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Bioavailability of phosphorus in meat and bone meal for swine^{1,2}

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ABSTRACT: Meat and bone meal (MBM), when supplemented with tryptophan, is an excellent protein source for pigs. It is also a rich source of Ca and P, but some research has suggested that the bioavailability of P is variable. Experiment 1 further examined the bioavailability of P in MBM. The MBM was obtained directly from a plant and was processed to pass through a 10-mesh screen. It contained 50.7% CP, 2.26% lysine, 10.0% Ca, and 5.0% P (air-dry basis). Individually penned pigs (n = 35; 17 kg initial BW) were fed (ad libitum basis) a low-P, corn-soybean meal-basal diet (0.95% lysine, 0.70% Ca, 0.34% P; as-fed basis) or the basal with graded levels of added P (0.067, 0.133, 0.200%) from monosodium phosphate (MSP) or MBM for 40 d. The Ca level was 0.70% in all diets. Diets were fortified with salt, vitamins, and trace minerals. At termination, the third and fourth metacarpals and metatarsals and femurs were removed from all pigs. Growth rate and feed:gain improved linearly ($P < 0.01$) with P addition, regardless of source, whereas ADFI was unaffected ($P = 0.20$). Bone strength and ash increased linearly ($P < 0.01$) with increasing level of P from either source. The main effect of P source (MSP vs. MBM) was not significant, except for the greater femur strength ($P < 0.05$) in the pigs fed the MSP-supplemented diets. Femur and metacarpal/metatarsal strength and meta-

carpals ash (grams) were regressed on grams of added P consumed for each P source, with the basal included in both regressions. Based on slope ratios (MSP considered as 100%), the relative bioavailability of P in MBM averaged 87% when the regression lines were forced through a common intercept and 95% when unforced. In Exp. 2, 100 pigs were fed fortified corn-soybean meal or corn-soybean meal-MBM diets from 45 to 110 kg BW to evaluate MBM as the sole source of supplemental P. The MBM (54% CP, 2.3% lysine, 9.2% Ca, 4.4% P; air-dry basis) was substituted for corn and soybean meal on a lysine basis, and crystalline lysine was added to all diets at 0.15%. Tryptophan was included in diets containing MBM. Treatments were arranged in a 2×2 factorial with P source (dicalcium phosphate or MBM) and P level as the two factors. The two levels of P and Ca were at the NRC requirement or the NRC level plus 0.10% additional P and Ca. Performance, carcass traits, and bone strength were not affected by source of P and Ca, but bone strength was greater ($P < 0.01$) at the higher P and Ca level. These results indicate that the bioavailability of P in MBM, relative to that in MSP, is high (approximately 91%) for growing pigs, and MBM can serve as the sole source of supplemental P and Ca for finishing pigs.

Key Words: Meat and Bone Meal, Phosphorus, Pigs

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Introduction

Rendered animal by-products, such as meat and bone meal (MBM), contain relatively high levels of protein, Ca, P, and B vitamins and are commonly included in

swine and poultry diets. Early research with pigs indicated that growth performance was decreased with increasing levels of MBM in diets (Peo and Hudman, 1962; Evans and Leibholz, 1979); however, subsequent studies showed that the decrease in performance associated with inclusion of high levels of MBM could be prevented with the inclusion of 0.03% tryptophan for every 10% addition of MBM to the diet (Cromwell et al., 1991).

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Although growth performance can be optimized using corn–soybean meal–meat meal diets supplemented with tryptophan, uncertainties remain about the digestibility or bioavailability of minerals, especially Ca and P, in MBM. Some estimates of the relative bioavailability of P in MBM have ranged from 64 to 93% (Huang and Allee, 1981; Burnell et al., 1988, 1989). Coffey and Cromwell (1993) also reported a low estimate of P bioavailability (69%). Poulsen (1995) reported that the apparent digestibility of P in MBM for pigs was quite low (54%), and his review of other studies showed a range of 69 to 80% for the apparent digestibility of P in MBM.

