Effects of sodium and chloride source and concentration on nursery pig growth performance[1]

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ABSTRACT: Three studies were conducted to determine the effects of source and concentration of Na and Cl on pig growth performance from 7 to 12 kg. In all three experiments, pigs were fed a common diet (0.33% Na and 0.77% Cl) for 7 or 8 d after weaning then randomly assigned to dietary treatments. In Exp. 1, 360 mixed-sex pigs were used in a 14-d study with 15 replications per treatment and six pigs per pen. Treatments included a 10% dried whey diet with 0.60% added salt (0.37% Na and 0.75% Cl); or three diets with 7.2% crystalline lactose with either: 0.35% added salt (0.18% Na and 0.47% Cl); 0.78% added salt (0.35% Na and 0.72% Cl); or 1.15% $NaHCO_3$ and 0.40% KCl (0.35% Na and 0.45% Cl). Pigs fed the 0.78% added salt-lactose diet had greater ($P < 0.05$) ADG than pigs fed the 0.35% added salt-lactose diet, with others intermediate. In Exp. 2, 360 barrows were used in a 14-d study with 12 replications per treatment and five pigs per pen. Treatments included two added salt diets (providing 0.13% Na and 0.35% Cl or 0.35% Na and 0.68% Cl), three diets with Na and Cl provided by KCl and $NaHCO_3$ (0.13%, 0.35%, or 0.57% Na and 0.50% Cl), or a diet with $NaHCO_3$ and $CaCl_2$ (0.35% Na and 0.50% Cl). Regardless of Na source, ADG and ADFI increased (quadratic, $P < 0.05$) as dietary Na increased from 0.13% to 0.35%, with no further benefits observed thereafter. There was no evidence for differences among pigs fed NaCl or $NaHCO_3$ nor evidence for differences among pigs fed the different Na and Cl sources at similar concentrations. In Exp. 3, 300 pigs were used in a 21-d trial with 10 replications per treatment and five pigs per pen. Treatments included a control diet with added salt to provide 0.33% Na and 0.55% Cl or five diets with 0.33 % Na and added KCl to provide 0.09, 0.21, 0.32, 0.45, or 0.55% Cl. ADG and G:F increased (quadratic, $P < 0.035$) as Cl increased from 0.09% to 0.32%. Pigs fed the control diet (added salt) and the 0.55% Cl diet had similar ADG. For ADG and ADFI, the broken line linear model indicated a breakpoint of 0.23% Cl. For G:F, the quadratic polynomial model suggested the maximum at 0.38% Cl. In conclusion, 7 to 12 kg pigs fed diets that contained at least 0.35% Na and 0.38% Cl had greater ADG and G:F compared to pigs fed diets with lower concentrations and minimal effects were observed among the sources of Na or Cl used in these studies.

Key words: chloride, pig, salt, sodium

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INTRODUCTION

Two of the most common electrolytes found in the body are Na and Cl. Each mineral has several specific roles including maintaining homeostasis of water and electrolytes and acid–base balance.

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Sodium regulates cellular osmolarity and plasma volume and is critical in cellular transport systems, muscle contraction, and nerve impulse. Chloride is a component of HCl, which is critical in the activation of pepsin. The NRC (1998) requirement estimates for Na and Cl are 0.20% and 0.20% for 5 to 10 kg pigs and 0.15% and 0.15% for 10 to 20 kg pigs. While evaluating Na and Cl independently, Mahan et al. (1996) observed improvements in ADG up to a dietary Na and Cl concentrations of 0.34% and 0.50% in pigs weighing ~6 to 9 kg. Mahan et al. (1999) noted improvements in ADG up to a dietary Cl concentration of 0.45% in 7 to 12 kg pigs; however, in two additional studies, improvements in ADG and N retention were observed up to a dietary Cl concentration of only 0.32% and 0.38% in pigs weighing ~6 to 13 kg. Based on these findings and others, the NRC (2012) increased the Na and Cl requirement estimates of 7 to 11 kg pigs to 0.35% and 0.45%. More recently, Shawk et al. (2018) observed that 0.59% added salt (0.34% Na and 0.58% Cl) maximized ADG of 7 to 10 kg pigs. A Na concentration of 0.34% is similar to the NRC (2012) requirement estimate of 0.35%; however, a Cl concentration of 0.58% is significantly greater than the NRC (2012) requirement estimate of 0.45%. When Na and Cl are independently evaluated, an accurate requirement estimate for each electrolyte can be determined; however, there is limited research available that documents how the dietary source of the Na and Cl influences the requirement. Therefore, the objective of these experiments was to evaluate the effects of source and concentration of Na and Cl on the growth performance of nursery pigs weighing ~7 to 12 kg.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. Pigs were weaned at ~21 d of age and at this time, randomly allotted to pens. Each pen was equipped with a four-hole, dry self-feeder, and a nipple waterer to provide ad libitum access to feed and water. Exps. 1 and 3 were conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Exp. 2 was conducted at the Kansas State University Segregated Early Weaning Research Facility in Manhattan KS. All experimental diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center.

