

# Requirement for digestible calcium by 25 to 50 kg pigs at different dietary concentrations of phosphorus as indicated by growth performance, bone ash concentration, and calcium and phosphorus balances<sup>1</sup>

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**ABSTRACT:** Two experiments were conducted to determine the requirement for standardized total tract digestible (STTD) Ca by 25 to 50 kg pigs at different concentrations of STTD P. Twenty corn-soybean meal based diets were formulated with diets containing 4 concentrations of STTD P (0.15, 0.31, 0.39, or 0.47%) and 5 concentrations of STTD Ca (0.13, 0.27, 0.42, 0.57, or 0.72%). Diets were mixed in 1 batch and were used in both experiments. In Exp. 1, 240 pigs (initial average BW: 24.70 ± 1.27 kg) were randomly allotted to the 20 diets in 6 blocks with 1 pen per diet in each block using a 4 × 5 factorial design. There was 1 gilt and 1 barrow in each pen. At the conclusion of the 28 d experiment, all barrows were euthanized and the right femur was collected. Results indicated that there were interactions ( $P < 0.001$ ) between concentration of STTD Ca and concentration of STTD P in diets for ADG, G:F, and bone ash. The predicted maximum ADG at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 0.76, 0.87, 0.90, and 0.92 kg at STTD Ca concentrations of 0.12, 0.36, 0.47, and 0.59%, respectively, which correspond to STTD Ca:STTD P ratios of 0.80:1, 1.16:1, 1.21:1, and 1.26:1. The predicted maximum G:F ratio at the 4 STTD P con-

centrations were 0.43, 0.46, 0.48, and 0.50 kg/kg at STTD Ca concentrations of 0.09, 0.38, 0.52, and 0.67%, respectively, and these values correspond to STTD Ca:STTD P ratios of 0.60:1, 1.23:1, 1.33:1, and 1.43:1. The predicted maximum bone ash at the 4 STTD P concentrations were 14.5, 21.0, 23.1, and 24.5 g at STTD Ca concentrations of 0.41, 0.56, 0.64, and 0.72%, respectively, which correspond to STTD Ca:STTD P ratios of 2.73:1, 1.81:1, 1.64:1, and 1.53:1. In Exp. 2, 120 pigs (initial average BW: 29.45 ± 2.15 kg) were placed in metabolism crates and randomly allotted to the 20 diets in 6 blocks with 1 pig per diet in each block. Fecal and urine samples were collected. Results indicated that the predicted maximum retention of Ca in the body at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 4.7, 7.1, 8.6, and 10.2 g/d at STTD Ca concentrations of 0.77, 0.96, 1.06, and 1.15%, respectively, which correspond to STTD Ca:STTD P ratios of 5.13:1, 3.10:1, 2.72:1, and 2.45:1. These observations indicate that if STTD P meets or exceeds the requirement, the STTD Ca:STTD P ratio needed to maximize ADG and G:F by 25 to 50 kg pigs is between 1.16:1 and 1.43:1. However, a greater ratio may be needed to maximize bone ash or Ca retention.

**Key words:** bone ash, calcium, digestible calcium, growth performance, pigs, requirements

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## INTRODUCTION

Inclusion of excess Ca in diets fed to pigs may increase P excretion due to formation of Ca-P complexes in the intestinal tract (Clark, 1969; Brink et al.,

**Table 1.** Analyzed composition of ingredients, as-fed basis, Exp. 1 and 2

Item	Ingredient					
	Corn	Soybean meal	Calcium carbonate	Monosodium phosphate	Monocalcium phosphate	Sodium chloride
GE, kcal/kg	3810	4199	–	–	–	–
DM, %	85.58	88.33	99.88	99.13	91.59	99.86
Ash, %	1.43	7.55	93.12	91.30	80.34	100.00
CP, %	7.91	48.49	–	–	–	–
Ca, %	0.02	0.52	38.20	0.17	17.10	ND <sup>3</sup>
P, %	0.23	0.63	0.06	24.60	20.60	ND
Na, %	ND	0.02	0.17	20.30	0.25	38.80
Cl, %	ND	0.01	ND	ND	ND	58.52
Phytate, %	0.69	1.60	–	–	–	–
Phytate-bound P, <sup>1</sup> %	0.19	0.45	–	–	–	–
Nonphytate P, <sup>2</sup> %	0.04	0.18	–	–	–	–

<sup>1</sup>Phytate-bound P was calculated as 28.2% of phytate (Tran and Sauvant, 2004).

<sup>2</sup>Nonphytate P was calculated as the difference between total P and phytate-bound P.

<sup>3</sup>ND = not detectable.

1992; Stein et al., 2011). However, if diets are formulated to meet requirements for standardized total tract digestible (STTD) Ca and STTD P, excesses of Ca and P can be minimized and maximum utilization of both minerals is expected. Requirements for STTD P by different categories of pigs have been reported (NRC, 2012), but requirements for STTD Ca have not been published because of a lack of information about Ca digestibility in feed ingredients. However, values for STTD of Ca in some Ca sources have been recently reported (González-Vega et al., 2014, 2015a, 2015b, 2016; Merriman and Stein, 2016), and as a consequence, requirements for STTD Ca in pigs can be determined. An attempt to determine the requirement for STTD Ca by 11 to 25 kg pigs was made (González-Vega et al., 2016), and results indicated that the STTD Ca to STTD P ratio was important in the diet. A negative effect of increasing concentration of dietary STTD Ca was observed for ADG and G:F, and ADG and G:F were maximized at a STTD Ca:STTD P ratio of approximately 1.35:1. However, bone ash and the quantity of Ca and P retained in the body were maximized if the STTD Ca:STTD P ratio was between 1.33:1 and 1.67:1. These ratios are in agreement with the ratio of Ca and P in the body of pigs, which has been reported to be in the range between 1.20:1 and 1.60:1 (Rymarz et al., 1982; Hendriks and Moughan, 1993; Mahan and Shields, 1998; Wiseman et al., 2009; Pettey et al., 2015). There are, however, no estimates for the STTD Ca requirement for 25 to 50 kg pigs. Thus, the present experiments were conducted to predict responses on pig growth performance, Ca and P balances, and bone mineralization to varying dietary concentrations of both STTD Ca and STTD P in diets fed to pigs from 25 to 50 kg.

## MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for 2 experiments. Pigs used in both experiments were the offspring of PIC 359 boars and F-46 sows (Pig Improvement Company, Hendersonville, TN).

### *Experiment 1: Requirements for Digestible Calcium to Maximize Growth Performance and Bone Ash*

**Animals, Diets, and Feeding.** Two hundred and forty pigs (initial average BW: 24.70 ± 1.27 kg) were randomly allotted to 20 diets in 6 blocks with 1 pen per diet in each block using a 4 × 5 factorial design. The Experimental Animal Allotment Program (Kim and Lindemann, 2007) was used to allot pigs to experimental diets. Pen was the experimental unit and there was 1 gilt and 1 barrow in each pen. Room temperature was controlled and each pen had a feeder, a nipple drinker, and a fully slatted concrete floor. Feed and water were available at all times.

Twenty corn-soybean meal based diets were formulated to contain different Ca and P concentrations, but to keep the concentration of phytate constant, all diets contained the same amount of corn and soybean meal (Table 1). Diets were formulated to contain 0.15, 0.31, 0.39, or 0.47% STTD P and 0.18, 0.42, 0.66, 0.90, or 1.14% total Ca, which corresponds to 0.13, 0.27, 0.42, 0.57, or 0.72% STTD Ca, respectively (Tables 2 and 3). Concentrations of P ranged from 48 to 152% of the STTD P requirement (NRC, 2012) and concentrations of Ca ranged from 27 to 173% of the total Ca requirement (NRC, 2012). The concentration of P was increased in the diets by adding increased concentrations of monosodium phosphate (MSP), but to maintain the same Na

**Table 2.** Ingredient composition and analyzed composition of experimental diets containing 0.15 or 0.31% standardized total tract digestible (STTD) P, as-fed basis, Exp. 1 and 2

Ingredient, %	0.15% STTD P					0.31% STTD P					
	Total Ca, %:	0.18	0.42	0.66	0.90	1.14	0.18	0.42	0.66	0.90	1.14
	STTD Ca, %:	0.13	0.27	0.42	0.57	0.72	0.13	0.27	0.42	0.57	0.72
	STTD Ca:STTD P:	0.87:1	1.80:1	2.80:1	3.80:1	4.80:1	0.42:1	0.87:1	1.35:1	1.84:1	2.32:1
Ground corn		65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00
Soybean meal		24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
Cornstarch		8.95	7.13	5.30	3.47	1.63	8.35	6.58	4.78	2.93	1.10
Soybean oil		–	1.20	2.40	3.60	4.80	0.40	1.55	2.73	3.95	5.15
Calcium carbonate		0.03	0.65	1.28	1.91	2.55	0.03	0.65	1.28	1.91	2.55
Monocalcium phosphate		0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Monosodium phosphate		–	–	–	–	–	0.70	0.70	0.70	0.70	0.70
Sodium bicarbonate		1.05	1.05	1.05	1.05	1.05	0.55	0.55	0.54	0.54	0.53
L-Lys HCl		0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
DL-Met		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
L-Thr		0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Sodium chloride		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Vitamin mineral premix <sup>1</sup>		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Total		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition											
NE, kcal/kg		2552	2552	2552	2552	2552	2552	2552	2552	2552	2552
CP, %		16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81
Indispensable SID <sup>2</sup> AA, %											
Arg		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
His		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Ile		0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Leu		1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Lys		0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Met		0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Phe		0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Thr		0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Trp		0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Val		0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
P, %		0.34	0.34	0.34	0.34	0.34	0.51	0.51	0.51	0.51	0.51
Na, %		0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Cl, %		0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
K, %		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Analyzed composition											
DM, %		85.83	86.50	86.61	86.66	86.80	86.64	86.83	86.83	85.21	86.21
CP, %		15.65	15.30	15.46	15.65	16.29	15.88	15.53	16.22	15.38	15.95
Ash, %		3.63	4.02	4.62	5.01	6.45	3.85	5.02	5.28	5.85	6.65
Ca, %		0.18	0.38	0.61	0.90	1.10	0.16	0.44	0.68	0.94	1.16
P, %		0.38	0.36	0.37	0.39	0.38	0.52	0.53	0.52	0.53	0.53
Phytate, <sup>3%</sup>		0.71	0.71	0.71	0.71	0.71	0.67	0.67	0.57	0.57	0.78
Phytate-bound P, %		0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.16	0.16	0.22
Non-phytate P, <sup>4%</sup>		0.18	0.16	0.17	0.19	0.18	0.33	0.34	0.36	0.37	0.31
Na, %		0.37	0.35	0.37	0.36	0.38	0.40	0.36	0.35	0.39	0.33
Cl, %		0.20	0.20	0.19	0.20	0.18	0.20	0.20	0.16	0.18	0.17
DCAD, <sup>5</sup> mEq/kg		297	288	300	292	307	310	292	299	311	288

