Novel procedure for estimating endogenous losses and measurement of apparent and true digestibility of phosphorus by growing pigs

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Novel procedure for estimating endogenous losses and measurement of apparent and true digestibility of phosphorus by growing pigs[1,2]

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ABSTRACT: An experiment was conducted to evaluate a novel procedure for estimating endogenous losses of P and for measuring the apparent total tract digestibility (ATTD) and true total tract digestibility (TTTD) of P in 5 inorganic P sources fed to growing pigs. The P sources were dicalcium phosphate (DCP), monocalcium phosphate (MCP) with 50% purity (MCP50), MCP with 70% purity (MCP70), MCP with 100% purity (MCP100), and monosodium phosphate (MSP). A gelatin-based, P-free basal diet was formulated and used to estimate endogenous losses of P. Five P-containing diets were formulated by adding 0.20% total P from each of the inorganic P sources to the basal diet. A seventh diet was formulated by adding 0.16% P from MCP70 to the basal diet. All diets were fed to 7 growing pigs in a 7 × 7 Latin square design, and urine and feces were collected during 5 d of each period. The endogenous loss of P was estimated as 139 ± 18 mg/kg of DMI. The ATTD of P in MSP was greater ($P < 0.05$) than in DCP, MCP50, and MCP70 (91.9 vs. 81.5, 82.6, and 81.7%, respectively). In MSP, the TTTD of P was 98.2%. This value was greater ($P < 0.05$) than the TTTD of P in DCP, MCP50, and MCP70 (88.4, 89.5, and 88.6%, respectively). The ATTD and the TTTD for MCP70 were similar in diets formulated to contain 0.16 and 0.20% total P. Results from the current experiment demonstrate that a P-free diet may be used to measure endogenous losses of P in pigs. By adding inorganic P sources to this diet, the ATTD of P can be directly measured and the TTTD of P may be calculated for each source of P.

Key words: apparent digestibility, endogenous loss, phosphorus, pig, true digestibility

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INTRODUCTION

Historically, differences in the availability of P among different sources of feed phosphates have been estimated by measuring the relative bioavailability of P using the slope ratio procedure (Cromwell, 1992). Although this procedure is useful in ranking different P sources, the procedure does not allow for estimating the apparent or true digestibility of P in different feed ingredients. In addition, the excretion of P from pigs fed various sources of P is not estimated if the slope ratio procedure is used. To generate such data, an alternative procedure is needed.

The apparent total tract digestibility (**ATTD**) of a nutrient can be measured by using the difference method or the direct method (Adeola, 2001). The difference procedure has been used on a few occasions to measure ATTD of P in feed phosphates (Huyghebaert et al., 1980; Jongbloed, 1987; Eeckhout and de Paepe, 1997). However, because of the absence of reliable values for endogenous losses of P, the true total tract digestibility (**TTTD**) for P in feed phosphates has not been reported.

Previous research has demonstrated that the AA in a gelatin-based diet fortified with crystalline AA are highly digestible to pigs (Petersen et al., 2005). Because gelatin is devoid of P, this diet can be formulated to contain no P. By feeding the gelatin-based diet to pigs, the only P that will be excreted is P of endogenous origin. If a feed phosphate is added to this P-free diet, the only P in the diet will originate from the feed phosphate. We hypothesized that this approach may be used to measure the basal total tract endogenous losses of P and the ATTD of P in feed phosphates using the direct method. By correcting the ATTD for endogenous losses, the TTTD may be calculated. The present experiment was conducted to test this hypothesis.