Experiment 1

A total of mixed-sex 360 pigs (Line 241 × 600; DNA, Columbus, NE; initially 6.9 kg) were used in a 14-d study. Pigs were fed a common diet (0.33% Na and 0.76% 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 randomly assigned to one of four dietary treatments with 15 replications per treatment and six pigs per pen. Each pen was 1.5 × 1.2 m providing 0.30 m^2 per pig. Four dietary treatments were used to determine if the source of lactose and the source and concentration of Na and Cl influence growth performance. Source of lactose was of interest because dried whey is a significant source of Na and Cl. The four treatments included a 10% dried whey diet with 0.60% added salt (0.37% Na and 0.75% Cl) and three diets with 7.2% crystalline lactose and either: 0.35% added salt (0.18% Na and 0.47% Cl), 0.78% added salt (0.35% Na and 0.72% Cl), or 1.15% $NaHCO_3$ and 0.40% KCl (0.35% Na and 0.45% Cl; Table 1). Thus, the dried whey diet and the lactose diet containing 0.78% added salt contained similar Na and Cl concentrations. The lactose diet containing $NaHCO_3$ and KCl had similar Na to these diets, but similar Cl content to the lactose diet containing 0.35% added salt. Nutrient values and standardized ileal digestibility coefficients of amino acids used in diet formulation were derived from NRC (2012). Experimental diets were fed for 14 d. Pens of pigs were weighed and feed disappearance was recorded on days 0, 7, and 14 to determine ADG, ADFI, andG:F. Dietary treatments were based on corn and soybean meal and were fed in meal form. Dried whey was replaced with crystalline lactose to equalize the lactose content of each diet, and all diets were formulated to the same net energy concentration. Salt, KCl, or $NaHCO_3$ replaced corn to create the experimental diets.

Experiment 2

A total of 360 barrows (Line 200 × 400; DNA, Columbus, NE; initially 7.1 kg) were used in a 21-d study. Pigs were fed a common diet (0.33% Na and 0.76% Cl) for 8 d after weaning. On day 8 after weaning, considered day 0 in the trial, pens of pigs were blocked by body weight and randomly assigned to one of six dietary treatments with 12 replications per treatment and five pigs per pen. Each pen was 1.2 × 1.2 m providing 0.28 m^2 per pig. Experimental treatments (Table 2) included two added salt diets (providing 0.13% Na and 0.35% Cl or 0.35% Na and 0.68% Cl), three diets with Na and Cl provided

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

Lactose source:	Dried whey	Lactose		
Na source:	0.60%	0.35%	0.78%	$NaHCO_3$
Cl source:	NaCl	NaCl	NaCl	KCl
Na, %	0.37	0.18	0.35	0.35
Cl, %	0.75	0.47	0.72	0.45
Ingredient, %				
Corn	50.36	50.47	49.76	48.59
Soybean meal (48% crude protein)	29.65	29.67	29.66	29.65
Lactose	—	7.20	7.20	7.20
Dried whey	10.00	—	—	—
HP 300[2]	5.00	7.75	7.80	7.88
Choice white grease	1.00	0.90	1.15	1.55
Monocalcium P (21% P)	1.05	1.33	1.33	1.15
Limestone	1.05	1.05	1.05	1.15
Potassium chloride	—	—	—	0.40
Sodium bicarbonate	—	—	—	1.15
Salt	0.60	0.35	0.78	—
Zinc oxide	0.25	0.25	0.25	0.25
Trace mineral premix[3]	0.15	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25	0.25
Phytase[5]	0.02	0.02	0.02	0.02
L-Lysine·HCl	0.30	0.30	0.30	0.30
DL-Methionine	0.18	0.17	0.17	0.17
L-Threonine	0.15	0.16	0.16	0.16
TOTAL	100	100	100	100
Calculated analysis				
Standard ileal digestible AA, %				
Lysine	1.35	1.35	1.35	1.35
Isoleucine:lysine	63	63	63	63
Leucine:lysine	123	123	123	122
Methionine:lysine	35	35	35	34
Methionine and cystine:lysine	58	58	58	57
Threonine:lysine	66	65	65	65
Tryptopahn:lysine	19.0	19.0	19.0	19.0
Valine:lysine	67	68	68	68
Total lysine, %	1.49	1.49	1.49	1.49
Net energy, kcal/kg	2,447	2,448	2,448	2,447
Crude protein, %	22.8	23.2	23.1	23.1
Calcium, %	0.78	0.78	0.78	0.78
Phosphorus, %	0.68	0.69	0.69	0.65
Available phosphorus, %	0.48	0.48	0.48	0.48
Sodium, %	0.37	0.18	0.35	0.35
Chloride, %	0.75	0.47	0.72	0.45
Potassium, %	1.14	1.02	1.01	1.22
dEB, mEq/kg[6]	240	205	207	337
Chemical analysis, %				
DM	88.45	90.12	88.83	89.22
Crude protein	19.51	22.97	20.63	21.50
Sodium	0.37	0.18	0.37	0.37
Chloride	0.67	0.36	0.60	0.35

[1]Experimental diets were fed from days 7 to 21 after weaning.

[2]Hamlet Protein, Findlay, OH.

[3]Provided per kilogram of diet: 27 mg Mn from manganese oxide, 110 mg Fe from iron sulfate, 110 mg Zn from zinc sulfate, 11 mg Cu from copper sulfate, 0.20 mg I from calcium iodate, and 0.20 mg Se from sodium selenite.

[4]Provided per kilogram of diet: 4,409 IU vitamin A, 661 IU vitamin D_3, 18 IU vitamin E, 1.8 mg vitamin K, 3.3 mg riboflavin, 11.0 mg pantothenic acid, 19.8 mg niacin, and 0.02 mg vitamin B_{12}.

[5]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.

[6]Dietary electrolyte balance; calculated as = (Na × 434.98) + (K × 255.74) – (Cl × 282.06).