<sup>1</sup>The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D<sub>3</sub> as cholecalciferol, 2208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B<sub>12</sub>, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg as D-biotin; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

<sup>2</sup>SID = standardized ileal digestible.

<sup>3</sup>Phytate was calculated by dividing the phytate-bound P by 0.282 (Tran and Sauvante, 2004).

<sup>4</sup>Non-phytate P was calculated as the difference between total P and phytate-bound P.

<sup>5</sup>DCAD = dietary cation-anion difference. The DCAD was calculated as Na + K – Cl.

**Table 3.** Ingredient composition and analyzed composition of experimental diets containing 0.39 or 0.47% standardized total tract digestible (STTD) P, as-fed basis, Exp. 1 and 2

Ingredient, %	0.39% STTD P					0.47% STTD P					
	Total Ca, %:	0.18	0.42	0.66	0.90	1.14	0.18	0.42	0.66	0.90	1.14
	STTD Ca, %:	0.13	0.27	0.42	0.57	0.72	0.13	0.28	0.42	0.57	0.72
	STTD Ca:STTD P:	0.33:1	0.69:1	1.08:1	1.46:1	1.85:1	0.28:1	0.60:1	0.89:1	1.21:1	1.53:1
Ground corn		65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00
Soybean meal		24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
Cornstarch		8.13	6.36	4.53	2.70	0.86	7.90	6.13	4.30	2.53	0.63
Soybean oil		0.55	1.70	2.90	4.10	5.30	0.70	1.85	3.05	4.20	5.45
Calcium carbonate		0.03	0.65	1.28	1.91	2.55	0.03	0.65	1.28	1.90	2.55
Monocalcium phosphate		0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Monosodium phosphate		1.05	1.05	1.05	1.05	1.05	1.40	1.40	1.40	1.40	1.40
Sodium bicarbonate		0.27	0.27	0.27	0.27	0.27	–	–	–	–	–
L-Lys HCl		0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
DL-Met		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
L-Thr		0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Sodium chloride		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Vitamin mineral premix <sup>1</sup>		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Total		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition											
NE, kcal/kg		2552	2552	2552	2552	2552	2552	2552	2552	2552	2552
CP, %		16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81	16.81
Indispensable SID <sup>2</sup> AA, %											
Arg		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
His		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Ile		0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Leu		1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Lys		0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Met		0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Phe		0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Thr		0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Trp		0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Val		0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
P, %		0.59	0.59	0.59	0.60	0.59	0.68	0.68	0.68	0.68	0.68
Na, %		0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Cl, %		0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
K, %		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Analyzed composition											
DM, %		85.68	85.38	86.51	86.44	85.99	86.16	86.32	86.44	86.90	87.12
CP, %		14.82	15.85	15.76	15.88	15.55	16.59	15.27	15.92	15.69	16.27
Ash, %		3.99	4.84	5.80	5.96	6.54	4.21	4.96	5.68	6.72	6.92
Ca, %		0.20	0.42	0.64	0.87	1.25	0.18	0.45	0.62	1.03	1.27
P, %		0.59	0.65	0.64	0.65	0.59	0.67	0.70	0.72	0.73	0.79
Phytate, <sup>3%</sup>		0.78	0.78	0.78	0.85	0.78	0.71	0.71	0.78	0.78	0.78
Phytate-bound P, %		0.22	0.22	0.22	0.24	0.22	0.20	0.20	0.22	0.22	0.22
Non-phytate P, <sup>4%</sup>		0.37	0.43	0.42	0.41	0.37	0.47	0.50	0.50	0.51	0.57
Na, %		0.36	0.40	0.38	0.37	0.36	0.36	0.41	0.34	0.35	0.37
Cl, %		0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.16	0.16	0.17
DCAD, <sup>5</sup> mEq/kg		301	310	301	297	292	292	314	295	299	305

<sup>1</sup>The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D<sub>3</sub> as cholecalciferol, 2208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B<sub>12</sub>, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg as D-biotin; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

<sup>2</sup>SID = standardized ileal digestible.

<sup>3</sup>Phytate was calculated by dividing the phytate-bound P by 0.282 (Tran and Sauvant, 2004).

<sup>4</sup>Non-phytate P was calculated as the difference between total P and phytate-bound P.

<sup>5</sup>DCAD = dietary cation-anion difference. The DCAD was calculated as Na + K – Cl.

concentration among diets, inclusion of sodium bicarbonate was reduced as MSP increased in the diets.

#### **Growth Performance and Bone Measurements.**

Pig weights were recorded on d 1 and 28. Pigs were allowed ad libitum access to feed and the amount of feed offered each day was recorded. To calculate feed intake, the amount of feed in the feeders on d 28 was subtracted from the total amount of feed offered. On d 28, all barrows were euthanized via captive bolt stunning. Stomach contents were immediately collected to measure pH. The right femurs were removed, cleaned, and stored at  $-20^{\circ}\text{C}$ . The frozen bones were later thawed, broken, and soaked in petroleum ether under a chemical hood for 72 h to remove bone marrow and fat. Bones were dried overnight at  $130^{\circ}\text{C}$  and then ashed at  $600^{\circ}\text{C}$  for 24 h.

**Sample Analysis.** Corn, soybean meal, calcium carbonate, MSP, monocalcium phosphate (MCP), NaCl, and diets were analyzed for DM by oven drying at  $135^{\circ}\text{C}$  for 2 h (Method 930.15; AOAC International, 2007), for ash (Method 942.05; AOAC International, 2007), for Na by flame emission photometry (Method 956.01; AOAC International, 2007), and for Cl by manual titration (Method 9.15.01, 943.01; AOAC, 2006). Ingredients, diets, and bone ash were analyzed for Ca and P by inductively coupled plasma–optical emission spectrometry (ICP–OES; Method 985.01 A, B, and C; AOAC International, 2007) after wet ash sample preparation [Method 975.03 B(b); AOAC International, 2007]. Corn, soybean meal, and diets were analyzed for N using the combustion procedure (Method 990.03; AOAC International, 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ) and CP was calculated as  $\text{N} \times 6.25$ . Corn and soybean meal were analyzed for GE using an isoperibol bomb calorimeter (Model 6300, Parr Instruments, Moline, IL) and for phytic acid (Megazyme method; AB Vista, Ystrad Mynach, UK). Diets were analyzed for phytate-P using a Foss near-infrared spectrometer with the phytate-P levels predicted using AUNIR calibration standards (AB Vista, Memphis, TN). The pH of the stomach content was measured using a pH meter (Oakton pH 11 Standard Portable Meter, Fisher Scientific, Pittsburgh, PA).

**Calculations and Statistical Analyses.** The percentage of phytate-bound P in corn and soybean meal was calculated as 28.2% of phytate (Tran and Sauvant, 2004). The percentage of phytate in diets was calculated by dividing the analyzed phytate-bound P by 0.282, and non-phytate P was calculated by subtracting the amount of phytate-bound P from total P. Dietary cation-anion difference (DCAD) was calculated using the following equation:

$$\text{DCAD, mEq/kg} = \frac{[\text{Na} \times 10000]}{23} + \frac{[\text{K} \times 10000]}{39} - \frac{[\text{Cl} \times 10000]}{35.5}, [1]$$

where Na, K, and Cl are expressed in percentage of inclusion in diet. The ADG, ADFI, and G:F were calculated. Bone ash percentage was calculated by dividing the quantity of bone ash by the quantity of fat-free dried bone and multiplying by 100.

