Phosphorus requirements of growing-finishing pigs reared in a commercial environment[1,2]

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ABSTRACT: The objective of this study was to identify available phosphorus (aP) requirements of pigs reared in commercial facilities. In a preliminary study, 600 gilts (PIC) were allotted randomly to low (0.30%) or high (0.37%) dietary aP from 43 to 48 kg BW, and later to 0.19 or 0.27% aP from 111 to 121 kg BW. No differences were observed (P = 0.42 to 0.88) in ADG, but G:F from 43 to 48 kg tended to improve (P = 0.07) for pigs fed low aP. Results suggested that the aP requirement was at or below 0.30 and 0.19%. These concentrations were used to titrate aP requirements in Exp. 1 and 2. In Exp. 1, 1,260 gilts (initially 33.8 kg) were allotted randomly to one of five dietary treatments containing 0.18, 0.22, 0.25, 0.29, or 0.32% aP, corresponding to 0.5, 0.6, 0.7, 0.8, or 0.9 g of aP/Mcal of ME. There were 28 pigs per pen and nine pens per treatment. From d 0 to 14, increasing aP increased ADG (linear, P = 0.03) and G:F (quadratic, P = 0.07), with the greatest response observed as aP increased from 0.18 to 0.22% (G:F breakpoint = 0.22%). However, from d 0 to 26, no differences (P = 0.12 to 0.81) were observed for any growth traits. Pooled bending moment of the femur, sixth rib, and third and fourth metatarsals increased (linear, P = 0.007) with increasing aP. In Exp. 2, 1,239 gilts (initially 88.5 kg BW) were randomly allotted to one of five dietary treatments containing 0.05, 0.10, 0.14, 0.19, or 0.23% aP, equivalent to 0.14, 0.28, 0.39, 0.53, or 0.64 g of aP/Mcal of ME. The diet with 0.05% aP contained no added inorganic P. From d 0 to 14, increasing aP increased (linear, P = 0.008 to 0.02) ADG and G:F; however, from d 0 to 28, increasing aP had no effect (P = 0.17 to 0.74) on growth performance. Increasing aP increased (linear, $P < 0.001$ to 0.04) metacarpal bone ash percent and bending moment. Results suggest that 33- to 55-kg pigs require approximately 0.22% aP, which corresponds to 0.60 g of aP/Mcal of ME or 3.30 g of aP/d to maximize ADG and G:F compared with NRC (1998) estimates of 0.23%, 0.70 g of aP/Mcal of ME, and 4.27 g of aP/d for 20- to 50-kg pigs. Finishing pigs (88 to 109 kg) require at least 0.19% aP, corresponding to 0.53 g of aP/Mcal of ME or 4.07 g aP/d compared with NRC (1998) estimates of 0.15%, 0.46 g of aP/Mcal of ME and 4.61 g of aP/d for 80- to 120-kg pigs. However, the percentage of bone ash and bending moment continued to increase with increasing aP. These data also suggest that complete removal of supplemental P in diets for finishing pigs (>88 kg) will decrease ADG and G:F.

Key Words: Growth Performance, Pigs, Phosphorus

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Introduction

A challenge in animal production today is to raise livestock within new environmental rules and regulations. Although most states in the United States regulate swine waste application based on N concentration, more are changing to P-based regulations. Because of the amounts of N and P in swine waste and their different rate of uptake by most plants, P concentration can be first limiting for waste application if soil P accumulation is not permitted. Therefore, reevaluation of P requirements of swine is an important step in minimizing its excretion.

In evaluating available P (**aP**) requirement estimates, several studies have demonstrated that growth performance will not be negatively affected by the partial (66%, Mavromichalis et al., 1999; Shaw et al., 2002)

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or complete removal of supplemental P from the diet (Lindemann et al., 1995; O'Quinn et al., 1997; McGlone, 2000). However, swine nutrition research trials conducted at universities typically involve relatively few pigs per pen and generous space allowances. As a result of these conditions, finishing pig growth rate and feed intake will often exceed that of pigs housed in commercial facilities. Although direct comparisons should be made with caution, pigs housed in a commercial research facility (1,200-animal barn, with 25 pigs per pen and 0.67 m^2 per pig) had approximately 33% lower ADFI than those fed similar diets in a university research facility (160-animal barn, with 10 pigs per pen and 0.88 m^2 per pig, De La Llata et al., 2002).