Table 2. Diet composition, Exp. 2 (as-fed basis)[1]

Na source:	NaCl		NaHCO$_3$				
Cl source:	NaCl		KCl			CaCl$_2$	
Na, %	0.13	0.35	0.13	0.35	0.57	0.35	
Cl, %	0.35	0.68	0.50	0.50	0.50	0.50	Common Phase 3 diet[2]
Ingredient, %							
Corn	54.72	54.72	54.72	54.72	54.72	54.72	60.28
Soybean meal (48% crude protein)[3]	23.36	23.36	23.36	23.36	23.36	23.36	34.65
Dried whey[4]	10.00	10.00	10.00	10.00	10.00	10.00	—
HP 300[5]	5.00	5.00	5.00	5.00	5.00	5.00	—
Choice white grease	0.95	0.95	0.95	0.95	0.95	0.95	1.30
Monocalcium P (21% P)	1.10	1.10	1.10	1.10	1.10	1.10	1.15
Calcium carbonate	0.81	0.81	0.81	0.81	0.81	0.50	0.88
L-Lysine·HCl	0.50	0.50	0.50	0.50	0.50	0.50	0.35
DL-Methionine	0.24	0.24	0.24	0.24	0.24	0.24	0.16
L-Threonine	0.24	0.24	0.24	0.24	0.24	0.24	0.14
L-Tryptophan	0.03	0.03	0.03	0.03	0.03	0.03	0.00
L-Valine	0.12	0.12	0.12	0.12	0.12	0.12	0.04
Trace mineral premix[6]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[7]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[8]	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	—
NaHCO$_3$	—	—	0.18	1.00	1.80	1.00	—
Potassium chloride	—	—	0.48	0.48	0.48	—	—
Calcium chloride	—	—	—	—	—	0.46	—
Salt	0.13	0.68	—	—	—	—	0.65
Sand	2.15	1.60	1.62	0.80	—	1.12	—
Total	100	100	100	100	100	100	100
Calculated analysis							
Standardized ileal digestible AA, %							
Lysine	1.35	1.35	1.35	1.35	1.35	1.35	1.30
Isoleucine:lysine	55	55	55	55	55	55	61
Leucine:lysine	111	111	111	111	111	111	124
Methionine:lysine	37	37	37	37	37	37	35
Methionine and cystine:lysine	58	58	58	58	58	58	58
Threonine:lysine	65	65	65	65	65	65	62
Tryptopahn:lysine	18.7	18.7	18.7	18.7	18.7	18.7	18.5
Valine:lysine	68	68	68	68	68	68	69
Total lysine, %	1.47	1.47	1.47	1.47	1.47	1.47	1.45
Net energy, kcal/kg	2,447	2,447	2,447	2,447	2,447	2,447	2,451
Crude protein, %	20.5	20.5	20.5	20.5	20.5	20.5	22.1
Calcium, %	0.71	0.71	0.71	0.71	0.71	0.71	0.7
Phosphorus, %	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Available phosphorus, %	0.48	0.48	0.48	0.48	0.48	0.48	0.43
Sodium, %	0.13	0.35	0.13	0.35	0.57	0.35	0.28
Chloride, %	0.35	0.68	0.50	0.50	0.50	0.50	0.50
Potassium, %	1.02	1.02	1.26	1.26	1.26	1.02	0.97
Dietary electrolyte balance, mEq/kg[9]	218	221	237	334	428	272	229
Chemical analysis, %							
DM	91.07	87.89	90.26	89.22	88.85	89.34	—
Crude protein	21.52	21.71	22.44	20.88	21.01	19.73	—
Sodium	0.18	0.39	0.19	0.40	0.60	0.39	—
Chloride	0.34	0.61	0.49	0.47	0.47	0.56	—

[1]Experimental diets were fed to pigs from days 7 to 21 after weaning. Sand was removed and replaced with sodium bicarbonate to create the treatment diets. Treatment diets containing 0.18% and 1.80% sodium bicarbonate were manufactured and blended at the feed mill to create the intermediate concentrations.

[2]Sodium and Cl values from NRC (1998) were used for soybean meal. Values for all other ingredients are from NRC (2012).

[3]Common phase 3 diet was fed 7 d following treatment feeding.

[4]Dried whey was analyzed for dietary Na (0.61%) and Cl (1.37%) and analyzed values were used in formulation.

[5]Hamlet Protein, Findlay, OH.

[6]Provided per kilogram of diet: 27 mg Mn from manganese oxide, 110 mg Fe from iron sulfate, 110 mg Zn from zinc sulfate, 11 mg Cu from copper sulfate, 0.20 mg I from calcium iodate, and 0.20 mg Se from sodium selenite.

[7]Provided per kilogram of diet: 4,409 IU vitamin A, 661 IU vitamin D$_3$, 18 IU vitamin E, 1.8 mg vitamin K, 3.3 mg riboflavin, 11.0 mg pantothenic acid, 19.8 mg niacin, and 0.02 mg vitamin B$_{12}$.

[8]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.

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

by $NaHCO_3$ and KCl (0.13%, 0.35%, or 0.57% Na and 0.50% Cl), and a diet with $NaHCO_3$ and $CaCl_2$ (0.35% Na and 0.50% Cl). Nutrient values used in diet formulation were derived from NRC (2012) with the exception of Na and Cl in soybean meal and dried whey. From Na and Cl analysis of ingredients, Shawk et al. (2018) observed the Cl concentration of soybean meal to be closer to 0.02% Cl, which is similar to the NRC (1998) value but much lower than the 0.49% estimated by NRC (2012). Thus, NRC (1998) Na and Cl values for soybean meal were used for diet formulation. Before manufacturing treatment diets, dried whey samples were collected at the mill, pooled, subsampled, and submitted for Na and Cl analysis (Cumberland Valley Analytical Service, Maugansville, MD). Analyzed Na and Cl values for dried whey were then used in diet formulation. Experimental diets were fed for 14 d with a common diet (0.28% Na and 0.50% Cl) fed from days 14 to 21. Pens of pigs were weighed and feed disappearance was recorded every 7 d to determine ADG, ADFI, and G:F. Dietary treatments were corn–soybean meal based and were fed in meal form. Sand was replaced by an equal amount of either salt, KCl, $CaCl_2$, or $NaHCO_3$ to create the treatment diets.

