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Energy concentration and phosphorus digestibility in whey powder, whey permeate, and low-ash whey permeate fed to weanling pigs

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Energy concentration and phosphorus digestibility in whey powder, whey permeate, and low-ash whey permeate fed to weanling pigs[1]

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ABSTRACT: Two experiments were conducted to determine DE and ME, the apparent total tract digestibility (ATTD) of P, and the standardized total tract digestibility (STTD) of P in whey powder (3,646 kcal/kg), whey permeate (3,426 kcal/kg), and low-ash whey permeate (3,657 kcal/kg) fed to weanling pigs. The DE and ME in the 3 whey products were determined using 32 barrows (9.2 ± 0.4 kg of BW). A basal diet based on corn, soybean meal, and fish meal and 3 diets containing 70% of the basal diet and 30% of each whey product were prepared. Each diet was fed to 8 pigs that were housed individually in metabolism cages. The total collection method was used for fecal and urine collections with 5-d adaptation and 5-d collection periods, and the difference procedure was used to calculate DE and ME in the 3 whey products. The concentrations of DE in whey powder and low-ash whey permeate were greater ($P < 0.001$) than in whey permeate (3,646 and 3,683 vs. 3,253 kcal/kg of DM). The concentrations of ME in whey powder and low-ash whey permeate were also greater ($P < 0.001$) than in whey permeate (3,462 and 3,593 vs. 3,081 kcal/kg of DM). The ATTD and STTD of P in the 3 whey products were determined using 32 barrows (11.0 ± 0.81 kg of BW). Three cornstarch-sucrose-based diets containing 30% of each whey product as the sole source of P were prepared. A P-free diet that was used to estimate the basal endogenous losses of P was also formulated. The ATTD of P in whey powder and in whey permeate was greater ($P < 0.001$) than in low-ash whey permeate (84.3 and 86.1 vs. 55.9%), but the STTD values for P were not different among the 3 ingredients (91.2, 93.1, and 91.8% in whey powder, whey permeate, and low-ash whey permeate, respectively). In conclusion, whey permeate contains less GE, DE, and ME than whey powder and low-ash whey permeate, but all 3 ingredients have an excellent digestibility of P.

Key words: digestibility, energy, phosphorus, pig, whey permeate, whey powder

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INTRODUCTION

Dried milk products have beneficial effects when included in diets fed to weaned pigs (Lepine et al., 1991; Tokach et al., 1995; Cromwell et al., 2008). Whole milk powder and skim milk powder may be fed to pigs, but these ingredients are usually not cost effective in commercial diets. However, whey powder, which is a coproduct of the cheese manufacturing industry, is more economical to use, and beneficial effects of including whey powder in diets fed to weanling pigs have been demonstrated (Tokach et al., 1989; Mahan et al., 1993, 2004). The improvements in growth performance that are often observed when whey powder is included in the diets are believed to be caused by the lactose fraction of whey powder (Tokach et al., 1989; Mahan, 1992; Cromwell et al., 2008).

Whey powder usually contains between 10 and 15% CP, but because of demand for whey protein from the human food industry, the proteins in whey are sometimes extracted and used for production of whey protein concentrate. The resulting deproteinized powder, which usually contains 80 to 85% lactose and 5 to 15% ash, is called whey permeate (Nessmith et al., 1997b). If the ash is removed from this product, a low-ash permeate, which contains 85 to 95% lactose, is produced. Thus, lactose for weanling pig diets may be supplied by whey powder, whey permeate, or low-ash whey permeate. Each of these 3 ingredients provides energy to the diets, and values for DE and ME for whey powder have been determined (Pals and Ewan, 1978). However, very few values for DE and ME in whey permeate and in low-ash whey permeate have been reported.

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Whey powder, whey permeate, and low-ash whey permeate also provide P to the diets, but the standardized total tract digestibility (**STTD**) of P in these 3 ingredients has not been reported. It was, therefore, the objective of the present work to determine the DE and ME and the STTD of P in whey powder, whey permeate, and low-ash whey permeate when fed to weanling pigs.

