FINAL REPORT

Phosphorus and amino acid digestibility in meat and bone meal fed to swine

Hans H. Stein

University of Illinois

Department of Animal Sciences

1207 West Gregory Drive

Urbana, IL 61801

April 12, 2011

1. **Summary to Date:** A total of 8 different commercial sources of meat and bone meal (MBM) have been received and used for this experiment. For the amino acid study, 9 growing barrows (initial BW: 25 kg, Genetiporc) were equipped with a T-cannula in the distal ileum and allotted to a 9 × 9 Latin square design with 9 diets and 9 periods in each square. The first 8 diets were cornstarch-based diets containing one source of MBM as the only AA containing ingredient and the last diet was a N-free diet that is used to measure the endogenous losses of AA. For the phosphorus digestibility experiment, a total of 72 growing pigs (initial BW: 18 kg) were randomly allotted to 9 dietary treatments using a randomized complete block design with 8 pigs per treatment. Eight of the diets contained one source of meat and bone meal as the only P-containing ingredient and the last diet was a P-free diet that is used to measure endogenous P losses. Samples of the different MBM sources and the experimental diets for both experiments have been collected and analyzed. Samples collected from the animals of both experiments have been collected, analyzed, and data have been summarized. A final report for the P-digestibility experiment has been written. However, data from the amino acid digestibility experiment indicated that something was wrong with this experiment and the experiment, therefore, needs to be completed. We are currently in the process of doing that.
2. **Objectives:** The objective of this experiment was to measure the standardized total tract digestibility (STTD) of P and standardized ileal digestibility (SID) of AA in 8 different sources of meat and bone meal to estimate variation among sources and create prediction equations for AA and P concentration in meat and bone meal.

3. Experimental Design:

Amino Acid Experiment

Nine growing barrows (initial BW: 25 kg, Genetiporc) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a 9 × 9 Latin square design with 9 diets and 9 periods in each square. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. A feeder and a nipple drinker were installed in each of the pens. A total of 9 cornstarch-based diets were formulated (Table 1). Eight of the diets contained one source of meat and bone meal as the only AA containing ingredient and the last diet was a N-free diet that is used to measure the endogenous losses of AA. All diets also contained 0.4% chromic oxide as an indigestible marker. Each period lasted 7 d and pigs were fed each diet during the course of the experiment during one period. The initial 5 d of each period was considered an adaptation period to the diets and ileal digesta were collected during the final 2 d of each period as previously described (Stein et al., 1998). At the conclusion of the experiment, ileal digesta samples were lyophilized, finely ground, and analyzed for DM, Cr, CP, and AA. Values for the apparent ileal digestibility (AID) and the SID of CP and AA were calculated calculated (Stein et al., 2007).

Phosphorus Digestibility Experiment

A total of 72 growing pigs (initial BW: 20 kg) were randomly allotted to 9 dietary treatments using a randomized complete block design with 8 pigs per treatment. Pigs were housed in metabolism cages that allow for the total collection of feces. A total of 9 diets were formulated (Table 2). Eight of the diets contained one source of meat and bone meal as the only P-containing ingredient and the last diet was a P-free diet that was used to measure the endogenous losses of P. Pigs were fed their respective diets for 12 d with the initial 5 d being the adaptation period to the diet. Fecal materials were collected according to the marker to marker approach as previously described (Widmer et al., 2007). At the conclusion of the experiment, all samples were dried and ground and analyzed for total P. Values for the ATTD and STTD of P in meat and bone meal were calculated as previously described (Widmer et al., 2007).

For both experiments, data were analyzed by ANOVA using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). Homogeneity of variances was tested using the UNIVARIATE procedure of SAS. The model included diet as the fixed effect and block as the random effect. Least squares means were calculated for each independent variable. When treatment was a significant source of variation, means were separated using the PDIFF option of SAS. The pig was the experimental unit for all calculations, and the α level used to determine significance between means was 0.05. For the P-digestibility study, a number of prediction equations were generated to predict the concentration of digestible Ca and P in MBM.

4. **Results to Date and Discussion:** For the P digestibility experiment, data were summarized and written into a manuscript that is ready for submission to Journal of Animal Science (See Appendix). Results of the experiment indicated that on an as-fed basis, the concentration of P in the MBM sources ranged from 2.6 to 5.6% with an average of 4.4 ± 0.9%, whereas Ca concentration ranged from 5.4 to 11.8% with an average of 9.0 ± 1.9% (Table 3). There was greater variation in Ca and P concentrations (CV = 21.1 and 20.4%, respectively) in the MBM samples than in any of the other

chemical components measured (CV = 5.1, 11.0, and 14.4% for acid-hydrolyzed ether extract, CP, and ash, respectively). The ATTD of P (52.1 to 80.1%, average = 65.9 ± 8.8%) and Ca (53.0 to 81.4%, average = 65.1 ± 9.2%) differed ($P < 0.05$) among MBM sources (Table 4). The basal EPL was determined at 106 ± 51 mg/kg DMI in pigs fed the P-free diet. The STTD of P was different (54.8 to 84.4%, average = 68.8 ± 9.3%; $P < 0.05$) among MBM sources. The ATTD of Ca (Table 5) and the STTD of P decreased ($P < 0.01$) as ash, Ca, and P concentration in MBM increased, and the ATTD of Ca was positively related ($R^2 = 0.99$; $P < 0.001$) with the STTD of P. The STTD of P (%) in MBM may be predicted as $66.345 + 4.225 \times \text{ash} - 13.126 \times \text{Ca}$ ($R^2 = 0.83$, RMSE = 4.61; $P < 0.01$), whereas ATTD of Ca (%) may be predicted as $67.316 + 3.833 \times \text{ash} - 12.398 \times \text{Ca}$ ($R^2 = 0.87$, RMSE = 3.97; $P < 0.01$). It was concluded that P and Ca digestibility varies among sources of MBM, but prediction equations using the concentration of mineral components of MBM may be used to estimate P and Ca digestibility in MBM fed to growing pigs. Data are discussed in detail in the attached appendix.

For the amino acid digestibility experiment, data were erratic and did not make sense. After careful consideration and much thinking, it was determined that something must have been wrong with this experiment. This conclusion was based on the fact that some of the values that were calculated for the SID of AA in MBM exceeded 100% (which of course cannot be correct). One of the reasons for these data was that the determined values for the endogenous losses of P were 3 to 5 times greater than what has previously determined in our laboratory. We have never previously determined values that were as high as those observed in this experiment. We are not certain why such high values were determined, but it is possible that the continuous feeding of with diets containing 16% MBM for 9 weeks somehow elicited release of extra endogenous intestinal proteins that were lost. It was remarkable that only in the first week, where pigs had not been fed an MBM diet before, did the pigs not show this response. It is, therefore, likely that the continuous feeding of diets containing 16% MBM results in some kind of incorrect digestion in the pigs and that this results in synthesis of extra endogenous protein. We have conducted more than 50 experiments to determine the ileal digestibility of AA in many different feed ingredients, - but we have never before seen data for endogenous losses of AA that are even close to the data obtained in this experiment. Based on these observations and the fact that really erratic data were calculated for the SID of AA in all sources of MBM, we determined that it is not in anyone's interest to publish data for the SID of amino acids in MBM that are incorrect. It was therefore, determined that diets containing less MBM need to be used in this kind of an experiment. We have subsequently formulated diets containing both MBM and corn and we are using these diets in the repetition of the experiment (Table 6). We are currently feeding these diets and collecting ileal digesta and we are hopeful that this change in diet formulation will result in us being able to calculate correct values for the AID and SID of amino acids in MBM. We believe that we will be able to submit the final report from this experiment in October, 2011. We do regret this delay in the results from our amino acid digestibility experiment, but as mentioned, we believe this is the correct thing to do.