Because research on the aP requirements of swine primarily has been conducted in university or experiment station settings, and these environments often result in greater feed intake in pigs than is observed in commercial environments, results of these experiments may have underestimated the aP requirements expressed as a percentage of the diet. Therefore, the purpose of these experiments was to estimate the aP requirements in a commercial environment.

Materials and Methods

General

Procedures used in these experiments were approved by the Kansas State University Animal Care and Use Committee. All three trials were conducted at a commercial research facility in southwestern Minnesota. The facility is made up of four individual barns, each 12.5 × 76.2 m, with 48 3.05- × 5.49-m pens. Each curtain-sided barn has a deep pit with completely slatted floors and operates on natural ventilation during the summer and mechanically assisted ventilation during the winter. Pens of pigs (Line C22 × 337 gilts, PIC, Franklin, KY) were weighed and allotted randomly to dietary treatments in a randomized complete block design. Each pen contained one four-hole dry self-feeder (Staco, Schaefferstown, PA) and one cup waterer to allow ad libitum access to feed and water. Pen and feeder weights were measured approximately every 14 d to calculate ADG, ADFI, and G:F. Before starting experimental diets, pigs were fed a diet containing 0.40% aP in the preliminary study and Exp. 1, and 0.27% aP in Exp. 2. All diets were formulated using NRC (1998) nutrient composition values for the respective ingredients. Available P values were also calculated using NRC (1998) estimates. Samples of the individual diets were collected and analyzed for CP (AOAC, 1995). Dietary Ca and P were determined using inductively coupled plasma emission spectroscopy with a Fisons ARL model 3410 (Ecublens, Switzerland; AOAC, 1995 Method 985.01).

Before conducting the titration studies, we conducted a preliminary trial to try to narrow the wide range of aP estimates used in commercial production. Results of the preliminary trial would allow us to decrease the interval in aP concentrations between treatments and potentially to improve the accuracy of determining a requirement estimate. A total of 600 gilts with an initial weight of 43.2 kg was blocked by weight and randomly allotted to low (0.30%) or high (0.37%) dietary aP treatments from 43 to 48 kg BW, and later to 0.19 or 0.27% aP from 111 to 121 kg BW. There were 25 pigs per pen and 12 pens per treatment. All diets were corn–soybean meal-based and contained 6% choice white grease. Varying the amounts of monocalcium phosphate and limestone attained the desired levels of Ca and P in the diets. A constant Ca:total P ratio of 1.1:1 was maintained in all diets (NRC, 1998). The differences in aP between the high and low regimen represented the variation in recommendations proposed by swine breeding stock companies and nutritionists for commercial production in the United States.

Experiment 1

A total of 1,260 gilts with an initial weight of 33.8 kg was blocked by weight and randomly allotted to one of five dietary treatments in a 26-d experiment. The corn–soybean meal-based diets contained 6% choice white grease and were formulated to 1.25% total lysine. Treatments consisted of five levels of aP; 0.18, 0.22, 0.25, 0.29, or 0.32%, which corresponded to 0.5, 0.6, 0.7, 0.8, or 0.9 g of aP/Mcal of ME (Table 1). These concentrations were selected based on results of the preliminary study. There were 28 pigs per pen and nine pens per treatment. A constant Ca:total P ratio of 1.1:1 was maintained in all diets (NRC, 1998). Varying the amounts of monocalcium phosphate and limestone attained the desired levels of Ca and P in the diets.

At the conclusion of Exp. 1, one pig from each pen was randomly selected and killed via captive bolt. The right fifth, sixth, and seventh ribs and the right rear leg were collected, labeled, placed in plastic bags, and stored in a cooler filled with ice for transport to Kansas State University (approximately 10 h). Samples were then stored in a freezer at –29°C.

Ribs were removed from the freezer and immediately cleaned of all connective tissue while still frozen. The three ribs were separated, labeled, and stored in individual plastic bags at –12°C. The sixth rib was used to obtain all bone data response variables.

The right rear legs were removed from the freezer and allowed to partially thaw for 12 h at 7°C. Legs were dissected to obtain the right femur and third and fourth metatarsals, which were then manually cleaned of connective tissue. The bones were labeled, placed in plastic bags, and stored in a freezer at –12°C.