Adequate amounts of Ca and P are present in MBM to meet the requirements of pigs provided that the bioavailability of these minerals is sufficiently high. A better understanding of the bioavailability of P in MBM is essential so that diets can be formulated to meet minimum requirements without oversupplementing P and causing environmental problems.

This study was conducted to determine the relative bioavailability of P in MBM using slope ratio procedures and to determine whether MBM could serve as the sole source of supplemental P in diets for finishing pigs.

Experimental Procedures

Two experiments were conducted to determine the bioavailability of P in MBM and to evaluate MBM as a sole source of supplemental P in diets for finishing pigs. Both experiments were conducted at the University of Kentucky Swine Research Unit in Lexington. The studies were conducted under protocols approved by the University of Kentucky Institutional Animal Care and Use Committee.

Meat and Bone Meal

The MBM used in the studies were blended products of bovine and porcine origin and processed to pass through a 10-mesh screen (Table 1). The MBM was provided by Griffin Industries (Cold Spring, KY).

Experiment 1

Thirty-five crossbred (Hampshire × Yorkshire-Landrace) pigs averaging 17.1 kg BW were used in the study. They were allotted randomly to seven treatments in five replications from outcome groups of weight and gender (two barrows and three gilts per treatment). The pigs were individually penned in elevated, wire mesh-floored pens (0.6 m × 1.2 m) in a temperature-controlled building. Diets were in meal form and were consumed from a stainless steel self feeder on an ad libitum basis. Water was provided from nipple waterers. Pig weights and feed intakes were determined weekly.

The experimental diets (as-fed basis) are shown in Table 2. Diet 1 was a low-P basal diet (0.34% P) consisting mainly of ground corn and dehulled soybean

Table 1. Composition of meat and bone meal (% air-dry basis)

Nutrient	Exp. 1	Exp. 2
CP	50.7	54.0
Crude fat	6.4	10.5
Ash	34.7	27.9
Ca	10.0	9.6
P	5.0	4.4
Amino acids		
Arginine	3.49	3.84
Histidine	0.82	0.80
Isoleucine	1.39	1.65
Leucine	3.01	3.32
Lysine	2.26	2.29
Methionine	0.57	0.63
Cystine	0.69	1.07
Phenylalanine	1.75	1.89
Tyrosine	1.06	1.18
Threonine	1.59	1.75
Tryptophan	0.25	0.30
Valine	2.26	2.64

meal with a small amount of cornstarch. All the P in this diet was supplied by the corn and soybean meal; thus, the P was largely in the form of phytate of which the P is poorly available. Diets 2, 3, and 4 consisted of the basal diet with three graded levels of supplemental P (0.067, 0.133, 0.200%) supplied by monosodium phosphate (MSP), a highly available source of P. The MSP was substituted for cornstarch. Diets 5, 6, and 7 included the basal diet with three levels of MBM (1.33, 2.67, 4.00%) substituted for cornstarch to supply the same levels of P as provided by the MSP in Diets 2, 3, and 4, respectively. Technical-grade calcium carbonate was included at a constant level in Diets 1 to 4, and the level was decreased in the MBM diets in relation to the amount of Ca and P supplied by the MSP. A constant amount of ground calcitic limestone was included in all diets so that Ca was maintained at 0.70% in all diets. In addition, L-lysine·HCl was added to all diets, and L-tryptophan was added to the MBM diets to provide 3 g of tryptophan/kg of MBM (Cromwell et al., 1991). Corn oil was adjusted to maintain a constant level of ME in all diets. All diets were fortified with salt, trace minerals, and vitamins to meet or exceed NRC (1998) requirements.

After a 40-d feeding period, all pigs were humanely slaughtered (electrically stunned followed by exsanguination). The femurs were removed and the front and rear feet were removed at the knee and hock joint, respectively. Both were sealed in plastic bags and frozen. Later, the feet were thawed and placed in an autoclave for 8 min to aid in removal of the third and fourth metacarpals and metatarsals. Following extraction, the bones were again frozen.