MATERIALS AND METHODS

The protocol for each experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois. Two digestibility experiments were conducted in an environmentally controlled room at the University of Illinois at Urbana-Champaign.

The same batches of whey powder, whey permeate, and low-ash whey permeate were used in both experiments (Table 1). Whey powder (Associated Milk Producers Inc., New Ulm, MN), whey permeate (Perlac 850, Arla Foods Amba, Viby, Denmark), and low-ash whey permeate (Variolac 960, Arla Foods Amba) were obtained from commercial sources. The pigs used in the 2 experiments were the offspring of Landrace boars mated to Large White × Duroc females (Pig Improvement Company, Henderson, TN).

Energy Measurements, Exp. 1

Experiment 1 was conducted to determine the DE and ME in whey powder, whey permeate, and low-ash whey permeate. Thirty-two weanling barrows with an initial BW of 9.2 ± 0.4 kg were allotted to 4 dietary treatments with 8 replicate pigs per diet in a randomized complete block design. Pigs were randomly allotted to their respective treatments (Kim and Lindemann, 2007). Pigs were placed in metabolism cages that were equipped with a feeder, a nipple drinker, a slatted floor, a screen floor, and an urine tray, which allowed for the total, but separate, collection of urine and fecal materials from each pig. A basal diet that mainly consisted of corn, soybean meal, and fish meal was formulated (Table 2). Three additional diets were formulated by mixing 70% of the basal diet with 30% whey powder, whey permeate, or low-ash whey permeate.

The quantity of feed provided daily per pig was calculated as 3 times the estimated energy requirement for maintenance (i.e., 106 kcal of ME per $kg^{0.75}$; NRC, 1998) and divided into 2 equal meals. Water was available at all times. The initial 5 d was considered an adaptation period to the diet, and urine and fecal materials were quantitatively collected during the next 5 d according to standard procedures using the marker to marker approach (Kim et al., 2009). Indigo blue was used as the marker. Urine was collected daily in urine buckets over 50 mL of 6 *N* hydrochloric acid. Fecal samples and 10% of the collected urine were stored at −20°C immediately after collection. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized (Kim et al., 2009).

All samples were analyzed in duplicates. Fecal samples were dried in a forced-air drying oven and ground before analysis. Samples of each of the 3 whey products and of each diet were analyzed for DM, CP, and ash (methods 927.05, 990.03, and 942.05, respectively; AOAC International, 2005). Whey powder, whey permeate, and low-ash whey permeate were also analyzed for lactose (Prager and Miskiewicz, 1979) and glucose, fructose, sucrose, and maltose (Reineccius et al., 1970). The concentration of GE in the 3 whey products and in the diets and fecal samples was determined using bomb calorimetry (model 6300, Parr Instruments, Moline, IL). Benzoic acid was used as the internal standard. Urine samples were also analyzed for GE as described by Kim et al. (2009).

Table 1. Analyzed nutrient composition of whey powder, whey permeate, and low-ash whey permeate (as-fed basis)[1]

	Ingredient[2]		
Composition	Whey powder	Whey permeate	Low-ash whey permeate
DM, %	95.82	97.65	98.44
GE, kcal/kg	3,647	3,426	3,657
Lactose, %	66.00	76.10	88.85
Glucose, %	1.25	1.17	0.18
Fructose, %	—	0.19	—
Sucrose, %	—	—	—
Maltose, %	0.09	—	0.08
CP, %	13.20	4.30	3.01
Ash, %	15.83	8.96	1.72
Ca, %	0.49	0.42	0.11
P, %	0.63	0.57	0.10

[1]Data are the means of duplicate analyses of each ingredient.