Normality of residuals and identification of outliers were determined by the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Data for BW, ADG, ADFI, G:F, bone ash, bone Ca, bone P, and stomach pH were analyzed using the Proc MIXED of SAS (SAS Inst. Inc., Cary, NC). The fixed effects of the model were dietary concentration of STTD Ca, dietary concentration of STTD P, and the interaction between STTD Ca and STTD P; the random effect was block. Effect of dietary STTD Ca, STTD P, or the interaction between STTD Ca and STTD P were considered significant at  $P \leq 0.05$ . If the interaction or the main effects were significant, the program NLREG version 5.3 (Sherrod, 2002) was used to determine parameter estimates for the surface response model to increasing concentrations of STTD Ca and STTD P as outlined by Khuri and Cornell (1996). The parameter estimates of the model that were not significant ( $P > 0.05$ ) and were not included in a significant interaction were removed from the model and the estimates were recalculated. The surface response full model was:

$$Y = a + b \times \text{STTD Ca} + c \times \text{STTD Ca}^2 + d \times \text{STTD P} + e \times \text{STTD P}^2 + f \times \text{STTD Ca} \times \text{STTD P}, [2]$$

where Y is the dependent variable, a is the intercept, b, c, d, e, and f are the coefficients, and STTD Ca and STTD P are the percentage concentrations of dietary STTD Ca and STTD P. If parameter estimate c was significant ( $P \leq 0.05$ ), the concentrations of STTD Ca at the maximum response values were calculated using the following equation:

$$\text{STTD Ca}_{\text{max}} = \frac{[-f \times \text{STTD P}] - b}{(2 \times c)}, [3]$$

where STTD Ca max is the concentration of STTD Ca at the maximum response and STTD P is the percentage concentration of STTD P in the diet. The maximum response values were, therefore, calculated using the respective model equations with the concentrations of STTD Ca at the maximum response in each concentration of STTD P. The LSMEANS procedure was used to calculate mean values for treatments and the pen was the experimental unit for all analyses.



## Experiment 2. Ca and P Balance

**Animals, Diets, and Feeding.** One hundred and twenty pigs (initial average BW:  $29.45 \pm 2.15$  kg) were randomly allotted to 20 diets in 6 blocks with 1 pig per diet in each block using a  $4 \times 5$  factorial design. The 20 diets used in Exp. 1 were also used in Exp. 2, and the amount of each diet that was needed for both experiments was mixed in 1 batch. Pigs were housed individually in metabolism crates that were equipped with a slatted floor, a feeder, and a nipple drinker. Pigs had free access to water throughout the experiment. Each crate had a screen floor for fecal collection and a urine pan with a urine bucket for total urine collection.

Pigs were fed 3 times the daily maintenance energy requirement (i.e., 197 kcal of ME/kg BW<sup>0.60</sup>; NRC, 2012). The daily allotments of feed were divided into 2 equal meals and provided at 0800 and 1700 h. Pigs were fed each diet for 13 d, the initial 5 d were an adaptation period to the diets and fecal samples were collected quantitatively from the feed provided from d 6 to 11 using the marker-to-marker approach (Adeola, 2001). The beginning of fecal collections was marked by adding a color marker (indigo carmine) to the morning meal on d 6, and the conclusion of fecal collection was marked by adding ferric oxide to the morning meal on d 11. Urine samples were collected every morning from d 6 to d 11 and 50 mL of 6N HCl was added to each bucket after they were emptied. Fecal samples and 20% of the collected urine were stored at  $-20^{\circ}\text{C}$  immediately after collection. Orts collected during the collection period were dried in a forced-air oven at  $65^{\circ}\text{C}$  and feed intake was calculated by subtracting the orts from feed allowance. Blood samples were collected on d 1 and d 13 by jugular venipuncture. Samples were immediately centrifuged and plasma samples were collected and stored at  $-20^{\circ}\text{C}$  for Ca and P analysis.

**Sample Analysis and Statistical Analyses.** Fecal samples were dried in a forced-air oven at  $65^{\circ}\text{C}$  and ground in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) using a 1-mm screen. Fecal samples were analyzed for DM as explained for Exp. 1. Fecal and urine samples were analyzed for Ca and P as explained for Exp. 1. Plasma samples were analyzed for Ca and P (Method 968.08 D(b); AOAC International, 2007). Values for retention of Ca and P were calculated as explained by González-Vega et al. (2013). Data were analyzed using PROC MIXED of SAS and parameter estimates for the surface response model to increasing levels of STTD Ca and STTD P were determined as explained for Exp. 1. For the urine Ca output and urine P output data, the surface response full model was:

$$Y = a + b \times \text{STTD Ca} + c \times \text{STTD Ca}^2 + d \times \text{STTD P} + e \times \text{STTD P}^2 + f \times \text{STTD Ca} \times$$

$$\text{STTD P} + g \times \text{STTD Ca}^2 \times \text{STTD P} + h \times \text{STTD Ca} \times \text{STTD P}^2 + i \times \text{STTD Ca}^2 \times \text{STTD P}^2, [4]$$

where Y is the dependent variable, a is the intercept, b, c, d, e, f, g, h, and i are the coefficients, STTD Ca and STTD P are the percentage concentrations of dietary STTD Ca and STTD P. The concentrations of STTD Ca at the maximum or minimum response values were calculated using the following equation:

$$\text{STTDCa}_{\text{max/min}} = [-(h \times \text{STTD P}^2 + f \times \text{STTD P} + b)] / [2 \times (i \times \text{STTD P}^2 + g \times \text{STTD P} + c)], [5]$$

where STTD Ca max/min is the percentage concentration of STTD Ca at the maximum or minimum response and STTD P is the percentage concentration of STTD P in the diet. The maximum or minimum response values were, therefore, calculated using the respective model equations with the concentrations of STTD Ca at the maximum or minimum response in each concentration of STTD P. Pig was the experimental unit for all analyses.

## RESULTS

### Experiment 1: Requirements for Digestible Ca to Maximize Growth Performance and Bone Ash

All pigs consumed their diets without apparent problems, but 1 gilt and 1 barrow fed the diet containing 0.13% STTD Ca and 0.47% STTD P died from blocks 3 and 4, respectively. The ADG, ADFI, and G:F of the pen for these pigs were adjusted (Lindemann and Kim, 2007). However, values for bone ash, bone Ca, and bone P from the dead barrow were missing.

The maximum BW, ADG, ADFI, and G:F at different dietary concentrations of STTD Ca and STTD P were predicted from the least squares means (Table 4). The predicted maximum BW at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% was 46.0, 49.0, 49.9, and 50.5 kg at STTD Ca concentrations of 0.14, 0.35, 0.45, and 0.56%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.93:1, 1.13:1, 1.15:1, and 1.19:1 (Fig. 1). The predicted maximum ADG at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% was 0.76, 0.87, 0.90, and 0.92 kg at STTD Ca concentrations of 0.12, 0.36, 0.47, and 0.59%, respectively, which correspond to STTD Ca:STTD P ratios of 0.80:1, 1.16:1, 1.21:1, and 1.26:1 (Fig. 2). The predicted maximum ADFI at the 4 STTD P concentrations was 1.80, 1.90, 1.89, and 1.85 kg at STTD Ca concentrations of 0.14, 0.33, 0.43, and 0.52%, respectively, and these values correspond to STTD Ca:STTD P ratios of 0.93:1, 1.06:1, 1.10:1, and 1.11:1 (Fig. 3). The predicted max-

**Table 4.** Least squares means for BW at d 28, and ADG, ADFI, and G:F from d 1 to 28 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P, Exp. 1<sup>1</sup>

Item	STTD Ca, %				
	0.13	0.27	0.42	0.57	0.72
BW, kg <sup>2,3</sup>					
0.15% STTD P	46.96	44.98	42.69	41.15	35.89
0.31% STTD P	47.03	48.68	50.17	49.28	44.47
0.39% STTD P	46.13	48.53	48.43	48.89	48.53
0.47% STTD P	45.42	49.89	49.05	50.84	49.36
ADG, kg <sup>4,5</sup>					
0.15% STTD P	0.80	0.72	0.64	0.58	0.41
0.31% STTD P	0.80	0.86	0.90	0.88	0.71
0.39% STTD P	0.78	0.85	0.85	0.86	0.86
0.47% STTD P	0.69	0.89	0.86	0.93	0.89
ADFI, kg <sup>6,7</sup>					
0.15% STTD P	1.82	1.74	1.66	1.54	1.35
0.31% STTD P	1.81	1.88	1.98	1.90	1.61
0.39% STTD P	1.79	1.88	1.82	1.79	1.78
0.47% STTD P	1.59	1.85	1.79	1.85	1.85
G:F, kg:kg <sup>8,9</sup>					
0.15% STTD P	0.44	0.41	0.39	0.38	0.30
0.31% STTD P	0.44	0.46	0.46	0.46	0.44
0.39% STTD P	0.43	0.45	0.47	0.48	0.49
0.47% STTD P	0.43	0.48	0.48	0.50	0.48

<sup>1</sup>Data are least square means of 6 observations.

<sup>2</sup>Results indicated that BW at different combinations of STTD Ca and STTD P can be described by the following model:  $41.8265 - 3.30995 \times \text{Ca} - 28.9672 \times \text{Ca}^2 + 35.4607 \times \text{P} - 77.1011 \times \text{P}^2 + 76.0425 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>3</sup>Standard error of the within treatments least squared means = 1.37.

<sup>4</sup>Results indicated that ADG at different combinations of STTD Ca and STTD P can be described by the following model:  $0.61476 - 0.20212 \times \text{Ca} - 0.98679 \times \text{Ca}^2 + 1.36823 \times \text{P} - 3.10677 \times \text{P}^2 + 2.92181 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>5</sup>Standard error of the within treatments least squared means = 0.04.