Table 1. Composition (as-fed basis) of diets for the amino acid digestibility experiment[1]

	Diet	
Item	Meat and bone meal	N-Free
Ingredient, %		
Meat and bone meal	16.00	-
Soybean oil	3.00	4.00
Solka floc	-	4.00
Monocalcium phosphate	-	2.40
Ground limestone	-	0.50
Sucrose	20.00	20.00
Chromic oxide	0.40	0.40
Cornstarch	59.90	67.50
Magnesium oxide	-	0.10
Potassium carbonate	-	0.40
Salt	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30
Total	100.00	100.00

---

[1] Diets 1-8 contained MBM as the sole source of AA in the diet; Diet 9 is the N-free diet.

[2] The vitamin-mineral premix provided the following quantities of vitamins and minerals per kilogram of complete diet: Vitamin A, 10,990 IU; vitamin D3, 1,648 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; thiamin, 3.3 mg; riboflavin, 9.9 mg; pyridoxine, 3.3 mg; vitamin B12, 0.044 mg; D-pantothenic acid, 33 mg; niacin, 55 mg; folic acid, 1.1 mg; biotin, 0.17 mg; Cu, 16 mg as copper sulfate; Fe, 165 mg as iron sulfate; I, 0.36 mg as potassium iodate; Mn, 44 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 165 mg as zinc oxide.

Table 2. Composition (as-fed basis) of diets for the phosphorus digestibility experiment[1]

	Diet	
Item	Meat and bone meal	P-free
Ingredient, %		
Meat and bone meal	8.00	-
Gelatin	-	20.00
Soybean oil	3.00	4.00
Solka floc	-	4.00
Ground limestone	-	0.80
Sucrose	15.00	20.00
Cornstarch	73.30	49.22
DL-Met	-	0.27
L-Thr	-	0.08
L-Trp	-	0.14
L-His	-	0.08
L-Ile	-	0.16
L-Val	-	0.05
Salt	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30
Potassium carbonate	-	0.40

Magnesium oxide	-	0.10
Total	100.00	100.00

---

[1] Diets 1-8 contained MBM as the sole source of P in the diet; Diet 9 is the P-free diet.

[2] The vitamin-mineral premix provided the following quantities of vitamins and minerals per kilogram of complete diet: Vitamin A, 10,990 IU; vitamin D_3, 1,648 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; thiamin, 3.3 mg; riboflavin, 9.9 mg; pyridoxine, 3.3 mg; vitamin B_{12}, 0.044 mg; D-pantothenic acid, 33 mg; niacin, 55 mg; folic acid, 1.1 mg; biotin, 0.17 mg; Cu, 16 mg as copper sulfate; Fe, 165 mg as iron sulfate; I, 0.36 mg as potassium iodate; Mn, 44 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; Zn, 165 mg as zinc oxide.

Table 3. Analyzed chemical composition (as-fed basis) of the meat and bone meal (MBM) sources

	MBM source										
Item	1	2	3	4	5	6	7	8	Mean	SD	% CV
DM, %	97.7	91.7	97.8	97.2	96.5	93.6	93.6	95.9	95.5	2.1	2.2
CP (N × 6.25), %	52.2	51.2	57.2	52.1	51.7	51.2	45.7	54.2	54.4	2.8	5.1
Acid-hydrolyzed ether extract, %	14.1	15.2	14.4	12.6	11.7	11.8	11.6	13.4	13.7	1.5	10.9
Ash, %	28.2	24.7	20.6	29.6	27.8	28.6	33.2	25.3	28.6	4.1	14.4
Ca, %	9.08	7.12	5.24	9.64	8.96	9.63	11.03	8.06	9.0	1.9	21.1
P, %	4.51	3.65	2.59	4.70	4.43	4.49	5.26	4.06	4.4	0.9	19.5
Ca:ash	0.32	0.29	0.25	0.33	0.32	0.34	0.33	0.32	0.31	0.03	8.8
P:ash	0.16	0.15	0.13	0.16	0.16	0.16	0.16	0.16	0.15	0.01	7.8
Ca:P	2.01	1.95	2.02	2.05	2.02	2.14	2.10	1.99	2.04	0.06	3.0
Indispensable AA, %											
Arg	3.41	3.34	3.55	3.37	3.65	3.62	3.48	3.81	3.53	0.16	4.5
His	1.01	1.11	1.52	1.00	1.06	0.82	0.77	1.01	1.04	0.23	21.9

Ile	1.67	1.60	1.89	1.45	1.47	1.45	1.33	1.63	1.56	0.17	11.2
Leu	3.25	3.31	4.16	3.15	3.37	3.03	2.72	3.33	3.29	0.41	12.5
Lys	3.07	3.16	3.21	2.75	2.92	2.65	2.63	3.07	2.93	0.23	7.8
Met	0.82	0.80	0.75	0.70	0.74	0.66	0.61	0.76	0.73	0.07	9.6
Phe	1.82	1.80	2.27	1.75	1.88	1.70	1.54	1.81	1.82	0.21	11.4
Thr	1.68	1.73	1.98	1.63	1.75	1.56	1.44	1.76	1.69	0.16	9.4
Trp	0.36	0.38	0.41	0.34	0.35	0.28	0.28	0.33	0.34	0.05	13.2
Val	2.35	2.30	2.76	2.20	2.40	2.14	1.96	2.35	2.31	0.23	10.1
Dispensable AA, %											
Ala	3.73	3.68	4.12	3.75	4.02	3.80	3.80	3.84	3.84	0.15	3.9
Asp	3.85	3.89	4.36	3.73	3.99	3.74	3.48	4.08	3.89	0.26	6.8
Cys	0.39	0.42	0.41	0.39	0.41	0.49	0.37	0.57	0.43	0.07	15.4
Glu	5.90	5.91	6.67	5.76	6.09	5.79	5.43	6.48	6.00	0.40	6.7
Gly	6.16	5.88	5.84	6.41	6.94	7.21	7.25	6.79	6.56	0.57	8.7
Pro	3.72	3.54	3.75	3.87	4.22	4.27	4.15	3.90	3.93	0.26	6.7
Ser	1.71	1.80	1.93	1.80	1.98	1.80	1.70	1.99	1.84	0.11	6.2

Tyr	1.32	1.32	1.58	1.24	1.29	1.16	1.06	1.39	1.30	0.15	11.9

Table 4. Apparent total tract digestibility (ATTD, %) and standardized total tract digestibility (STTD, %) of P in 8 different meat and bone meal (MBM) sources fed to weanling pigs[1]

	MBM source									
Item	1	2	3	4	5	6	7	8	SEM	*P* <
Feed intake, g/d	530	503	483	508	519	527	489	513	22	0.78
Fecal output, g/d	13.42	10.20	11.70	14.64	14.38	13.15	10.76	12.88	1.62	0.46
P in feces, %	6.87	4.06	2.02	4.72	5.03	7.66	8.51	5.15	0.77	< 0.001
P intake, g/d	2.38	1.56	1.19	2.29	1.99	2.08	2.20	1.98	0.08	< 0.001
P output, g/d	0.94	0.40	0.23	0.71	0.72	1.02	0.92	0.66	0.14	0.002
P absorbed, g/d	1.44	1.16	0.96	1.58	1.27	1.06	1.28	1.32	0.12	0.02
ATTD of P, %	61.6	73.5	80.1	70.2	63.8	52.1	58.6	67.1	5.6	0.03
Basal EPL, mg/d	282	268	257	270	276	281	260	273	12	0.78
STTD of P, %	64.0	76.9	84.4	72.6	66.6	54.8	61.0	69.8	5.6	0.02

[1] Data are least squares means of 8 observations for all treatments.

[2] EPL = endogenous P loss. This value was measured from pigs fed the P-free diet at 106 ± 51 mg/kg DMI. The daily

---

basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg DMI) by the daily DMI of each diet.