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Table 1. Ingredient composition of experimental diets (g/kg, as-fed basis)

	Diet and P source[1]						
Ingredient	P-free	DCP	MCP50	MCP70	MCP100	MSP	MCP70low
DCP	—	11.0	—	—	—	—	—
MCP50	—	—	11.0	—	—	—	—
MCP70	—	—	—	9.7	—	—	8.0
MCP100	—	—	—	—	8.5	—	—
MSP	—	—	—	—	—	8.0	—
Potassium carbonate	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Magnesium oxide	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Solka floc[2]	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Gelatin[3]	300.0	300.0	300.0	300.0	300.0	300.0	300.0
Cornstarch	404.9	399.9	398.9	399.4	400.2	400.9	400.4
Sucrose	190.0	190.0	190.0	190.0	190.0	190.0	190.0
Soybean oil	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Limestone	8.0	2.0	3.0	3.8	4.2	8.0	4.5
DL-Met	3.4	3.4	3.4	3.4	3.4	3.4	3.4
L-Trp	1.4	1.4	1.4	1.4	1.4	1.4	1.4
L-His	0.5	0.5	0.5	0.5	0.5	0.5	0.5
L-Ile	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Salt	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin premix[4]	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mineral premix[5]	1.0	1.0	1.0	1.0	1.0	1.0	1.0

[1]DCP = dicalcium phosphate; MCP50 = monocalcium phosphate with 50% MCP; MCP70 = monocalcium phosphate with 70% MCP; MCP100 = monocalcium phosphate with 100% MCP; MSP = monosodium phosphate; MCP70low = monocalcium phosphate with 70% MCP included at low concentration.
[2]Fiber Sales and Development Corp., Urbana, OH.
[3]Pork gelatin obtained from Gelita Gelatine USA Inc., Sioux City, IA.
[4]Provided the following quantities of vitamins per kilogram of complete diet: 10,032 IU of vitamin A acetate; 992 IU of vitamin D_3 as D-activated animal sterol; 88 IU of vitamin E as alpha tocopheryl acetate; 1.5 mg of vitamin K as menadione dimethypyrimidinol bisulfate; 0.4 mg of biotin; 60 mg of niacin; 25 mg of pantothenic acid; 10 mg of riboflavin; and 0.05 mg of vitamin B_{12}.
[5]Provided the following quantities of micro minerals per kilogram of complete diet: Cu, 23 mg as copper sulfate; Fe, 110 mg as iron sulfate; I, 0.275 mg as potassium iodate; Mn, 23 mg as manganese sulfate; Se, 0.275 mg as sodium selenite; Zn, 114 mg as zinc oxide.

MATERIALS AND METHODS

Diets and Experimental Design

The ATTD and TTTD of P were measured in a commercial dicalcium phosphate (**DCP**), in 2 commercial monocalcium phosphates (**MCP50** and **MCP70**, respectively), in purified monocalcium phosphate (**MCP100**), and in monosodium phosphate (**MSP**). Dicalcium phosphate, MCP50, and MCP70 contained varying amounts of monocalcium phosphate (**MCP**) and DCP. The quantities of MCP and DCP in these 3 feed phosphates were estimated by the producing companies at approximately 29 and 57%, 50 and 15%, and 70 and 10% for DCP, MCP50, and MCP70, respectively. The remaining compounds in these phosphates are the sum of unreacted calcium carbonate, magnesium phosphate, ferrous phosphate, aluminum phosphate, calcium sulfate, and various other compounds (Baker, 1989). The DCP included in the feed phosphates may have been either in the anhydrate or the dihydrate form, but all the MCP was in the monohydrate form. The DCP and the MCP50 was analyzed at 18.8% P and MCP70 at 21.0% P. The concentration of Ca was analyzed at 21.3, 20.3, and 15.6% for DCP, MCP50, and MCP70, respectively. The MCP100 was a purified food-grade source that analyzed 23.96% P and 16.06% Ca. The MSP was a purified food-grade anhydrous ortho-phosphate that analyzed 25.7% P and 19.1% sodium.

Seven diets were formulated (Tables 1 and 2). The basal diet was a gelatin-cornstarch-based P-free diet. Five additional diets were formulated by adding 0.2% P from each of the 5 inorganic P sources to the basal diet at the expense of cornstarch. To confirm that the ATTD and TTTD for each of the inorganic P sources were not influenced by the level of P in the experimental diets, a seventh diet containing 0.16% P from MCP70 (**MCP70low**) was also included in the experiment. Inorganic Ca in the form of limestone was added to all diets to maintain the total Ca at 0.30%. Vitamins and minerals other than Ca and P were included at similar concentrations in all diets at levels that met or exceeded current requirement estimates for growing pigs (NRC, 1998).

