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Comparison of values for standardized total tract digestibility and relative bioavailability of phosphorus in dicalcium phosphate and distillers dried grains with solubles fed to growing pigs

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ABSTRACT: Two experiments were conducted to compare values for the standardized total tract digestibility (STTD) and the relative bioavailability of P in dicalcium phosphate (DCP) and distillers dried grains with solubles (DDGS) when fed to growing pigs. In Exp. 1, the apparent total tract digestibility (ATTD), the basal endogenous P loss (EPL), and the STTD of P in DCP and DDGS were determined. Eighteen pigs (initial BW: 34.93 ± 1.04 kg) were allotted to 3 cornstarch-based diets in a randomized complete block design and housed individually in metabolism cages. Two diets contained DCP and DDGS, respectively, as the sole source of P and the last diet was a P-free diet that was used to measure EPL from the pigs. Results indicated that the ATTD of P in DCP and DDGS were 86.1 and 58.8%, respectively, and the STTD of P in DCP and DDGS were 93.1 and 63.1%, respectively. The EPL was determined at 174 mg/kg DMI. In Exp. 2, 42 pigs (initial BW: 29.02 ± 2.03 kg) were allotted to 7 dietary treatments in a randomized complete block design. Pigs were housed individually and allowed ad libitum access to feed and water. A basal diet (0.22% P) based on corn, casein, cornstarch, and potato protein concentrate was formulated. Three additional diets were formulated by adding 0.04, 0.08, or 0.12% P from DCP to the basal diet to create diets containing 0.26, 0.30, or 0.34% P. The last 3 diets were formulated by adding 0.04, 0.08, or 0.12% P from DDGS to the basal diet at the expense of cornstarch. Pigs were fed experimental diets for 28 d. They were then euthanized and the third and fourth metacarpals from the right front foot were collected. Metacarpal bone ash and bone P were regressed against P intake for each ingredient and via slope ratio methodology, it was determined that the bioavailability of P in DDGS was 87% relative to that in DCP. It was concluded from this work that the value for relative bioavailability of P in DDGS overestimates the digestibility of P in DDGS and values for the STTD of P, therefore, can not be accurately calculated from values for the relative bioavailability of P. As a consequence, it is necessary to determine the STTD of P in feed ingredients included in diets fed to pigs.

Key words: bioavailability, dicalcium phosphate, distillers dried grains with solubles, phosphorus, pigs, standardized digestibility

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INTRODUCTION

Traditionally, the availability of P in feed ingredients has been determined by measuring the relative bioavailability (**RBV**) of P using a slope ratio method (Cromwell, 1992). This method works well if the objective is to compare and rank different sources of P. However, the RBV procedure does not allow for calculation of the digestibility of P in a specific ingredient and RBV values do not allow for calculation of the quantities of P absorbed and excreted by the pig. If the total tract digestibility of P in individual feed ingredients is determined, the amount of P absorbed by the pig as well as the amount of P excreted in the feces from the pig can be calculated (Petersen and Stein, 2006).

Total tract digestibility of P may be determined as apparent total tract digestibility (**ATTD**) or standardized total tract digestibility (**STTD**). Values for ATTD and STTD may be measured directly in P-containing ingredients and values are not expressed relative to values for a standard or a control diet. Endogenous P loss (**EPL**) represents a small yet substantial source of P excretion that needs to be accounted for when calculating digestibility values (Fan et al., 2001). Values for STTD

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of P are calculated by correcting values for ATTD of P by basal endogenous losses and, unlike values for ATTD of P, values for STTD of P are believed to be additive in mixed diets (Almeida and Stein, 2010). Basal EPL may be measured using a P-free diet (Petersen and Stein, 2006). To our knowledge, however, there are no reports on the comparison of values for STTD of P and the RBV of P and it is not known if values for the STTD of P can be calculated from values for the RBV of P. Therefore, the objective of this experiment was to determine the STTD of P in distillers dried grains with solubles (**DDGS**) and in dicalcium phosphate (**DCP**) and to compare these values to determine if values for STTD of P can be calculated from values for the RBV of P.