[3] Values for STTD were calculated by correcting values of ATTD for basal endogenous losses.

Table 5. Apparent total tract digestibility (ATTD, %) of Ca in 8 different meat and bone meal (MBM) sources fed to weanling pigs[1]

	MBM source									
Item	1	2	3	4	5	6	7	8	SEM	*P* <
Ca in feces, %	14.21	8.38	4.03	10.03	10.39	15.61	18.34	10.53	1.61	< 0.001
Ca intake, g/d	4.87	3.18	2.44	4.68	3.97	4.32	4.46	3.79	0.17	< 0.001
Ca output, g/d	1.95	0.83	0.44	1.53	1.47	2.08	1.98	1.36	0.29	0.002
Ca absorbed, g/d	2.93	2.35	1.99	3.15	2.50	2.24	2.48	2.43	0.25	0.05
ATTD of Ca, %	61.2	73.2	81.4	68.7	62.7	53.0	56.0	64.8	5.8	0.02

[1] Data are least squares means of 8 observations for all treatments.

Table 6. Composition (as-fed basis) of diets for the AA digestibility experiment-2[1]

	Diet		
Item	Corn	Meat and bone meal	N-Free
Ingredient, %			
Corn	94.40	87.9	-
Meat and bone meal	-	8.00	-
Soybean oil	3.00	3.00	4.00
Solka floc	-	-	4.00
Monocalcium phosphate	0.60	-	2.40
Ground limestone	0.90	-	0.50
Sucrose	-	-	20.00
Chromic oxide	0.40	0.40	0.40
Cornstarch	-	-	67.50
Magnesium oxide	-	-	0.10
Potassium carbonate	-	-	0.40
Salt	0.40	0.40	0.40

Vitamin-mineral premix[2]	0.30	0.30	0.30
Total	100.00	100.00	100.00

---

[1] Diet 1 is the corn diet, diets 2-9 contain MBM as the sole source of AA in the diet; Diet 10 is the N-free diet.

[2] The vitamin-mineral premix provide the following quantities of vitamins and minerals per kilogram of complete diet: Vitamin A, 10,990 IU; vitamin D3, 1,648 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; thiamin, 3.3 mg; riboflavin, 9.9 mg; pyridoxine, 3.3 mg; vitamin B12, 0.044 mg; D-pantothenic acid, 33 mg; niacin, 55 mg; folic acid, 1.1 mg; biotin, 0.17 mg; Cu, 16 mg as copper sulfate; Fe, 165 mg as iron sulfate; I, 0.36 mg as potassium iodate; Mn, 44 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 165 mg as zinc oxide.

APPENDIX 1.

Running head: P digestibility in meat and bone meal for pigs

Digestibility of phosphorus and calcium in meat and bone meal fed to growing pigs[1]

R. C. Sulabo and H. H. Stein[2]

Department of Animal Sciences, University of Illinois, Urbana, 61801

ABSTRACT: Seventy-two growing pigs (initial BW: 18.0 ± 1.6 kg) were used to determine the apparent total tract digestibility (ATTD) of P and Ca and the standardized total tract digestibility (STTD) of P in 8 different sources of meat and bone meal (MBM) and to develop equations to predict digestibility of P and Ca in MBM. Pigs were housed individually in metabolism cages and were randomly allotted to 9 diets with 8 replicate pigs per diet. Eight diets were formulated by mixing cornstarch and sucrose with each source of MBM and MBM was the sole source of P in each diet. A P-free diet was used to measure basal endogenous P losses (EPL) by the pigs.

---

[1] Financial support for this research from the Fats and Proteins Research Foundation, Inc., Alexandria, VA, 22314, is appreciated.

[2] Corresponding author: hstein@uiuc.edu

Feces were collected for 5 d based on the marker to marker approach after a 5-d adaptation period. On an as-fed basis, the concentration of P in the MBM sources ranged from 2.6 to 5.6% with an average of 4.4 ± 0.9%, whereas Ca concentration ranged from 5.4 to 11.8% with an average of 9.0 ± 1.9%. There was greater variation in Ca and P concentrations (CV = 21.1 and 20.4%, respectively) in the MBM samples than in any of the other chemical components measured (CV = 5.1, 11.0, and 14.4% for acid-hydrolyzed ether extract, CP, and ash, respectively). The ATTD of P (52.1 to 80.1%, average = 65.9 ± 8.8%) and Ca (53.0 to 81.4%, average = 65.1 ± 9.2%) differed ($P < 0.05$) among MBM sources. The basal EPL was measured at 106 ± 51 mg/kg DMI in pigs fed the P-free diet. The STTD of P was different (54.8 to 84.4%, average = 68.8 ± 9.3%; $P < 0.05$) among MBM sources. The ATTD of Ca and the STTD of P decreased ($P < 0.01$) as ash, Ca, and concentration in MBM increased, and the ATTD of Ca was positively related ($R^2 = 0.99$; $P < 0.001$) with the STTD of P. The STTD of P (%) in MBM may be predicted as $66.345 + 4.225 \times \text{ash} - 13.126 \times \text{Ca}$ ($R^2 = 0.83$, RMSE = 4.61; $P < 0.01$), whereas ATTD of Ca (%) may be predicted as $67.316 + 3.833 \times \text{ash} - 12.398 \times \text{Ca}$ ($R^2 = 0.87$, RMSE = 3.97; $P < 0.01$). In conclusion, P and Ca digestibility varies among sources of MBM, but prediction equations using the concentration of mineral components of MBM may be used to estimate P and Ca digestibility in MBM fed to growing pigs.

Key words: calcium, digestibility, meat and bone meal, phosphorus, pigs, standardized total tract digestibility

INTRODUCTION

Meat and bone meal (**MBM**) is a product of the rendering industry composed primarily of the offal and bones of slaughtered livestock, fat from unmarketable animal tissues, unsellable retail meat products, and whole condemned carcasses excluding animal hair, blood, hooves, horns, and contents of the gastrointestinal tract (Garcia et al., 2006). Traditionally used as an animal protein source in swine diets, MBM also contains greater concentrations of Ca and P than all plant feed ingredients (NRC, 1998). Meat and bone meal can, therefore, replace inorganic phosphates in swine diets without negatively affecting bone integrity and growth performance (Traylor et al., 2005a).

The effective use of MBM as a P and Ca source in swine diets is dependent on an accurate assessment of the digestibility of these minerals when fed to pigs. Relatively high variability has, however, been reported for the concentration of P and Ca (Mendez and Dale, 1998; Hua et al., 2005) and for the relative bioavailability of P (Huang and Allee, 1981; Burnell et al., 1988) among sources of MBM. Utilization of P in feed ingredients may be expressed as standardized total tract digestibility (**STTD**) of P, which is calculated by correcting values for the apparent total tract digestibility (**ATTD**) of P for basal endogenous P losses (Almeida and Stein, 2010). Values for STTD of P are believed to be additive in mixed diets fed to pigs (Almeida and Stein, 2010), but to our knowledge, values for the STTD of P in MBM have not been reported. There is also limited information about the digestibility of Ca in MBM. Therefore, the objectives of this experiment were 1) to determine the ATTD and STTD of P and the ATTD of Ca in 8 different sources of MBM, 2) to estimate variation among MBM sources, and 3) to develop equations to predict digestibility of P and Ca in MBM.

MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois. Pigs used in the experiment were the offsprings of G-Performer boars that were mated to Fertilium 25 females (Genetiporc, Alexandria, MN).