<sup>6</sup>Results indicated that ADFI at different combinations of STTD Ca and STTD P can be described by the following model:  $1.5745 - 0.1117 \times \text{Ca} - 1.41036 \times \text{Ca}^2 + 2.01723 \times \text{P} - 4.76539 \times \text{P}^2 + 3.36731 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

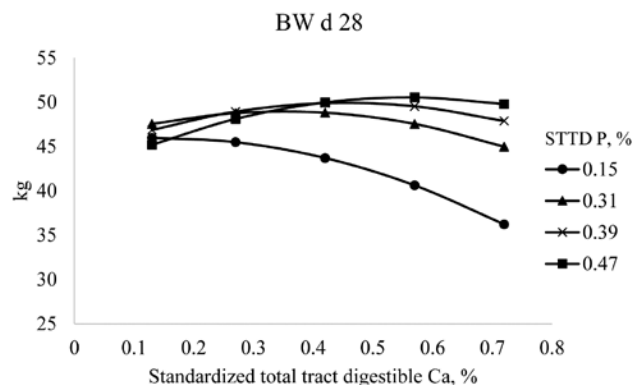
<sup>7</sup>Standard error of the within treatments least squared means = 0.08.

<sup>8</sup>Results indicated that G:F at different combinations of STTD Ca and STTD P can be described by the following model:  $0.3896 - 0.09482 \times \text{Ca} - 0.26695 \times \text{Ca}^2 + 0.35043 \times \text{P} - 0.77095 \times \text{P}^2 + 0.95727 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

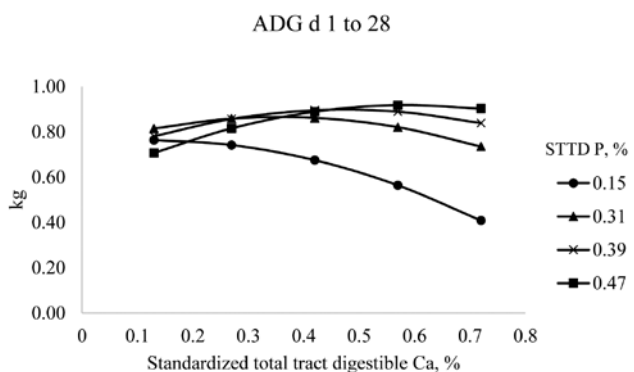
<sup>9</sup>Standard error of the within treatments least squared means = 0.02.

imum G:F at the 4 STTD P concentrations was 0.43, 0.46, 0.48, and 0.50 kg/kg at STTD Ca concentrations of 0.09, 0.38, 0.52, and 0.67%, respectively, which correspond to STTD Ca:STTD P ratios of 0.60:1, 1.23:1, 1.33:1, and 1.43:1 (Fig. 4).

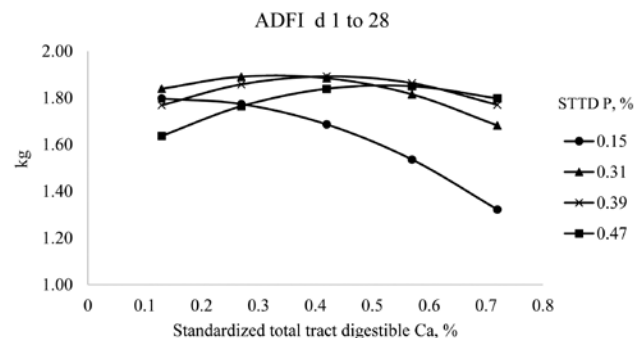
The maximum bone ash, bone Ca, and bone P at different dietary concentrations of STTD Ca and STTD P were predicted from the least squares means (Table 5). The predicted maximum bone ash at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% was 14.5, 21.0, 23.1, and 24.5 g at STTD Ca concentrations of 0.41, 0.56, 0.64, and 0.72%, respectively. These values correspond to STTD Ca:STTD P ratios of



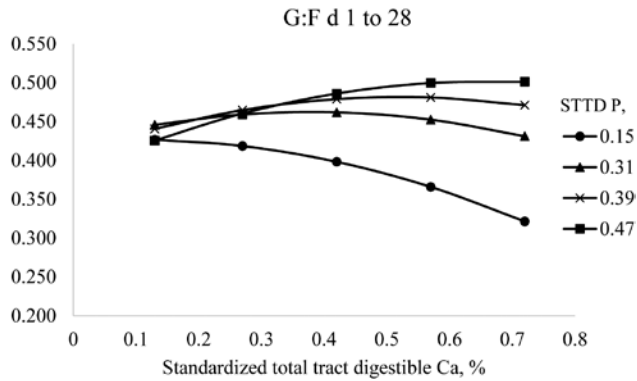
**Figure 1.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for BW at d 28 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum BW at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 46.0, 49.0, 49.9, and 50.5 kg at STTD Ca concentrations of 0.14, 0.35, 0.45, and 0.56%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.93:1, 1.13:1, 1.15:1, and 1.19:1.



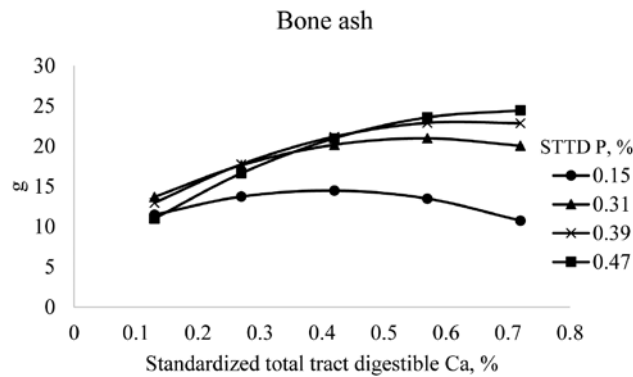
**Figure 2.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for average daily gain (ADG) from d 1 to 28 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum ADG at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 0.76, 0.87, 0.90, and 0.92 kg at STTD Ca concentrations of 0.12, 0.36, 0.47, and 0.59%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.80:1, 1.16:1, 1.21:1, and 1.26:1.



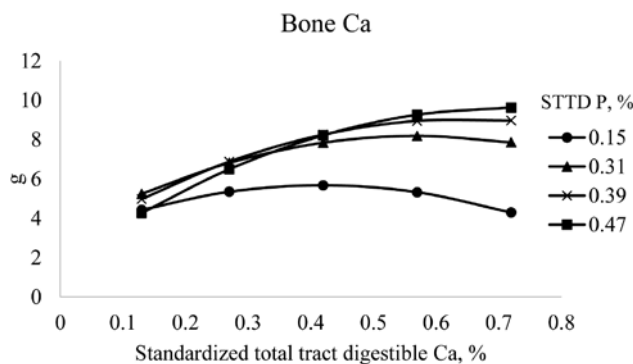
**Figure 3.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for average daily feed intake (ADFI) from d 1 to 28 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum ADFI at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 1.80, 1.90, 1.89, and 1.85 kg at STTD Ca concentrations of 0.14, 0.33, 0.43, and 0.52%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.93:1, 1.06:1, 1.10:1, and 1.11:1.



**Figure 4.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for gain to feed ratio (G:F) from d 1 to 28 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum G:F ratio at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 0.43, 0.46, 0.48, and 0.50 kg/kg at STTD Ca concentrations of 0.09, 0.38, 0.52, and 0.67%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.60:1, 1.23:1, 1.33:1, and 1.43:1.



**Figure 5.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for bone ash (g) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum bone ash at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 14.5, 21.0, 23.1, and 24.5 g at STTD Ca concentrations of 0.41, 0.56, 0.64, and 0.72%, respectively. These values correspond to STTD Ca:STTD P ratios of 2.73:1, 1.81:1, 1.64:1, and 1.53:1.



**Figure 6.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for bone Ca (g) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum bone Ca at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 5.7, 8.2, 9.1, and 9.6 g at STTD Ca concentrations of 0.42, 0.57, 0.65, and 0.73%, respectively. These values correspond to STTD Ca:STTD P ratios of 2.80:1, 1.84:1, 1.67:1, and 1.55:1.

**Table 5.** Least squares means for bone ash, bone Ca, bone P, and stomach pH in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P, Exp. 1<sup>1</sup>

Item	STTD Ca, %				
	0.13	0.27	0.42	0.57	0.72
Bone ash, g <sup>2,3</sup>					
0.15% STTD P	12.49	13.48	12.95	13.11	11.63
0.31% STTD P	13.59	17.44	21.76	21.71	19.49
0.39% STTD P	12.98	15.71	21.14	23.86	22.02
0.47% STTD P	12.44	18.56	20.29	23.67	24.37
Bone Ca, g <sup>4,5</sup>					
0.15% STTD P	4.80	5.30	5.13	5.14	4.63
0.31% STTD P	5.16	6.76	8.49	8.47	7.65
0.39% STTD P	5.02	6.12	8.20	9.24	8.74
0.47% STTD P	4.82	7.26	7.95	9.32	9.58
Bone P, g <sup>6,7</sup>					
0.15% STTD P	2.32	2.51	2.41	2.37	2.10
0.31% STTD P	2.53	3.29	4.09	4.03	3.57
0.39% STTD P	2.47	2.95	3.93	4.42	4.11
0.47% STTD P	2.35	3.53	3.82	4.46	4.55
Ca:P in bone					
0.15% STTD P	2.07	2.11	2.13	2.17	2.20
0.31% STTD P	2.04	2.05	2.08	2.10	2.14
0.39% STTD P	2.03	2.07	2.09	2.09	2.13
0.47% STTD P	2.05	2.06	2.08	2.09	2.11
Stomach pH <sup>7,8,9</sup>					
	2.27b	2.86a	2.73ab	3.19a	3.07a

<sup>a,b</sup>Within a row, means without a common superscript differ ( $P < 0.05$ ).

<sup>1</sup>Data are least square means of 6 observations.

<sup>2</sup>Results indicated that bone ash at different combinations of STTD Ca and STTD P can be described by the following model:  $2.9550 + 20.3139 \times \text{Ca} - 38.5764 \times \text{Ca}^2 + 48.1313 \times \text{P} - 95.6806 \times \text{P}^2 + 75.0046 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>3</sup>Standard error of the within treatments least squared means = 1.15.

