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

R. C. Sulabo and H. H. Stein

J ANIM SCI 2013, 91:1285-1294.
doi: 10.2527/jas.2011-4632 originally published online December 10, 2012

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, sucrose, soybean oil, sodium chloride, vitamin–mineral premix, and 8% of each source of MBM, and MBM was the sole source of P and Ca in each diet. A P-free diet was used to measure basal endogenous P losses (EPL) by the pigs. 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 5.3% with an average of 4.3 ± 0.8% whereas Ca concentration ranged from 5.1 to 11.0% with an average of 9.2 ± 2.0%. The variation among MBM samples in Ca and P concentrations was calculated (CV = 22.1 and 20.0%, respectively) as was the variation in the concentration of other chemical components (CV = 6.2, 10.5, and 13.8% for CP, acid-hydrolyzed ether extract, and ash, respectively). The ATTD of P (52.1 to 80.1%, average = 65.9 ± 8.8%) and Ca (53.0 to 81.0%, average = 63.9 ± 9.4%) 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 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 107.857 – 8.8 × total P [$R^2 = 0.68$, root mean square error (RMSE) = 5.73, $P < 0.01$] whereas ATTD of Ca (%) may be predicted as 105.375 – 9.327 × total P ($R^2 = 0.75$, RMSE = 4.70, $P < 0.01$). In conclusion, P and Ca digestibility varies among sources of MBM, but prediction equations using the concentration of total P in 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

J. Anim. Sci. 2013.91:1285–1294
doi:10.2527/jas2011-4632

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. Use of P in feed ingredients may be expressed as standardized total tract digestibility (**STTD**) of P, which is calculated by

[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

Received August 25, 2011.
Accepted November 18, 2012.

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 the concentrations of digestible 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.

Eight sources of MBM were procured from 5 commercial companies in the United States (Table 1). Three of the companies each provided 2 sources of MBM and 2 companies provided 1 source; however, the 8 sources of MBM were produced at 8 different production facilities. Seven of the MBM sources were labeled as being produced from "mixed species" whereas 1 source was produced from tissue obtained from pigs.

Animals, Diets, and Experimental Design

A total of 72 growing barrows (initial BW: 18.0 ± 1.6 kg; G-Performer boars × Fertilium 25 females; Genetiporc, Alexandria, MN) were divided into 2 blocks of 36 pigs based on date of birth. Within each block, pigs were randomly allotted to 9 dietary treatments based on initial BW. There were 4 replicate pigs within each block for a total of 8 replicate pigs per diet in a generalized randomized block design. 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 (Tables 2 and 3). Eight of the diets were formulated by mixing cornstarch, sucrose, soybean oil, sodium chloride, vitamin–mineral premix, and 8% of each source of MBM. The last diet was a P-free diet that was used to measure the basal endogenous P losses (**EPL**). Vitamins

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

	Meat and bone meal 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	51.9	3.2	6.2
Acid hydrolyzed ether extract, %	14.1	15.2	14.4	12.6	11.7	11.8	11.6	13.4	13.1	1.4	10.5
Ash, %	28.2	24.7	20.6	29.6	27.8	28.6	33.2	25.3	27.3	3.8	13.8
Ca, %	9.69	7.12	5.09	10.42	8.96	9.63	11.03	8.30	9.20	2.00	22.1
P, %	4.72	3.65	2.59	5.05	4.43	4.49	5.26	4.06	4.30	0.80	20.0
Ca:ash	0.34	0.29	0.25	0.35	0.32	0.34	0.33	0.33	0.32	0.03	10.8
P:ash	0.16	0.15	0.13	0.16	0.16	0.16	0.16	0.16	0.16	0.01	6.9
Ca:P	2.05	1.95	1.97	2.22	2.02	2.14	2.10	2.04	2.06	0.09	4.3
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 of experimental diets (as-fed basis)

Ingredient, %	Diet	
	Meat and bone meal[1]	P-free
Meat and bone meal	8.00	–
Gelatin[2]	–	20.00
Soybean oil	3.00	4.00
Solka floc[3]	–	4.00
Ground limestone	–	0.80
Sucrose	15.00	20.00
Cornstarch	73.30	49.22
Sodium chloride	0.40	0.40
Vitamin–mineral premix[4]	0.30	0.30
Potassium carbonate	–	0.40
Magnesium oxide	–	0.10
AA mixture[5]	–	0.78
Total	100.00	100.00

[1]Eight diets containing meat and bone meal were formulated based on 8 different sources of meat and bone meal.