MATERIALS AND METHODS

Animal protocols concerning this work were reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois. Pigs with similar genetic makeup (G-Performer boars × Fertilium 25 females; Genetiporc, Alexandria, MN) were used in both experiments.

Digestibility of Phosphorus in Dicalcium Phosphate and Distillers Dried Grains with Solubles – Experiment 1

Pigs, Diets, Experimental Design, and Housing. Commercial sources of DCP (PCS Sales LLC, Northbrook, IL) and corn DDGS (LincolnlandAgri Energy LLC, Palestine, IL) were obtained (Table 1). Two diets containing DCP or DDGS as the sole source of P were formulated (Tables 2 and 3). A P-free diet that was used to measure basal endogenous losses of P was also formulated.

Eighteen growing barrows with an initial BW of 34.93 ± 1.04 kg were randomly allotted to the 3 diets with 6 replicate pigs per diet using a randomized complete block design. Pigs were placed in metabolism cages that were equipped with a feeder and a nipple drinker and had expanded metal floors. Screens were placed under the floors, which allowed for total collection of feces. Metabolism cages were placed in an environmentally controlled room with ambient temperature maintained at 22°C.

Table 1. Analyzed composition of dicalcium phosphate and distillers dried grains with solubles (DDGS), as-fed basis, Exp. 1 and 2[1]

	Ingredient	
Item	Dicalcium phosphate	DDGS
GE, cal/g	–	4,804
CP, %	–	28.18
DM, %	96.89	89.37
Ash, %	82.54	4.31
P, %	19.77	0.89
Ca, %	20.88	0.02
NDF, %	–	34.35
ADF, %	–	9.87

[1]Amino acids (%) were analyzed in DDGS as follows: Arg, 1.31; His, 0.76; Ile, 1.06; Leu, 3.18; Lys, 0.93; Met, 0.55; Phe, 1.23; Thr, 0.98; Trp, 0.19; Val, 1.43; Ala, 1.92; Asp, 1.74; Cys, 0.62; Glu, 3.75; Gly, 1.09; Pro, 2.10; Ser, 1.08; and Tyr, 0.90.

Table 2. Ingredient composition of experimental diets (as-fed basis), Exp. 1

	Diet		
Ingredient	P-free	Dicalcium phosphate	DDGS[1]
Dicalcium phosphate	–	1.25	–
DDGS	–	–	40.00
Cornstarch	49.22	47.97	43.10
Sucrose	20.00	20.00	15.00
Soybean oil	4.00	4.00	–
Solka floc[2]	4.00	4.00	–
Ground limestone	0.80	0.80	1.20
Gelatin[3]	20.00	20.00	–
DL-Met	0.27	0.27	–
L-Thr	0.08	0.08	–
L-Trp	0.14	0.14	–
L-His	0.08	0.08	–
L-Ile	0.16	0.16	–
L-Val	0.05	0.05	–
Salt	0.40	0.40	0.40
Vitamin and mineral premix[4]	0.30	0.30	0.30
Potassium carbonate	0.40	0.40	–
Magnesium oxide	0.10	0.10	–

[1]DDGS = distillers dried grains with solubles.

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

[3]Gelita Gelatine USA Inc., Sioux City, IA.

[4]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadionenicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 3. Analyzed composition of experimental diets (as-fed basis), Exp. 1

	Diet		
Item	P-free	Dicalcium phosphate	Distillers dried grains with solubles
ME, kcal/kg[1]	3,452	3,403	3,660
DM, %	92.62	92.72	90.96
Ash, %	1.25	2.21	3.02
P, %	–	0.23	0.37
Ca, %	0.36	0.57	0.59
NDF, %	4.03	6.79	16.73
ADF, %	2.96	1.72	5.08

[1]Values for ME were calculated (NRC, 1998) rather than analyzed.