[2]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

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

	Diet[1]			
Item	Basal	Whey powder	Whey permeate	Low-ash whey permeate
Ingredient, %				
Ground corn	60.00	42.00	42.00	42.00
Whey product	—	30.00	30.00	30.00
Soybean meal, 48% CP	28.00	19.60	19.60	19.60
Fish meal	8.00	5.60	5.60	5.60
Soybean oil	2.50	1.75	1.75	1.75
Ground limestone	0.70	0.49	0.49	0.49
Sodium chloride	0.40	0.28	0.28	0.28
Vitamin-mineral premix[2]	0.40	0.28	0.28	0.28
Analyzed composition				
DM, %	88.22	89.63	90.88	93.10
GE, kcal/kg	4,188	3,994	3,913	4,029
CP, %	23.82	18.85	14.89	14.61
Ash, %	4.90	5.89	5.81	3.45

[1]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kilogram of basal diet and 70% of this amount in the other diets: vitamin A as retinyl acetate, 14,837 IU; vitamin D_3 as cholecalciferol, 2,939 IU; vitamin E as DL-α-tocopheryl acetate, 88 IU; vitamin K as menadione nicotinamide bisulfite, 1.89 mg; thiamine as thiamine mononitrate, 0.32 mg; riboflavin, 8.77 mg; pyridoxine as pyridoxine hydrochloride, 0.32 mg; vitamin B_{12}, 0.04 mg; D-pantothenic acid as D-calcium pantothenate, 31.3 mg; niacin as nicotinamide, 1.3 mg, and nicotinic acid, 57.3 mg; folic acid, 2.11 mg; biotin, 0.59 mg; Cu, 13 mg as copper sulfate; Fe, 167 mg as iron sulfate; I, 1.68 mg as potassium iodate; Mn, 80 mg as manganese sulfate; Se, 0.4 mg as sodium selenite; and Zn, 133 mg as zinc oxide.

After chemical analyses, the daily amount of energy that was excreted in the feces and in the urine, respectively, was determined, and the concentration of DE and ME in each of the 4 diets was calculated (Adeola, 2001). The DE and ME in the basal diet were used to calculate the contribution from this diet to the DE and ME in the 3 diets containing one of the whey products and DE and ME of whey powder, whey permeate, or low-ash whey permeate were calculated by difference (Adeola, 2001).

Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC). The model included diet or ingredient as the fixed variable and replicate as the random effect. Outliers were tested using the UNIVARIATE procedure, but no outliers were identified. Least squares means were calculated and the means were separated using the PDIFF option with the Tukey's adjustment. The mean separation output was converted to letter groupings using a macro program (Saxton, 1998). The pig was the experimental unit for all calculations, and an α level of 0.05 was used to assess significance among means.

Phosphorus Digestibility, Exp. 2

Experiment 2 was conducted to determine the apparent total tract digestibility (**ATTD**) and the STTD of P in whey powder, whey permeate, and low-ash whey permeate. A total of 32 weanling barrows with an initial BW of 11.0 ± 0.8 kg were used. Pigs were assigned to 4 dietary treatments with 8 replicate pigs per treatment. Four diets were formulated. Three diets contained cornstarch, sugar, and 30% whey powder, whey permeate, or low-ash whey permeate (Table 3). Vitamins and all minerals except P were added to these diets according to current requirement estimates (NRC, 1998). No inorganic P was used, and the only source of P in the diets, therefore, was that contributed by the whey powder, whey permeate, or low-ash whey permeate. A P-free diet that was used to estimate the basal endogenous loss of P was also formulated.

Feeding procedures, fecal collection methods, and sample preparation for analyses were similar to those described for the energy experiment with the exception that urine was not collected in this experiment. The concentration of DM was determined in diet and fecal samples as described for Exp. 1. Calcium and P concentrations in the 3 whey products and in the diets and fecal samples were determined using atomic absorption spectroscopy (method 968.08; AOAC International, 2005) and inductively coupled plasma spectroscopy (method 975.03; AOAC International, 2005), respectively.