[2]Pork gelatin obtained from Gelita USA Inc. (Sioux City, IA).

[3]Fiber Sales and Development Corp. (Urbana, OH).

[4]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, 1648 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; and Zn, 165 mg as zinc oxide.

[5]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.

and minerals other than Ca and P 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 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 spectroscopy (Method 985.01 A,

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

Item	Diet								
	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), %	4.25	4.19	4.59	4.34	3.87	4.15	3.71	4.46	23.47
Acid-hydrolyzed ether extract, %	5.96	5.04	3.20	3.62	4.61	5.91	4.63	4.64	–
Ash, %	2.77	2.38	2.15	2.70	3.18	2.78	3.12	2.40	1.97
Ca, %	0.78	0.59	0.46	0.80	0.72	0.77	0.85	0.64	0.35
P, %	0.39	0.29	0.22	0.40	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

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/N apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as N × 6.25. Amino acids were analyzed in diets and ingredients using an AA analyzer (Model L8800; Hitachi High Technologies America Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Before analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C (Method 982.30 E; AOAC Int., 2007). Methionine and Cys were analyzed as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C. 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 an automated analyzer (Soxtec 2050; 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 was the only P-contributing ingredient in the diets, the calculated ATTD of P in 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):

$$ATTD = [(P_{intake} - P_{feces})/P_{intake}] \times 100,$$

in which P_{intake} is the average daily P intake (g) from d 6 to 11 and P_{feces} is the average daily fecal P output (g) from the feed that was provided from d 6 to 11.

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

$$\text{Basal EPL} = ([P_{feces}/F_{intake}] \times 1000 \times 1000),$$

in which P_{feces} is the average daily fecal P output (g) and F_{intake} is the average daily feed intake (g of DM) from d 6 to 11. The daily basal EPL in pigs fed the P-containing diets was calculated by multiplying the calculated EPL per kilogram of DMI by the daily DMI of each pig.

By correcting ATTD values for the basal EPL, the STTD (%) of P was calculated for each ingredient (Almeida and Stein, 2010):

$$STTD = [P_{intake} - (P_{feces} - \text{basal EPL})/P_{intake}] \times 100.$$

Values for the ATTD (%) of Ca were calculated using this equation:

$$ATTD = [(Ca_{intake} - Ca_{feces})/Ca_{intake}] \times 100,$$

in which Ca_{intake} is the average daily Ca intake (g) from d 6 to 11 and Ca_{feces} is the average daily fecal P output (g) originating from the feed that was provided from d 6 to 11.

Statistical Analysis

Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC) with pig as the experimental unit. The model included source of MBM as the fixed effect and block and replicate within block as random effects. 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 criterion [**C(p)**], which determines candidate models that maximize explained variability with as few variables as possible. Good candidate models are those in which C(p) < p, in which p is the number of variables in the candidate model + 1. The second step was multiple regression analyses using PROC REG of SAS, in which 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 in which the 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 Meat and Bone Meal

The concentration of CP, acid hydrolyzed ether extract, and ash in the 8 sources of MBM ranged

from 45.7 to 57.2, 11.6 to 15.2, and 20.6 to 33.2%, respectively (Table 1). On average, MBM contained 51.9, 13.1, and 27.3% CP, acid hydrolyzed ether extract, and ash, respectively. The CV for the concentrations of CP, acid hydrolyzed ether extract, and ash were 6.2, 10.5, and 13.8%, respectively. There was greater variation in Ca and P concentrations (CV = 22.1 and 20.0%, respectively) than in CP, acid hydrolyzed ether extract, and ash concentrations. The concentration of Ca ranged from 5.09 to 11.03% with an average of 9.2 ± 2.0% whereas the concentration of P ranged from 2.59 to 5.26% with an average of 4.3 ± 0.8%. However, the Ca:ash (0.25 to 0.35), P:ash (0.13 to 0.16), and Ca:P (1.97 to 2.05) in the MBM samples were relatively consistent (CV = 10.8, 6.9, and 4.3%, respectively).