Animals, Diets, and Experimental Design

A total of 72 growing pigs (initial BW: 18.0 ± 1.6 kg) were randomly allotted to 9 dietary treatments using a randomized complete block design with 8 replicate pigs per diet. Pigs were placed in metabolism cages that allowed for total collection of feces. Each metabolism cage was equipped with a feeder and a nipple drinker. A total of 9 diets were formulated (Table 1). Eight of the diets were formulated by mixing cornstarch, sucrose, and each source of MBM. The last diet was a P-free diet that was used to measure the basal endogenous losses of P (**EPL**). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates for growing pigs (NRC, 1998). No inorganic P or Ca was added to the diets that contained MBM, and the only source of P and Ca in these diets, therefore, was the P and Ca contributed by MBM.

Pigs were fed at a level of 3 times their estimated maintenance energy requirement (i.e., 106 kcal ME per kg$^{0.75}$; NRC, 1998) and the daily feed allotments were divided into 2 equal meals. Water was available at all times. The initial 5 d were considered an adaptation period to the diet. Feces were collected from d 6 to 11 according to the marker to marker approach (Adeola, 2001). Chromic oxide and ferric oxide were used to determine the beginning and the conclusion of collections, respectively. Fecal samples were stored at -20°C immediately after collection.

Chemical Analyses

At the conclusion of the experiment, fecal samples were dried in a forced air oven and finely ground. All samples of MBM, diets, and feces were analyzed for DM by oven drying duplicate samples at 135°C for 2 h (method 930.15; AOAC Int., 2007). Calcium and P in these samples were analyzed using inductively coupled plasma (**ICP**) spectroscopy (method 985.01 A, B, and C; AOAC Int., 2007) after wet ash sample preparation (method 975.03 B(b); AOAC Int., 2007). The concentration of N in MBM and diet samples was determined using the combustion procedure (method 990.03; AOAC Int., 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as N × 6.25. Total ether extract in MBM and diet samples was analyzed after acid hydrolysis using 3*N* HCl followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). The MBM and diet samples were also analyzed for dry ash (method 942.05; AOAC Int., 2007).

Calculations

Because MBM is the only P-contributing ingredient in the diets, the calculated digestibility value for each diet also represents the ATTD of P in the source of MBM that was included in that diet. The ATTD (%) of P in each diet was calculated according to the following equation (Almeida and Stein, 2010):

$$\text{ATTD (\%)} = [(\text{Pi} - \text{Pf})/\text{Pi}] \times 100,$$

where Pi is the P intake (g) from d 6 to 11 and Pf is the total fecal P output (g) originating from the feed that was provided from d 6 to 11.

The basal EPL (mg/kg of DMI) were determined from pigs fed the P-free diet according to the following equation(Almeida and Stein, 2010):

$$\text{EPL (mg/kg of DMI)} = ([\text{Pf}/\text{Fi}] \times 1{,}000 \times 1{,}000),$$

where Fi is the total feed (g of DM) intake from d 6 to 11. The daily EPL in pigs fed the P-containing diets was calculated by multiplying the calculated EPL per kilogram of DMI by the DMI of each pig.

By correcting ATTD values for the basal EPL that was determined from pigs fed the P-free diet, the STTD of P was calculated for each ingredient (Almeida and Stein, 2010):

$$\text{STTD (\%)} = [\text{Pi} - (\text{Pf} - \text{EPL})/\text{Pi}] \times 100.$$

Values for the ATTD of Ca were calculated by using the same equation as the one used to calculate the ATTD of P.

Statistical Analysis

Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) with pig as the experimental unit. The model included source of MBM as the fixed effect and block as the random effect. Least squares means were calculated for each independent variable and the α-level used to determine significance among means was 0.05. Descriptive statistics for each proximate component of MBM and correlation coefficients among chemical components, STTD of P, and ATTD of Ca in MBM were determined using PROC CORR of SAS. For the development of prediction equations, regression diagnostics (studentized residuals, h value, DFFITS, DFBETA, Cook's D, and CovRatio) were used on all observations to identify influential, high leverage, or extreme outliers. None of the observations exceeded the critical value for any of the regression diagnostics criteria and no outliers were removed.

The first step in prediction equation development was using the Conceptual predictive [**C(p)**] criterion, which determines candidate models that maximize explained variability with as few variables as possible. Good candidate models are those where $C(p) < p$, where p is the number of variables in the candidate model + 1. The second step was multiple regression analyses using PROC REG of SAS, where variables in each of the candidate models were included as the independent variables in the model statement. The best regression models were determined using multiple criteria analyses where the coefficient of determination (**R^2**), Akaike information criterion (**AIC**), root mean square error (**RMSE**), and the *P*-value of the model were considered. The prediction equation with the least AIC, which is a measure of fit, and the least RMSE, which is a measure of precision, was considered the optimal model.

RESULTS

Chemical Composition of MBM

The concentration of CP, acid hydrolyzed ether extract, and ash in the 8 sources of MBM ranged from 48.8 to 58.5%, 12.1 to 16.6%, and 21.1 to 35.5%, respectively (Table 1). On average, MBM contained 54.4, 13.7, and 28.6% CP, acid hydrolyzed ether extract, and ash, respectively. The CV for the concentrations of CP, acid hydrolyzed ether extract, and ash were 5.1, 11.0, and 14.4%, respectively. There was greater variation in Ca and P concentrations (CV = 21.1 and 19.5%, respectively) than in CP, acid hydrolyzed ether extract, and ash concentrations. The concentration of Ca ranged from 5.4 to 11.8% with an average of 9.0 ± 1.9%, whereas the concentration of P ranged from 2.6 to 5.6% with an average of 4.4 ± 0.9%. However, the Ca:ash (0.25 to 0.34), P:ash (0.13 to 0.16), and Ca:P (1.95 to 2.14) ratios in the MBM samples were relatively consistent (CV = 8.8, 7.8, and 3.0%, respectively).

Phosphorus and Ca Digestibility of MBM

There were no differences in daily feed intake or daily fecal output of pigs fed the different MBM sources (Table 4). However, the P concentration of feces differed ($P < 0.001$)

among pigs fed the different MBM sources ranging from 2.02 to 8.51%. Likewise, the daily P intake and daily P output were different ($P < 0.01$) among MBM sources and ranged from 1.19 to 2.38 g/d and from 0.23 to 1.02 g/d, respectively. Thus, differences ($P < 0.05$) in the daily amount of P absorbed (0.96 to 1.58 g/d) were also observed among MBM sources. The ATTD of P differed (52.1 to 80.1%, average = 65.9 ± 8.8%; $P < 0.05$) among MBM sources. The basal EPL was determined at 106 ± 51 mg/kg DMI in pigs fed the P-free diet. There were no differences in daily basal EPL among treatments, but the STTD of P (54.8 to 84.4%) was different ($P < 0.05$) among MBM sources, and the average was 68.8 ± 9.3%.

The concentration of Ca in feces differed ($P < 0.01$) among MBM sources, ranging from 4.03 to 18.34% (Table 5). Likewise, pigs had different ($P < 0.01$) daily Ca intake (2.44 to 4.87 g/d) and daily Ca output (0.44 to 2.08 g/d). The daily amount of Ca absorbed also differed (1.99 to 3.15 g/d; $P < 0.05$) among pigs fed the different MBM sources, and the ATTD of Ca was different among MBM sources (53.0 to 81.4%, average = 65.1 ± 9.2%; $P < 0.05$).

