocking factor. An initial model was evaluated for each experiment where dietary treatment was considered as a categorical fixed effect and block was considered a random effect with pen as the experimental unit. Models were evaluated separately for individual experiments. The base model was used to evaluate the heterogeneity of residual variance using Bayesian Information Criteria (BIC) to determine the best fit. For experiment 1, heterogenous variance was used for ADFI and G:F while homogenous variance was used for ADG. For experiment 2, heterogenous variance was used

Table 3. Diet composition, experiment 3 (as-fed basis)[1]

	Added salt, %			
Item	0.10	0.33	0.55	0.75
Ingredient[2], %				
Corn	54.15	53.75	53.35	52.97
Soybean meal (48% crude protein)	22.72	22.75	22.78	22.81
Dried distillers grain with solubles[3]	20.00	20.00	20.00	20.00
Beef tallow	0.75	0.90	1.05	1.20
Monocalcium P (21% P)	0.20	0.20	0.20	0.20
Limestone	1.26	1.25	1.25	1.24
Salt	0.10	0.33	0.55	0.75
Vitamin and trace mineral premix[4]	0.15	0.15	0.15	0.15
L-Lysine HCl	0.48	0.48	0.48	0.48
DL-Methionine	0.05	0.05	0.05	0.05
L-Threonine	0.11	0.11	0.11	0.11
L-Tryptophan	0.02	0.02	0.02	0.02
Phytase[5]	0.01	0.01	0.01	0.01
Total	100	100	100	100
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lysine	1.17	1.17	1.17	1.17
Isoleucine:lysine	61	61	61	61
Leucine:lysine	147	147	146	146
Methionine:lysine	31	31	31	31
Methionine and cystine:lysine	56	56	56	56
Threonine:lysine	62	62	62	62
Tryptophan:lysine	18.5	18.5	18.5	18.5
Valine:lysine	70	70	70	70
Total lysine, %	1.34	1.34	1.34	1.34
Net energy, kcal/kg	2,474	2,474	2,474	2,474
Crude protein, %	20.8	20.8	20.8	20.8
Calcium, %	0.58	0.57	0.57	0.57
Phosphorus, %	0.52	0.52	0.52	0.52
Available phosphorus, %	0.34	0.34	0.34	0.34
Sodium, %	0.10	0.19	0.28	0.36
Chloride, %	0.23	0.36	0.49	0.61
Potassium, %	0.68	0.68	0.68	0.68
Dietary electrolyte balance, mEq/kg[6]	155	156	157	158
Chemical analysis, %				
Dry matter	85.90	87.39	85.83	86.56
Crude protein	16.57	17.23	15.64	17.72
Sodium	0.11	0.22	0.25	0.34
Chloride	0.26	0.46	0.50	0.61

[1]Experimental diets were fed for 44 d from approximately 27 to 64 kg.

[2]Analyzed Na and Cl values from experiment 1, were used in diet formulation. Nutrient profiles for all other ingredients are from NRC (2012).

[3]Dried distillers grain with solubles were analyzed for dietary Na (0.22%) and Cl (0.19%) and analyzed values were used in diet formulation.

[4]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite; 3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.

[5]Optiphos 2000 (Huvepharma, Sofia, Bulgaria) provided an estimated release of 0.11% available P.

[6]Calculated as = (Na*434.98) + (K*255.74) – (Cl*282.06).

for ADG and G:F while homogenous variance was used for ADFI. For G:F, block was removed from the model as it did not contribute to the model fit but degrees of freedom were adjusted manually to account for the degrees of freedom contributed by block. Linear and quadratic polynomials (QP) were used to evaluate increasing salt.

For experiments 1 and 2, added salt dose response curves were predicted using PROC GLIMMIX and PROC NLMIXED to optimize ADG, ADFI, and

G:F following the procedure outlined by Gonçalves et al. (2016). The dose response models that were evaluated were linear, QP, broken-line linear (BLL), and broken-line quadratic. Bayesian Information Criterion was used to determine best fit, with a decrease in two or more points indicating a better fit of the model (Raftery, 1996). As with the base model, heterogeneous variance was accounted for where appropriate. Individual pen means and the response curves were plotted for the best fitting models. For the BLL models, the breakpoints and 95% CI are reported. For the QP model, the maximum response and 95% CI are reported. The CI was calculated by plotting the regression equation with the 95% CI across the doses and projecting the maximum response across the y-axis using a horizontal line. The intersection between the horizontal line and CI boundaries of the predicted line is then projected onto the x-axis to estimate the CI of the optimum dose level (Gonçalves et al., 2016).