Phosphorus and Ca Digestibility of Meat and Bone Meal

There were no differences in daily feed intake or daily fecal output among 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 and ranged 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 (2.39 to 4.46 g/d) and daily Ca output (0.44 to 2.08 g/d). The ATTD of Ca was different among MBM sources (53.0 to 81.0%, average = 63.9 ± 9.4%; $P < 0.05$), but no differences in the daily amount of Ca absorbed were observed among pigs fed the different MBM sources.

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 ($r = 0.96$ and 0.98, respectively; $P < 0.001$) 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 these equations:

$$\%Ca = 0.47564 \times ash – 4.38727$$
($R^2 = 0.93$, RMSE = 0.59, $P < 0.001$)

$$\%P = 0.20497 \times ash – 1.41282$$
($R^2 = 0.94$, RMSE = 0.23, $P < 0.001$)

Concentrations of ash, Ca, and P were negatively correlated ($r = –0.94$, –0.88, and –0.90, respectively; $P < 0.01$) with the concentration of CP in MBM. However, no statistically significant correlation was observed between ether extract concentration and the concentration of ash, Ca, or P. The ATTD of Ca was negatively correlated ($r = –0.79$, –0.86, and –0.87, respectively; $P < 0.01$) with concentrations of ash, Ca, and P but positively correlated with the STTD of P ($r = 0.98$, $P < 0.001$).

To predict the STTD of P, a total of 24 candidate models were determined [C(p) < p], with 1 to 4 independent variables included in each model (Table 7). However, including only P as the independent variable in

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

	Meat and bone meal source									
Item	1	2	3	4	5	6	7	8	SEM	*P*-value
Feed intake, g DM/d	530	503	483	508	519	527	489	513	22	0.78
Fecal output, g DM/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[2], mg/d	56	54	51	54	55	56	52	55	2	0.78
STTD of P[3], %	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 losses. 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 the daily basal EPL.

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

	Meat and bone meal source									
Item	1	2	3	4	5	6	7	8	SEM	*P*-value
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	4.42	3.18	2.39	4.36	3.97	4.32	4.46	3.51	0.16	<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	2.47	2.35	1.94	2.83	2.50	2.24	2.48	2.16	0.25	0.38
ATTD of Ca, %	57.2	73.2	81.0	66.3	62.7	53.0	56.0	62.1	6.0	0.03

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

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, 5 prediction equations were developed (Table 8). The models explained 60 to 73% of the variability in STTD of P in MBM. The best model for predicting STTD of P in MBM was Eq. [1] (Table 8), which had the least AIC and RMSE. Therefore, the optimal prediction model for STTD of P (%) in MBM was

$$\text{STTD of P} = 107.857 - 8.8 \times \text{total P} \quad (R^2 = 0.68, \text{RMSE} = 5.73, P < 0.01).$$

To predict the ATTD of Ca, a total of 20 candidate models were determined [C(p) < p], with 1 to 4 independent variables included in each model (Table 9). The candidate model that included only P as the independent variable had the least C(p). Using R^2, AIC, and RMSE as selection criteria for the final model, 10 prediction equations for ATTD of Ca in MBM were developed (Table 10). The models explained 73 to 85% of the variability in ATTD of Ca in MBM. The best model was Eq. [1] (Table 10), which had the least AIC and RMSE. Therefore, the optimal prediction model for ATTD of Ca (%) in MBM was

$$\text{ATTD of Ca} = 105.375 - 9.327 \times \text{total P} \quad (R^2 = 0.75, \text{RMSE} = 4.70, P < 0.01).$$

DISCUSSION

Composition of Meat and Bone Meal

Based on the official definition of the Association of American Feed Control Officials (**AAFCO**, 2011), an animal-rendered product is considered MBM if it contains at least 4.0% P and if the Ca:P is not greater than 2.2. Samples that contain less than 4.0% P are considered meat meal. Two of the samples included 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 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 including rendered products 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.,

Table 6. Correlation coefficients between chemical components and digestibilities of P and Ca in meat and bone meal[1]

	Correlation coefficient						
Item	CP	AEE	Ash	Ca	P	STTD of P	ATTD of Ca
CP	–	0.57	–0.94***	–0.88**	–0.90**	0.65	0.67
AEE		–	–0.59	–0.64	–0.61	0.63	0.62
Ash			–	0.96***	0.98***	–0.78*	–0.79*
Ca				–	0.99***	–0.85**	–0.86**
P					–	–0.81*	–0.87**
STTD of P						–	0.98***
ATTD of Ca							–

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

[1]AEE = acid hydrolyzed ether extract; STTD = standardized total tract digestibility; ATTD = apparent total tract digestibility.