The STTD of P in MBM was negatively correlated (r = -0.78, -0.85, and -0.81, respectively; $P < 0.05$) with the concentration of ash, Ca, and P (Table 6), but the concentration of ash in MBM was positively correlated (r = 0.98, $P < 0.001$) with the concentration of Ca and P. Using ash concentration as the independent variable, the concentrations of Ca and P in MBM can be predicted using the following equations:

$$\%\ \text{Ca} = 0.456 \times \text{ash} - 4.015\ (R^2 = 0.97,\ \text{RMSE} = 0.36;\ P < 0.001)$$

$$\%\ \text{P} = 0.2044 \times \text{ash} - 1.424\ (R^2 = 0.96,\ \text{RMSE} = 0.19;\ P < 0.001)$$

Concentrations of ash, Ca, and P were negatively correlated (r = -0.94, -0.90, and -0.90, respectively; $P < 0.01$) with the concentration of CP in MBM. However, no correlation was observed between ether extract concentration and the concentration of ash, Ca, or P. The ATTD of Ca was negatively correlated (r = -0.81, -0.88, and -0.86, respectively; $P < 0.01$) with concentrations of ash, Ca, and P, but positively correlated with the STTD of P ($R^2 = 0.99$; $P < 0.001$).

To predict the STTD of P, 6 candidate models were determined to be optimal [C(p) < p], with 2 to 4 independent variables included in each model (Table 7). However, including ash and Ca as independent variables in the model resulted in the least C(p), which is the optimal set of variables that explain the variability in STTD of P in MBM. Using R^2, AIC, and RMSE as selection criteria for the final model, 3 prediction equations were developed (Table 8). The models explained 83 to 85% of the variability in STTD of P in MBM. The best model for predicting STTD of P in MBM was Equation 1, which had the least AIC and RMSE. Adding P concentration to the model only improved the R^2 by 2%, and it was, therefore, decided to use a model only with Ca and ash. Therefore, the final prediction model for STTD of P (%) in MBM was:

$$\text{STTD of P (\%)} = 66.345 + 4.225 \times \text{ash} - 13.126 \times \text{Ca} \ (R^2 = 0.83, \text{RMSE} = 4.61; P < 0.01).$$

To predict the ATTD of Ca, 13 candidate models were determined to be optimal [C(p) < p], with 1 to 4 independent variables included in each model (Table 9). The candidate model that included ash and Ca as independent variables had the least C(p); however, including Ca as the only independent variable was the second most optimal and simplest candidate model. Using R^2, AIC, and RMSE as selection criteria for the final model, 7 prediction equations for ATTD of Ca in MBM were developed (Table 10). The models explained 78 to 88% of the variability in

ATTD of Ca in MBM. The best model was Equation 1, which had the least AIC and RMSE. Therefore, the final prediction model for ATTD of Ca (%) in MBM was:

$$\text{ATTD of Ca } (\%) = 67.316 + 3.833 \times \text{ash} - 12.398 \times \text{Ca } (R^2 = 0.87, \text{RMSE} = 3.97; P = 0.01).$$

DISCUSSION

Composition of MBM

Based on the official definition of AAFCO (2000), an animal-rendered product is considered MBM if it contains at least 4.0% P and if the Ca:P ratio is not greater than 2.2. Samples that contain less than 4.0% P are considered meat meal. Two of the samples that were used in this experiment (sources 2 and 3) had P concentrations less than 4.0% and these samples would, therefore, be considered meat meal according to AAFCO definitions. However, all samples had Ca:P ratios less than 2.2. Variability in the concentration of P and Ca among the MBM sources used in the experiment was intended to determine the relationship between the concentration and the digestibility of P and Ca and to develop prediction equations that can be used on a greater range of MBM quality that are inclusive of rendered products that are not officially defined as MBM.

On average, the sources of MBM that were included in this experiment had concentrations of CP that were similar to values reported by NRC (1998), but the concentrations of acid hydrolyzed ether extract and indispensable AA were greater, whereas the concentration of P and Ca were less, than values reported by NRC (1998). The values for nutrient concentrations in the samples of MBM used in this experiment were, however, within the range of values reported from other experiments (Mendez and Dale, 1998; Karakas et al., 2001; Adedokun and Adeola, 2005; Hua et al., 2005; Olukosi and Adeola, 2009).

The negative linear relationship between the concentration of protein and the concentration of ash, Ca, and P is in agreement with previous work (Mendez and Dale, 1998; Hua et al., 2005; Garcia and Phillips, 2009). Regardless of the species used to produce the MBM, bone particles in dry, defatted MBM contain 64% ash and 31% CP, mostly in the form of collagen, whereas soft tissue particles contain 11% ash and 81% CP (Garcia and Phillips, 2009). These observations indicate that the variation in protein and ash concentration in MBM directly reflects the differences in bone-to-soft tissue ratios among sources. The major sources of variation in MBM are the type of raw material used in the rendering process and the soft-tissue-to bone ratio (Donkoh et al., 1994; Johnson and Parsons, 1997). The majority of the MBM produced by renderers in the United States is produced from a mixture of material from cattle, swine, and poultry, whereas a few renderers use material from a single species (Garcia et al., 2006). Rendered materials from cattle contain significantly greater amounts of bone than those derived from swine and poultry, and thus, differences in the proportion of cattle tissue in the mixture is positively related to the ash concentration in the final product (Garcia et al., 2006; Garcia and Phillips, 2009). Rendering plants that process mainly condemned animal carcasses and unmarketable retail meat products produce MBM with the least bone-to-soft tissue ratio (Garcia and Phillips, 2009). However, it is standard practice for renderers to blend batches of MBM to achieve a specified proximate composition, usually for CP and P concentration (National Renderers Association, 2003). Other sources of variation such as the rendering process (batch or continuous dry rendering) and processing conditions during rendering (Hendriks et al., 2004), affect protein quality and digestibility more than the concentration and digestibility of minerals in MBM.

The fact that P and Ca concentrations were 2 to 4 times more variable among sources of MBM than the concentrations of protein and acid hydrolyzed ether extract indicates that it is important to estimate the concentration of P and Ca in a given source of MBM. Use of book values for the concentration of P and Ca in MBM may result in an overestimation or an underestimation of the actual concentrations in a given source of MBM. If MBM is used in swine diets, most of the dietary P and Ca are often furnished by MBM, and variability in the concentrations of P and Ca in MBM may result in significant deficiencies or excesses of these 2 minerals. Therefore, developing means to account for this variability and to predict the total and digestible P and Ca concentrations in different sources is important to effectively use MBM in swine diets.

Phosphorus Digestibility of MBM

The average ATTD of P in MBM that was determined in this experiment (65.9%) is within the range of values (54 to 85%) observed in other experiments (Jongbloed and Kemme, 1990; Poulsen, 1995; Rodehutscord et al., 1997; King et al., 2005; Bünzen et al., 2009). To our knowledge, there has been no previous work conducted to determine the STTD of P in MBM. The average STTD of P in MBM (68.8%) was similar to that in fish meal (67.3%, Kim and Stein, 2010), but less than the STTD of P in dicalcium phosphate, monocalcium phosphate, and monosodium phosphate (88.4 to 98.2%; Petersen and Stein, 2006). Therefore, P in MBM is about 70% as digestible as the P in monosodium phosphate, but the STTD of P in MBM is much greater than the STTD of P in corn (26.4%) and soybean meal (48.3 to 56.7%, Almeida and Stein, 2010; Kim and Stein, 2010).

The range in values for the STTD of P (54.8 to 84.4%) that was observed among sources of MBM used in this experiment is relatively similar to the range in values for the relative bioavailability of P among different sources of MBM (Huang and Allee, 1981; Burnell et al., 1988, 1989; Coffey and Cromwell, 1993; Traylor et al., 2005a,b). If the relative bioavailability values were obtained using dicalcium phosphate as the standard, and if it is assumed that the STTD of P in dicalcium phosphate is 88% (Petersen and Stein, 2006), then the range of reported values for the relative bioavailability of P in MBM corresponds to values for STTD of P between 55.4 and 81.8%, which is very close to the values determined for STTD of P in this experiment.