Experiment 3

A total of mixed-sex 300 pigs (Line 241 × 600; DNA, Columbus, NE; initially 7.1 kg) were used in a 21-d growth trial. At weaning, pigs were assigned to pens (1.5 × 1.2 m providing 0.36 m^2 per pig) with five pigs per pen (sex-balanced) and fed a common diet (0.33% Na and 0.77% 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 randomly assigned to one of six dietary treatments with 10 replications per treatment and five pigs per pen. Experimental treatments included a control diet containing 0.33% Na and 0.55% Cl provided by added salt and five diets with 0.33% Na and added KCl to provide 0.09%, 0.21%, 0.32%, 0.45%, or 0.55% Cl (Table 3). Treatment diets were fed for 14 d with a common diet (0.18% Na and 0.49% Cl) fed from days 14 to 21. Nutrient values used in diet formulation were derived from NRC (2012) with the exception of Cl concentration of soybean meal for which the NRC (1998) value was used. Pens of pigs were weighed and feed disappearance was recorded every 7 d to determine ADG, ADFI, and G:F. Dietary treatments were corn–soybean meal-based with 7.2% crystalline lactose and were fed in meal from. Salt, KCl, or $NaHCO_3$ replaced sand to create the different dietary treatments.

Chemical Analysis

In each experiment, diet samples were collected from six to nine feeders, blended, and subsampled. In Exp. 1, samples were submitted to a commercial laboratory for analysis of Na and Cl (Ward Laboratories, Kearney, NE). Briefly, OM and lipids were removed from the samples via HNO_3, HCl, and H_2O_2 (Campbell et al., 1991; Wolf et al., 2003) and then analyzed for Na by inductively coupled plasma spectroscopy (Kovar, 2003). The Cl concentrations were determined by the titration of sliver nitrate until all Cl ions were precipitated and then the concentration of free silver ions was determined by using a Metrohm 855 Robitic Titrosampler and a Metrohm 6.0430.100 Ag Titrode (Metrohm USA Inc., Riverview, FL; AOAC 969.10, 1990; Kalra et al., 1991; Mills et al., 1991). Samples from Exps. 2 and 3 were also submitted to a commercial laboratory for Na and Cl analysis (Cumberland Valley Analytical Service, Maugansville, MD). Sodium samples were ashed, digested with HNO_3 and then analyzed via inductively coupled plasma emission spectroscopy (Perkin Elmer 5300 DV ICP, Perkin Elmer, Shelton, CT; AOAC 985.01, 2000). Chloride samples were extracted with HNO_3 and then analyzed via potentiometric titration with sliver nitrate 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 CP (Method 990.03; Kansas State University 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. In all studies, data were analyzed using PROC GLIMMIX in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. The statistical model contained the fixed effect of dietary treatment and the random effect of BW block. Results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

For Exp. 1, treatment means were separated with the Tukey–Kramer multiple comparison adjustment. For Exp. 2, preplanned contrasts were used to determine the linear and quadratic response of increasing Na concentration. Preplanned contrasts were also used to determine the source and concentration effect of Na and Cl: (1) 0.13% Na and 0.35% Cl diet provided by added salt vs. 0.35% Na and 0.68% Cl diet provided by added salt; (2) 0.35% Na and 0.50% Cl diet provided by $NaHCO_3$

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

Item	Chloride, %					0.78% added salt	Common phase 3 diet[2]
	0.09	0.21	0.32	0.45	0.55		
Ingredient, %							
Corn	47.41	47.41	47.41	47.41	47.41	47.41	62.92
Soybean meal (48% crude protein)[3]	29.82	29.82	29.82	29.82	29.82	29.82	33.68
Lactose	7.20	7.20	7.20	7.20	7.20	7.20	—
HP 300[4]	7.80	7.80	7.80	7.80	7.80	7.80	—
Choice white grease	1.95	1.95	1.95	1.95	1.95	1.95	—
Monocalcium P (21% P)	1.10	1.10	1.10	1.10	1.10	1.10	1.15
Limestone	1.30	1.30	1.30	1.30	1.30	1.30	0.95
L-Lysine·HCl	0.30	0.30	0.30	0.30	0.30	0.30	0.30
DL-Methionine	0.17	0.17	0.17	0.17	0.17	0.17	0.12
L-Threonine	0.16	0.16	0.16	0.16	0.16	0.16	0.12
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	—
Trace mineral premix[5]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[6]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[7]	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sand	0.98	0.73	0.49	0.23	—	1.35	—
Potassium chloride	—	0.25	0.49	0.75	0.98	—	—
Sodium bicarbonate	1.15	1.15	1.15	1.15	1.15	—	—
Salt	—	—	—	—	—	0.78	0.35
Total	100	100	100	100	100	100	100
Calculated analysis							
Standardized ileal digestible AA, %							
Lysine	1.35	1.35	1.35	1.35	1.35	1.35	1.24
Isoleucine:lysine	63	63	63	63	63	63	63
Leucine:lysine	122	122	122	122	122	122	129
Methionine:lysine	35	35	35	35	35	35	33
Methionine and cystine:lysine	58	58	58	58	58	58	57
Threonine:lysine	65	65	65	65	65	65	63
Tryptopahn:lysine	19	19	19	19	19	19	19
Valine:lysine	67	67	67	67	67	67	69
Total lysine, %	1.49	1.49	1.49	1.49	1.49	1.49	1.39
Net energy, kcal/kg	2,446	2,446	2,446	2,446	2,446	2,446	2,403
Crude protein, %	23.0	23.0	23.0	23.0	23.0	23.0	21.7
Calcium, %	0.82	0.82	0.82	0.82	0.82	0.82	0.70
Phosphorus, %	0.68	0.68	0.68	0.68	0.68	0.68	0.65
Available phosphorus, %	0.51	0.51	0.51	0.51	0.51	0.51	0.43
Sodium, %	0.33	0.33	0.33	0.33	0.33	0.33	0.18
Chloride, %	0.09	0.21	0.32	0.45	0.55	0.55	0.49
Potassium, %	1.01	1.14	1.26	1.40	1.51	1.01	0.96
Dietary electrolyte balance, mEq/kg[8]	375	375	375	375	374	244	185
Chemical analysis, %							
DM	88.31	88.38	89.31	88.89	89.06	88.63	—
Crude protein	21.21	20.14	22.72	22.28	22.07	21.96	—
Sodium	0.32	0.30	0.30	0.28	0.42	0.26	—
Chloride	0.15	0.24	0.32	0.46	0.45	0.47	—

[1]Experimental diets were fed from days 7 to 21 after weaning.