Feeding and Sample Collection. Animals were fed their respective diets for 12 d at 2.5 times the daily maintenance requirement for energy (i.e., 106 kcal ME per kilogram $BW^{0.75}$; NRC, 1998). The daily quantity of feed was provided in 2 equal meals at 0500 and 1700 h. Water was available at all times. The initial 5 d adaptation period to the diets was followed by a 5 d collection period. A marker was added to the morning meals on d 6 and 11 and feces were collected using the marker to marker approach (Adeola, 2001). Fecal samples were stored at –20°C immediately after collection.

Data Recording and Chemical Analysis. Initial and final BW of the pigs were recorded along with feed intake and feed refusals. At the conclusion of the experiment, fecal samples were removed from storage, dried in a forced air oven, and finely ground (Model 4 Thomas-Wiley Laboratory Mill with a 1.0-mm sieve; Thomas Scientific, Philadelphia, PA). Fecal samples and diets were analyzed for DM by forced air oven drying at 135°C for 2 h (Method 930.15; AOAC Int., 2007). Fecal samples, diets, DCP, and DDGS were also analyzed for Ca and P by inductively coupled plasma spectroscopy (Method 985.01; AOAC Int., 2007) after wet ashing (Method 975.03; AOAC Int., 2007) with the standards (catalog number ICAL 1 and catalog number PLP9-3X, for Ca and P, respectively; SpexCertiprep, Metuchen, NJ). The DDGS sample was analyzed for CP (Method 990.03, AOAC Int., 2007) and AA [Method 982.30 E (a, b, c); AOAC Int., 2007], and GE was analyzed in this sample using an adiabatic bomb calorimeter (Model 6300; Parr Instruments, Moline, IL). Diets and the DDGS sample were also analyzed for ADF (Method 973.18; AOAC Int., 2007) and NDF (Holst, 1973).

Calculations and Statistical Analyses. Values for ATTD, EPL, and STTD were calculated as described by Almeida and Stein (2010). Data were analyzed by ANOVA using the Proc GLM procedure (SAS Inst. Inc., Cary, NC). The main effect was treatment and treatment means were calculated using the LSMeans procedure. The pig was the experimental unit and an alpha value of 0.05 was used to assess significance between means. Homogeneity of the variances between treatments was confirmed using the UNIVARIATE procedure in SAS. The UNIVARIATE procedure was also used to identify outliers as values that had treatment means of more than 3 times the interquartile range (Devore and Peck, 1993).

Relative Bioavailability of Phosphorus – Experiment 2

Pigs, Diets, Experimental Design, and Housing. Forty-two barrows weighing 29.02 ± 2.03 kg were allotted to 7 dietary treatments with 6 replicate pigs per diet in a randomized complete block design using an animal allotment program (Kim and Lindemann, 2007). Pigs were housed individually in pens (0.9 × 1.8 m) that had a fully slatted concrete floor and a feeder and a nipple drinker.

A corn-based basal diet containing 0.22% P was formulated (Tables 4 and 5). This diet contained potato protein concentrate (Avebe U.A., Veendam, The Netherlands) and casein (International Ingredients Company, St. Louis, MO) as protein sources. Three additional diets were formulated by adding 0.04, 0.08, or 0.12% P from DCP to the basal diet, resulting in diets containing 0.26, 0.30, or 0.34% P. The last 3 diets were formulated by adding 0.04, 0.08, or 0.12% P from DDGS to the basal diet at the expense of cornstarch. The DCP and DDGS that were used in this experiment were from the same batches as those used in Exp. 1.

Feeding and Sample Collection. Individual pig BW were recorded at the beginning and at the conclusion of the experiment. Animals were allowed ad libitum access to feed and water throughout the 28-d experiment. Daily feed allowances and feed refusals were recorded. Subsamples of all diets were collected and stored at –20°C in zip lock freezer bags until analyzed. Feed refusals were stored at –20°C as well.