<sup>4</sup>Results indicated that bone Ca at different combinations of STTD Ca and STTD P can be described by the following model:  $1.2282 + 8.2355 \times \text{Ca} - 15.0966 \times \text{Ca}^2 + 17.3926 \times \text{P} - 34.9669 \times \text{P}^2 + 29.1245 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>5</sup>Standard error of the within treatments least squared means = 0.46.

<sup>6</sup>Results indicated that bone P at different combinations of STTD Ca and STTD P can be described by the following model:  $0.5601 + 3.7735 \times \text{Ca} - 7.3960 \times \text{Ca}^2 + 8.8805 \times \text{P} - 17.5142 \times \text{P}^2 + 14.2338 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

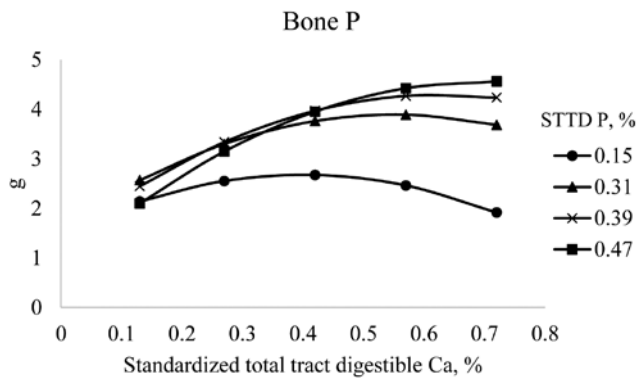
<sup>7</sup>Standard error of the within treatments least squared means = 0.22.

<sup>8</sup>Concentration of STTD Ca in diet affect ( $P < 0.016$ ) pH in stomach.

<sup>9</sup>Standard error of means = 0.24.

2.73:1, 1.81:1, 1.64:1, and 1.53:1 (Fig. 5). The predicted maximum bone Ca and bone P at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 5.7, 8.2, 9.1, and 9.6 g Ca at STTD Ca concentrations of 0.42, 0.57, 0.65, and 0.73%, and 2.7, 3.9, 4.3, and 4.6 g P at STTD Ca concentrations of 0.40, 0.55, 0.63, and 0.71%, respectively. These values correspond to STTD Ca:STTD P ratios of 2.80:1, 1.84:1, 1.67:1, and 1.55:1 for bone Ca (Fig. 6) and 2.67:1, 1.77:1, 1.62:1, and 1.51:1 for bone P (Fig. 7). The stomach pH was less ( $P = 0.016$ ) in pigs fed the diet containing 0.13% STTD Ca than in pigs fed diets containing 0.27, 0.57, or 0.72% STTD Ca, but not different from the pH of the diet containing 0.42% STTD Ca.



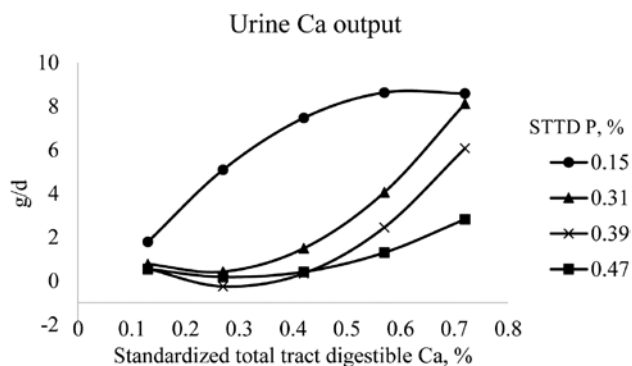


**Figure 7.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for bone P (g) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum bone P at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 2.7, 3.9, 4.3, and 4.6 g at STTD Ca concentrations of 0.40, 0.55, 0.63, and 0.71%, respectively. These values correspond to STTD Ca:STTD P ratios of 2.67:1, 1.77:1, 1.62:1, and 1.51:1.

### Experiment 2. Ca and P Balance

Pigs consumed the diets without problems throughout the experiment, but 1 barrow fed the diet containing 0.57% STTD Ca and 0.31% STTD P was euthanized on d 9 of the experiment due to an injured leg. Therefore, this diet had 1 missing observation.

The maximum urine output of Ca and P and the maximum retention of Ca and P at different dietary concentrations of STTD Ca and STTD P were predicted from the least squares means (Table 6). The predicted maximum urine Ca output at 0.15% STTD P was 8.8 g/d at STTD Ca concentration of 0.64%, which correspond to STTD Ca:STTD P ratio of 4.27:1 (Fig. 8). However, the predicted minimum urine Ca output at STTD P concentrations of 0.31, 0.39, and 0.47% were 0.4, -0.3, and 0.2 g/d at



**Figure 8.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for urine Ca output (g/d) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum urine Ca output at STTD P concentrations of 0.15% was 8.8 g/d at STTD Ca concentrations of 0.64%, which correspond to STTD Ca:STTD P ratios of 4.27:1. However, the predicted minimum urine Ca output at STTD P concentrations of 0.31, 0.39, and 0.47% were 0.4, -0.3, and 0.2 g/d at STTD Ca concentrations of 0.24, 0.29, and 0.29%, respectively. These values correspond to STTD Ca:STTD P ratios of 0.77:1, 0.74:1, and 0.62:1.

**Table 6.** Least squares means for retention of Ca and P in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P, Exp. 2<sup>1</sup>

Item	STTD Ca, %				
	0.13	0.27	0.42	0.57	0.72
Urine Ca output, g/d <sup>2,3</sup>					
0.15% STTD P	1.30	6.12	7.73	8.78	9.13
0.31% STTD P	0.22	0.31	1.93	4.16	8.73
0.39% STTD P	0.89	0.39	0.61	1.64	5.90
0.47% STTD P	0.28	0.30	0.46	1.07	3.13
Urine P output, g/d <sup>4,5</sup>					
0.15% STTD P	0.28	0.13	0.16	0.20	0.15
0.31% STTD P	7.79	3.29	0.50	0.47	0.42
0.39% STTD P	8.45	6.85	3.76	2.33	0.71
0.47% STTD P	14.83	10.03	5.95	3.57	1.17
Retention of Ca in the body, g/d <sup>6,7</sup>					
0.15% STTD P	0.94	2.39	3.77	4.17	5.13
0.31% STTD P	1.26	3.23	5.00	6.44	6.67
0.39% STTD P	0.90	3.22	5.45	6.99	7.63
0.47% STTD P	1.11	3.00	5.28	6.92	8.38
Retention of P in the body, g/d <sup>8,9</sup>					
0.15% STTD P	1.86	1.55	1.36	1.21	0.87
0.31% STTD P	2.21	2.53	3.15	2.95	2.45
0.39% STTD P	2.76	2.71	3.37	3.33	3.35
0.47% STTD P	2.37	2.88	3.53	3.79	3.87

<sup>1</sup>Data are least square means of 6 observations.

<sup>2</sup>Results indicated that urine Ca output at different combinations of STTD Ca and STTD P can be described by the following model:  $-11.2788 + 133.541 \times \text{Ca} - 154.747 \times \text{Ca}^2 + 76.1041 \times \text{P} - 104.612 \times \text{P}^2 - 830.115 \times \text{Ca} \times \text{P} + 1084.04 \times \text{Ca}^2 \times \text{P} + 1124.03 \times \text{Ca} \times \text{P}^2 - 1541.08 \times \text{Ca}^2 \times \text{P}^2$  ( $P < 0.001$ ).

<sup>3</sup>Standard error of the within treatments least squared means = 0.72.

<sup>4</sup>Results indicated that urine P output at different combinations of STTD Ca and STTD P can be described by the following model:  $-14.6788 + 70.134 \times \text{Ca} - 68.942 \times \text{Ca}^2 + 121.048 \times \text{P} - 124.258 \times \text{P}^2 - 622.705 \times \text{Ca} \times \text{P} + 631.354 \times \text{Ca}^2 \times \text{P} + 917.568 \times \text{Ca} \times \text{P}^2 - 1026.05 \times \text{Ca}^2 \times \text{P}^2$  ( $P < 0.001$ ).

<sup>5</sup>Standard error of the within treatments least squared means = 0.63.

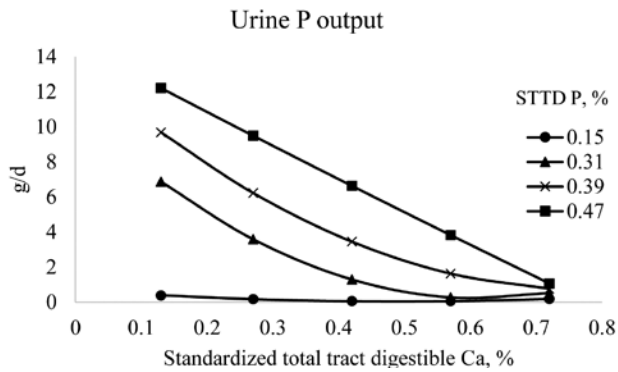
<sup>6</sup>Results indicated that retention of Ca in the body at different combinations of STTD Ca and STTD P can be described by the following model:  $-0.1145 + 10.5371 \times \text{Ca} - 8.8014 \times \text{Ca}^2 - 2.8922 \times \text{P} + 20.6228 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>7</sup>Standard error of the within treatments least squared means = 0.35.