[2]Common phase 3 diet was fed 7 d following treatment feeding.

[3]Sodium and Cl values from NRC (1998) were used for soybean meal. Values for all other ingredients are from NRC (2012).

[4]Hamlet Protein, Findlay, OH.

[5]Provided per kilogram of diet: 27 mg Mn from manganese oxide, 110 mg Fe from iron sulfate, 110 mg Zn from zinc sulfate, 11 mg Cu from copper sulfate, 0.20 mg I from calcium iodate, and 0.20 mg Se from sodium selenite.

[6]Provided per kilogram of diet: 4,409 IU vitamin A, 661 IU vitamin D_3, 18 IU vitamin E, 1.8 mg vitamin K, 3.3 mg riboflavin, 11.0 mg pantothenic acid, 19.8 mg niacin, and 0.02 mg vitamin B_{12}.

[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).

and KCl vs. 0.35% Na and 0.50% Cl diet provided by $NaHCO_3$ and $CaCl_2$; (3) 0.13% Na and 0.50% Cl diet provided by $NaHCO_3$ and KCl vs. 0.13% Na and 0.35% Cl diet provided by added salt; and (4) 0.35% Na and 0.50% Cl diet provided by $NaHCO_3$ and KCl vs. 0.35% Na and 0.50% Cl diet provided by $NaHCO_3$ and $CaCl_2$ vs. 0.35% Na and 0.68% Cl diet provided by added salt.

For Exp. 3, linear and quadratic contrasts were used to evaluate increasing Cl. Additionally, the 0.78% added salt control and 0.55% Cl treatment provided by KCl were compared. Chloride dose–response curves for ADG, ADFI, and G:F were predicted following the procedure described by Goncalves et al. (2016) and using PROC GLIMMIX and PROC NLMIXED in SAS (SAS Institute, Inc., Cary, NC). Linear, quadratic polynomial (**QP**), broken-line linear (**BLL**), and broken-line quadratic were the dose–response models that were evaluated. The best-fitting model was determined by using the Bayesian Information Criterion (**BIC**) with a decrease of two or more units indicating a better fit (Raftery, 1996). Models accounting for heterogeneous residual variances were used when they improved model fit. For the best-fitting models, the response curves and individual pen means were plotted. The breakpoints and 95% CI were reported for the BLL models. The maximum response and 95% CI were reported for the QP model. The CI of the QP model was calculated by plotting the regression equation with the 95% CI across doses and projecting the maximum response across the *y*-axis via 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 (Goncalves et al., 2016).

RESULTS AND DISCUSSION

Chemical Analysis

For Exp. 1, chemical analysis indicated that the dietary Na concentration of the treatment diets was similar to formulated values, but the analyzed Cl concentrations were slightly less than formulated (Table 1). From Na and Cl analysis of ingredients, Shawk et al. (2018) observed the Cl concentration of soybean meal to be closer to 0.02% Cl, which is similar to the NRC (1998) value, but much lower than the 0.49% estimated by NRC (2012). This explained the discrepancy between formulated and analyzed Cl values. For Exp. 2, results of the chemical analysis indicated that Na concentration of the diets was slightly greater than formulated values but followed similar patterns as the designed treatment structure (Table 2). Dietary Cl concentrations were similar to the calculated values. For Exp. 3, chemical analysis indicated that the dietary Na and Cl concentrations of the treatment diets were reasonably similar to formulated values (Table 3).

Experiment 1

From days 0 to 14, pigs fed the 0.78% added salt-lactose diet had greater ($P < 0.05$) ADG than pigs fed the 0.35% added salt-lactose diet, with intermediate performance observed for pigs fed the 0.60% added salt-dried whey diet and 1.15% $NaHCO_3$ and 0.40% KCl-lactose diet (Table 4). Pigs fed the 0.60% added salt-dried whey diet had greater ADFI ($P < 0.05$) compared to those fed the 0.35% added salt-lactose diet, with pigs fed the other treatments intermediate. There was no evidence to indicate that dietary treatment influenced G:F or final BW.

Table 4. Effects of Na and Cl source and concentration on nursery pig performance, Exp. 1[1]

Lactose source:	Dried whey	Lactose			
Na source: Cl source:	0.60% NaCl	0.35% NaCl	0.78% NaCl	NaHCO KCl	
Na, %	0.37	0.18	0.35	0.35	
Cl, %	0.75	0.47	0.72	0.45	SEM
Days 0 to 14					
ADG, g	281[ab]	251[b]	287[a]	270[ab]	9.5
ADFI, g	445[a]	390[b]	427[ab]	408[ab]	11.2
G:F, g/kg	631	643	671	661	13.1
BW, kg					
Day 0	6.9	6.9	6.9	6.9	0.06
Day 14	10.9	10.5	11.0	10.7	0.15

[ab]Means with common superscripts differ ($P < 0.05$).

[1]A total of 360 barrows (Line 241 × 600; DNA, Columbus, NE) were used in a 14-d study with six pigs per pen and 15 pens per treatment. Pigs were weaned at ~21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets.