Experiment 2

A total of 1,239 gilts with an initial weight of 88.5 kg was blocked by weight and randomly allotted to one of five dietary treatments in a 28-d experiment. Pigs

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

	Dietary available P (aP), %				
Item	0.18	0.22	0.25	0.29	0.32
Ingredient, %					
Corn	59.93	59.56	59.18	58.81	58.43
Soybean meal, 46.5% CP	31.98	32.01	32.05	32.08	32.11
Choice white grease	6.00	6.15	6.30	6.45	6.60
Monocalcium P, 21% P	0.51	0.68	0.85	1.02	1.20
Limestone	0.85	0.87	0.89	0.91	0.93
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[b]	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[c]	0.15	0.15	0.15	0.15	0.15
L-Lysine HCl	0.15	0.15	0.15	0.15	0.15
Calculated composition					
Lysine, %	1.25	1.25	1.25	1.25	1.25
ME, kcal/kg	3,601	3,601	3,601	3,601	3,601
CP, %	20.13	20.11	20.09	20.08	20.06
Ca, %	0.54	0.58	0.62	0.66	0.70
aP, g/Mcal of ME	0.50	0.60	0.70	0.80	0.90
P, %	0.49	0.53	0.57	0.60	0.64
Analyzed values, %					
Ca	0.53	0.53	0.56	0.59	0.67
P	0.45	0.46	0.50	0.55	0.57

[a]Diet composition was calculated using NRC (1998) composition values for ingredients.
[b]Provided per kilogram of diet: 6,615 IU of vitamin A; 992 IU of vitamin D_3; 26 IU of vitamin E; 3 mg of vitamin K; 0.03 mg of B_{12}; 6 mg of riboflavin; 20 mg of pantothenic acid; and 33 mg of niacin.
[c]Provided per kilogram of diet: 165 mg of Zn from Zn oxide; 165 mg of Fe from Fe sulfate; 39.7 mg of Mn from Mn oxide; 16.5 mg of Cu from Cu sulfate; 0.298 mg of I from Ca Iodate; and 0.298 mg of Se from Na selenite.

were fed diets with 0.05, 0.10, 0.14, 0.19, or 0.23% aP, which corresponds to 0.14, 0.28, 0.39, 0.53 or 0.64 g of aP/Mcal (Table 2). These concentrations were again selected based on results of the preliminary trial. There were 27 or 28 pigs per pen and nine pens per treatment. A constant Ca:total P ratio of 1.1:1 was maintained in

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

	Dietary available P (aP), %				
Item	0.05	0.10	0.14	0.19	0.23
Ingredient, %					
Corn	75.68	75.68	75.68	75.68	75.68
Soybean meal, 46.5 CP %	15.90	15.90	15.90	15.90	15.90
Choice white grease	6.00	6.00	6.00	6.00	6.00
Monocalcium P, 21% P		0.21	0.43	0.64	0.86
Limestone	0.73	0.76	0.78	0.81	0.83
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[b]	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[c]	0.15	0.15	0.15	0.15	0.15
Sand	0.96	0.72	0.48	0.24	0.00
L-Lysine HCl	0.15	0.15	0.15	0.15	0.15
Calculated composition					
Lysine, %	0.80	0.80	0.80	0.80	0.80
ME, Mcal/kg	3,596	3,596	3,596	3,596	3,596
Ca, %	0.35	0.40	0.45	0.50	0.55
aP, g/Mcal of ME	0.14	0.28	0.39	0.53	0.64
P, %	0.32	0.37	0.41	0.46	0.50
Analyzed values %					
Ca	0.36	0.42	0.43	0.55	0.49
P	0.30	0.35	0.37	0.40	0.45

[a]Diet composition was calculated using NRC (1998) composition values for ingredients.
[b]Provided per kilogram of diet: 6,615 IU of vitamin A; 992 IU of vitamin D_3; 26 IU of vitamin E; 3 mg of vitamin K; 0.03 mg of B_{12}; 6 mg of riboflavin; 20 mg of pantothenic acid; and 33 mg of niacin.
[c]Provided per kilogram of diet: 165 mg of Zn from Zn oxide; 165 mg of Fe from Fe sulfate; 39.7 mg of Mn from Mn oxide; 16.5 mg of Cu from Cu sulfate; 0.298 mg of I from Ca Iodate; and 0.298 mg of Se from Na selenite.

all diets. Varying the amounts of monocalcium phosphate and limestone attained the desired levels of Ca and P in the diets.