At the conclusion of the experiment, all animals were euthanized via captive bolt stunning and the right front foot was removed at the hock joint. The third and fourth metacarpals of the right foot were removed and cleaned to remove soft tissue. Bones were then sealed in plastic freezer bags and stored at –20°C. The metacarpals were later removed from storage and thawed, and bones were broken to expose the marrow and soaked in petroleum ether to remove fat and marrow. Bones were then placed under a chemical hood and air dried for 24 h and dried overnight at 130°C in a gravity convection oven (Isotemp 500 series; Fisher Scientific, Pittsburg, PA) before ashing in a muffle furnace (Isotemp Furnace; Fisher Scientific) for 6 h at 600°C (Method 975.03; AOAC Int., 2007). The weight of the ash was recorded. Diets were analyzed for DM, CP, GE, ash, ADF, and NDF. Diets and the ash from all bones were also analyzed for P and Ca. Procedures for all chemical analyses were identical to those used in Exp. 1.

Calculations and Statistical Analyses. Data were analyzed as a complete randomized block design using the MIXED procedure of SAS with pig as the experimental unit. Data were tested for outliers using the same procedure as described for Exp. 1. Orthogonal polynomial contrasts were used to test for linear and quadratic responses to increasing P intake on bone ash and bone P concentrations. Relative bioavailability of P in DDGS was determined by multiple linear regressions and the slope ratio method using DCP as the stan-

Table 4. Ingredient composition of experimental diets (as-fed basis), Exp. 2

		Diets						
		Basal	Dicalcium phosphate			Distillers dried grains with solubles		
Ingredient	% P:	0.22	0.26	0.30	0.34	0.26	0.30	0.34
Ground corn		64.95	64.81	64.81	64.81	64.81	64.81	64.81
Potato protein concentrate[1]		6.00	6.00	6.00	6.00	6.00	6.00	6.00
Casein[2]		2.40	2.40	2.40	2.40	2.40	2.40	2.40
Cornstarch		22.00	22.05	21.97	21.88	17.52	12.90	8.24
Soybean oil		1.80	1.80	1.80	1.80	1.38	0.95	0.52
Dicalcium phosphate		–	0.22	0.44	0.66	–	–	–
Distillers dried grains with solubles		–	–	–	–	5.20	10.40	15.60
Ground limestone		1.42	1.29	1.15	1.02	1.41	1.40	1.38
L-Lys HCl		0.40	0.40	0.40	0.40	0.35	0.31	0.26
DL-Met		0.12	0.12	0.12	0.12	0.06	0.01	–
L-Thr		0.10	0.10	0.10	0.10	0.07	0.03	–
L-Trp		0.06	0.06	0.06	0.06	0.05	0.04	0.04
Salt		0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin and mineral premix[3]		0.30	0.30	0.30	0.30	0.30	0.30	0.30
Tylan premix[4]		0.05	0.05	0.05	0.05	0.05	0.05	0.05

[1]Avebe U. A., Veendam, The Netherlands.

[2]International Ingredients Company, St. Louis, MO.

[3]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadionenicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[4]The Tylan premix (Elanco Animal Health, Greenfield, IN) included at 0.05% provided 44 mg tylosin in the form of tylosin phosphate per kilogram of complete diet.

dard source. Bone ash weight and bone P concentration were regressed on supplemental P intake using the basal diet as a common intercept as described by Littell et al. (1997). Regression using bone ash weight and bone P data met all 3 assumptions for the slope-ratio assay: the responses were linear, the lines shared a common intercept, and the response at the 0 level was equal to the common intercept. The RBV of P in DDGS was then calculated by dividing the slope of the regression line for DDGS by the slope of the regression line for DCP (Cromwell, 1992). An α-level of 0.05 was used in all data analyses and $0.05 < P < 0.10$ was used to indicate a tendency.