Later, the femurs, metatarsals, and metacarpals were allowed to thaw for 5 to 6 h, and then subjected to breaking strength determinations with an Instron machine (model TM 1123, Instron Corp., Canton, MA).

Table 2. Composition of diets (as-fed basis, %) in Exp. 1

Item	Added P, %:	Basal	MSP ^a			MBM ^a		
		0.00	0.067	0.133	0.200	0.067	0.133	0.200
Ground corn		70.38	70.38	70.37	70.39	70.38	70.38	70.38
Dehulled soybean meal		21.99	21.99	21.99	21.99	21.99	21.99	21.99
Cornstarch		4.00	3.45	2.89	2.32	2.78	1.54	0.25
Corn oil		1.00	1.25	1.52	1.78	1.22	1.45	1.71
Monosodium phosphate		—	0.297	0.595	0.893	—	—	—
Meat and bone meal		—	—	—	—	1.33	2.67	4.00
Ground calcitic limestone		0.60	0.60	0.60	0.60	0.60	0.60	0.60
Calcium carbonate ^b		0.98	0.98	0.98	0.98	0.64	0.31	—
Iodized salt		0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin-trace mineral premix ^c		0.17	0.17	0.17	0.17	0.17	0.17	0.17
L-Lysine·HCl		0.13	0.13	0.13	0.13	0.13	0.13	0.13
L-Tryptophan		—	—	—	—	0.005	0.010	0.015
Antibiotic ^d		0.25	0.25	0.25	0.25	0.25	0.25	0.25
Calculated analysis ^e								
CP, %		16.4	16.4	16.4	16.4	17.1	17.8	18.4
Lysine, %		0.95	0.95	0.95	0.95	0.98	1.02	1.05
Ca, %		0.70	0.70	0.70	0.70	0.70	0.70	0.70
P, %		0.34	0.41	0.47	0.54	0.41	0.47	0.54
ME, Mcal/kg		3.365	3.365	3.365	3.365	3.365	3.365	3.365

^aMSP = monosodium phosphate; MBM = meat and bone meal.

^bTechnical grade.

^cProvided the following per kilogram of diet: vitamin A, 6,600 IU (2,204 µg of retinyl acetate); vitamin D₃, 880 IU (22.0 µg of cholecalciferol); vitamin E, 22 IU (22 mg of DL-α-tocopherol acetate); vitamin K (as menadione sodium bisulfite complex), 6.4 mg; riboflavin, 8.8 mg; pantothenic acid, 22 mg; niacin, 44 mg; vitamin B₁₂, 0.022 mg; D-biotin, 0.22 mg; folic acid, 1.1 mg; Zn, 135 mg (ZnO); Fe, 135 mg (FeSO₄·H₂O); Mn, 45 mg (MnO); Cu, 13 mg (CuSO₄·5H₂O); I, 1.5 mg (CaI₂O₆); and Se, 0.3 mg (NaSeO₃).

^dMecadox (Phibro Animal Health, Fairfield, NJ) provided 55 mg of carbadox/kg of diet.

^eBased on referenced analysis of corn and soybean meal (NRC, 1998) and determined analysis of meat and bone meal.

Breaking strength is defined as the peak amount of force, before fracture, applied by a wedge mounted on a pressure-sensitive compression cell at the center of the fresh bone when placed horizontally on two supports spaced 7.0 cm (femurs) or 3.2 cm (metacarpals and metatarsals) apart. The metacarpals were cut in half to remove the marrow. After drying in an oven, they were wrapped in cheesecloth and extracted with fresh petroleum ether three times at 24-h intervals. They were then air-dried at room temperature under a chemical hood for 24 h, dried in an oven overnight, and then ashed in a muffle furnace at 600°C for at least 6 h. Ash weight was recorded and the ash percent in dry, fat-free bone was determined.