At the conclusion of Exp. 2, two pigs from each pen where randomly selected, tattooed, and shipped to a commercial meatpacking facility for slaughter (Sioux-Preme, Sioux Center, IA). After pigs were processed, the lower third of the front right leg was removed, labeled, placed in plastic bags, and stored in a cooler on ice for transport to Kansas State University (approximately 7 h). Samples were then stored in a freezer at −29°C. Samples were removed from the freezer and the metacarpals were dissected and immediately cleaned of all connective tissue while still frozen. Cleaned bones were labeled and stored in individual plastic bags at −12°C.

Bone Analyses

Bones were removed from the freezer and placed in a cooler at 7°C for 12 h, and then removed and allowed to thaw at room temperature (24°C) in plastic bags for 24 h. Bones were then measured for bending moment using a three-point flexure test (Crenshaw et al., 1981) with force applied by an Instron Universal Testing Machine (model 4201, Instron Corp., Canton MA). Crosshead speed was 100 mm/min. Ribs (Exp. 1), metatarsals (Exp. 1), and metacarpals (Exp. 2) were oriented to the crosshead such that the force applied was medial-lateral, whereas the femurs (Exp. 1) were oriented such that force was applied dorsal-ventral. The distance between the two fulcra points for metatarsals, metacarpals, and ribs was 2 cm, whereas the bridge or fulcra for femurs was 4 cm.

After analysis, bones were cut in half with a model 5215 Hobart meat saw (Hobart Corp., Troy, OH) with a blade that was 0.32 cm thick. Bones were then placed in petroleum ether for 7 d, and then dried for 12 h at 105°C three times to determine the absolute dry, fat-free weight. Bones were then ashed at 600°C for 24 h to determine percentage of ash. Ash is expressed as a percentage of dried, fat-free bone weight.

Statistical Analyses

Treatments were arranged in a randomized complete block design. Analysis of variance was conducted on all data using the PROC MIXED procedure of SAS (Version 8.01, SAS Inst., Inc., Cary, NC), with a Kenward and Roger error correction for degrees of freedom. Pen was used as the experimental unit of analysis for all treatment effects. For growth performance, the statistical model included treatment as a fixed effect and block as a random effect. A repeated-measures analysis was used to analyze the bone criteria (Littell et al., 1996). In Exp. 1, the model included the fixed effects of treatment × bone interaction, with the random effects of block and repeated measures of bone within pig (pen). Because one pig per pen was sampled in Exp. 1, the individual pig represented the pen mean. A similar statistical model was used for Exp. 2, with the exception that the repeated measure was bone within pig within pen. Linear and quadratic orthogonal polynomial contrasts (Peterson, 1985) were used to further characterize treatment effects. Breakpoint analysis was conducted according to Robbins (1986).

Results and Discussion

In the preliminary study (data not reported), there were no differences observed (P = 0.10 to 0.81) in ADG or ADFI. Pigs fed the low-aP diets had improved (P = 0.07) G:F compared with those fed the high-aP diets from 43 to 48 kg, but there were no differences (P = 0.46) in G:F from 111 to 121 kg BW. These results suggest that the aP requirement necessary for maximum growth for these pigs was at or above the concentrations in the low-aP diets. These values (with minor extrapolation for differences in initial BW) were used to establish our highest aP concentrations in the two subsequent titration studies with 33- to 55- and 88- to 109-kg pigs. We also expanded our response criteria to include bone mechanical properties because, typically, aP requirements to maximize bone strength are greater than those required to maximize growth (Crenshaw et al., 1981).

In Exp. 1, from d 0 to 14, increasing aP increased (linear, P = 0.03) ADG and tended to increase (quadratic, P = 0.07) G:F (Table 3). The greatest improvement in both ADG and G:F was observed as aP increased from 0.18 to 0.22% of the diet (G:F breakpoint of 0.22%), corresponding with intakes of 2.70 and 3.21 g of aP/d. However, from d 14 to 26 and for the overall study, no differences were observed (P = 0.12 to 0.81) in ADG, ADFI, or G:F. Although not different, numerical trends similar to those observed from d 0 to 14 were observed for overall ADG and G:F as aP increased from 0.18 to 0.22% corresponding to 2.74 and 3.30 g of aP/d.