RESULTS

Digestibility of Phosphorus in Dicalcium Phosphate and Distillers Dried Grains with Solubles – Experiment 1

All pigs easily consumed their respective diets and remained healthy throughout the experiment. However, 1 pig on the DCP treatment was identified as an outlier and was removed from the data because data for ADFI, ATTD of P, and STTD of P for this pig were greater than 3 times the interquartile range. Pigs fed the DCP diet consumed more ($P < 0.05$) feed than pigs fed the DDGS diet (Table 6). Daily intake of P and the fecal output of P were greater ($P < 0.001$) for pigs fed the DDGS diet than

Table 5. Analyzed composition of experimental diets (as-fed basis), Exp. 2

		Diet						
		Basal diet	Dicalcium phosphate			Distillers dried grains with solubles		
Ingredient	% P:	0.22	0.26	0.30	0.34	0.26	0.30	0.34
ME, kcal/kg[1]		3,567	3,564	3,561	3,557	3,526	3,484	3,440
DM, %		88.42	88.50	88.85	89.24	89.02	88.44	88.17
Ash, %		2.58	2.62	2.71	2.95	2.81	2.93	3.51
CP, %		11.24	11.38	11.49	11.25	13.11	13.96	15.31
P, %		0.24	0.23	0.28	0.35	0.23	0.28	0.32
Ca, %		0.52	0.59	0.66	0.62	0.60	0.63	0.64
NDF, %		8.22	6.37	6.40	8.08	7.66	10.88	11.85
ADF, %		1.92	1.56	1.54	2.10	2.38	3.33	3.83

[1]Values for ME were calculated (NRC, 1998) rather than analyzed.

Table 6. Intake, output, and digestibility of P in dicalcium phosphate (DCP) and distillers dried grains with solubles (DDGS) fed to growing pigs, Exp. 1

	Diet			
Item	DCP	DDGS	SEM	*P*-value
Feed intake, g/d	1,023	925	20	0.005
P intake, g/d	2.5	3.8	0.2	<0.001
Fecal P output, g/d	0.3	1.6	0.2	<0.001
ATTD,[1] %	86.1	58.8	3.8	<0.001
STTD,[2] %	93.1	63.1	3.8	<0.001

[1]ATTD = apparent total tract digestibility.

[2]STTD = standardized total tract digestibility. Values for STTD were calculated by correcting ATTD values for basal endogenous losses. Basal endogenous losses of P were determined to be 174 mg/kg DMI.

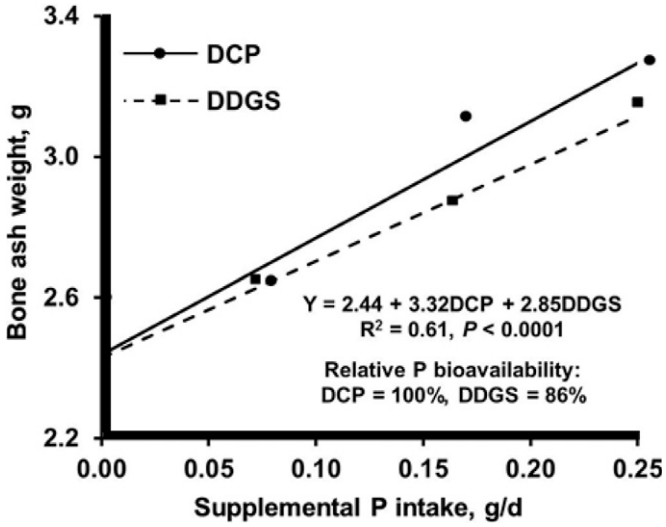

Figure 1. Linear regression of bone ash on supplemental P intake and relative bioavailability of P. DCP = dicalcium phosphate; DDGS = distillers dried grains with solubles. Values on the *x*-axis are based on analyzed values for P in the diets.

pigs fed the DCP diet. The ATTD and STTD of P, however, were greater for DCP than for DDGS ($P < 0.001$).

Bioavailability of Phosphorus – Experiment 2

One pig that was fed the basal diet died during the experiment and was not included in the statistical analysis. One pig consuming the DCP diet with 0.30% P and 1 pig fed the DCP diet with 0.34% P were identified as outliers and were also excluded from calculations.

All pigs gained BW during the experiment. Final BW, ADG, ADFI, and G:F increased (linear; $P < 0.05$) as the dietary concentration of P from DDGS increased (Table 7). There was also a tendency ($P < 0.10$) for a linear increase in the final BW, and there was an increase ($P < 0.05$) in ADFI and ADG as increasing levels of P from DCP were included in the diet.