RESULTS AND DISCUSSION

Chemical Analysis

Chemical analysis of the salt sample indicated a Na concentration of 40.26% and a Cl concentration of 58.72%, which would be similar to the NRC (2012) Na and Cl concentration estimates of 39.5% and 59% (Table 4). Analysis of the L-Lys-HCl samples indicated a Na concentration of 0.01% and a Cl concentration of 19.37%. Results of the chemical analysis indicated a Na concentration of 0.22% and a Cl concentration of 0.19% for dried distillers grain with solubles. The Na and Cl concentration of the soybean meal sample was 0.01% and 0.02%, respectively. The NRC (2012) Na and Cl concentration estimate for soybean meal is 0.08% and 0.49% while the NRC (1998) Na and Cl concentration estimate for soybean meal is 0.02% and 0.05%. While the Na concentration of the soybean meal sample (0.01%) is similar to NRC (2012) and NRC (1998) concentration estimates, the Cl concentration (0.02%) of soybean meal is significantly less than NRC (2012) concentration estimate of 0.49%. Ingredients were not analyzed in advance of diet formulation in experiment 1; however, the diets in experiments 2 and 3 used the results of the analyses of experiment 1 in diet formulation.

For experiment 1, chemical analysis of diets indicated that analyzed values for Na and Cl were similar to calculated values with dietary Na concentrations ranging from 0.09% to 0.40% and dietary Cl concentrations ranging from 0.23% to 0.72% (Table 5). Results for experiment 2 closely matched calculated concentrations except for the 0.80% added salt diet, which was slightly lower in Na and Cl when compared to calculated concentrations (Table 6). Diets contained increasing Na concentrations that ranged from 0.11% to 0.30% and Cl concentrations that ranged from 0.23% to 0.50%. For experiment 3, analyzed Na and Cl concentrations were similar to calculated values with dietary Na concentration ranging from 0.11% to 0.34% and dietary Cl concentrations ranging from 0.26% to 0.61% (Table 3).

Table 4. Chemical analysis of feed ingredients, (as-fed basis)[1]

Item	Na, %	Cl, %
Salt	40.26	58.72
L-Lysine-HCl	0.01	19.37
Soybean meal (48% crude protein)	0.01	0.02
Dried distillers grain with solubles	0.22	0.19

[1]Samples were collected from the mill, homogenized, and then subsampled for analysis.

Experiment 1

From day 0 to 14, increasing salt increased (linear, $P < 0.015$) ADG, ADFI, and day 14 BW (Table 7). Despite the linear response, there were only small improvements observed beyond 0.60% added salt. Gain to feed increased (quadratic,

Table 5. Chemical analysis of experimental diets, experiment 1, (as-fed basis)[1]

	Added salt, %				
Item, %	0	0.20	0.40	0.60	0.80
Dry matter	88.83	89.07	89.57	89.01	89.03
Crude protein	21.50	19.51	19.29	19.52	20.70
Na	0.09	0.17	0.23	0.38	0.40
Cl	0.23	0.37	0.46	0.56	0.72

[1]Multiple samples were collected of each diet throughout the study, homogenized, and then subsampled for analysis.

Table 6. Chemical analysis of experimental diets, experiment 2 (as-fed basis)[1]

	Added salt, %				
Item, %	0.20	0.35	0.50	0.65	0.80
Dry matter	86.89	87.63	88.22	87.68	87.40
Crude protein	19.77	20.26	21.64	21.15	23.37
Na	0.11	0.14	0.20	0.28	0.30
Cl	0.23	0.29	0.39	0.48	0.50

[1]Multiple samples were collected of each diet throughout the study, homogenized, and then subsampled for analysis.