Based on improved ADG and G:F observed during d 0 to 14 in our study, the aP requirement for 20- to 50-kg pigs seems to be relatively similar on a percentage basis to NRC (1998) estimates (0.22 vs. 0.23%). However, relative to the energy content of the diet (0.60 g of aP/Mcal of ME compared with 0.71 g of aP/Mcal of ME), and on a grams-per-day basis (3.30 compared with 4.27 g of aP/d), the requirement estimates observed in this study are lower than those suggested by NRC (1998). The linear nature of the response from d 0 to 14, followed by no overall response to increasing aP, makes estimating a requirement difficult. The d-0 to -14 data may provide a more applicable requirement estimate because of the potential for P mobilization from bone tissue being directed to meet requirements for lean tissue growth. We speculate that d-0 to -14 ADG and G:F were decreased immediately by low dietary aP concentrations, but by d 14 to 28, P was mobilized from bone tissue to meet the requirement for growth of pigs fed low aP concentrations. However, this resulted in low bone ash concentration. An alternative hypothesis

Table 3. Effects of increasing available phosphorus (aP) on growing pig growth performance, Exp. 1[a]

	Dietary aP, %					P-value		
Item	0.18	0.22	0.25	0.29	0.32	Linear	Quadratic	SEM
d 0 to 14								
ADG, g	792	840	826	854	837	0.03	0.12	15
ADFI, g[b]	1,500	1,459	1,475	1,449	1,487	0.66	0.24	26
G:F	0.529	0.577	0.560	0.592	0.566	0.06	0.07	0.014
aP intake, g/d[c]	2.70	3.21	3.69	4.20	4.76	0.01	0.62	0.07
d 14 to 26								
ADG, g	881	886	889	891	883	0.89	0.70	19
ADFI, g[b]	1,548	1,548	1,563	1,592	1,568	0.45	0.79	35
G:F	0.570	0.574	0.570	0.563	0.566	0.68	0.93	0.016
aP intake, g/d[c]	2.79	3.41	3.91	4.62	5.02	0.01	0.51	0.01
d 0 to 26								
ADG, g	833	861	855	871	858	0.12	0.19	12
ADFI, g[b]	1,522	1,500	1,516	1,515	1,524	0.81	0.63	26
G:F	0.548	0.575	0.565	0.577	0.565	0.35	0.22	0.012
aP intake, g/d[c]	2.74	3.30	3.79	4.39	4.89	0.01	0.89	0.07

[a]A total of 1,260 gilts, initially 33.8 kg BW, was used. Values represent the means of 28 pigs per pen and nine pens per treatment.
[b]As-fed basis.
[c]Calculated dietary aP values multiplied by the ADFI.

is that the pig's aP requirement for growth simply decreased between the first 14 d of the study to the last 12 d. Because the apparent requirement estimate changed so dramatically over the 26-d study and because of the possibility of bone P mobilization meeting the pig's requirement, we believe the d-0 to -14 aP estimate of 0.22% corresponding to 0.60 g of aP/Mcal of ME and 3.30 g of aP/d to be a conservative and more accurate requirement for the entire 26-d period.

There were no individual bone × treatment interactions for bone criteria. Rib and femur bending moment increased (quadratic $P = 0.03$ and linear $P = 0.01$, respectively) with increasing aP (Table 4). However, increasing aP had no effect ($P = 0.18$ to 0.82) on metatarsal bending moment. The percentage of bone ash increased (linear, $P = 0.01$) with increasing aP in the fourth metatarsal, but not in the third metatarsal or rib. Femurs were only evaluated for bending moment. Based on the repeated-measures analysis, the main effect of dietary aP was significant, with increasing aP increasing (linear, $P = 0.007$) bending moment, but the percentage of bone ash was not affected.

Other studies have reported that maximum bone strength and mineralization require total dietary Ca

Table 4. Effects of increasing available phosphorus (aP) on growing pig bone properties, Exp. 1[a]

	Dietary aP, %					P-value		
Item	0.18	0.22	0.25	0.29	0.32	Linear	Quadratic	SEM
Metatarsal 3								
Bending moment, kg·cm	36.1	27.8	24.0	28.2	32.8	0.77	0.18	7.6
Ash, %	49.1	52.1	50.1	50.3	49.8	0.97	0.51	1.9
Metatarsal 4								
Bending moment, kg·cm	36.7	31.8	37.2	37.1	32.2	0.82	0.76	4.7
Ash, %	46.3	49.5	48.1	48.4	49.8	0.01	0.40	0.6
Rib								
Bending moment, kg·cm	18.7	25.5	24.8	27.7	27.6	0.001	0.03	1.2
Ash, %	47.1	48.1	48.3	48.8	48.3	0.16	0.64	0.9
Femur								
Bending moment, kg·cm	289.1	338.2	319.1	339.4	338.1	0.01	0.17	11.8
Main effects of bone[b]								
Bending moment, kg·cm	95.1	105.8	101.3	108.1	107.7	0.007	0.35	3.1
Ash, %[c]	47.5	49.9	48.8	49.2	49.5	0.24	0.40	0.9

[a]One pig from each pen was randomly selected for harvest of bones. Values represent the mean of nine observations per treatment.
[b]Values represent means of bones combined by treatment using repeated-measures analysis.
[c]Percentage of bone ash was not conducted on femurs. Values represent the main effects of metatarsals and rib.