The NRC (2012) Na and Cl requirement estimates for 7 to 11 kg pigs are 0.35% and 0.45%, respectively. Based on the chemical analysis, the 0.78% added salt-lactose diet (analyzed 0.37% Na and 0.60% Cl) and 0.60% added salt-dried whey diet (analyzed 0.37% Na and 0.67% Cl) met the NRC (2012) requirement estimate for Na and exceeded the Cl requirement estimate. The $NaHCO_3$ and KCl diet (analyzed 0.37% Na and 0.35% Cl) would have met the NRC (2012) requirement estimate for Na; however, it would be considered deficient in Cl based on the chemical analysis, even though the formulated target was to meet the NRC (2012) requirement estimate. The numerically decreased ADG and ADFI of pigs fed the $NaHCO_3$ and KCl diet compared with those fed 0.78% added salt-lactose diet could be due to the Na and Cl source ($NaHCO_3$ and KCl) or a deficiency of Cl. In two separate studies, Mahan et al. (1999) noted improvements in ADG and N retention up to a dietary Cl concentration of 0.32% and 0.38% in corn–soybean meal diets with lactose, spray-dried animal plasma, and added HCl. However, in a different study, Mahan et al. (1999) observed improvements in ADG up to a dietary Cl concentration of 0.45% in corn–soybean meal diets with lactose and spray dried animal plasma and added Na_2PO_4 and HCl. Overall, results of this trial indicate pigs fed an added salt diet that contains a Na concentration of 0.35% and a Cl concentration of 0.60% had greater growth performance compared to pigs fed a diet deficient in Na and Cl based on the NRC (2012) requirement estimate. However, more research is needed to investigate the source effect of Na and Cl and to verify the growth responses to Cl deficiency, which led us to conduct the following two experiments.

Experiment 2

From days 0 to 14 (~7 to 11 kg), ADG and ADFI improved (quadratic, $P < 0.05$) as dietary Na concentration increased from 0.13% to 0.35%, with no further benefits observed thereafter (Table 5). Day 14 BW tended ($P = 0.089$) to increase as dietary Na concentration increased from 0.13% to 0.35%, with no further benefits observed thereafter. G:F was not influenced by the dietary Na concentration. There was no evidence to indicate differences in growth performance due to Na or Cl source.

From days 14 to 21 when pigs were fed a common diet, pigs previously fed increasing Na had decreased (linear, $P < 0.05$) ADG and G:F regardless of Na source. It is likely that pigs previously fed 0.13% Na had compensatory gain compared with pigs previously fed 0.35% Na; however, pigs fed 0.57% Na had consistently poorer growth performance than other treatments during both periods. Previous source and concentration of Cl did not affect subsequent ADG

Table 5. Effects of Na, K, and Cl source and concentrations on nursery pig performance, Exp. 2[1]

Na source:	NaCl		$NaHCO_3$					Probability, $P<$[2]							
Cl source:	NaCl		KCl			$CaCl_2$		$NaHCO_3$ and KCl		Na					
Na, %	0.13	0.35	0.13	0.35	0.57	0.35									
Cl, %	0.35	0.68	0.50	0.50	0.50	0.50	SEM	Linear	Quadratic	Linear	Quadratic	1	2	3	4
Days 0 to 14[3]															
ADG, g	307	316	287	301	281	314	11.8	0.726	0.262	0.273	0.038	0.587	0.430	0.232	0.877
ADFI, g	403	410	382	398	378	404	10.8	0.785	0.163	0.259	0.039	0.654	0.706	0.159	0.682
G:F, g/kg	762	770	750	751	744	777	16.3	0.795	0.827	0.542	0.222	0.713	0.239	0.591	0.737
Days 14 to 21 (post-treatment)															
ADG, g	556	487	540	507	494	518	14.6	0.021	0.554	0.002	0.159	0.001	0.549	0.420	0.115
ADFI, g	760	684	705	710	692	726	19.3	0.629	0.634	0.090	0.743	0.007	0.537	0.049	0.124
G:F, g/kg	736	715	767	715	712	714	14.0	0.006	0.154	0.021	0.148	0.290	0.941	0.112	0.945
BW, kg															
Day 0	7.1	7.1	7.1	7.1	7.1	7.1	0.08	0.601	0.955	0.797	0.998	0.846	0.684	0.549	0.831
Day 14	11.4	11.5	11.1	11.3	11.1	11.5	0.18	0.887	0.390	0.568	0.089	0.617	0.403	0.206	0.907
Day 21	15.4	14.9	14.9	14.8	14.6	15.1	0.22	0.319	0.663	0.036	0.516	0.137	0.328	0.093	0.511

[1]A total of 360 barrows (Line 200 × 600; DNA, Columbus, NE) were used in a 14-d study with five pigs per pen and 12 pens per treatment. Pigs were weaned at ~21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets.

[2]Contrasts were (1) 0.13% Na and 0.35% Cl provided by added salt vs. 0.35% Na and 0.68% Cl provided by added salt (2) 0.35% Na and 0.50% Cl provided by $NaCHCO_3$ and KCl vs. 0.35% Na and 0.50% Cl provided by $NaHCO_3$ and $CaCl_2$, (3) 0.13% Na and 0.50% Cl provided by $NaCHCO_3$ and KCl vs. 0.13% Na and 0.35% Cl provided by NaCl, and (4) 0.35% Na and 0.50% Cl provided by $NaHCO_3$ and KCl vs. 0.35% Na and 0.50% Cl provided by $NaHCO_3$ and $CaCl_2$ vs. 0.35% Na and 0.68% Cl provided by NaCl.

[3]Experimental diets were fed from days 0 to 14 and a common phase 3 diet was fed from days 14 to 21.

or G:F. Pigs previously fed 0.13% Na and 0.35% Cl provided by NaCl had increased (P = 0.049) ADFI compared with those previously fed 0.13% Na and 0.50% Cl from $NaHCO_3$ and KCl, potentially due to a compensatory gain from Cl deficiency.

Overall, the most consistent response observed in this experiment was improvement in growth performance up to a Na concentration of 0.35%. This observation is in agreement with the NRC (2012) requirement estimate and confirmed the findings from Exp. 1. In this experiment, there was no evidence to indicate that the source of Na and Cl ion influenced the growth performance of the pigs. However, it is surprising that there were no statistical differences between the two added salt diets (0.13% and 0.35% Na).