The STTD of P in MBM decreased with increasing ash, Ca, and P concentration and between 61 and 72% of the variability in values for the STTD of P in MBM was explained by differences in the concentration of ash, Ca, and P. This observation is not in agreement with Traylor et al. (2005b), who reported that low-ash MBM has relative bioavailability of P that is less than in high-ash MBM. However, Jongbloed and Kemme (1990) reported that the ATTD of P in bone meal, meat and bone meal, and meat meal were 68, 80, and 85%, respectively, which indicates that P in bone tissue has a reduced digestibility compared with P in soft tissue. A greater proportion of bones in the rendered material will, therefore, negatively affect P digestibility, and because of the greater concentration of P in bone tissue than in soft tissue, it can be assumed that the greater the concentration of P in MBM is, the greater is the proportion of bone in the product, which in turn explains why the digestibility is less if the concentration of P is increased.

Calcium Digestibility of MBM

There is limited data on the digestibility of Ca in most feed ingredients, which is likely a result of the fact that the requirement for dietary Ca to pigs usually is expressed on the basis of total Ca (NRC, 1998). Recently, values for the ATTD of Ca in corn and soybean meal of 47 to 49% were reported (Bohlke et al., 2005), and the ATTD of Ca in calcium carbonate is between 60.9 and 70.9% (Stein et al., 2011). The ATTD for Ca in MBM that were determined in this experiment are within this range of values reported for the ATTD of Ca in calcium carbonate. This observation was expected because one of the major components of bones is calcium carbonate. The negative relationship between the concentration of ash in MBM and the ATTD of Ca and the strong correlation between the ATTD of Ca and the STTD of P indicate that sources of MBM with greater bone-to-soft tissue ratios, and therefore greater ash concentrations, have reduced digestibility of both Ca and P compared with MBM with reduced bone-to-soft tissue ratios.

The fact that the ATTD of Ca is less than 100% in most feed ingredients indicates that dietary Ca requirements may be calculated more accurately if diets are formulated on the basis of digestible Ca rather than total Ca (Stein et al., 2011). However, more research is needed to determine Ca digestibility in more feed ingredients before diets can be formulated on the basis of digestible Ca.

In conclusion, the digestibilities of P and Ca varied among sources of MBM. However, prediction equations using the concentration of chemical and mineral components of MBM may be used to estimate P and Ca digestibility in MBM fed to growing pigs.

LITERATURE CITED

AAFCO. 2000. Official Publication of the Association of American Feed Control Officials. AAFCO, Washington, DC.

Adeola, O. 2001. Digestion and balance techniques in pigs. Pages 903-916 in Swine Nutrition, 2nd ed. A. J. Lewis, and L. L. Southern, ed. CRC Press, Washington, DC.

AOAC International. 2007. Official Methods of Analysis.18th ed. Rev. 2. W. Howitz, and G. W. Latimer Jr., ed. AOAC International, Gaithersburg, MD.

Adedokun, S. A., and O. Adeola. 2005. Metabolizable energy value of meat and bone meal for pigs. J. Anim. Sci. 83:2519–2526.

Almeida, F. N., and H. H. Stein. 2010. Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus. J. Anim Sci. 88:2968-2977.

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396-2403.

Bünzen, S., H. S. Rostagno, D. C. Lopes, P. C. Gomes, F. A. M. Hashimoto, L. R. Apolônio, and C. G. Borsatto. 2009. Apparent and true digestibility of phosphorus from animal origin feedstuffs for swine. Arq. Bras. Med. Vet. Zootec. 61:903-909.

Burnell, T. W., G. L. Cromwell, and T. S. Stahly. 1988. Bioavailability of phosphorus in high-protein feedstuffs for pigs. J. Anim. Sci. 66(Suppl. 1):317. (Abstr.)

Burnell, T. W., G. L. Cromwell, and T. S. Stahly. 1989. Bioavailability of phosphorus in meat and bone meal for pigs. J. Anim. Sci. 67(Suppl. 2):38. (Abstr.)

Coffey, R. D., and G. L. Cromwell. 1993. Evaluation of the biological availability of phosphorus in various feed ingredients for growing pigs. J. Anim. Sci. 71(Suppl. 1):66. (Abstr.)

Donkoh, A., P. J. Moughan, and W. C. Smith. 1994. True ileal digestibility of amino acids in meat and bone meal for the growing pig-application of a routine rat digestibility assay. Anim. Feed Sci. Technol. 49:73-86.

Garcia, R. A., K. A. Rosentrater, and R. A. Flores. 2006. Characteristics of North American meat and bone meal relevant to the development of non-feed applications. Appl. Eng. Agric. 22:729-736.

Garcia, R. A., and J. G. Phillips. 2009. Physical distribution and characterisitics of meat and bone meal protein. J. Sci. Food Agric. 89:329-326.

Hendriks, W. H., C. A. Butts, D. V. Thomas, K. A. C. James, P. C. A. Morel, and M. W. A. Verstegen. 2002. Nutritional quality and variation of meat and bone meal. Asian-Aust. J. Anim. Sci. 15:1507-1516.

Hua, K., L. Liu, and D. P. Bureau. 2005. Determination of phosphorus fractions in animal protein ingredients. J. Agric. Food Chem. 53:1571-1574.

Huang, K. C., and G. L. Allee. 1981. Bioavailability of phosphorus in selected feedstuffs for young chicks and pigs. J. Anim. Sci. 53(Suppl. 1):248. (Abstr.)

Johnson, M. L., and C. M. Parsons. 1997. Effects of raw material source, ash content, and assay length on protein efficiency ratio and net protein values for animal protein meals. Poult. Sci. 76:1722-1727.

Jongbloed, A. W., and P. A. Kemme. 1990. Apparent digestible phosphorus in the feeding of pigs in relation to availability, requirement, and environment. 1. Digestible phosphorus in feedstuffs from plant and animal origin. Neth. J. Agric. Sci. 38:567–575.

Karakas, P., H. A. J. Versteegh, Y. van der Honing, J. Kogut, and A. W. Jongbloed. 2001. Nutritive value of the meat and bone meals from cattle or pigs in broiler diets. Poultry Sci. 80:1180–1189.

Kim, B. G., and H. H. Stein. 2010. Energy concentration and phosphorus digestibility in yeast products, fish meal, and soybean meal fed to pigs. J. Anim. Sci. 88 (E-Suppl. 3):86. (Abstr.)

King, R. H., J. Cauduro, and P. J. Eason. 2005. The apparent digestibility of phosphorus from a range of inorganic sources is less than 100% in pigs. Page 156 in Manipulating Pig Production. X. J. E. Paterson, ed. Austr. Pig Sci. Assn. Victoria, Australia.

Mendez, A., and N. Dale. 1998. Rapid assay to estimate calcium and phosphorus in meat and bone meal. J. Appl. Poultry Res. 7:309-312.

National Renderers Association. 2003. Pocket information manual: A buyer's guide to rendered products. Natl. Renderers Assoc. Alexandria, VA.

NRC. 1998. Nutrient Requirements of Swine. 10th ed. Natl. Acad. Press, Washington, DC.

Olukosi, O. A., and O. Adeola. 2009. Estimation of the metabolizable energy content of meat and bone meal for swine. J. Anim. Sci. 87:2590–2599.

Petersen, G. I., and H. H. Stein. 2006. Novel procedure for estimating endogenous losses and measurement of apparent and true digestibility of phosphorus by growing pigs. J. Anim. Sci. 84:2126-2132.

Poulsen, H. D. 1995. Phosphorus digestibility in phosphates and meat and bone meal. Rep. No. 34. Natl. Inst. Anim. Sci., Foulum, Denmark.

Rodehutscord, M., M. Faust, and C. Hof. 1997. Digestibility of phosphorus in protein-rich ingredients for pig diets. Arch. Anim. Nutr. 50:201-211.

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. doi:10.2527/jas.2010-3522.

Traylor, S. L., G. L. Cromwell, and M. D. Lindemann. 2005. Bioavailability of phosphorus in meat and bone meal for swine. J. Anim. Sci. 83:1054–1061.