Table 5. Effects of increasing available phosphorus (aP) on finishing pig growth performance, Exp. 2[a]

	Dietary aP, %					P-value		
Item	0.05	0.10	0.14	0.19	0.23	Linear	Quadratic	SEM
d 0 to 14								
ADG, g	621	683	691	734	707	0.008	0.14	26
ADFI, g[b]	1,919	2,006	2,006	2,030	1,962	0.43	0.10	45
G:F	0.325	0.341	0.344	0.361	0.361	0.02	0.66	0.012
aP intake g/d[c]	0.96	2.00	2.81	3.86	4.51	0.01	0.01	0.05
d 14 to 28								
ADG, g	763	738	760	756	763	0.89	0.82	43
ADFI, g[b]	2,249	2,188	2,282	2,242	2,283	0.49	0.73	56
G:F	0.336	0.336	0.334	0.337	0.332	0.92	0.93	0.014
aP intake g/d[c]	1.12	2.19	3.19	4.26	5.25	0.01	0.78	0.08
d 0 to 28								
ADG, g	696	713	728	746	737	0.17	0.63	26
ADFI, g[b]	2,095	2,103	2,153	2,143	2,134	0.34	0.52	39
G:F	0.331	0.339	0.338	0.348	0.345	0.19	0.74	0.009
aP intake g/d[c]	1.05	2.10	3.01	4.07	4.91	0.01	0.11	0.05

[a]1,236 gilts, initially 88.5 kg BW, were used. Values represent the means of 27 or 28 pigs per pen and nine pens per treatment.
[b]As-fed basis.
[c]Calculated dietary aP values multiplied by the ADFI.

and P levels at least 0.1% higher than that for maximizing growth (Nimmo et al., 1980; Kornegay et al., 1981; Maxson and Mahan, 1983). Crenshaw (1986) suggests that to adequately describe Ca and P requirements, bone strength measurements need to be considered. Our data agree with previous findings. Growth rate was maximized at 0.22%, but bending moment continued to increase linearly, although the greatest increase, like ADG, was observed as aP increase from 0.18 to 0.22% aP. These results suggest that 0.22% or 0.60 g of aP/Mcal of ME is adequate to maintain growth and bone strength in pigs from 33 to 55 kg. The 3.30 g of aP/d intake observed in our study is similar to that found by O'Quinn et al. (1997; 3.59 g of aP/d from 25 to 50 kg), but the ratio of aP relative to ME in our study is higher, 0.60 g of aP/Mcal of ME, than the 0.52 g of aP/Mcal used by O'Quinn et al. (1997).

In Exp. 2, from d 0 to 14, increasing aP increased (linear, $P = 0.008$ to 0.02) ADG and G:F (Table 5). Although the response in ADG and G:F to increasing aP was linear, the greatest ADG and G:F was observed in pigs fed 0.19% aP, corresponding to 3.86 g aP/d intake. Average daily feed intake tended to increase (quadratic, $P = 0.10$), with the greatest increase observed as aP increased from 0.05 to 0.10% aP. From d 14 to 28 and from d 0 to 28, no differences ($P = 0.17$ to 0.93) were observed for ADG, ADFI, or G:F. As in Exp. 1, we believe the d-0 to -14 data to be a more accurate estimate of the pig's aP for the 28-d study because of the potential for P mobilization from bone tissue to meet requirements for growth.

Although no individual bone × treatment interactions were observed, bending moment increased (linear, $P = 0.003$) with increasing aP in the third but not the fourth metacarpal (Table 6). Repeated measures analysis of both bones indicated a linear increase ($P = 0.04$) with increasing aP. Bone ash percent increased (linear, $P = 0.001$) in both metacarpals; this relationship was also evident with repeated measures analysis.