A 7 × 7 Latin square design with 7 periods and 7 animals was used. At the conclusion of the experiment, all 7 pigs had been fed each of the 7 diets during 1 period. Each period was 12 d.

Animals, Housing, and Feeding

The experiment was approved by the Institutional Animal Care and Use Committee at South Dakota State

Table 2. Nutrient composition of experimental diets (as-fed basis)[1]

	Diet and P source[2]						
Item	P-free	DCP	MCP50	MCP70	MCP100	MSP	MCP70low
ME, Mcal/kg	3.28	3.26	3.26	3.26	3.26	3.27	3.26
CP,[3] %	27.0	27.0	27.0	27.0	27.0	27.0	27.0
Ca, %	0.30	0.30	0.30	0.30	0.30	0.30	0.30
P, %	0.01	0.19	0.19	0.19	0.19	0.21	0.16

[1]Values for P were analyzed, but all other values were calculated (NRC, 1998).
[2]DCP = dicalcium phosphate; MCP50 = monocalcium phosphate with 50% MCP; MCP70 = monocalcium phosphate with 70% MCP; MCP100 = monocalcium phosphate with 100% MCP; MSP = monosodium phosphate; MCP70low = monocalcium phosphate with 70% MCP included at low concentration.
[3]All diets were formulated to contain the following quantities of indispensable AA: Arg, 2.49%; His, 0.39%; Ile, 0.51%; Leu, 0.93%; Lys, 1.25%; Met, 0.57%; Phe, 0.63%; Thr, 0.66%; Trp, 0.15%; Val, 0.72%.

University (#02-A055). Seven growing barrows (initial and final BW, 27.4 ± 2.4 kg and 78.8 ± 9.3 kg, respectively) were used in the experiment. The barrows originated from the mating of Duroc × Hampshire boars to Landrace × Yorkshire × Duroc sows. Pigs were housed individually in metabolism cages that were equipped with a feeder and a nipple drinker. The cages had expanded-metal slatted floors, a screen-based floor for total collection of fecal matter, and a tray for total urine collection. Room temperature was maintained at 22°C.

During each period, feed was supplied at a level of 2.5 times the estimated maintenance requirement (i.e., 106 kcal of ME/kg of $BW^{0.75}$; NRC, 1998). The daily rations were divided into 2 equal meals and fed at 0800 and 1800. Water was available from nipple drinkers at all times.

Data Recording and Sample Collection

Pigs were weighed at the beginning of each period and at the conclusion of the experiment. The amount of feed supplied to each pig was recorded on a daily basis. Orts were collected and weighed before each feeding.

The initial 5 d of each period was considered a period of adaptation to the diet. Urine collection was initiated on the morning of d 6 and continued until the morning of d 11. Urine was collected over a preservative of 50 mL of 6 *N* sulfuric acid, which was added to the collection buckets. The buckets were emptied twice daily. For each collection, urine was weighed and mixed, and 20% of the total volume was stored at –20°C. In the morning meal on d 6 and 11, 1 g of chromic oxide was mixed into the meal and used as a fecal marker. Fecal collections were initiated the first time that the marker appeared after d 6 and ceased when the marker appeared again after d 11. All fecal samples that were collected were stored at –20°C.

Chemical Analysis

At the conclusion of the experiment, urine samples were thawed, pooled within animal and diet, thoroughly mixed, and a subsample was taken for chemical analysis. A sample of each diet and of each of the P sources was also taken. Fecal samples were dried using a forced-air oven at 60°C and finely ground before chemical analysis. Diets and fecal samples were analyzed for DM (procedure 4.1.06, AOAC, 2000). Feed, diets, urine, and fecal samples were digested in perchloric acid (procedure 2.3.01, AOAC, 2000), and P concentration was determined on a UV-vis spectrophotometer at 650 nm (procedure 3.4.11, AOAC, 2000). Accuracy of the procedure was verified using National Institute of Standards and Technology (US Department of Commerce) reference standard 1570a (standard reference material).