The ATTD of Ca and P in each of the whey product-containing diets was calculated (Almeida and Stein, 2010). Because whey powder, whey permeate, or low-ash whey permeate were the only sources of P in these diets, the ATTD value for each diet also represents the ATTD for P in the whey product that was included in the diet. The basal endogenous losses of P were calculated from pigs fed the P-free diet (Almeida and Stein, 2010). Values for the ATTD of P were then corrected for the basal endogenous losses, and values for the STTD of P in whey powder, whey permeate, and low-ash whey permeate were calculated (Almeida and Stein, 2010). Data were analyzed as described for Exp. 1.

Table 3. Ingredient composition of experimental diets (as-fed basis), Exp. 2

	Diet[1]			
Item	Whey powder	Whey permeate	Low-ash whey permeate	P-free
Ingredient, %				
Cornstarch	44.45	44.45	44.45	29.22
Whey product	30.00	30.00	30.00	—
Lactose	—	—	—	20.00
Sucrose	20.00	20.00	20.00	20.00
Soybean oil	4.00	4.00	4.00	4.00
Gelatin	—	—	—	20.00
Solka-Floc[2]	—	—	—	4.00
AA mixture[3]	—	—	—	0.78
Limestone	0.85	0.85	0.85	0.80
Potassium carbonate	—	—	—	0.40
Magnesium oxide	—	—	—	0.10
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin-mineral premix[4]	0.30	0.30	0.30	0.30
Analyzed composition				
Ca	0.37	0.28	0.27	0.12
P	0.20	0.20	0.04	—

[1]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

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

[3]The AA mixture provided the following quantities (%, as-fed basis) of AA to the complete diet: 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.

[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-α-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamine 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, 1.0 mg, and nicotinic acid, 43.0 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.

RESULTS AND DISCUSSION

Energy Measurements, Exp. 1

All pigs easily consumed their daily allotments of feed, and feces and urine samples were successfully collected from all pigs. The fecal energy excretion was less ($P < 0.01$) from pigs fed the diets containing whey powder, whey permeate, or low-ash whey permeate than from pigs fed the basal diet (828, 889, and 836 vs. 1,130 kcal; Table 4). The reason for this reduction in fecal excretion was that pigs fed the diets containing whey powder, whey permeate, or low-ash whey permeate had a greater ($P < 0.01$) ATTD of energy compared with pigs fed the basal diet (91.1, 90.5, and 91.3 vs. 88.3%). Addition of whey powder to a corn-soybean meal diet results in an increase in diet energy digestibility (Pals and Ewan, 1978; Tokach et al., 1989), and results of this experiment indicate that whey permeate and low-ash whey permeate also are effective in improving diet energy digestibility. These observations indicate that the energy in all 3 whey products used in this experiment is highly digestible.

The DE in the diet containing whey permeate was less ($P < 0.001$) than the DE in the basal diet, the whey powder diet, and the low-ash whey permeate diet (3,543 vs. 3,699, 3,638, and 3,677 kcal/kg, as-fed basis). There were no differences among experimental diets in urinary energy excretion, and the ME, therefore, was also less ($P < 0.001$) in the whey permeate diet compared with the basal diet, the whey powder diet, and the low-ash whey permeate diet (3,366 vs. 3,520, 3,459, and 3,525 kcal/kg, as-fed basis).

The DE in whey permeate was less ($P < 0.01$) than in whey powder and low-ash whey permeate (3,177 vs. 3,494, and 3,626 kcal/kg, as-fed basis; Table 5) and the ME in whey permeate was also less ($P < 0.001$) than in the other 2 ingredients (3,009 vs. 3,317 and 3,537 kcal/kg, as-fed basis, respectively). On a DM basis, the DE and the ME in whey permeate were less ($P < 0.001$) than in whey powder and low-ash whey permeate (3,253 vs. 3,646 and 3,683 kcal of DE/kg of DM and 3,081 vs. 3,462 and 3,593 kcal of ME/kg of DM, respectively), but no differences between whey powder and low-ash whey permeate were observed.