Table 7. Effects of increasing salt on growth performance of 7 to 10 kg pigs (experiment 1)[1]

Item	Added salt, %[2]					SEM	Probability, $P <$	
	0	0.20	0.40	0.60	0.80		Linear	Quadratic
Day 0–14								
ADG, g	194	216	234	254	253	10.2	0.001	0.218
ADFI, g	309	305	319	326	334	9.3	0.015	0.609
G:F, g/kg	626	705	732	779	758	20.9	0.001	0.019
Post-treatment (day 14–21)								
ADG, g	432	353	361	379	334	24.6	0.013	0.318
ADFI, g	557	523	548	550	531	24.5	0.701	0.911
G:F, g/kg	772	672	652	683	623	24.1	0.001	0.135
BW, kg								
Day 0	6.6	6.6	6.6	6.6	6.6	0.05	0.630	0.789
Day 14	9.4	9.7	9.9	10.2	10.2	0.15	0.001	0.297
Day 21	12.4	12.1	12.4	12.8	12.5	0.25	0.229	0.982

[1]A total of 325 barrows (Line 200 × 400; DNA, Columbus, NE) were used in a 14-d study with 5 pigs per pen and 13 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 7 d postweaning, then placed on experimental diets.

[2]Experimental diets were fed from day 0 to 14 and a common phase 3 diet was fed from day 14 to 21. Treatment diets with 0 and 0.80% added salt were manufactured and blended at the feed mill to create the intermediate levels of 0.20, 0.40, and 0.60% added salt.

$P < 0.019$) as salt increased from 0% to 0.60%, with no further benefits observed thereafter.

From day 14 to 21, when pigs were fed a common diet with 0.35% added salt, those previously fed low salt diets appeared to have compensatory ADG and G:F (linear, $P < 0.013$) compared with those previously fed high salt diets. There was no evidence of difference to indicate that previous dietary treatments influenced ADFI or day 21 BW.

For ADG, the linear, QP, and BLL models were competing with similar BIC. The predicted response for the QP model was indicated as ADG = 193.22 + 139.12 × (added salt, %) − 76.936 × (added salt, %)^2 with the predicted maximum greater than the highest amount fed (0.90%; 95% CI [0.45, >0.80%]) though a 0.59% added salt inclusion could obtain 97% of the maximum performance. The BLL model breakpoint was 0.59% salt with ADG = 253.50 – 99.58 × (0.59 – added salt, %), when salt < 0.59% and ADG = 253.8, if added salt ≥ 0.59%. For ADFI, the QP and linear models were competing with similar BIC. The predicted response for the QP model was indicated as ADFI = 193.05 + 144.74 × (added salt, %) – 83.963 × (added salt, %)^2 with the predicted maximum greater than the highest amount fed (0.86%; 95% CI [0.45, >0.80%]) while 95% of the maximum performance could be obtained with 0.47% salt. For G:F, the QP and BLL models were competing with similar BIC. The predicted response for the QP model was indicated as G:F = 626.61 + 429.91 × (added salt, %) – 321.92 × (added salt)^2 with the maximum performance obtained with 0.67% (95% CI [0.37, >0.80%]) added salt while 95% of the predicted maximum performance could be obtained with 0.33% added salt. For the BLL model, the breakpoint was at 0.33% added salt with G:F = 756.47 – 394.82 × (0.33 – added salt, %), when added salt < 0.33% and G:F = 756.7, if added salt ≥ 0.33%.

Based on the results of the BLL and QP models, the inclusion concentration in which maximum performance was obtained was 0.59% (BLL) and 0.90% (QP) added salt for ADG, 0.86% (QP) added salt for ADFI, and 0.33% (BLL) and 0.67% (QP) for G:F. If the goal of production system was to capture maximum ADG while maintaining G:F then the QP models would indicate the optimal salt inclusion to be between 0.67% and 0.90% added salt. However, 0.59% added salt would still obtain 97% of the ADG and G:F performance based on the QP ADG and G:F model. An inclusion of 0.59% added salt would result in diets that would have a Na concentration of approximately 0.34% and Cl concentration of 0.58%.