Calculations and Statistical Analysis

At the conclusion of the experiment, data for pig BW were summarized and ADG was calculated for each pig. Data for the daily feed supplies were summarized, and orts were subtracted to calculate ADFI. The P intake for each diet and period was calculated by multiplying ADFI by the analyzed P concentration in the diet.

The ATTD of P in each of the 6 P-containing diets was calculated using the following equation:

$$ATTD = ([Pi - Pf]/Pi) \times 100,$$

where ATTD is the apparent total tract digestibility, in %; Pi is the total P-intake from d 6 to 11 of each experimental period, in grams; and Pf is the total fecal output of P originating from the feed fed from d 6 to 11, in grams.

Phosphorus retention for each pig and period was calculated using the following equation:

$$Pr = ([Pi - \{Pf + Pu\}]/Pi) \times 100,$$

where Pr is the P retention, in %; and Pu is the urinary output of P from d 6 to 11, in grams.

The basal endogenous losses of P were expressed relative to the DMI of the animals and calculated from the P-free diet using the following equation:

$$TTP_{end} = ([Pf/Fi] \times 1{,}000 \times 1{,}000),$$

Table 3. Phosphorus balance and digestibility of P in inorganic P sources by growing pigs[1]

	Diet and P source[2]						
Item	DCP	MCP50	MCP70	MCP100	MSP	MCP70low	SEM
Feed intake, g of DM	1,522	1,530	1,493	1,563	1,567	1,550	168
P intake, g	3.05	3.08	2.98	3.10	3.41	2.62	0.30
Fecal P output, g	0.56^{x}	0.54^{x}	0.55^{x}	0.37^{xy}	0.28^{y}	0.49^{x}	0.06
P absorption, g	2.49^{xy}	2.54^{xy}	2.43^{xy}	2.73^{xy}	3.13^{y}	2.13^{x}	0.31
ATTD,[3] %	81.49^{xy}	82.55^{xy}	81.68^{xy}	87.96^{yz}	91.88^{z}	81.11^{x}	2.18
Urine P output, g	0.03^{x}	0.03^{x}	0.11^{x}	0.11^{x}	0.82^{y}	0.04^{x}	0.12
P retention, g	2.46	2.51	2.32	2.62	2.30	2.09	0.31
P retention, %	80.22^{x}	81.35^{x}	77.85^{xy}	84.77^{x}	67.49^{y}	79.70^{x}	3.66
Endogenous P, g	0.21	0.21	0.21	0.22	0.22	0.22	0.02
Undigested dietary P, g	0.34^{x}	0.32^{x}	0.34^{x}	0.16^{xy}	0.05^{y}	0.25^{x}	0.06
TTTD,[4] %	88.41^{x}	89.45^{x}	88.64^{x}	94.93^{xy}	98.20^{y}	90.32^{x}	2.24

[x–z]Means within a row lacking a common superscript letter are different ($P < 0.05$).
[1]Data are presented as the average daily P balance. n = 7.
[2]DCP = Dicalcium phosphate; MCP50 = monocalcium phosphate with 50% MCP; MCP70 = monocalcium phosphate with 70% MCP; MCP100 = monocalcium phosphate with 100% MCP; MSP = monosodium phosphate; MCP70low = monocalcium phosphate with 70% MCP included at low concentration.
[3]ATTD = apparent total tract digestibility of P.
[4]TTTD = true total tract digestibility of P. This value was calculated by correcting ATTD for the endogenous loss (139 mg/kg of DMI) that was calculated for pigs fed the P-free diet. Average values for daily feed intake, daily fecal P output, and daily urine P output for the pigs fed the P-free diet were 1.55 kg of DM, 0.21 g, and 0.026 g, respectively.

where TTP_{end} is the endogenous loss of P, in milligrams per kilogram of DMI; and Fi is total feed intake, in grams of DM.