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

No. of variables in model	C(p)	R^2	AIC[2]	Variables in model
1	–0.11	0.68	29.6	P
1	0.11	0.66	30.1	Ca
1	0.77	0.60	31.3	Ash
2	1.26	0.73	30.2	CP, P
2	1.48	0.71	30.8	AEE,[3] P
2	1.79	0.68	31.4	Ash, P
2	1.84	0.68	31.5	AEE, Ca
2	1.89	0.68	31.6	Ca, P
2	1.89	0.68	31.7	CP, Ca
2	1.97	0.67	31.8	CP, ash
2	2.11	0.66	32.1	Ash, Ca
2	2.22	0.65	32.3	AEE, ash
3	2.73	0.77	30.8	CP, AEE, P
3	3.19	0.73	32.1	CP, ash, P
3	3.20	0.73	32.1	CP, Ca, P
3	3.33	0.72	32.4	Fat, ash, P
3	3.36	0.72	32.5	Fat, Ca, P
3	3.37	0.72	32.5	CP, AEE, ash
3	3.61	0.70	33.1	CP, AEE, Ca
3	3.68	0.69	33.2	CP, ash, Ca
3	3.79	0.68	33.4	Ash, Ca, P
3	3.84	0.68	33.5	AEE, ash, Ca
4	4.28	0.81	31.4	CP, AEE, Ca, P
4	4.69	0.78	32.7	CP, AEE, ash, P

[1]C(p) = criterion that determines candidate models, which maximize explained variability with as few variables as possible. Candidate models are those where C(p) < p, in which p is the number of variables in the candidate model + 1.

[2]AIC = Akaike information criterion, which measures fit of the model. Smaller AIC is a better fit of the model.

[3]AEE = acid hydrolyzed ether extract.

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 indicated that the variation in CP and ash concentration in MBM may reflect differences in bone to soft tissue ratios among sources although other factors may also influence CP and ash concentrations in MBM. 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 considerably 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., 2002), 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 published mean values for the concentration of P and Ca in MBM may result in an overestimation or an

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

Equation no.	Estimate									
	Intercept	CP, %	AEE[3], %	Ash, %	Ca, %	P, %	R^2	AIC	RMSE	*P*-value
1	107.857	–	–	–	–	–8.800	0.68	29.6	5.73	0.01
2	102.912	–	–	–	–3.712	–	0.66	30.1	5.89	0.01
3	227.117	–1.766	–	–	–	–14.024	0.73	30.2	5.75	0.04
4	82.146	–	1.410	–	–	–7.369	0.71	30.8	5.94	0.04
5	118.893	–	–	–1.754	–	–	0.60	31.3	6.35	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 are on a DM basis.

[3]AEE = acid hydrolyzed ether extract.

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 considerable 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 for an effective use of MBM in swine diets.

Phosphorus Digestibility in Meat and Bone Meal

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 close 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). However, 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).

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

No. of variables in model	C(p)	R^2	AIC[2]	Variables in model
1	0.11	0.75	27.0	P
1	0.44	0.73	28.2	Ca
2	0.97	0.82	27.6	CP, P
2	1.34	0.80	27.9	Ash, P
2	1.80	0.77	29.0	AEE[3], P
2	2.02	0.76	29.4	CP, Ca
2	2.10	0.75	29.6	Ca, P
2	2.17	0.75	29.7	Ash, Ca
2	2.29	0.74	30.0	AEE, Ca
3	2.52	0.85	27.7	CP, AEE, P
3	2.88	0.83	28.8	CP, Ca, P
3	2.90	0.82	28.8	CP, ash, P
3	2.91	0.82	28.9	AEE, ash, P
3	3.33	0.80	29.9	Ash, Ca, P
3	3.70	0.78	30.8	AEE, Ca, P
3	3.85	0.77	31.1	CP, AEE, Ca
4	4.00	0.88	27.8	CP, AEE, Ca, P
4	4.44	0.85	29.4	CP, AEE, ash, P
4	4.85	0.83	30.7	CP, ash, Ca, P
4	4.86	0.83	30.7	AEE, ash, Ca, P

[1]C(p) = criterion that determines candidate models, which maximize explained variability with as few variables as possible. Candidate models are those where C(p) < p, in which p is the number of variables in the candidate model + 1.