Lindemann et al. (1995), O'Quinn et al. (1997), and McGlone (2000) reported that complete removal of inorganic P sources for the last 41 kg of gain had no effect on growth performance or bone strength of finishing pigs. Mavromichalis et al. (1999) and Shaw et al. (2002) observed that aP concentrations in late finishing diets could be decreased by 66% without negatively affecting pig performance. Contrary to these findings, Dritz et al. (2000) reported a case study where dietary aP concentrations were decreased in a production system to minimize P excretion. Growth and feed efficiency were not affected; however, there was a twofold increase in loin trim loss as a result of vertebral fractures during the stunning process at slaughter. Results of our study agree with those of Dritz et al. (2000) and suggest that some added inorganic P (in diets without added phytase) is necessary in corn–soybean meal-based finishing diets for pigs from 88 to 109 kg BW.

In previous studies (Lindemann et al., 1995; O'Quinn et al., 1997; Mavromichalis et al., 1999; McGlone, 2000; Shaw et al., 2002) where a complete or up to 66% removal of inorganic P had no affect on pig growth performance, feed intake was much higher than that observed in our study. Therefore, those pigs were able to meet or exceed their aP requirements on a grams-per-day basis despite the low percentage of aP in the diet. Factors influencing feed intake, such as housing, environment, stocking density, and diet, need to be evaluated before adapting a requirement estimate to a particular production system.

Table 6. Effects of increasing available phosphorus (aP) on finishing pig bone properties, Exp. 2[a]

	Dietary aP, %					*P*-value		
Item	0.05	0.10	0.14	0.19	0.23	Linear	Quadratic	SEM
Metacarpal 3								
Bending moment, kg·cm	100.2	111.3	118.4	112. 9	120.0	0.003	0.24	4.36
Ash %	50.1	50.7	51.9	52.0	52.1	0.001	0.14	0.36
Metacarpal 4								
Bending moment, kg·cm	92.8	95.6	92.6	97.3	95.5	0.59	0.93	4.34
Ash %	51.2	51.6	51.8	52.7	53.3	0.001	0.48	0.52
Main effects of bone[b]								
Bending moment, kg·cm	96.5	103.3	105.5	105.1	107.7	0.04	0.41	3.50
Ash %	50.6	51.2	51.9	52.3	52.7	0.001	0.65	0.40

[a]Two pigs were randomly selected from each pen for harvest of bones. Values represent the mean of nine observations per treatment.
[b]Values represent means combined Metacarpal 3 and 4 using repeated measures analysis.

Cera and Mahan (1988) suggest that previous levels of dietary Ca and P fortification are likely to affect the requirements of pigs in late finishing. Pigs in our studies were fed adequate levels of Ca and P before being fed their respective experimental diets. Because of this, responses in these current studies may be different than responses in pigs fed Ca and P deficient diets for the entire growing-finishing period.

Another consideration in interpreting our results is the Ca:P ratio used. A wide range of total Ca to total P has been shown to decrease P absorption (Qian et al., 1996; Liu et al., 2000). Thus, pigs fed diets with wide Ca:P ratios may show signs of P deficiency even though adequate P is provided. Estimates by NRC (1998) suggest that corn-soybean meal-based diets should be between 1:1 and 1:1.25 Ca:P.

Several factors can influence ADFI, and because pigs studied in university research conditions generally consume more feed than those raised in commercial environments, there may be differences in nutrient requirement estimates when expressed as a percentage or on a g/d basis. If percentage requirements for pigs are based on research from university environments, they may underestimate requirements because of the low feed intake in commercial facilities. Differences in the energy density of the diets between studies can also occur (i.e., use of added dietary fat), which may also influence ADFI (De La Llata et al., 2001). Therefore, expressing aP as a ratio of grams of aP required per unit of dietary energy will more accurately match the grams of aP per day requirement of pigs raised in commercial facilities.

Implications

Phosphorus requirements of commercially reared pigs in these studies are similar on a percentage basis when compared with the current requirements suggested by the National Research Council. However, these estimates are lower than National Research Council estimates on a grams-per-day basis. From 33 to 55 kg of body weight, pigs raised in commercial facilities require 0.22% available phosphorus corresponding to 3.30 g of available phosphorus per day. From 88 to 109 kg of body weight, pigs raised in commercial facilities require at least 0.19% available phosphorus, corresponding to 4.07 g of available phosphorus per day. These data also suggest that complete removal of supplemental phosphorus in late finishing diets will result in decreased growth performance.

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