The endogenous losses for each of the P-containing diets were calculated by multiplying TTP_{end} by the DMI of each pig for the 5-d collection period. The endogenous losses were then subtracted from the total fecal output of P, and the total amount of fecal P was partitioned into P originating from endogenous losses and P originating from undigested dietary P.

To calculate TTTD, values for TTP_{end} were subtracted from the total fecal output of P, and the difference was then subtracted from the intake of P, according to the following equation:

$$TTTD = ([Pi - \{Pf - TTP_{end}\}/Pi]) \times 100,$$

where TTTD represented the true total tract digestibility of P, in %; and TTP_{end} is calculated as described above.

Data were analyzed using the PROC GLM procedure of SAS (SAS Inst. Inc., Cary, NC). The model included diet, pig, and period as the main effects. An analysis of variance was conducted to detect differences among the P-containing diets. If diet effects were detected, then treatment means were separated using the LSMeans statement and the PDIFF option in SAS. The pig was the experimental unit, and an alpha level of 0.05 was used to assess significance among treatment means.

RESULTS

Pigs were healthy throughout the experiment and readily consumed their diets. The ADG for all pigs throughout the experiment was 612 g, which was considered normal because the pigs were fed a restricted amount of feed during the experiment. Data on P digestibility and P retention are presented in Table 3. There were no significant effects of pig or period for any of the variables measured. The ADFI did not differ among diets. This result was expected because the pigs were fed a restricted amount of feed every day. Likewise, there were no significant differences in the intake of P among diets, although pigs fed the MCP70low diet had the numerically lowest P intake, as expected.

The fecal output of P was greater ($P < 0.05$) from the pigs fed the DCP diet, the MCP50 diet, the MCP70 diet, and the MCP70low diet compared with pigs fed the MSP diet, but the P output from pigs fed the MCP100 diet was not different from pigs fed any of the other diets. The absorption of P did not differ among pigs fed any of the diets with the exception that pigs fed the MSP diet absorbed more P ($P < 0.05$) than did pigs fed the MCP70low diet.

The ATTD of P in MSP was not different from the ATTD in MCP100 but was greater ($P < 0.05$) than the ATTD for all other diets. The ATTD of P in MCP100 was also greater ($P < 0.05$) than the ATTD in the MCP70low diet. There were no differences in the ATTD of P among pigs fed the DCP diet, the MCP50 diet, the MCP70 diet, and the MCP70low diet.

Pigs fed the MSP diet had the greatest ($P < 0.05$) urinary output of P, but there were no differences among the other diets. The P retention did not differ among the diets if measured in grams per day. However, if calculated as a percentage of P intake, pigs fed the MSP diet had a lower ($P < 0.05$) retention of P than pigs fed any of the other diets.

The basal endogenous loss of P, calculated from pigs fed the P-free diet, averaged 139 ± 18 mg/kg of DMI. Calculated total endogenous losses did not differ among treatments. However, there was more ($P < 0.05$) undigested dietary P excreted by pigs fed DCP, MCP50, MCP70, and MCP70low than by pigs fed MSP, but the amount excreted by pigs fed MCP100 was not different from that of pigs fed any of the other diets.

The TTTD of P in MSP was greater ($P < 0.05$) than in DCP, MCP50, MCP70, and MCP70low, but the TTTD of P in the MCP100 diet was not different from any of the other diets. Likewise, the TTTD of P in DCP, MCP50, MCP70, and MCP70low were similar.