A dietary Na concentration of 0.34% would agree with the NRC (2012) requirement estimates of 0.35% while a Cl concentration of 0.58% would be greater than the Cl requirement estimate of 0.45% for the 7 to 11 kg pig. In two studies evaluating Na and Cl independently with Na_2PO_4 and HCl in corn-soybean meal-based diets that also contained dried whey, Mahan (1996) observed improvements in growth performance up to a dietary Na concentration of 0.34% in 7 to 8 kg pigs and a dietary Cl concentration of 0.50% in 6 to 9 kg pigs. Mahan et al. (1999) did not observe an interaction between Na and Cl, sourced from Na_2PO_4 and HCl in corn-soybean meal diets with lactose and spray dried animal plasma; however, ADG increased with increasing dietary Cl concentrations up to 0.45% in 7 to 11 kg pigs. In a different study, HCl was used to evaluate Cl concentrations in a corn-soybean meal diet with lactose and spray dried animal plasma (Mahan et al., 1999). ADG improved up to a dietary Cl concentration of 0.32%. Considering both of these trials, a Cl concentration of 0.32% to 0.45% would be significantly lower than the 0.58% Cl which corresponded to the optimal salt inclusion concentration (0.59% added salt) observed in our experiment. However, it is important to remember that in the study herein, Na and Cl concentrations were not evaluated independently as added salt was the source for both ions.

Mahan et al. (1996) observed a quadratic response to added salt with improvements in ADG up to 0.40% added salt (0.44% Na and 0.51% Cl) in corn-soybean meal diets with 20% spray dried whey for 7 to 9 kg pigs. Mahan et al. (1999) also suggested 0.40% added salt (0.36% Na and 0.49% Cl) in a corn-soybean meal diet with lactose and spray dried animal plasma was needed to maximize growth of 7 to 15 kg pigs. The addition of 0.40% salt is lower than the calculated optimal inclusion observed in our study of 0.59% (0.34% Na and 0.58% Cl); but because of the added spray dried animal plasma and the higher inclusion of dried whey used in their studies, the actual Na and Cl concentrations are similar.

Experiment 2

From day 0 to 14, ADG and ADFI increased (quadratic, $P < 0.001$ and 0.089) as added salt increased from 0.20% to 0.65%, with no further benefits observed thereafter (Table 8). Gain to feed ratio and day 14 BW increased (quadratic, $P < 0.029$ and 0.088) with increasing added salt.

From day 14 to 27, there was no evidence of difference to indicate dietary treatment affected ADG. ADFI improved (linear, $P < 0.015$) with increasing added salt and G:F tended (linear, $P < 0.084$) to slightly worsen with increasing salt with the optimal G:F obtained with 0.50% added salt diet.

From day 0 to 27, ADG improved (quadratic, $P < 0.005$; Table 9) as added salt increased from 0.20% to 0.80%, with the greatest marginal improvement observed from 0.20% to 0.50% added salt. ADFI increased (linear, $P < 0.001$) with increasing added salt. Gain to feed ratio and day 27 BW tended (quadratic, $P < 0.064$ and 0.088, respectively) to

Table 8. Effects of increasing salt on growth performance of 11 to 30 kg pig (experiment 2)[1]

	Added salt, %[2]						Probability, *P* <	
Item	0.20	0.35	0.50	0.65	0.80	SEM	Linear	Quadratic
Day 0–14								
ADG, g	527	593	609	634	629	12.1	0.001	0.001
ADFI, g	844	879	889	919	903	15.7	0.001	0.089
G:F, g/kg	625	676	685	691	697	11.2	0.001	0.029
Day 14–27								
ADG, g	806	804	835	814	827	14.9	0.213	0.672
ADFI, g	1,323	1,316	1,360	1,383	1,377	20.2	0.002	0.766
G:F, g/kg	609	611	614	588	601	6.9	0.084	0.819
Day 0–27								
ADG, g	661	695	718	721	723	10.0	0.001	0.005
ADFI, g	1,075	1,089	1,116	1,142	1,129	15.8	0.001	0.211
G:F, g/kg	616	638	643	631	641	6.0	0.024	0.064
Post-treatment period (day 27–34)								
ADG, g	916	879	916	895	881	16.8	0.316	0.884
ADFI, g	1,673	1,700	1,747	1,780	1,764	24.6	0.001	0.272
G:F, g/kg	548	517	525	503	500	7.7	0.001	0.345
BW, kg								
Day 0	11.3	11.3	11.3	11.3	11.3	0.22	0.875	0.894
Day 14	18.7	19.6	19.9	20.2	20.4	0.34	0.001	0.061
Day 27	29.2	30.0	30.7	30.8	31.1	0.45	0.001	0.088
Day 34	35.6	36.2	37.1	37.1	37.3	0.47	0.001	0.112