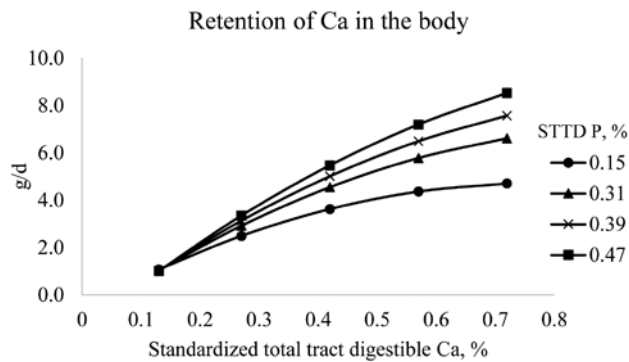
<sup>8</sup>Results indicated that retention of P in the body at different combinations of STTD Ca and STTD P can be described by the following model:  $1.7735 - 1.0789 \times \text{Ca} - 3.9067 \times \text{Ca}^2 - 0.0664 \times \text{P} + 14.9090 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>9</sup>Standard error of the within treatments least squared means = 0.23.

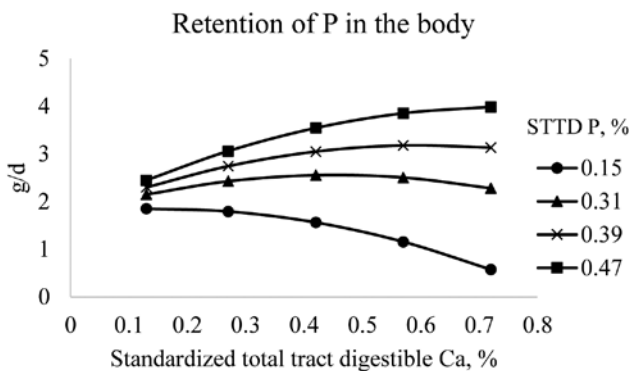
STTD Ca concentrations of 0.24, 0.29, and 0.29%, respectively, which correspond to STTD Ca:STTD P ratios of 0.77:1, 0.74:1, and 0.62:1. The predicted minimum urine P output at STTD P concentrations of 0.15, 0.31, and 0.39% were 0.0, 0.2, and 0.7 g/d at STTD Ca concentrations of 0.49, 0.62, and 0.78%, respectively, which correspond to STTD Ca:STTD P ratios of 3.27:1, 2.00:1, and 2.00:1, respectively (Fig. 9). The values for minimum urine P output at 0.47% STTD P was not estimated due to a nearly linear response. The predicted maximum retention of Ca in the body at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 4.7, 7.1, 8.6, and



**Figure 9.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for urine P output (g/d) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted minimum urine P output at STTD P concentrations of 0.15, 0.31, and 0.39% were 0.0, 0.2, and 0.7 g/d at STTD Ca concentrations of 0.49, 0.62, and 0.78%, respectively. These values correspond to STTD Ca:STTD P ratios of 3.27:1, 2.00:1, and 2.00:1. The values for minimum urine P output at 0.47% STTD P was not estimated due to a nearly linear response.



**Figure 10.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for retention of Ca in the body (g/d) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum retention of Ca in the body at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 4.7, 7.1, 8.6, and 10.2 g/d at STTD Ca concentrations of 0.77, 0.96, 1.06, and 1.15%, respectively. These values correspond to STTD Ca:STTD P ratios of 5.13:1, 3.10:1, 2.72:1, and 2.45:1. These STTD Ca concentrations needed to maximize retention of Ca in the body were extrapolations of the model.



**Figure 11.** Predicted values, based on the interaction between Ca and P ( $P < 0.001$ ), for retention of P in the body (g/d) in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P. The predicted maximum retention of P in the body at STTD P concentrations of 0.15, 0.31, 0.39, and 0.47% were 1.8, 2.6, 3.2, and 4.0 g/d at STTD Ca concentrations of 0.15, 0.45, 0.61, and 0.76%, respectively. These values correspond to STTD Ca:STTD P ratios of 1.00:1, 1.46:1, 1.55:1, and 1.61:1.

**Table 7.** Least squares means for Ca and P in plasma (mg/dL) at d13 in pigs fed diets containing from 0.13 to 0.72% standardized total tract digestible (STTD) Ca and from 0.15 to 0.47% STTD P, Exp. 2<sup>1</sup>

Item	STTD Ca, %				
	0.13	0.27	0.42	0.57	0.72
Plasma Ca, mg/dL <sup>2,3</sup>					
0.15% STTD P	10.1	11.0	12.6	12.7	14.7
0.31% STTD P	9.4	10.3	10.2	10.9	12.5
0.39% STTD P	10.1	10.3	10.3	10.2	11.3
0.47% STTD P	10.1	10.1	10.2	10.1	10.2
Plasma P, mg/dL <sup>4,5</sup>					
0.15% STTD P	15.8	17.1	14.9	12.7	9.7
0.31% STTD P	16.7	19.2	17.6	15.4	14.5
0.39% STTD P	18.8	18.6	18.5	16.4	16.0
0.47% STTD P	19.0	16.9	17.0	18.5	18.0

<sup>1</sup>Data are least square means of 6 observations.

<sup>2</sup>Results indicated that Ca in plasma at different combinations of STTD Ca and STTD P can be described by the following model:  $10.5277 + 10.6516 \times \text{Ca} - 13.5555 \times \text{P} + 27.7143 \times \text{P}^2 - 22.8713 \times \text{Ca} \times \text{P}$  ( $P < 0.001$ ).

<sup>3</sup>Standard error of the within treatments least squares means = 0.32.

<sup>4</sup>Results indicated that P in plasma at different combinations of STTD Ca and STTD P can be described by the following model:  $14.7573 - 6.16262 \times \text{Ca} + 12.7857 \times \text{P}$  ( $P = 0.003$ ).

<sup>5</sup>Standard error of the within treatments least squares means = 2.59.

10.2 g/d at STTD Ca concentrations of 0.77, 0.96, 1.06, and 1.15%, respectively, and these values correspond to STTD Ca:STTD P ratios of 5.13:1, 3.10:1, 2.72:1, and 2.45:1 (Fig. 10). The STTD Ca concentrations needed to maximize retention of Ca in the body were extrapolations of the model. The predicted maximum retention of P in the body at the 4 STTD P concentrations were 1.8, 2.6, 3.2, and 4.0 g/d at STTD Ca concentrations of 0.15, 0.45, 0.61, and 0.76%, respectively, which correspond to STTD Ca:STTD P ratios of 1.00:1, 1.46:1, 1.55:1, and 1.61:1 (Fig. 11).

Calcium in plasma increased ( $P < 0.001$ ) in pigs fed diets containing 0.15% STTD P as the concentration of dietary Ca increased, but for pigs fed diets containing 0.31, 0.39, or 0.47% STTD P no change in plasma concentration of Ca was observed as dietary Ca increased (interaction,  $P < 0.001$ ; Table 7). However, P in plasma linearly decreased ( $P = 0.003$ ) as the concentration of STTD Ca increased, and linearly increased ( $P = 0.003$ ) as the concentration of STTD P increased. Due to the linear response for Ca and P in plasma, maximum values were not estimated.

## DISCUSSION

The concentration of Ca, P, Na, and Cl in corn, calcium carbonate, MSP, MCP, and NaCl were in agreement with reported values (Sauvant et al., 2004; de Blas et al., 2010; Rostagno et al., 2011; NRC, 2012).

The concentration of P, Na, and Cl in soybean meal were close to reported values (Sauvant et al., 2004; de Blas et al., 2010; Rostagno et al., 2011; NRC, 2012), but the concentration of Ca was greater than expected (Sauvant et al., 2004; de Blas et al., 2010; Rostagno et al., 2011; NRC, 2012). However, diets were formulated based on analyzed values for Ca and P in all ingredients and the concentration of Ca, P, Na, and Cl in all diets were, therefore, close to calculated values.

Utilization of Ca and P in the body is dependent on the excess or deficiency of 1 mineral or the other (Crenshaw, 2001), therefore, the ratio between Ca and P needs to be considered in diet formulations. Studies that are designed to determine Ca or P requirements usually are designed to contain a constant dietary concentration of 1 mineral with graded levels of the other mineral, or alternatively, a constant Ca:P ratio may be used. Results obtained from a previous experiment that aimed at determining STTD Ca requirements by 11 to 25 kg pigs, indicated that the ratio between STTD Ca and STTD P was important for maximizing ADG, G:F, the quantity of deposited bone ash, Ca retained, and P retained (González-Vega et al., 2016). Due to the negative effect of increasing the concentration of STTD Ca in diets with a constant concentration of STTD P on ADG and G:F (González-Vega et al., 2016), the current experiments were designed to include 4 concentrations of STTD P and 5 concentrations of STTD Ca, which allowed us to determine requirements of STTD Ca at different concentrations of STTD P.

The fact that increasing concentrations of STTD Ca had a negative effect on growth performance of pigs fed diets containing concentrations of STTD P between 48.4 and 151.6% of the requirement (NRC, 2012), especially at low P concentration, is in agreement with results obtained in our previous study with 11 to 25 kg pigs (González-Vega et al., 2016). The negative effect of increasing dietary Ca on growth performance was also observed in fast-growing Cobb broiler chickens (Hurwitz et al., 1995). This may be caused by formation of Ca-P complexes in the gastrointestinal tract due to excess Ca in diets, which reduces digestibility of P (Clark, 1969; Brink et al., 1992; Stein et al., 2011; González-Vega et al., 2014). However, the negative effect of increasing concentration of STTD Ca on growth performance of pigs was ameliorated as concentration of STTD P increased, which further indicates that the negative effects of high dietary concentrations of STTD Ca may have been caused by reduced P digestibility.