DISCUSSION

In the current experiment, the direct procedure was used to measure ATTD and TTTD of P for 5 feed phosphates. This could be achieved because of the development of a P-free basal diet that made it possible to formulate diets containing P from the feed phosphates only. The P-free diet also was used to estimate basal endogenous losses of P from the pigs. This in turn allowed for the partitioning of the fecal output of P into fractions originating from endogenous and dietary sources, respectively. It was assumed that basal endogenous losses were not influenced by dietary treatments and that the level of endogenous losses measured using the P-free diet was representative of the endogenous losses for all treatments. To our knowledge, this approach has not previously been used, and data for ATTD in inorganic P sources have not previously been determined using the direct procedure. Likewise, to our knowledge, this is the first time that values for endogenous losses of P have been measured using a P-free diet and the first time that TTTD for P in inorganic P sources have been reported.

The lack of a period effect on P digestibility and P absorption indicates that the pig's ability to digest and absorb P is not influenced by BW during the interval from 27 to 78 kg. This conclusion is in agreement with Kemme et al. (1997) who reported that the ATTD for P by pigs at 60, 75, and 90 kg of BW is similar if pigs are kept in metabolism crates and the total collection procedure is used to estimate ATTD.

Previously, endogenous losses of P by growing pigs have been estimated by regressing P excretion from pigs fed graded levels of P from a specific feed ingredient back to zero P intake. Values ranging from approximately 70 mg/kg of DMI (Dilger and Adeola, 2006; Pettey et al., 2006) and up to 670 mg/kg of DMI (Shen et al., 2002) have been reported. In the present experiment, the endogenous losses were estimated at 139 mg/kg of DMI. This value is within the range of previous estimates and close to the value of 210 mg/kg of DMI that was reported by Ajakaiye et al. (2003). It has been suggested that the endogenous loss of P depends on the dietary concentration of P (Jongbloed, 1987). If the P intake is considerably below the P requirement, low values for endogenous P would be expected (Jongbloed, 1987). As a consequence, the values obtained using a P-free diet would be expected to represent the lowest possible values for endogenous losses of P. Therefore, the values obtained in the present experiment may be representative of the minimum or basal endogenous losses of P by growing pigs. It is possible that dietary factors such as high concentrations of fiber or antinutritional factors may induce specific diet-dependent endogenous losses and thereby increase the total endogenous losses in diets containing commonly used feed ingredients, but this hypothesis remains to be tested. If this is correct it might explain why much greater values for endogenous losses of P were obtained in other studies (Fan et al., 2001; Shen et al., 2002) because the endogenous losses in these experiments were estimated in diets containing corn and soybean meal. In contrast, it is not clear why Dilger and Adeola (2006) and Pettey et al. (2006) estimated values for endogenous losses that were lower than the values obtained in the present experiment. However, it has been suggested that variations in the estimates for endogenous losses may be relatively large if the regression procedure is used (Dilger and Adeola, 2006), which may explain some of these differences.

The ATTD of P for DCP that was measured in the present experiment (81.49%) is greater than the values of 69 and 73% reported by Jongbloed et al. (1991) and Eeckhout and de Paepe (1997), respectively, but lower than the value of 87% reported by von Rodehutscord et al. (1994). All the previously reported values were derived using the difference procedure. It has been demonstrated that the biological availability of P in DCP is influenced by the proportions of anhydrous and dihydrous DCP included in the source (Grimbergen et al., 1985). This may explain the different results obtained among experiments.

All reported values for the ATTD of P in DCP are lower than the 95 to 100% relative availability that is suggested by NRC (1998). It has been suggested that values for ATTD may be estimated by multiplying values for relative availability by 0.9 (Jongbloed et al., 1991). If the NRC value is multiplied by 0.9, then the ATTD for P in DCP would be 85 to 90%. This value is within the range of ATTD reported in the earlier experiments.

The values for ATTD in MCP50 and MCP70 (82.55 and 81.68%, respectively) are within the range of values for ATTD of P in MCP (75 to 84%) reported by Jongbloed et al. (1991) but lower than the values of 90 to 92% reported by von Rodehutscord et al. (1994) and Eeckhout and de Paepe (1997). It has been suggested that there may be some variation in the ATTD of P among sources of MCP (Jongbloed et al., 1991).