Experiment 3

From days 0 to 14 (~7 to 12 kg), ADG, ADFI, G:F, and day 14 BW improved (quadratic, $P < 0.05$) as dietary Cl concentration increased from 0.09% to 0.32% with no further benefits observed thereafter (Table 6). Pigs fed the 0.55% Cl diet had similar ADG, increased (P = 0.046) ADFI, but a tendency for poorer (P = 0.069) G:F compared with pigs fed the control diet with 0.55% Cl from added salt. From days 14 to 21 when pigs were fed a common diet, compensatory gain was observed for pigs previously fed the low-chloride diets. ADG decreased (linear, P = 0.045), ADFI increased (linear, P = 0.033), and G:F decreased (quadratic, P = 0.004) with increasing dietary Cl previously fed from days 0 to 14. Pigs previously fed the 0.55% Cl from KCl diet had greater (P = 0.009) ADFI and tended (P = 0.080) to have poorer G:F than pigs previously fed the diet with 0.55% Cl from added salt. For overall period (days 0 to 21), increasing dietary Cl concentration during days 0 to 14 increased overall ADG (quadratic, P = 0.002) and ADFI (linear, P = 0.002), but did not affect overall G:F. Pigs fed the 0.55% Cl from KCl diet during days 0 to 14 had greater (P = 0.006) overall ADFI but decreased (P = 0.017) overall G:F compared with pigs fed the diet with 0.55% Cl from added salt.

From days 0 to 14, the BLL model was the best fitting model for ADG and ADFI and indicated a breakpoint of 0.23% Cl (Figures 1 and 2). For the ADG BLL model, ADG, g = 357.87 – 619.42 × (0.23 – Cl, %) when Cl < 0.23% and ADG, g = 359.5 when Cl ≥ 0.23%. For the ADFI BLL model, ADFI, g = 494.45 – 415.5 × (0.23 – Cl, %) when Cl < 0.23% and ADFI, g = 495.2 when Cl ≥ 0.23%. The best-fitting model for G:F was the QP

Table 6. Effects of increasing Cl for 7 to 12 kg nursery pigs on growth performance, Exp. 3[1]

								Probability, P<		
	Chloride, %[2]							0.78% added salt diet vs. 0.55% Cl diet	Cl	
Item	0.09	0.21	0.32	0.45	0.55	0.78% added salt diet[3]	SEM		Linear	Quadratic
Treatment period (days 0 to 14)[4]										
ADG, g	273	348	372	349	356	351	10.0	0.676	0.001	0.001
ADFI, g	436	491	507	477	504	469	13.6	0.046	0.003	0.035
G:F, g/kg	627	712	734	733	708	749	15.8	0.069	0.001	0.001
Post-treatment period (days 14 to 21)										
ADG, g	554	496	522	497	510	489	14.6	0.271	0.045	0.079
ADFI, g	789	818	848	817	860	782	20.9	0.009	0.033	0.652
G:F, g/kg	704	611	614	609	592	624	13.6	0.080	0.001	0.004
Overall (days 0 to 21)										
ADG, g	367	398	422	399	407	397	7.9	0.305	0.001	0.002
ADFI, g	554	600	621	591	623	573	13.5	0.006	0.002	0.095
G:F, g/kg	664	666	680	676	655	692	11.1	0.017	0.836	0.111
BW, kg										
Day 0	7.0	7.1	7.1	7.1	7.1	7.1	0.11	0.997	0.913	0.756
Day 14	10.9	12.0	12.3	12.0	12.1	12.0	0.20	0.674	0.001	0.001
Day 21	14.7	15.4	15.9	15.5	15.6	15.4	0.24	0.362	0.004	0.006

[1]A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE) were used in a 21-d study with five pigs per pen and 10 pens per treatment. Pigs were weaned at ~21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets.

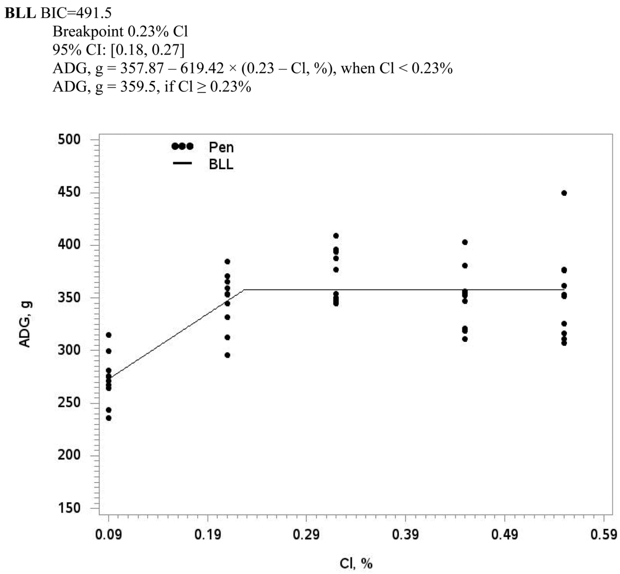
[2]Experimental diets were formulated to a dietary Na concentration of 0.33% with 1.15% sodium bicarbonate and dietary Cl concentrations were formulated with increasing added potassium chloride.

[3]0.78% added salt diet contained 0.33% Na and 0.55% Cl.

[4]Experimental diets were fed from days 0 to 14 and a common phase 3 diet was fed from days 14 to 21.