Bone strength and ash weight were regressed on the daily quantity of added P consumed by pigs fed the two sources of P. Results from pigs fed the basal diet were used to calculate the regression slope for each P source. A comparison of the two slopes gives the bioavailability of the P in MBM relative to the bioavailability of P in MSP (given a value of 100%). The P bioavailabilities based on the femurs, mean of metacarpals-metatarsals, and ash content in grams of the metacarpals were then averaged to give an overall estimate of the relative bioavailability of P in the MBM. The relative bioavailabilities were calculated both with and without a forced y-intercept.

Experiment 2

One hundred crossbred (Hampshire × Yorkshire-Landrace) pigs initially averaging 45.1 kg BW were used in the study. They were grouped by gender and initial weight and allotted at random to five replications of four dietary treatments from outcome groups of initial weight within gender. Each pen consisted of five pigs with equal gender ratio within replication (i.e., two barrows and three gilts or three barrows and two gilts per pen).

Pigs were housed in an open-front building in 1.2 m × 6.7 m, concrete-floored pens, with approximately half of the pen covered. Pigs were allowed to consume their diets (meal form) and water on an ad libitum basis from wooden, two-hole self-feeders and automatic watering fountains. The pens were cleaned two or three times per week. The pigs were individually weighed, and feed consumption was determined on a pen basis at weekly or biweekly intervals during the experiment. The study was conducted during the summer.

Four dietary treatments, factorially arranged, were fed during two finishing phases (Phase 1 = 45 to 78 kg BW; Phase II = 78 to 110 kg BW; Table 3). Two fortified corn-soybean meal diets used feed-grade dicalcium phosphate (DCP) as the source of supplemental P. Two additional diets used MBM as the source of supplemen-

Table 3. Composition of diets (as-fed basis, %) in Exp. 2

Item	Source of P: Dietary P, %: ^b Dietary Ca, %: ^b	Finishing phase I				Finishing phase II			
		DCP ^a		MBM ^a		DCP		MBM	
		0.45	0.50	0.45	0.55	0.40	0.50	0.40	0.50
		0.55	0.65	0.50	0.65	0.45	0.55	0.45	0.55
Ground corn		83.66	82.94	84.94	85.13	87.84	87.35	88.11	87.85
Dehulled soybean meal		13.02	13.09	9.15	6.56	9.02	9.01	6.82	4.89
Meat and bone meal		—	—	3.86	6.50	—	—	2.88	5.45
Dicalcium phosphate		0.80	1.35	—	—	0.61	1.16	—	—
Ground calcitic limestone		0.73	0.83	0.24	—	0.74	0.69	0.38	—
Iodized salt		0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Choice white grease		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
L-Lysine·HCl		0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
L-Tryptophan		—	—	0.02	0.02	—	—	0.02	0.02
Vitamin-trace mineral premix ^c		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Antibiotic ^d		0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

^aMSP = monosodium phosphate; MBM = meat and bone meal.

^bBased on referenced analysis of corn, soybean meal, and dicalcium phosphate (NRC, 1998) and determined analysis of meat and bone meal. Phase I and II diets were formulated to contain 0.76 and 0.65% lysine, respectively.

^cProvided the following per kilogram of diet: vitamin A, 4,950 IU (1,703 µg of retinyl acetate); vitamin D₃, 660 IU (16.5 µg of cholecalciferol); vitamin E, 16.5 IU (16.5 mg of DL-α-tocopherol acetate); vitamin K (as menadione sodium bisulfite complex), 4.8 mg; riboflavin, 6.6 mg; pantothenic acid, 16.5 mg; niacin, 33 mg; vitamin B₁₂, 0.016 mg; D-biotin, 0.165 mg; folic acid, 0.83 mg; Zn, 135 mg (ZnO); Fe, 135 mg (FeSO₄·H₂O); Mn, 45 mg (MnO); Cu, 13 mg (CuSO₄·5H₂O); I, 1.5 mg (CaI₂O₆); and Se, 0.3 mg (NaSeO₃).