The dry fat free bone weight increased (linear; $P < 0.05$) as DCP was added to the basal diet, but there was no effect on bone weight of adding increasing levels of DDGS to the diet (Table 8). The amount of bone ash increased as dietary P increased (linear; $P < 0.01$), regardless of the source of P. The concentration of P and Ca, if measured as a percent of bone, was not influenced by dietary treatments. However, the total amount of P and Ca increased (linear; $P < 0.01$) as P in the diet increased regardless of the source of P. The bioavailability of P in DDGS relative to the bioavailability of P in DCP was 86% if calculated from total bone ash weight and 88% if calculated from the amount of P in the bone ash (Table 9; Figs. 1 and 2).

DISCUSSION

Inorganic P sources such as DCP are added to diets as P supplements and DCP may also be used as the standard when the RBV of other ingredients is determined (Cromwell, 1992). The ATTD of P in DCP that was calculated in this experiment is in agreement with values reported by Von Rodehutscord et al. (1994) and Petersen and Stein (2006), but greater than the value of 73% reported by Eeckhout and de Paepe (1997). However, differences in the ATTD of P among different sources of DCP have been reported (Jongbloed, 1987).

The value for the basal EPL (174 g/kg DMI) that was measured for pigs fed the P-free diet is within the range of reported values between 139 and 211 mg/kg

Table 7. Effects of dietary P from dicalcium phosphate (DCP) or distillers dried grains with solubles (DDGS) on pig growth performance, Exp. 2

		Diet and P source								DCP			DDGS	
		Basal	DCP			DDGS				*P*-value			*P*-value	
Item	% P:	0.22	0.26	0.30	0.34	0.26	0.30	0.34	SEM	Lin[1]	Q[1]	SEM	Lin[1]	Q[1]
Initial BW, kg		29.82	29.03	29.48	29.78	29.03	29.10	28.60	0.84	0.93	0.55	0.84	0.37	0.87
Final BW, kg		46.94	48.82	49.94	52.26	45.50	51.55	52.96	2.00	0.08	0.92	2.00	0.01	0.49
ADG, kg		0.61	0.71	0.73	0.81	0.59	0.80	0.87	0.06	0.04	0.85	0.06	<0.01	0.45
ADFI, kg		1.70	1.89	2.11	2.15	1.65	2.01	2.06	0.09	<0.01	0.47	0.09	<0.01	0.62
G:F		0.35	0.37	0.35	0.37	0.36	0.40	0.42	0.02	0.71	0.90	0.02	<0.01	0.58

[1]Lin = linear effect; Q = quadratic effect.

Table 8. Effects of dietary P from dicalcium phosphate (DCP) or distillers dried grains with solubles (DDGS) on bone traits, Exp. 2

		Diet and P source							DCP			DDGS		
		Basal	DCP			DDGS				*P*-value			*P*-value	
Item	% P:	0.22	0.26	0.30	0.34	0.26	0.30	0.34	SEM	Lin[1]	Q[1]	SEM	Lin[1]	Q[1]
Bone wt, g[2]		6.98	6.94	7.75	8.29	6.42	6.93	7.48	0.45	0.04	0.55	0.45	0.34	0.24
Bone ash wt, g		2.61	2.63	3.12	3.38	2.63	2.87	3.16	0.10	<0.01	0.25	0.10	<0.01	0.21
Bone ash P, %		19.90	19.95	20.09	19.79	19.66	20.21	19.86	0.25	0.89	0.50	0.25	0.71	0.81
Bone P, g		0.52	0.52	0.63	0.67	0.52	0.58	0.63	0.61	<0.01	0.42	0.61	<0.01	0.32
Bone ash Ca, %		40.75	40.60	40.30	40.58	41.23	40.27	40.04	0.49	0.74	0.68	0.49	0.17	0.47
Bone Ca, g		1.06	1.07	1.26	1.37	1.08	1.16	1.26	0.04	<0.01	0.17	0.04	<0.01	0.29

[1]Lin = linear effect; Q = quadratic effect.