[1]A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE) were used in a 34-d study with 5 pigs per pen and 12 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 25 d postweaning, then placed on experimental diets.

[2]Experimental diets were fed from day 0 to 27 and a common grower diet was fed from day 27 to 34.

Table 9. Effects of increasing salt for 27 to 65 kg pigs (experiment 3)[1]

Item	Added salt, %				SEM	Probability, $P <$	
	0.10	0.33	0.55	0.75		Linear	Quadratic
Day 0–44							
ADG, g	852	847	851	847	8.3	0.690	0.919
ADFI, g	1,670	1,689	1,712	1,679	34.6	0.734	0.470
G:F, g/kg	512	502	499	506	8.7	0.598	0.337
BW, kg							
Day 0	27.2	27.1	27.1	27.1	0.31	0.205	0.872
Day 44	64.7	64.4	64.6	64.5	0.54	0.855	0.747

[1]A total of 1,188 pigs (PIC 337 × 1050) were used in a 44-d study with 27 pigs per pen and 11 replications per treatment.

increase from 0.20% to 0.80% added salt with the greatest incremental benefit up to 0.50% added salt.

From day 27 to 34, when pigs were fed a common diet, there was no evidence to indicate previous dietary treatments affected ADG. However, pigs previously fed increasing salt had increased ADFI (linear, $P < 0.001$) and poorer (linear, $P < 0.001$) G:F.

For ADG, the QP and BLL models were competing with similar BIC. The predicted response for the QP model was indicated as ADG = 600.44 + 358.82 × (added salt, %) – 258.68 × (added salt, %)^2 with the maximum performance obtained with 0.69% added salt (95% CI [0.45, >0.80%]) while 99% of maximum performance could be obtained with 0.51% added salt. For the BLL model, the breakpoint was at 0.51% with ADG = 722.07 – 187.83 × (0.51 – added salt, %), when added salt < 0.51% and ADG = 721.2 if added salt ≥ 0.51%. For ADFI, the QP, linear, and BLL models were competing with similar BIC with the predicted response for the QP model indicated as ADFI = 1,020.22 + 284.61× (added salt, %) -177.15 × (added salt, %)^2 with the maximum amount tested (0.80%; 95% CI [0.45, > 0.80%]) giving the greatest ADFI, although 99.6% of the performance could be obtained with 0.65% added salt. For the BLL model, the breakpoint was at 0.65% with ADFI = 1135.5 – 139.76 × (0.65 – added salt, %), when salt < 0.65% and ADFI = 1,135.4 if added salt ≥ 0.65%. For G:F, the linear and BLL were competing models with the breakpoint for BLL at 0.35% salt and G:F = 638.57 – 150.04 × (0.35 – added salt, %) when added salt < 0.35% and G:F = 638.0, if added salt ≥ 0.35%.

The QP models would indicate an optimal addition of 0.69% added salt; however, the BLL models would suggest a lower addition of 0.51%. An inclusion of 0.51% salt would obtain 99% performance of the ADG QP model thus giving confidence in the BLL model. The addition of 0.51% salt would have a Na concentration of approximately of 0.22% and a Cl concentration of approximately 0.42%. A Na concentration of 0.22% would be intermediate between the NRC (2012) requirement estimate for 11 to 25 kg pigs (0.28%) and the NRC (2012) requirement estimate for 25 to 75 kg pigs (0.10%). A Cl concentration of 0.42% is significantly greater than the NRC (2012) estimate for both 11 to 25 kg pigs (0.32%) and 25 to 75 kg pigs (0.08%).