It was suggested that P in MCP has a greater digestibility than P in DCP (Jongbloed et al., 1991; von Rodehutscord et al., 1994; Eeckhout and de Paepe, 1997). Therefore, a greater content of MCP in a feed phosphate is expected to increase the digestibility of P. The data

obtained in the present experiment do not support this hypothesis because the P in DCP had ATTD and TTTD that were similar to the ATTD and TTTD for P in MCP50 and MCP70. In addition, there were no differences in P digestibility between MCP50 and MCP70, although there is a greater concentration of MCP in MCP70 compared with MCP50. These observations suggest that P in DCP may be as digestible as P in MCP and that the concentration of DCP and MCP in a specific source of feed phosphate is not important. This conclusion is supported by data that indicate that the relative bioavailability of P in DCP is similar to that in MCP (Cromwell, 1992; NRC, 1998). However, as mentioned, there is some variability in the ATTD of P among sources of DCP dependent on the amount of crystalline water associated with the DCP molecule (Grimbergen et al., 1985; de Groote and Huyghebaert, 1997).

The true digestibility of P has not previously been reported for inorganic sources of P. However, it has been demonstrated that standardized ileal digestibility coefficients for AA are more additive in a mixed diet than are apparent ileal digestibility coefficients (Stein et al., 2005). Therefore, it is believed that digestibility coefficients for P based on TTTD are also more additive in a mixed diet than are values based on ATTD (Fan et al., 2001). If this is true, TTTD for P in organic as well as inorganic sources of P are needed to accurately estimate the digestibility of P in mixed diets. The present experiment provides data for commercial sources of DCP and MCP that may be used to formulate diets based on TTTD.

The high TTTD of P in MSP suggests that P in MSP is almost completely digested and absorbed. Previously, it was reported that the ATTD of P in MSP is 96% (von Rodehutscord et al., 1994), which is greater than the 91.88% that was estimated in the present experiment. However, considering the high value for TTTD in MSP that was obtained in the present experiment, it is not likely that the ATTD was underestimated.

The ATTD and the TTTD for P in MCP70 were similar regardless of whether the total P concentration in the diet was 0.20 or 0.16%. This observation indicates that the values for ATTD and TTTD that were obtained in the present experiment were not influenced by the amount of P that was included in the diets.

The quantity of P that was retained by pigs did not differ among the P sources, although pigs fed the MSP diet absorbed more P than pigs fed the other diets. Pigs fed MSP also excreted more P in the urine than pigs fed any of the other diets. This observation indicates that the requirement for P by the pigs used in this experiment was met when they were fed diets containing DCP and MCP. When they were fed MSP, they absorbed more P than required, and the excess was excreted in the urine. This observation also suggests that pigs will absorb as much P from the intestinal tract as possible even if P is supplied in excess of the requirement. The excess P will subsequently be eliminated via the urine. Therefore, urinary P excretion seems to be important in the overall regulation of P homeostasis of the pig.

In conclusion, a novel procedure based on a P-free diet was successfully used to estimate the ATTD, endogenous losses, and the TTTD in 5 inorganic sources of P fed to growing pigs. The new P-free diet allows for the direct determination of ATTD in inorganic sources of P as well as the estimation of the basal endogenous losses of P, which in turn allows for the calculation of TTTD in inorganic P sources. The procedure is faster and less tedious than the difference procedure, and results that are comparable with results obtained using the difference procedure were obtained. Using this procedure, it is not necessary to kill the animals and harvest bones to measure bone bending moment or bone ash content, which is often done when the relative bioavailability of P is measured using the slope ratio procedure. This new procedure may be used in future studies to measure ATTD and TTTD in organic as well as inorganic sources of P. By generating such data, diets based on TTTD may be formulated, which is expected to improve the additivity of values for digestibility coefficients of P. This in turn will allow for a more accurate formulation of diets fed to pigs, which may contribute to a reduction in the excretion of P from the animals without negatively affecting pig performance.

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