[2]Dry fat-free weight.

of DMI (Petersen and Stein, 2006; Stein et al., 2006; Almeida and Stein, 2010). Correction of the ATTD values for basal EPL allows for calculation of STTD values for P, which are believed to be additive in mixed diets and, therefore, more relevant for practical feed formulation than values for ATTD (Almeida and Stein, 2010). The STTD of P in DCP (93.12%) concurs with the value determined by Petersen and Stein (2006) in a different source of DCP. This value indicates that the source of DCP that was used in this experiment was of high quality because it had excellent digestibility of P.

The ATTD of P in DDGS that was obtained in this experiment is in agreement with previous values that ranged from 50 to 69% (Pedersen et al., 2007; Stein et al., 2009) and is very close to the average ATTD of P in DDGS, which is 59% (Stein and Shurson, 2009). The STTD of P in DDGS, however, was slightly less than the value of 72.9% reported by Almeida and Stein (2010), but it is recognized that some differences in the digestibility of P among sources of DDGS exist (Stein and Shurson, 2009). Variability in the digestibility of P among sources of DDGS may be attributed to differences in production systems among ethanol plants (Pedersen et al., 2007). Some plants are using microbial phytase in the enzyme mixture, which may be one of the reasons differences in the STTD of P among DDGS sources have been observed.

The concentration of P in the diets used to determine digestibility of P was 0.23% in the DCP diet and 0.37% in the DDGS diet. The ATTD of P is not influenced if dietary P concentration varies between 0.26 and 0.64% (Stein et al., 2008) and therefore, it is unlikely that the differences in the concentration of P in the diets used in the present experiment influenced values for the ATTD or STTD of P. It is, however, possible that the increased concentration of fiber in the DDGS diet compared with the DCP diet induced a greater specific endogenous loss of P in pigs fed the DDGS diet. However, to calculate values for STTD of P, only the basal endogenous loss is used (Almeida and Stein, 2010), and the basal endogenous loss, by definition, is not influenced by specific dietary factors, but only by the DMI of the animal. As a consequence, the values for STTD of P that were determined in the experiment are independent of the fiber concentrations in the diets.

The fact that pigs fed the basal diet in Exp. 2 had the least bone ash and that ash weight increased with increased P concentration in the diets is in agreement with Cromwell et al. (1970) and Traylor et al. (2005). The total quantity of P in bone ash is a measure of P deposition in bones because P is stored in a mineral form, which is analyzed as bone ash. As more P is absorbed,

Table 9. Linear regression and relative bioavailability (RBV) of P, Exp. 2

Variable	Source[1]	Slope	Intercept	*P*-value	RBV
Bone ash wt, g	DCP	3.32	2.44	<0.01	100
× P intake, g	DDGS	2.85	2.44	0.03	86
Bone P, g	DCP	0.67	0.48	<0.01	100
× P intake, g	DDGS	0.59	0.48	0.04	88

[1]DCP = dicalcium phosphate; DDGS = distillers dried grains with solubles.

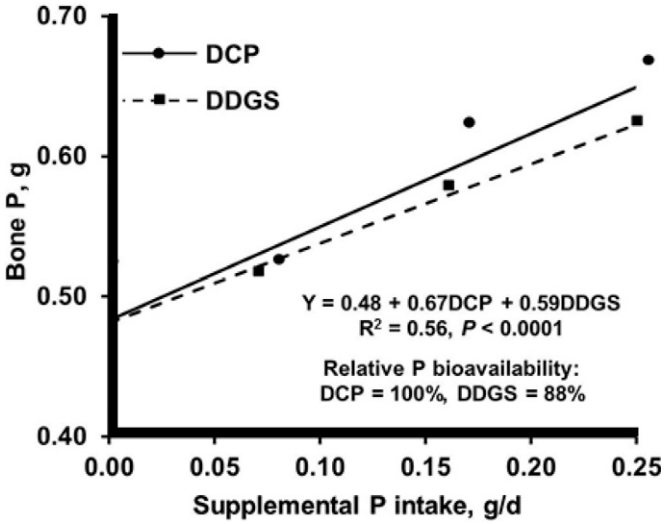

Figure 2. Linear regression of bone P on supplemental P intake and relative bioavailability of P. DCP = dicalcium phosphate; DDGS = distillers dried grains with solubles. Values on the x-axis are based on analyzed values for P in the diets.