^dAureomycin (Alpharma, Ft. Lee, NJ) provided 110 mg of chlortetracycline/kg of diet.

tal P. These diets were formulated to contain 0.45 or 0.55% P (as-fed basis) during Phase I and 0.40 or 0.50% P during Phase II. The Ca levels were 0.50 or 0.65% during Phase I and 0.45 or 0.55% during Phase II. Except for the Ca and P supplied by corn and soybean meal, all the P and most of the Ca in the MBM diets were supplied by the MBM. The diets with the lower levels of Ca and P were formulated to meet NRC (1998) requirements for these two minerals, and the diets with the higher levels of Ca and P represented slight overages of the two minerals that are somewhat typical of recommendations of many universities and feed companies. L-lysine·HCl was included to provide 0.15% lysine to all diets, and L-tryptophan was included in the MBM diets. Adjustments were made in the amounts of corn and soybean meal such that all diets contained 0.76 and 0.65% lysine during the two phases, respectively. Dietary lysine concentrations were sufficient to meet the NRC (1998) estimated requirements for gilts with medium-high rates of fat-free carcass lean gain (i.e., 325 g/d). All diets were fortified with trace minerals and vitamins to meet NRC (1998) standards. An antimicrobial agent also was included in the diets.

At a mean BW of 105 kg, all pigs were scanned with real-time ultrasound (User's Manual for AUSKey System; AUSKey System v. 2.0, Animal Ultrasound Services, Ithaca, NY) by an experienced technician. A longitudinal transducer was used to estimate the mean backfat and LM depth at five locations between the 10th and 15th ribs, 5 cm off the midline, of each animal. From LM depth, cross-sectional area of the LM was estimated, and LM areas were adjusted to a common final BW. From backfat depth and LM depth, the per-

centage of carcass lean was estimated. Equations were as provided by the User's Manual for AUSKey System adapted to metric units. The carcass percentage of lean was assumed to contain between 5 and 10% fat (i.e., not fat-free), although this is not specifically identified in the manual. Equations were as follows:

$$\text{Area of LM, cm}^2 = 4.174 + (5.987 \times \text{LM depth, cm})$$

$$\begin{aligned} \text{Carcass lean, \%} &= 58.46 - (6.00 \times \text{backfat, cm}) \\ &+ (1.181 \times \text{LM depth, cm}) \end{aligned}$$

Carcass lean gain was estimated by subtracting the kilograms of initial lean for each pig from the kilograms of final lean and dividing by the number of days. The initial lean was from the NPPC (2000) equation (adapted to metric units) as follows:

$$\text{Initial lean, kg} = (0.418 \times \text{initial BW, kg}) - 1.66$$

The experiment was terminated on a pen basis when the mean weight of the pen reached 109 kg BW. The overall final BW averaged 109.7 kg. All pigs were transported to a commercial packing plant (Swift Packing Co., Louisville, KY), and the front legs were collected to obtain the third and fourth metacarpals. Procedures for removal of the metacarpals and determination of breaking strength were as described for pigs in Exp. 1.

Chemical Analyses

Representative samples of MBM were analyzed in duplicate or triplicate for CP by a N analyzer (N × 6.25),

for crude fat based on ether extraction, and for ash in a muffle furnace. After wet ashing, Ca was determined by atomic absorption chromatography, and P was determined by a gravimetric procedure. All methods were based on standard procedures (AOAC, 1995). Amino acids were analyzed with ion exchange chromatography after acid hydrolysis. Methionine and cystine were oxidized to methionine sulfone and cysteic acid by treatment with performic acid before hydrolysis. Tryptophan was analyzed after alkaline hydrolysis. Calcium and AA assays were conducted at the University of Missouri Experiment Station Chemical Laboratories (Columbia) and the other assays were conducted at the University of Kentucky.

Statistical Analyses

The data were analyzed as a randomized complete block design (Steel and Torrie, 1980) using the GLM procedure of SAS (SAS Inst., Inc., Cary, NC). The statistical model included the effects of replication, diet, and replication \times diet (error). Preplanned treatment comparisons in Exp. 1 were as follows: basal vs. mean of other treatments, linear and nonlinear effects of P level within MSP and MBM (with the basal diet included in both regressions), and the mean of MSP vs. the mean of MBM. In Exp. 2, the main effects of P source and P level, and the interaction were tested. In all instances, pen was considered the experimental unit. Unless stated otherwise, an alpha level of 0.05 was considered statistically significant.