[2]AIC = Akaike information criterion, which measures fit of the model. Smaller AIC is a better fit of the model.

[3]AEE = acid hydrolyzed ether extract.

The STTD of P in MBM decreased with increasing ash, Ca, and P concentration and between 60 and 68% of the variability in STTD values 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.

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

		Estimate								
Equation no.	Intercept	CP, %	AEE[3], %	Ash, %	Ca, %	P, %	R^2	AIC	RMSE	*P*-value
1	105.375	–	–	–	–	–9.327	0.75	27.0	4.70	0.01
2	242.595	–2.032	–	–	–	–15.338	0.82	27.6	4.80	0.01
3	228.474	–2.166	1.269	–	–	–14.445	0.85	27.7	4.84	0.04
4	88.869	–	–	2.021	–	–18.608	0.80	27.9	4.98	0.02
5	100.14	–	–	–	–3.935	–	0.73	28.2	5.25	0.01
6	86.33	–	1.045	–	–	–8.267	0.77	29.0	5.32	0.02
7	172.754	–1.106	–	–	–5.291	–	0.76	29.4	5.46	0.03
8	105.619	–	–	–	0.23	–9.859	0.75	29.6	5.53	0.03
9	88.646	–	–	1.081	–6.043	–	0.75	29.7	5.57	0.03
10	86.006	–	0.783	–	–3.566	–	0.74	30.0	5.65	0.03

[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 are on DM basis.

[3]AEE = acid hydrolyzed ether extract.

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, the greater is the proportion of bone in the product, which in turn explains the reduction in P digestibility as P concentration increases. The fact that the optimal prediction equation that was developed to estimate the STTD of P in MBM includes only P as a variable supports this assumption.

Calcium Digestibility in Meat and Bone Meal

There are 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 the range of values reported for the ATTD of Ca in calcium carbonate. This observation was expected because one of the components of bones is calcium carbonate (Gerrard and Grant, 2003).

The equation developed to predict ATTD of Ca in MBM was similar to the equation calculated to predict the STTD of P in MBM because only the concentration of P in MBM is needed for the prediction. 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. These data also indicate that factors that are positive for the digestibility of P in MBM are also positive for the digestibility of Ca.

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.

Conclusions

The concentrations and the digestibility values for P and Ca varied among sources of MBM. However, prediction equations using the concentrations of total P in MBM may be used to estimate P and Ca digestibility in MBM fed to growing pigs. There is a strong positive correlation between the concentrations of ash and Ca and P in MBM, indicating that sources of MBM that have a relatively high concentration of ash also have relatively high concentrations of Ca and P. Likewise, there is a strong positive correlation between the ATTD of Ca and the STTD of P, but there is a negative correlation between the digestibility of Ca and P and the concentration of Ca and P in MBM.

LITERATURE CITED

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

Adeola, O. 2001. Digestion and balance techniques in pigs. In: A. J. Lewis and L. L. Southern, editors, Swine nutrition, 2nd ed. CRC Press, Washington, DC. p. 903–916.

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.

AOAC Int. 2007. Official methods of analysis.18th ed. Rev. 2. W. Howitz, and G. W. Latimer, Jr., editors. AOAC Int., Gaithersburg, MD.

Association of American Feed Control Officials (AAFCO). 2011. Official publication of the Association of American Feed Control Officials. AAFCO, Washington, DC.

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 swines. 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., and J. G. Phillips. 2009. Physical distribution and characteristics of meat and bone meal protein. J. Sci. Food Agric. 89:329–326.

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.

Gerrard, D. E., and A. L. Grant. 2003. Tissue structure and organization. Pages 7-41 In: Principles of animal growth and development. Kendall/Hunt Publishing Company, Dubuque, IA.

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. Poult. 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. In: Manipulating pig production. X. J. E. Paterson, editor, Austr. Pig Sci. Assoc., Victoria, Australia. p. 156.

Mendez, A., and N. Dale. 1998. Rapid assay to estimate calcium and phosphorus in meat and bone meal. J. Appl. Poult. 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 rev. 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. 89:2139–2144.

Traylor, S. L., G. L. Cromwell, and M. D. Lindemann. 2005a. 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. 2005b. 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.