Traylor, S. L., G. L. Cromwell, and M. D. Lindemann. 2005. Effects of particle size, ash content, and processing pressure on the bioavailability of phosphorus in meat and bone meal for swine. J. Anim. Sci. 83:2554–2563.

Table 1. Analyzed chemical composition (as-fed basis) of the meat and bone meal (MBM) sources

	MBM source										
Item	1	2	3	4	5	6	7	8	Mean	SD	% CV
DM, %	97.7	91.7	97.8	97.2	96.5	93.6	93.6	95.9	95.5	2.1	2.2
CP (N × 6.25), %	52.2	51.2	57.2	52.1	51.7	51.2	45.7	54.2	54.4	2.8	5.1
Acid-hydrolyzed ether extract, %	14.1	15.2	14.4	12.6	11.7	11.8	11.6	13.4	13.7	1.5	10.9
Ash, %	28.2	24.7	20.6	29.6	27.8	28.6	33.2	25.3	28.6	4.1	14.4
Ca, %	9.08	7.12	5.24	9.64	8.96	9.63	11.03	8.06	9.0	1.9	21.1
P, %	4.51	3.65	2.59	4.70	4.43	4.49	5.26	4.06	4.4	0.9	19.5
Ca:ash	0.32	0.29	0.25	0.33	0.32	0.34	0.33	0.32	0.31	0.03	8.8
P:ash	0.16	0.15	0.13	0.16	0.16	0.16	0.16	0.16	0.15	0.01	7.8
Ca:P	2.01	1.95	2.02	2.05	2.02	2.14	2.10	1.99	2.04	0.06	3.0
Indispensable AA, %											
Arg	3.41	3.34	3.55	3.37	3.65	3.62	3.48	3.81	3.53	0.16	4.5
His	1.01	1.11	1.52	1.00	1.06	0.82	0.77	1.01	1.04	0.23	21.9

Ile	1.67	1.60	1.89	1.45	1.47	1.45	1.33	1.63	1.56	0.17	11.2
Leu	3.25	3.31	4.16	3.15	3.37	3.03	2.72	3.33	3.29	0.41	12.5
Lys	3.07	3.16	3.21	2.75	2.92	2.65	2.63	3.07	2.93	0.23	7.8
Met	0.82	0.80	0.75	0.70	0.74	0.66	0.61	0.76	0.73	0.07	9.6
Phe	1.82	1.80	2.27	1.75	1.88	1.70	1.54	1.81	1.82	0.21	11.4
Thr	1.68	1.73	1.98	1.63	1.75	1.56	1.44	1.76	1.69	0.16	9.4
Trp	0.36	0.38	0.41	0.34	0.35	0.28	0.28	0.33	0.34	0.05	13.2
Val	2.35	2.30	2.76	2.20	2.40	2.14	1.96	2.35	2.31	0.23	10.1
Dispensable AA, %											
Ala	3.73	3.68	4.12	3.75	4.02	3.80	3.80	3.84	3.84	0.15	3.9
Asp	3.85	3.89	4.36	3.73	3.99	3.74	3.48	4.08	3.89	0.26	6.8
Cys	0.39	0.42	0.41	0.39	0.41	0.49	0.37	0.57	0.43	0.07	15.4
Glu	5.90	5.91	6.67	5.76	6.09	5.79	5.43	6.48	6.00	0.40	6.7
Gly	6.16	5.88	5.84	6.41	6.94	7.21	7.25	6.79	6.56	0.57	8.7
Pro	3.72	3.54	3.75	3.87	4.22	4.27	4.15	3.90	3.93	0.26	6.7
Ser	1.71	1.80	1.93	1.80	1.98	1.80	1.70	1.99	1.84	0.11	6.2

Tyr	1.32	1.32	1.58	1.24	1.29	1.16	1.06	1.39	1.30	0.15	11.9

Table 2. Composition (as-fed basis) of experimental diets

	Diet	
Ingredient, %	Meat and bone meal	P-free
Meat and bone meal	8.00	-
Gelatin[1]	-	20.00
Soybean oil	3.00	4.00
Solka floc[2]	-	4.00
Ground limestone	-	0.80
Sucrose	15.00	20.00
Cornstarch	73.30	49.22
Salt	0.40	0.40
Vitamin-mineral premix[3]	0.30	0.30
Potassium carbonate	-	0.40
Magnesium oxide	-	0.10
AA mixture[4]	-	0.78
Total	100.00	100.00

---

[1] Pork gelatin obtained from Gelita Gelatine USA Inc., Sioux City, IA.

[2] Fiber Sales and Development Corp., Urbana, OH.

[3] The vitamin-mineral premix provided the following quantities of vitamins and minerals per kilogram of complete diet: Vitamin A, 10,990 IU; vitamin D_3, 1,648 IU; vitamin E, 55 IU; vitamin K, 4.4 mg; thiamin, 3.3 mg; riboflavin, 9.9 mg; pyridoxine, 3.3 mg; vitamin B_{12}, 0.044 mg; D-pantothenic acid, 33 mg; niacin, 55 mg; folic acid, 1.1 mg; biotin, 0.17 mg; Cu, 16 mg as copper sulfate; Fe, 165 mg as iron sulfate; I, 0.36 mg as potassium iodate; Mn, 44 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; Zn, 165 mg as zinc oxide.

[4] Provided the following quantities (%) of AA: DL-Met, 0.27; L-Thr, 0.08; L-Trp, 0.14; L-His, 0.08; L-Ile, 0.16; and L-Val, 0.05.

Table 3. Analyzed chemical composition (as-fed basis) of experimental diets

	Diet								
Item	1	2	3	4	5	6	7	8	P-free
DM, %	93.5	93.3	93.2	93.2	94.0	94.0	93.2	93.4	93.6
CP (N × 6.25), %	4.71	5.58	5.98	4.57	4.76	4.31	4.05	5.05	23.47
Acid-hydrolyzed ether extract, %	5.96	5.04	3.20	3.62	4.61	5.91	4.63	4.64	2.83
Ash, %	2.77	2.38	2.15	2.70	3.18	2.78	3.12	2.40	1.97
Ca, %	0.86	0.59	0.47	0.86	0.72	0.77	0.85	0.69	0.35
P, %	0.42	0.29	0.23	0.42	0.36	0.37	0.42	0.36	0.01
Indispensable AA, %									
Arg	0.29	0.24	0.29	0.29	0.29	0.26	0.26	0.30	1.63
His	0.09	0.08	0.13	0.09	0.09	0.06	0.06	0.08	0.25
Ile	0.18	0.14	0.19	0.16	0.15	0.13	0.10	0.13	0.42
Leu	0.31	0.27	0.36	0.30	0.30	0.24	0.21	0.28	0.60
Lys	0.29	0.24	0.28	0.25	0.25	0.21	0.21	0.26	0.81
Met	0.07	0.05	0.07	0.07	0.06	0.05	0.05	0.06	0.42

Phe	0.16	0.14	0.19	0.15	0.15	0.13	0.12	0.15	0.40
Thr	0.15	0.13	0.16	0.14	0.14	0.12	0.12	0.15	0.42
Trp	0.04	0.04	0.04	< 0.04	< 0.04	< 0.04	0.04	< 0.04	0.12
Val	0.21	0.18	0.24	0.20	0.20	0.16	0.15	0.19	0.52
Dispensable AA, %									
Ala	0.35	0.29	0.36	0.35	0.33	0.29	0.30	0.33	1.84
Asp	0.36	0.30	0.38	0.34	0.34	0.29	0.29	0.36	1.21
Cys	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.03
Glu	0.60	0.51	0.65	0.58	0.57	0.50	0.49	0.61	2.09
Gly	0.57	0.45	0.51	0.58	0.56	0.54	0.56	0.56	4.89
Pro	0.36	0.28	0.39	0.36	0.35	0.33	0.37	0.39	2.78
Ser	0.16	0.14	0.16	0.16	0.16	0.14	0.13	0.16	0.60
Tyr	0.11	0.10	0.12	0.10	0.10	0.09	0.07	0.09	0.13