Results

Composition of Meat and Bone Meals

The composition of the MBM is shown in Table 1. The protein and fat contents were higher in the MBM used in Exp. 2 compared with that used in Exp. 1, as were all the essential AA except histidine. Ash, Ca, and P concentrations were slightly higher in the MBM used in Exp. 1 than in Exp. 2. The variation in composition of the two MBM is common to this ingredient (Knabe, 1995).

Most of the nutrients in the two MBM sources approximated the levels listed by the NRC (1998) for MBM. Crude fat tended to be slightly less than the 10.9% listed by NRC (1998), but CP, Ca, and P were close to the levels listed by NRC (1998). The values listed by NRC (1998) are slightly higher for lysine (2.51%) and histidine (0.91%), but were lower for arginine, isoleucine, cystine, phenylalanine, and valine compared with the MBM sources (Table 1).

Experiment 1

Body weight gain, efficiency of feed utilization, and all the bone traits were improved linearly ($P < 0.01$) when P was added to the basal diet, but feed intake

was not significantly affected by additional P (Table 4). The responses were similar for the two P sources, except for femur strength. For that trait, MSP inclusion resulted in stronger bones ($P < 0.05$) than MBM inclusion.

Slope ratio analysis of the femur and metatarsal-metacarpal strength and metacarpal ash weight data were used to compute P bioavailability estimates (Table 5). Regression of treatment means for the two sources of P on daily supplemental P intake resulted in good fits with r^2 values averaging 0.994 for femur strength, 0.978 for metacarpal-metatarsal strength, and 0.952 for metacarpal ash in grams. Because the basal diet was used to calculate the slopes of the two regression lines when regressed on added P intake, both slopes, in theory, should intersect zero on the y-axis. Forcing the y-intercept resulted in bioavailability estimates of 80 to 95%, with an average of 87%. When the regressions were unforced, the bioavailability estimates for P were slightly higher, from 83 to 106%, with an overall average of 95%. An average of these estimates obtained from these two procedures gives an overall average of 91% for the relative bioavailability of P in MBM. In most instances, the r^2 values were slightly higher when the y-intercept was unforced vs. forced.

Experiment 2

Growth rate, daily feed intake, and feed:gain of finishing pigs were not affected by the source of supplemental P nor by the level of added P (Table 6). Feeding the MBM- vs. the DCP-supplemented diet during the second finishing phase seemed to increase growth rate, but the difference was not significant. There was no evidence of a P source \times level interaction for any of the other performance traits.

Scanned carcass backfat depth, LM depth or area, and estimated carcass lean were not affected by source or level of added P (Table 6), and there was no evidence of any interaction between source and level of added P. The calculated carcass lean gain (mean = 333 g/d) is equivalent to 316 g of carcass fat-free lean gain, assuming the former value includes 5% fat in the lean. The fat-free lean gain of the pigs in this study was intermediate to pigs with an average (300 g/d) to high-medium (325 g/d) lean growth rate, as defined by NRC (1998).

Metacarpal breaking strength was similar for the two sources of added P (Table 6). Bone strength was increased ($P < 0.01$) by feeding the higher level of P during the two finishing stages, and this increase occurred with both the DCP- and MBM-supplemented diets.