While independently evaluating Na and Cl with 8.5 to 19.7 kg pigs, Honeyfield and Froseth (1985) observed improved ADG up to a Na concentration of 0.11% and no improvements beyond Cl concentration of 0.10% in corn-soybean meal diets with added ammonium chloride and sodium tripolyphospahtae. A Na and Cl concentration of 0.11% and 0.10%, respectively would be significantly lower than the Na (0.22%) and Cl (0.42%) concentration associated with 0.51% added salt. However, in the present experiment, salt was used instead of ammonium chloride and triployphosphate. Also, the models predicting the optimal salt inclusion are based on the BW range of 11.3 to 30.4 kg pigs whereas the BW range of the pigs in the experiment conducted by Honeyfield and Froseth (1985) was 8.5 to 19.7 kg. Hagsten and Perry (1976) observed improvements in ADG up to 0.13% added salt in corn-soybean meal diets for 12 to 24 kg pigs and 0.14% added salt in diets for 17 to 32 kg pigs. Alcantara et al. (1980) also observed improvements in ADG up to 0.14% added salt (0.089% Na) in 9.5 to 25.0 kg pigs. A Na concentration of 0.089% would be significantly lower than the 0.22% Na associated with 0.51% added salt and would be significantly lower than the optimal salt inclusion determined in our experiment.

Experiment 3

From day 0 to 44, there was no evidence of difference to indicate that ADG, ADFI, G:F or d 44

BW improved beyond 0.10% added salt (Table 9). According to the chemical analysis, the 0.10% added salt diet had a Na concentration of 0.11% and a Cl concentration of 0.26%. A Na concentration of 0.11% would be similar to the NRC (2012) Na estimate for 25 to 75 kg pigs (0.10%). A Cl concentration of 0.26% would be significantly greater than the NRC (2012) requirement estimate for 25 to 75 kg pigs (0.08%).

Honeyfield et al. (1985) noted improvement in ADG of 36 to 89 kg pigs up to Cl concentration of 0.18% and no improvements beyond a Na concentration of 0.08%, in corn-soybean meal diets with added sodium tripolyphosphate and ammonium chloride. A Na concentration of 0.18% would be slightly greater than the Na concentration of 0.11% in our lowest added salt diet. A Cl concentration of 0.08% would be significantly lower than the Cl concentration of the 0.10% added salt diet (0.26%). Previous research conducted by Alcantara et al. (1980) indicted an optimal inclusion of 0.08% salt (0.065% Na) in diets for 25 to 50 kg pigs, which is similar to the optimal level observed in our experiment. Hagsten et al. (1976) also observed an optimal level of 0.10% added salt in diets for 18 to 91 kg pigs.

The NRC (2012) Na and Cl estimates are based on the results of Na, Cl, and added salt studies. By independently evaluating Na and Cl, researchers have been able to predict the requirement estimate of the pig for each ion independently. It is important to note that in our studies Na and Cl were not independently evaluated but rather in the form of added salt. In added salt diets, Na could be considered the limiting ion because the Na and Cl requirements are similar and salt is composed of approximately 39% Na and 61% Cl. Because Na is the limiting ion, a lower inclusion of salt is needed to meet the Cl requirement but a higher inclusion is needed to meet the Na requirement. Thus, if the NRC (2012) Na and Cl estimates are accurate, optimal amounts of salt will meet the pig's Na requirement and exceed the Cl requirement. This would suggest that when titrating added salt, performance will increase with increasing Na and Cl concentrations until the Cl requirement of pig is met and then any additional performance observed would be due to meeting the pig's Na requirement. This is supported by results of our study in which the diets that met the NRC (2012) Na requirement estimate and exceeded the Cl requirement estimate for the appropriate BW range had optimal growth performance compared to diets that were deficient in Na or Cl.

In conclusion, the BLL models for ADG suggest pigs weighing 7 to 10 and 11 to 30 kg, required 0.59% (0.34% Na and 0.58% Cl) and 0.51% added salt (0.22% Na and 0.42% Cl), respectively. There was no evidence to indicate that growth of 27 to 65 kg pigs was improved beyond 0.10% (0.11% Na and 0.26% Cl) added salt.