Table 4. Apparent total tract digestibility (ATTD, %) and standardized total tract digestibility (STTD, %) of P in 8 different meat and bone meal (MBM) sources fed to weanling pigs[1]

	MBM source									
Item	1	2	3	4	5	6	7	8	SEM	*P* <
Feed intake, g/d	530	503	483	508	519	527	489	513	22	0.78
Fecal output, g/d	13.42	10.20	11.70	14.64	14.38	13.15	10.76	12.88	1.62	0.46
P in feces, %	6.87	4.06	2.02	4.72	5.03	7.66	8.51	5.15	0.77	< 0.001
P intake, g/d	2.38	1.56	1.19	2.29	1.99	2.08	2.20	1.98	0.08	< 0.001
P output, g/d	0.94	0.40	0.23	0.71	0.72	1.02	0.92	0.66	0.14	0.002
P absorbed, g/d	1.44	1.16	0.96	1.58	1.27	1.06	1.28	1.32	0.12	0.02
ATTD of P, %	61.6	73.5	80.1	70.2	63.8	52.1	58.6	67.1	5.6	0.03
Basal EPL, mg/d	282	268	257	270	276	281	260	273	12	0.78
STTD of P, %	64.0	76.9	84.4	72.6	66.6	54.8	61.0	69.8	5.6	0.02

[1] Data are least squares means of 8 observations for all treatments.

[2] EPL = endogenous P loss. This value was measured from pigs fed the P-free diet at 106 ± 51 mg/kg DMI. The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg DMI) by the daily DMI of each diet.

---

[3] Values for STTD were calculated by correcting values of ATTD for basal endogenous losses.

Table 5. Apparent total tract digestibility (ATTD, %) of Ca in 8 different meat and bone meal (MBM) sources fed to weanling pigs[1]

	MBM source									
Item	1	2	3	4	5	6	7	8	SEM	*P* <
Ca in feces, %	14.21	8.38	4.03	10.03	10.39	15.61	18.34	10.53	1.61	< 0.001
Ca intake, g/d	4.87	3.18	2.44	4.68	3.97	4.32	4.46	3.79	0.17	< 0.001
Ca output, g/d	1.95	0.83	0.44	1.53	1.47	2.08	1.98	1.36	0.29	0.002
Ca absorbed, g/d	2.93	2.35	1.99	3.15	2.50	2.24	2.48	2.43	0.25	0.05
ATTD of Ca, %	61.2	73.2	81.4	68.7	62.7	53.0	56.0	64.8	5.8	0.02

[1] Data are least squares means of 8 observations for all treatments.

Table 6. Correlation coefficients (r) between chemical components and digestibilities of P and Ca in meat and bone meal

	Correlation coefficient, r						
Item	CP	AEE[1]	Ash	Ca	P	STTD of P	ATTD of Ca
CP	-	0.57	-0.94***	-0.90**	-0.90**	0.65	0.69
Fat		-	-0.59	-0.67	-0.61	0.63	0.65
Ash			-	0.98***	0.98***	-0.78*	-0.81**
Ca				-	0.99***	-0.85**	-0.88**
P					-	-0.81*	-0.86**
STTD of P						-	0.99***
ATTD of Ca							-

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

[1] AEE = acid hydrolyzed ether extract.

Table 7. Model selection using Conceptual predictive criterion [C(p)] as criteria for equations that predict standardized total tract digestibility (STTD, %) of P in meat and bone meal[1]

No. of variables in model	C(p)	R^2	AIC	Variables in model
2	1.73	0.83	26.69	Ash, Ca
2	2.51	0.79	28.20	CP, Ca
3	3.18	0.85	27.41	Ash, Ca, P
3	3.60	0.83	28.40	AEE[2], ash, Ca
3	3.71	0.83	28.63	CP, ash, Ca
4	4.41	0.89	27.18	AEE[2], ash, Ca, P

[1] C(p) = criterion that determine candidate models that maximizes explained variability with as few variables as possible. Candidate models are those where C(p) < p, where p is the number of variables in the candidate model + 1. AIC = Akaike Information Criterion (AIC), measures fit of the model. Smaller AIC is a better fit of

---

the model.

[2] AEE = acid hydrolyzed ether extract.

Table 8. Prediction equations for standardized total tract digestibility (STTD, %) of P in meat and bone meal[1,2]

Equation No.		Parameter estimate							
	Intercept	AEE[3], %	Ash, %	Ca, %	P, %	R^2	AIC	RMSE	*P*-value
1	66.345		4.225	-13.126		0.83	26.69	4.61	0.01
2	63.690		3.947	-18.600	13.566	0.85	27.41	4.76	0.04
3	74.873	-0.753	4.795	-14.732		0.83	28.40	5.06	0.05

[1] Prediction equation with the lowest Akaike Information Criterion (AIC), which is a measure of fit, and root mean square error (RMSE), which is a measure of precision, is the optimal model.

[2] Parameters and predicted values are on as-fed basis.

[3] AEE = acid hydrolyzed ether extract.

Table 9. Model selection using Conceptual predictive criterion [C(p)] as criteria for equations that predict apparent total tract digestibility (ATTD, %) of Ca in meat and bone meal[1]

No. of variables in model	C(p)	R^2	AIC	Variables in model
2	1.03	0.87	24.31	Ash, Ca
1	1.10	0.78	26.48	Ca
2	1.91	0.83	26.35	CP, Ca
2	2.66	0.80	27.77	Ca, P
3	2.80	0.88	25.70	ash, Ca, P
3	2.92	0.87	26.01	AEE[2], ash, Ca
2	2.93	0.78	28.21	AEE[2], Ca
3	3.02	0.87	26.31	CP, ash, Ca
3	3.70	0.84	27.92	CP, Ca, P
3	3.81	0.83	28.16	CP, AEE[2], Ca
4	4.35	0.90	26.28	AEE[2], ash, Ca, P
4	4.80	0.88	27.69	CP, ash, Ca, P
4	4.90	0.87	27.97	CP, AEE[2], ash, Ca

---

[1] C(p) = criterion which determines candidate models that maximize explained variability with as few variables as possible. Candidate models are those where $C(p) < p$, where p is the number of variables in the candidate model + 1. AIC = Akaike Information Criterion (AIC), measures fit of the model. Smaller AIC is a better fit of the model.

[2] AEE = acid hydrolyzed ether extract.

Table 10. Prediction equations for apparent total tract digestibility (ATTD, %) of Ca in meat and bone meal[1, 2]

Equation	Parameter estimate									
No.	Intercept	CP, %	AEE[3], %	Ash, %	Ca, %	P, %	R^2	AIC	RMSE	*P*-value
1	67.316			3.833	-12.398		0.87	24.31	3.97	0.006
2	65.698			3.664	-15.735	8.268	0.88	25.70	4.27	0.03
3	74.676		-0.650	4.325	-13.784		0.87	26.01	4.36	0.03
4	72.935	-0.071		3.742	-12.301		0.87	26.31	4.44	0.03
5	103.408				-4.250		0.78	26.48	4.71	0.004
6	98.958				-9.372	11.457	0.80	27.77	4.93	0.02
7	90.282		0.711		-3.877		0.78	28.21	5.07	0.02

[1] Prediction equation with the lowest Akaike Information Criterion (AIC), which is a measure of fit, and root mean square error (RMSE), which is a measure of precision, is the optimal model.

[2] Parameters and predicted values are on as-fed basis.

[3] AEE = acid hydrolyzed ether extract.