Discussion

Meat and bone meal and meat meal have been widely used in animal feeds for many years (Franco and Swanson, 1996). According to AAFCO (2000), MBM is described as the rendered product from mammal tissues, including bone, exclusive of any added blood, hair, hoof, horn, hide trimmings, manure, stomach, and ruminal

Table 4. Source (monosodium phosphate vs. meat and bone meal) and level of P on performance and bone traits of growing pigs, Exp. 1^a

Item	Added P:	Basal	MSP ^b			MBM ^b			SE
		—	0.067	0.133	0.200	0.067	0.133	0.200	
ADG, kg ^c		0.498	0.643	0.634	0.680	0.608	0.671	0.701	0.034
ADFI, kg (as-fed basis)		1.31	1.44	1.42	1.39	1.45	1.43	1.43	0.09
Feed:gain ^c		2.62	2.24	2.25	2.05	2.36	2.13	2.05	0.08
Added P intake, g/d ^c		0.00	0.96	1.89	2.79	0.96	1.89	2.86	0.09
Bone strength, kg									
Femur ^{cd}		85.3	156.4	215.1	262.4	130.9	190.7	233.1	13.6
MT and MC, avg ^{ce}		26.54	38.18	45.16	55.48	31.59	44.98	56.05	3.03
MC ash, g ^c		1.62	2.05	2.41	2.71	1.84	2.33	2.65	0.08
MC ash, % ^c		43.7	46.3	49.5	50.2	45.4	49.3	49.9	0.7

^aEach diet was fed to five individually-penned pigs per treatment. Initial and final BW averaged 17.1 and 42.3 kg, respectively, for the 40-d experiment.

^bMSP = monosodium phosphate; MBM = meat and bone meal.

^cBasal vs. others, $P < 0.01$; linear within basal and MSP diets, $P < 0.01$; linear within the basal and MBM diets, $P < 0.01$.

^dMSP vs. MBM, $P < 0.05$.

^eThird and fourth metatarsal (MT) and metacarpal (MC).

contents, except such amounts as may occur unavoidably in good processing practices. It should contain a minimum of 4.0% P, and Ca should not be more than 2.2 times the P level. Although not included in the official definition, CP is approximately 50%. Both of the MBM sources in this study were within these limits.

Few studies have been conducted to assess the bioavailability of P in MBM. Huang and Allee (1981) reported a bioavailability value of 93% based on a slope ratio study, and that estimate was included in the NRC (1988) publication. Subsequently, Burnell et al. (1988, 1989), using similar procedures, determined that the bioavailability of P was considerably less (64 and 72%), and these low values were later confirmed (69%) by Coffey and Cromwell (1993). The low value of 64% reported by Burnell et al. (1988) was attributed to large particles of bone in their source of MBM.

Table 5. Estimates of relative P bioavailability in meat and bone meal

Response	Relative bioavailability of P, % ^a	
	Forced y-intercept ^b	Unforced y-intercept ^c
Femur strength	80	83
Metacarpal-metatarsal strength	95	106
Metacarpal ash, g	88	95
Average	87	95
Overall average ^d	91	

^aBased on a slope ratio comparison of the regressed response for MBM (meat and bone meal) relative to MSP (monosodium phosphate).

^bThe r^2 for treatment means of femur strength, metacarpal-metatarsal strength, and metacarpal ash were 0.992, 0.991, and 0.957 for MSP, and 0.995, 0.960, and 0.927 for MBM.

^cThe r^2 for treatment means of femur strength, metacarpal-metatarsal strength, and metacarpal ash were 0.994, 0.993, and 0.996 for MSP, and 0.995, 0.971, and 0.927 for MBM.

^dSE = 6.0.

Estimates of apparent digestibilities of Ca and P in MBM also are variable. Poulsen (1995) reported that the apparent digestibility of P in MBM for pigs ranged from 54 to 80%. In two studies in our laboratory, the true digestibility of P in MBM ranged from 76 to 85% compared with the true digestibility values of 86 and 88% for MSP (Traylor et al., 1999a,b). A comparison of the true digestibility coefficients in the two studies of Traylor et al. (1999a,b) indicate that the P in MBM was 91 to 94% as digestible as the P in MSP, which agrees with the slope ratio comparison of P in MBM and MSP in our present study.