Regardless of the concentration of STTD P in the diet, final BW, ADG, and G:F were less affected by Ca concentrations below the requirement than if Ca was provided above the requirement, which indicates that at low concentrations of dietary Ca, pigs were able to

mobilize Ca from Ca stores to compensate for the deficiency of dietary Ca. Theoretically, it could also be possible that the absorption efficiency of Ca increased at the lower dietary Ca concentrations, but the apparent total tract digestibility of Ca was almost constant among treatments (data not shown) indicating that dietary Ca concentration only marginally influenced efficiency of absorption. These results are in agreement with previous reports (Eklou-Kalonji et al., 1999; González-Vega et al., 2016). The implications of the results obtained for growth performance is that the STTD Ca:STTD P ratio is important in diet formulation and excess Ca needs to be avoided because maximum animal growth performance is achieved only if diets are formulated based on the optimum STTD Ca:STTD P ratio.

Results from our study with 11 to 25 kg pigs indicated that the quantity of STTD Ca that was needed to maximize bone ash and retention of Ca was greater than the quantity needed to maximize growth performance (González-Vega et al., 2016). Results obtained from the current experiments support this observation, and these results are also in agreement with data from studies that aimed at determining P requirements in pigs (Ketaren et al., 1993; Partanen et al., 2010; Adeola et al., 2015). It is possible that these responses are a result of the fact that depositions of Ca and P in bones and in soft tissue are independent (Crenshaw, 2001). However, it is also possible that the results for bone ash and Ca retention simply reflect that the pig is able to deposit significantly more Ca and P in bones than what is needed to maximize ADG and G:F. Thus, bones seem to be the default storage site for Ca and P if availability exceeds the requirement to maximize growth performance.

If diets met or exceeded the STTD P requirement (NRC, 2012), the STTD Ca values to maximize ADG and G:F ranged from 0.36 to 0.67%, which corresponded to a STTD Ca:STTD P ratios between 1.16:1 and 1.43:1. However, the STTD Ca values to maximize bone ash, bone Ca, and bone P ranged from 0.55 to 0.73%, which corresponded to a STTD Ca:STTD P ratio between 1.55:1 and 1.77:1. These values are close to the Ca:P ratio in the body, which ranges between 1.25:1 and 1.70:1 for a 50 kg pig (Rymarz et al., 1982; Hendriks and Moughan, 1993; Mahan and Shields, 1998; Wiseman et al., 2009; Pettey et al., 2015).

Requirements for STTD Ca to maximize bone ash were expected to be close to requirements to maximize Ca retention, because 96 to 99% of Ca is believed to be stored in skeletal tissue (Crenshaw, 2001). However, results from Exp. 2 indicated that the STTD Ca values to maximize Ca retention ranged from 0.96 to 1.15%, which corresponded to a STTD Ca:STTD P ratio between 2.45:1 and 3.10:1. There is not a clear explanation for the greater quantities needed to maximize Ca



retention than the quantities needed to maximize bone ash, but similar results were observed previously in 11 to 25 kg pigs (González-Vega et al., 2016). Thus, results from our 2 experiments indicate that there may be Ca stored in tissues other than bones, that the Ca:P ratio in bone ash is not constant, or that retention of ash in the femur is not representative of deposition of ash in all skeletal tissue. Results from the present experiment demonstrate that plasma Ca is influenced by dietary Ca if P is deficient, but plasma Ca concentration was not increased as dietary Ca increased for pigs fed a diet that was not deficient in P, which indicates that it is unlikely that significant quantities of Ca are stored in plasma if dietary Ca is increased. The reason for the lack of response in plasma Ca is most likely that concentrations of Ca in the blood are regulated by parathyroid hormone, calcitonin and vitamin D, and plasma Ca is, therefore, usually relatively constant.

Deposition of minerals in bones is a result of the exchange of minerals among 3 compartments: the hydration shell, the crystal surface, and the crystal interior (Szymendera, 1970). Because bone ash accounts only for the crystalline mineral, minerals present in the hydration shell are not included in values for bone ash. This may explain the difference between the concentration of Ca needed to maximize bone Ca concentration and Ca needed to maximize Ca retention, however, it is not clear, why this difference was not also observed for P retention. Accumulation of minerals in the cecum has been observed in rats fed diets varying in the concentration of inulin (Levrat et al., 1991). However, if minerals are deposited in the cecum it is expected that not only Ca, but also P, are deposited. In the present experiment, the quantity of P required to maximize P in bone ash was in very good agreement with the quantity needed to maximize P retention. It is, therefore, unlikely, that deposition of minerals in the cecum contributed to the discrepancy between Ca needed to maximize Ca retention and Ca needed to maximize Ca in bone ash.

Although deposition of Ca in soft tissue is negligible (Crenshaw, 2001; Pettey et al., 2015), calcification of soft tissue has been reported. A tenfold increase of Ca concentration in kidneys was observed in dogs fed phosphates (Laflamme and Jowsey, 1972), and calcification of soft tissues has been observed in rats and rabbits (Spaulding and Walser, 1970; Jowsey and Balasubramaniam, 1972). The Ca:P ratios in the bones in 11 to 25 kg pigs were between 2.03:1 and 2.14:1 (González-Vega et al., 2016) and the Ca:P ratios in the bones from pigs in the current study ranged between 2.03:1 and 2.20:1, which are close to the ratio of 2.15:1 that is needed to form hydroxyapatite [ $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$ ]. Bones differ in size and mineral content (Han et al., 2015), which may result in

challenges to quantify deposition of ash in all skeletal tissue, however, data from Crenshaw et al. (1981, 2009) indicated that the femur is an accurate indicator of whole body bone mineral content. Therefore, the observation that greater quantities of STTD Ca are needed to maximize Ca retention than the quantities needed to maximize bone ash is likely a result of accumulation of Ca in soft tissues. However, further research is needed to confirm this hypothesis.

The fact that pigs fed diets that were deficient in either Ca or P excreted Ca and P in the urine indicates that there are obligatory losses of Ca and P in urine. A minimum urinary loss of P of 7 mg/kg BW per d was reported by NRC (2012); therefore, a minimum of 0.21 g P excreted in the urine per d was expected in Exp. 2. The predicted value (0.20 g/d) for the diet containing 0.31% STTD P was in very good agreement with this estimate, indicating that for pigs that are fed diets that do not exceed the requirement for P, at least 7 mg of P per kg BW will be excreted in the urine every d. There is also an obligatory loss of Ca in humans (Nordin and Morris, 1989), but to our knowledge, the obligatory losses of Ca in pigs have not been quantified. However, results of this experiment indicate that the obligatory loss of Ca likely is less than the obligatory loss of P because estimates that were close to zero were observed.

The observation that the concentration of Ca in plasma from pigs fed diets containing the least concentration of STTD P increased as the concentration of STTD Ca increased, may be a result of deficiency of P, which limited Ca deposition in bones. Therefore, absorbed Ca that could not be deposited in bones was circulating in blood to be excreted in the urine at a later time. Increased concentration of Ca in plasma as the concentration of dietary Ca increased has also been observed in chickens (Hurwitz et al., 1995).

## Conclusions

Data from these experiments indicate that utilization of both Ca and P is influenced by the STTD Ca:STTD P ratio. Therefore, if STTD P is below the recommended requirement (NRC, 2012), the STTD Ca:STTD P ratio needed to maximize ADG and G:F is between 0.60:1 and 0.80:1, but the STTD Ca:STTD P ratio needed to maximize bone ash, bone Ca, and bone P is between 2.67:1 and 2.80:1. However, the ratio needed to maximize bone ash will negatively affect growth performance of pigs. In contrast, if STTD P meets or exceeds the requirement (NRC, 2012), a STTD Ca:STTD P ratio between 1.16:1 and 1.43:1 is needed to maximize ADG and G:F. A greater ratio will reduce growth performance, although a ratio between 1.55:1 and 1.77:1 is needed to maximize bone ash,



bone Ca, and bone P. The implication of this observation is that the ratios needed to maximize bone ash, bone Ca, and bone P may reduce growth performance. As a consequence, it is recommended that, for commercial production of growing-finishing pigs, diets should be formulated using a ratio of STTD Ca: STTD P between 1.16:1 and 1.43:1. It is, however, possible that pigs that are destined to be kept for breeding should be fed a diet that maximizes bone ash rather than growth performance to increase longevity.