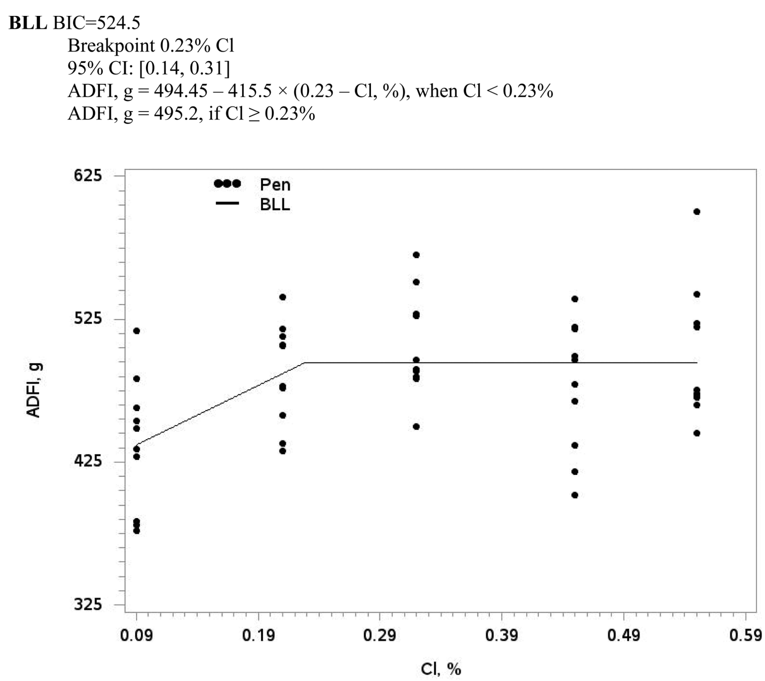
with the predicted response indicated as G:F, g/kg = 549.77 + 1,016.45 × (Cl, %) – 1,331.57 × (Cl, %)^2. The maximum performance was achieved at a Cl concentration of 0.38% (95% CI [0.26, 0.51%]); however, a 0.23% Cl concentration could obtain 96% of the maximum performance (Figure 3). Maximum ADG could be obtained with a Cl concentration of 0.23%; however, this would only capture 96% of the G:F performance. Thus to maximize ADG and G:F, a Cl concentration of 0.38% would be needed. A Cl concentration of 0.38% would be slightly less than the current NRC (2012) Cl requirement estimate of 0.45%. The literature has suggested a wide range of Cl requirements from 0.32% (Mahan et al., 1999) to 0.50% (Mahan et al., 1996) for maximum ADG for pigs of weight range tested in the present study. Our requirement estimate for ADG (0.23%) was considerably less than this range. It is worth noting that the studies conducted by Mahan et al. (1996, 1999) used HCl to increase the dietary Cl concentrations, while KCl was used in this experiment. It is unknown if the difference in Cl source would have contributed to the discrepancy among Cl requirements reported.

In conclusion, results of these studies indicate that 0.35% Na (similar to the NRC, 2012 estimates) appears to optimize ADG in pigs from 7 to 11 kg. The optimal Cl concentration that optimizes ADG was 0.23% and that of G:F was 0.38% which are less than NRC (2012) requirement estimate of 0.45%. Source of Na or Cl had minimal effect on growth performance.



[1] A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE) were used with 5 pigs per pen and 10 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets. Experimental diets were fed for 14 d. Linear polynomial, quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit for the experimental period to estimate the optimal dietary Cl concentration for ADG. Bayesian Information Criterion (BIC) was used to determine the best fitting model.

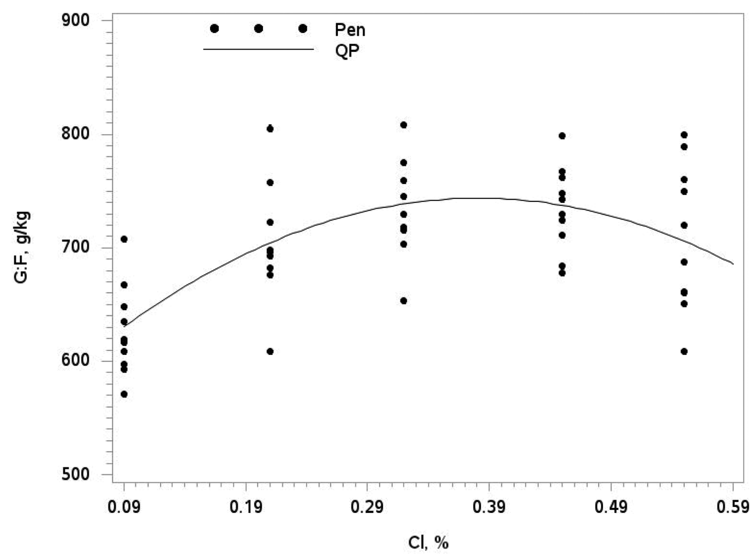
Figure 1. Estimated optimal Cl concentration to maximize ADG for 7 to 12 kg nursery pigs, Exp. 3[1]



[1] A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE) were used with 5 pigs per pen and 10 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets. Experimental diets were fed for 14 d. Linear polynomial, quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit for the experimental period to estimate the optimal dietary Cl concentration for ADFI. Bayesian Information Criterion (BIC) was used to determine the best fitting model.

Figure 2. Estimated optimal Cl concentration to maximize ADFI for 7 to 12 kg nursery pigs, Exp. 3[1]

G:F **QP** BIC=523.4
Predicted maximum response at 0.38% Cl (95% CI: 0.26, 0.51)
96% of maximum at 0.23% Cl
G:F, g/kg = 549.77 + 1,016.45 × (Cl, %) – 1,331.57 × $(Cl, \%)^2$



[1] A total of 300 pigs (Line 241 × 600; DNA, Columbus, NE) were used with 5 pigs per pen and 10 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 7 d post-weaning, then placed on experimental diets. Experimental diets were fed for 14 d. Linear polynomial, quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit for the experimental period to estimate the optimal dietary Cl concentration for G:F. Bayesian Information Criterion (BIC) was used to determine the best fitting model.

Figure 3. Estimated optimal Cl concentration to maximize G:F for 7 to 12 kg nursery pigs, Exp. 3[1]

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