The reason for the wide range in estimates of P bioavailability is not clear. However, the relatively high bioavailability of P in MBM that we obtained in the present study agrees more closely with the estimate of 93% reported by Huang and Allee (1981) than the results of the other studies cited. Furthermore, results of other studies conducted by our group showed P bioavailability estimates for MBM ranging from 72 to 94%, with an overall mean of 85% (Traylor et al., 1998, 1999a,b). In those studies, particle size and processing pressure/temperature of MBM had little effect on P bioavailability, but source of MBM (bovine vs. porcine) had a significant effect, in that the availability of P in low-ash MBM of porcine origin was lower than in high-ash MBM of bovine origin (72 vs. 89%; Traylor et al., 1999a). Studies with chicks at our laboratory also indicated that the P from the same sources of MBM as used in the pig studies was relatively high in bioavailability, ranging from 73 to 90%, with a mean of 82% (Traylor et al., 2000).

The results of the second study with finishing pigs confirm the relatively high bioavailability of P in MBM. Growth performance and bone strength of pigs fed diets in which MBM supplied all the P and most of the Ca were equivalent to the growth and bone strength of pigs

Table 6. Dicalcium phosphate vs. meat and bone meal as sources of P at two levels on performance, carcass traits, and bone strength of finishing pigs, Exp. 2^a

Item	Phase I P, %: Phase II P, %:	DCP ^b		MBM ^b		SE
		0.45	0.40	0.45	0.40	
		0.55	0.50	0.55	0.50	
Finishing phase I (45 to 78 kg)						
ADG, kg		0.82	0.85	0.84	0.85	0.03
ADFI, kg (as-fed basis)		2.35	2.43	2.41	2.39	0.07
Feed:gain		2.87	2.86	2.87	2.82	0.05
Finishing phase II (78 to 110 kg)						
ADG, kg		0.89	0.91	0.94	0.95	0.03
ADFI, kg (as-fed basis)		2.95	3.18	3.03	3.08	0.07
Feed:gain		3.32	3.49	3.23	3.24	0.08
Overall (45 to 110 kg)						
ADG, kg		0.85	0.88	0.89	0.89	0.02
ADFI, kg (as-fed basis)		2.63	2.77	2.70	2.71	0.06
Feed:gain		3.10	3.15	3.05	3.03	0.04
Scanned carcass traits ^c						
Backfat depth, mm		21.1	21.2	21.4	21.7	0.7
LM depth, mm		61.7	58.0	59.0	59.0	1.0
LM area, cm ²		40.8	39.0	39.8	39.7	0.5
Estimated lean, %		53.1	52.6	52.6	52.4	0.45
Lean gain, g/d		330	337	333	332	12
Metacarpal strength, kg ^d		178	194	182	194	5

^aEach diet was fed to 25 finishing pigs in five replications of five pigs per pen during a 77-d experimental period. Average initial and final BW were 45.1 and 109.7 kg, respectively.

^bDCP = dicalcium phosphate; MBM = meat and bone meal.

^cPigs were scanned at an average weight of 105 kg (68 d on test). Fat depth and LM depth were adjusted to a common weight of 105 kg BW.

^dMain effect of P level, $P < 0.01$.

fed diets supplemented with DCP in diets calculated to meet NRC requirements. Even when MBM was included in the diets to provide 0.1 percentage point additional P, performance was not decreased compared with feeding corn-soybean meal diets. The decrease in growth performance from moderate to high levels of MBM inclusion reported by Peo and Hudman (1962) and Evans and Leibholz (1979) was apparently due to deficient levels of tryptophan and the low bioavailability of tryptophan (Knabe et al., 1989) in MBM. The studies by Cromwell et al. (1991) clearly demonstrated that the decreased performance associated with inclusion of high levels of MBM could be prevented with the inclusion of 3 g of tryptophan/kg of MBM.

Implications

The results of this study indicate that for swine, the bioavailability of phosphorus in meat and bone meal is approximately 91% relative to that in monosodium phosphate. Meat and bone meal, when supplemented with tryptophan, can supply all the supplemental phosphorus and nearly all the supplemental calcium in corn-soybean meal diets for finishing pigs without negatively affecting growth performance or bone integrity.

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