### LITERATURE CITED

- Adeola, O. 2001. Digestion and balance techniques in pigs. In: A. J. Lewis and L. L. Southern, editors, *Swine nutrition*. 2nd ed. CRC Press, Washington, DC. p. 903–916.
- Adeola, O., M. J. Azain, S. D. Carter, T. D. Crenshaw, M. J. Estienne, B. J. Kerr, M. D. Lindemann, C. V. Maxwell, P. S. Miller, M. C. Shannon, and E. van Heugten. 2015. A cooperative study on the standardized total-tract digestible phosphorus requirement of twenty-kilogram pigs. *J. Anim. Sci.* 93:5743–5753. doi:10.2527/jas.2015-9509
- AOAC. 2006. *Official Methods of Analysis*. 18th ed. Assoc. Off. Anal. Chem., Arlington, VA.
- AOAC International. 2007. *Official Methods of Analysis of AOAC International*. 18th ed. Rev. 2. W. Hortwitz and G. W. Latimer, Jr., editors. AOAC Int., Gaithersburg, MD.
- Brink, E. J., A. C. Beynen, P. R. Dekker, E. C. H. van Beresteijn, and R. van der Meer. 1992. Interaction of calcium and phosphate decreases ileal magnesium solubility and apparent magnesium absorption in rats. *J. Nutr.* 122:580–586.
- Clark, I. 1969. Importance of dietary Ca:PO<sub>4</sub> ratios on skeletal, Ca, Mg, and PO<sub>4</sub> metabolism. *Am. J. Physiol.* 217:865–870.
- Crenshaw, T. D. 2001. Calcium, phosphorus, vitamin D, and vitamin K in swine nutrition. In: A. J. Lewis and L. L. Southern, editors, *Swine nutrition*. 2nd ed. CRC Press, Boca Raton, FL. p. 187–212.
- Crenshaw, T. D., J. R. Danielson, L. E. Hoffman, and D. K. Schneider. 2009. Femurs are more accurate than fibulas as predictors of whole body bone mineral content in growing pigs. *J. Anim. Sci.* 87.(E-Suppl 2):510 (Abstr.)
- Crenshaw, T. D., E. R. Peo, A. J. Lewis, B. D. Moser, and D. Olson. 1981. Influence of age, sex, and calcium and phosphorus levels on the mechanical properties of various bones in swine. *J. Anim. Sci.* 52:1319–1329. doi:10.2527/jas1981.5261319x
- de Blas, C., G. G. Mateos, and P. García-Rebollar. 2010. *Tablas FEDNA de composición y valor nutritivo de alimentos para la fabricación de piensos compuestos*. 3ra ed. C. de Blas, G. G. Mateos, and P. García-Rebollar, editors. Fund. Esp. Desarrollo Nutr. Anim., Madrid, Spain.
- Eklou-Kalonji, E., E. Zerath, C. Colin, C. Lacroix, X. Holy, I. Denis, and A. Pointllart. 1999. Calcium-regulating hormones, bone mineral content, breaking load and trabecular remodeling are altered in growing pigs fed calcium-deficient diets. *J. Nutr.* 129:188–193.
- González-Vega, J. C., Y. Liu, J. C. McCann, C. L. Walk, J. J. Looor, and H. H. Stein. 2016. Requirement for digestible calcium by 11 to 25 kg pigs as determined by growth performance, bone ash concentration, calcium and phosphorus balances, and expression of genes involved in transport of calcium in intestinal and kidney cells. *J. Anim. Sci.* 94:3321–3334. doi:10.2527/jas.2016-0444
- González-Vega, J. C., C. L. Walk, Y. Liu, and H. H. Stein. 2013. Determination of endogenous intestinal losses of Ca and true total tract digestibility of calcium in canola meal fed to growing pigs. *J. Anim. Sci.* 91:4807–4816. doi:10.2527/jas.2013-6410
- González-Vega, J. C., C. L. Walk, Y. Liu, and H. H. Stein. 2014. The site of net absorption of Ca from the intestinal tract of growing pigs and effect of phytic acid, Ca level and Ca source on Ca digestibility. *Arch. Anim. Nutr.* 68:126–142. doi:10.1080/1745039X.2014.892249
- González-Vega, J. C., C. L. Walk, and H. H. Stein. 2015a. Effects of microbial phytase on apparent and standardized total tract digestibility of calcium in calcium supplements fed to growing pigs. *J. Anim. Sci.* 93:2255–2264. doi:10.2527/jas.2014-8215
- González-Vega, J. C., C. L. Walk, and H. H. Stein. 2015b. Effect of phytate, microbial phytase, fiber, and soybean oil on calculated values for apparent and standardized total tract digestibility of calcium and apparent total tract digestibility of phosphorus in fish meal fed to growing pigs. *J. Anim. Sci.* 93:4808–4818. doi:10.2527/jas.2015-8992
- Han, J. C., H. X. Qu, J. G. Wang, G. H. Chen, Y. F. Yan, J. L. Zhang, F. M. Hu, L. Y. You, and Y. H. Cheng. 2015. Comparison of the growth and mineralization of the femur, tibia, and metatarsus of broiler chicks. *Braz. J. Poult. Sci.* 17:333–340.
- Hendriks, W. H., and P. J. Moughan. 1993. Whole-body mineral composition of entire male and female pigs depositing protein at maximal rates. *Livest. Prod. Sci.* 33:161–170. doi:10.1016/0301-6226(93)90247-F
- Hurwitz, S., I. Plavnik, A. Shapiro, E. Wax, H. Talpaz, and A. Bar. 1995. Calcium metabolism and requirements of chickens are affected by growth. *J. Nutr.* 125:2679–2686.
- Jowsey, J., and P. Balasubramaniam. 1972. Effect of phosphate supplements on soft-tissue calcification and bone turnover. *Clin. Sci.* 42:289–299. doi:10.1042/cs0420289
- Ketaren, P. P., E. S. Batterham, and E. White. 1993. Phosphorus studies in pigs. 1. Available phosphorus requirements of grower/finisher pigs. *Br. J. Nutr.* 70:249–268. doi:10.1079/BJN19930121
- Khuri, A. I., and J. A. Cornell. 1996. *Response surfaces: Designs and analyses*. 2nd ed. CRC Press, Boca Rotan, FL.
- Kim, B. G., and M. D. Lindemann. 2007. A new spreadsheet method for the experimental animal allotment. *J. Anim. Sci.* 85(Suppl. 2):218 (Abstr.)
- Laffamme, G. H., and J. Jowsey. 1972. Bone and soft tissue changes with oral phosphate supplements. *J. Clin. Invest.* 51:2834–2840. doi:10.1172/JCI107106
- Levrat, M. A., C. Révész, and C. Demigné. 1991. High propionic acid fermentations and mineral accumulation in the cecum of rats adapted to different levels of inulin. *J. Nutr.* 121:1730–1737.
- Lindemann, M. D., and B. G. Kim. 2007. Technical note: A model to estimate individual feed intake of swine in group feeding. *J. Anim. Sci.* 85:972–975. doi:10.2527/jas.2006-412
- Mahan, D. C., and R. G. Shields, Jr. 1998. Macro- and micromineral composition of pigs from birth to 145 kilograms of body weight. *J. Anim. Sci.* 76:506–512. doi:10.2527/1998.762506x
- Merriman, L. A., and H. H. Stein. 2016. Particle size of calcium carbonate does not affect apparent and standardized total tract digestibility, retention of calcium, or growth performance of growing pigs. *J. Anim. Sci.* 94:3844–3850. doi:10.2527/jas.2015-0252
- Nordin, B. E. C., and H. A. Morris. 1989. The calcium deficiency model for osteoporosis. *Nutr. Rev.* 47:65–72. doi:10.1111/j.1753-4887.1989.tb02794.x
- NRC. 2012. *Nutrient Requirements of Swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC.

- Partanen, K., H. Siljander-Rasi, M. Karhapää, K. Ylivainio, and T. Tupasela. 2010. Responses of growing pigs to different levels of dietary phosphorus- Performance, bone characteristics, and solubility of faecal phosphorus. *Livest. Sci.* 134:109–112. doi:10.1016/j.livsci.2010.06.113
- Petty, L. A., G. L. Cromwell, Y. D. Jang, and M. D. Lindemann. 2015. Estimation of calcium and phosphorus content in growing and finishing pigs: Whole empty body components and relative accretion rates. *J. Anim. Sci.* 93:158–167. doi:10.2527/jas.2014-7602
- Rostagno, H. S., L. F. T. Albino, J. L. Donzele, P. C. Gomes, R. F. de Oliveira, D. C. Lopes, A. S. Ferreira, S. L. T. Barreto, and R. F. Euclides. 2011. Brazilian tables for poultry and swine. H. S. Rostagno, editor, 3rd ed. Universidade Federal de Viçosa, Viçosa, BR.
- Rymarz, A., H. Fandrejewski, and J. Kielanowski. 1982. Content and retention of calcium, phosphorus, potassium and sodium in the bodies of growing gilts. *Livest. Prod. Sci.* 9:399–407. doi:10.1016/0301-6226(82)90045-8
- Sauvant, D., J.-M. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials: Pig, poultry, sheep, goats, rabbits, horses, fish. 2nd ed. Wageningen Academic Publishers, Wageningen, the Netherlands. doi:10.3920/978-90-8686-668-7
- Sherrod, P. H. 2002. Nonlinear regression analysis program NLREG version 5.3. Philip H. Sherrod, Nashville, TN.
- Spaulding, S. W., and M. Walser. 1970. Treatment of experimental hypercalcemia with oral phosphate. *J. Clin. Endocrinol. Metab.* 31:531–538. doi:10.1210/jcem-31-5-531
- Stein, H. H., O. Adeola, G. L. Cromwell, S. W. Kim, D. C. Mahan, and P. S. Miller. 2011. Concentration of dietary calcium supplied by calcium carbonate does not affect the apparent total tract digestibility of calcium, but reduces digestibility of phosphorus by growing pigs. *J. Anim. Sci.* 89:2139–2144. doi:10.2527/jas.2010-3522
- Szymendera, J. 1970. General outlines of bone tissue metabolism. In: J. Szymendera, editor, Bone mineral metabolism in cancer. William Heinemann Medical Books Ltd., London, UK. p. 1–12.
- Tran, G., and D. Sauvant. 2004. Chemical data and nutritional value. In: D. Sauvant, J.-M. Perez, and G. Tran, editors, Tables of composition and nutritional value of feed materials: Pig, poultry, sheep, goats, rabbits, horses, fish. 2nd ed. Wageningen Academic Publishers, Wageningen, the Netherlands. p. 17–24.
- Wiseman, T. G., D. C. Mahan, and N. R. St-Pierre. 2009. Mineral composition of two genetic lines of barrows and gilts from twenty to one hundred twenty-five kilograms of body weight. *J. Anim. Sci.* 87:2306–2314. doi:10.2527/jas.2006-545