more bone may be synthesized, and if that is the case, more bone ash is retained. Phosphorus is deposited in bone ash at a relatively constant concentration (Petersen et al., 2011), which is the reason there was no difference in the percent of P in bone ash among treatments. This observation indicates that the regulation of P deposition is at the level of total bone ash synthesis whereas the composition of the bone ash does not change. This conclusion is in agreement with data reported by Petersen et al. (2011) and indicates that both total bone ash and total bone P are accurate measures of P deposition in bones whereas P as a percent of bone ash does not change with the P status of the pig.

The bioavailability of P in DDGS relative to P in monosodium phosphate has been reported to be 77 and 84% (Fent et al., 2004; Jenkin et al., 2007). The RBV of P in DDGS that was determined in this experiment is slightly greater than these values, but the bioavailability of P in monosodium phosphate is greater than the RBV of P in DCP (Petersen et al., 2011). It is therefore expected that the RBV of P in DDGS is less relative to P in monosodium phosphate than to DCP. However, the value for the RBV of P in DDGS obtained in the present experiment was in agreement with the value of 89% reported by Whitney and Shurson (2001), but greater than the value of 70% reported by Burnell et al. (1989) although DCP was used as the standard in both of these experiments. These differences among experiments are most likely a consequence of the aforementioned differences among sources of DDGS.

Use of STTD values for P is assumed to allow for more accurate formulation of mixed diets than if values for RBV of P or ATTD of P are used because STTD values are additive in mixed diets, which is not always the case for values for ATTD and RBV. It was the hypothesis for the present work that it may be possible to calculate values for STTD of P in a given feed ingredient by multiplying the RBV value by the STTD value for the standard used to determine the RBV value. The STTD of P in DDGS, therefore, was calculated using this principle by multiplying the RBV of P in DDGS (87%) by the STTD of P in DCP (93%), which resulted in a calculated STTD value of 81%. This value is greater than the determined STTD of P in DDGS (63.1%) and therefore, it is apparent that the hypothesis is incorrect and it is not possible to accurately predict the STTD of P in feed ingredients from RBV values.

It is possible that the reason for the discrepancy between RBV and STTD values for P is that between 20 and 40% of absorbed P is deposited in soft tissue (Crenshaw, 2001), which is not accounted for when the RBV values are calculated because these values are based only on P deposited in bone tissue. Differences among different genetic lines of pigs may result in differences in lean deposition, and the age of pigs also influences lean deposition. It is therefore possible that both age and genetic origin of pigs may influence P retention in soft tissue, which may also contribute to differences in determined values for RBV among experiments. It is also possible that the regression procedure used to calculate the slopes for P deposition in bone or bone ash deposition yields less accurate results than the fecal collection procedure because even small changes in estimate values for P or ash deposition may result in changes in the slope values, and therefore, also in the estimated values for RBV. At this point, it is not possible to verify if the differences observed in the present work can be observed for other ingredients. Nevertheless, the practical implication of the results obtained in the present experiments is that it is not always possible to directly convert values for RBV of P in feed ingredients to values for STTD of P. It is, therefore, necessary to determine STTD values of all P-containing feed ingredients used in diets fed to pigs.

Conclusions

Results of the present experiment indicate that it is not always possible to accurately predict values for STTD of P in a feed ingredient from the value for RBV of P in that ingredient. It is, therefore, necessary that values for the STTD of P are determined in all feed ingredients used in diets fed to pigs. Current results also confirm that the STTD of P in DCP is close to 90% and that the STTD of P in DDGS is around 60%. However, values for the STTD of P in DDGS may vary among different sources.

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