LITERATURE CITED

Alcantara, P. F., L. E. Hanson, and J. D. Smith. 1980. Sodium requirements, balance and tissue composition of growing pigs. J. Anim. Sci. 50:1092–1101. doi:10.2527/jas1980.5061092x

AOAC. 2000. Official methods of analysis AOAC International. 17th ed. Gaithersburg (MD): Assoc. Anal. Chem.

AOAC. 2006. Official methods of analysis AOAC International. 18th ed. Gaithersburg (MD): Assoc. Anal. Chem.

Campbell, C. R., and C. O. Plank. 1991. Sample Preparation. In: C. Owen Plank, editor. Plant analysis reference procedures for the southern region of the United States. Raleigh (NC): North Carolina Department of Agriculture. Southern Cooperative Series Bulletin #368. p. 1–11. www.ncagr.gov/agronomi/saaesd/scsb394.pdf

Gonçalves, M. A., N. M. Bello, S. S. Dritz, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, and R. D. Goodband. 2016. An update on modeling dose-response relationships: accounting for correlated data structure and heterogeneous error variance in linear and nonlinear mixed models. J. Anim. Sci. 94:1940–1950. doi:10.2527/jas.2015-0106

Hagsten, I., T. R. Cline, T. W. Perry, and M. P. Plumlee. 1976. Salt supplementation of corn-soy diets for swine. J. Anim. Sci. 42:12–15.doi: 10.2527/jas1976.42112x

Hagsten, I. B., and T. W. Perry. 1976. Evaluation of dietary salt levels for swine. II effect on blood and excretory patterns. J. Anim. Sci. 42:1191–1195. doi:10.2527/jas1976.4251187

Honeyfield, D. C., and J. A. Froseth. 1985. Effects of dietary sodium and chloride on growth, efficiency of feed utilization, plasma electrolytes and plasma basic amino acids in young pigs. J. Nutr. 115:1366–1371. doi:10.1093/jn/115.10.1366

Honeyfield, D. C., J. A. Froseth, and R. J. Barke. 1985. Dietary sodium and chloride levels for growing-finishing pigs. J. Anim. Sci. 60:691–698. doi:10.2527/jas1985.603691x

Kalra, Y. P., and D. G. Maynard. 1991. Chloride plant analysis. In: Methods manual for forest soil and plant analysis. Edmonton (Alberta): For Can., Northwest Reg., North. For. Cent.. Inf. Rep. NOR-X-319, p. 103–106.

Kovar, J. L. 2003. Method 6.3 Inductively coupled plasma spectroscopy. In John Peters, editor. Recommended methods of manure analysis. Madison: University of Wisconsin-Extension, WI publication A3769. p. 41–43.

Mahan, D. C., E. A. Newton, and K. R. Cera. 1996. Effect of supplemental sodium chloride, sodium phosphate, or hydrochloric acid in starter pig diets containing dried whey. J. Anim. Sci. 74:1217–1222. doi:10.2527/1996.7461217x

Mahan, D. C., T. D. Wiseman, E. Weaver, and L. Russell. 1999. Effect of supplemental sodium chloride and hydrochloric acid added to initial starter diets containing spray-dried blood plasma and lactose on resulting performance and nitrogen digestibility of 3-week-old weaned pigs. J. Anim. Sci. 77:3016–3021. doi:10.2527/1999.77113016x

Mills, H., A. Jones Jr., and J. Benton. 1991. Chlorine (Cl). In Plant analysis handbook II. Athens (GA): MicroMacro Publishing, Inc., p. 39–41.

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. Washington (DC): Natl. Acad. Press.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Washington (DC): Natl. Acad. Press.

Raftery, A. E. 1996. Approximate Bayes factors and accounting for model uncertainty in generalized linear regression models. Biometrika. 83:251–266. doi:10.1093/biomet/83.2.251

Wolf, A., M. Watson, and N. Wolf. 2003. Method 5.4 Nitric and Hydrochloric acid digestion with peroxide. In John Peters, editor. Recommended methods of manure analysis. Madison: University of Wisconsin-Extension, WI publication A3769. p. 35–36.