The reduced DE and ME in whey permeate was partly due to the decreased GE in whey permeate compared with the other 2 ingredients (3,426 vs. 3,647 and 3,657 kcal/kg, as fed). The reason for the reduced GE in whey permeate compared with whey powder is most likely that the protein concentration in whey permeate is much less than in whey powder because whey permeate is produced by removing the whey protein from whey. However, by removing the ash from whey permeate, a low-ash permeate, which mainly contains lactose, is generated. Because ash does not contribute energy to the ingredient, the energy concentration is increased when ash is removed, and the energy concentration in low-ash whey permeate is, therefore, greater than in conventional whey permeate.

Table 4. Energy digestibility and retention of pigs fed diets containing whey powder, whey permeate, and low-ash whey permeate (as-fed basis)[1,2]

	Diet[3]					
Item	Basal	Whey powder	Whey permeate	Low-ash whey permeate	SEM	*P*-value
Diet intake, kg	2.31	2.31	2.40	2.37	0.06	0.598
GE intake, kcal	9,684	9,239	9,387	9,541	232	0.517
Dry feces output, kg	0.232[a]	0.172[b]	0.188[b]	0.171[b]	0.012	0.001
GE in dry feces, kcal/kg	4,868[a]	4,783[ab]	4,728[b]	4,871[a]	42	0.047
Fecal GE output, kcal	1,130[a]	828[b]	889[b]	836[b]	58	0.002
ATTD,[4] GE %	88.3[b]	91.1[a]	90.5[a]	91.3[a]	0.5	0.001
DE in diet, kcal/kg	3,699[a]	3,638[a]	3,543[b]	3,677[a]	21	<0.001
Urine output, kg	16.6	16.2	14.3	10.2	3.4	0.523
GE in urine, kcal/kg	36.3	30.2	38.5	45.8	8.1	0.571
Urinary GE output, kcal	409	411	422	362	28	0.424
ME in diet, kcal/kg	3,520[a]	3,459[a]	3,366[b]	3,525[a]	23	<0.001

[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Each least squares mean represents 8 observations.

[2]Diet intake, fecal output, and urine output were based on 5 d of collection.

[3]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

[4]ATTD = apparent total tract digestibility.

The DE and ME in whey powder that were determined in this experiment (3,646 and 3,462 kcal/kg of DM) are slightly greater than the DE and ME (3,500 and 3,350 kcal/kg of DM) reported by Pals and Ewan (1978) and also greater than the DE and ME (3,474 and 3,323 kcal/kg of DM) reported by NRC (1998). Values from this experiment are also slightly greater than the DE and ME (3,511 and 3,321) in acidic whey powder (Sauvant et al., 2004), but close to the DE and ME (3,669 and 3,569) in sweet whey powder (Sauvant et al., 2004). These observations indicate that the source of whey powder that was used in this experiment was of average or above average quality.

The DE and ME in whey permeate (3,253 and 3,081 kcal/kg of DM), which were determined in this experiment, are less than previously published values (3,578 and 3,438 kcal/kg of DM; NRC, 1998). The whey permeate used in this experiment contained 8.96% ash, and it is possible that the source of whey permeate used to generate the DE and ME published by NRC (1998) contained less ash because the sum of Ca, P, Na, Cl, and K only adds up to 6.85%. It was shown in this experiment that removal of ash from whey permeate improved the GE, DE, and ME.

The DE and ME in low-ash whey permeate (3,683 and 3,593 kcal/kg of DM), which were determined in this experiment, are similar to the DE and ME (3,672 and 3,578 kcal/kg of DM) in lactose (NRC, 1998). This was expected because of the high concentration of lactose in the low-ash whey permeate.

Combined, these results indicate that the energy in whey powder and whey permeate is easily digested by young pigs and that the 3 whey products used in this experiment can be used as energy sources in diets fed to weanling pigs. The DE and ME in whey powder and in whey permeate are close to the DE and ME in complete diets fed to weanling pigs, which is likely the reason that feed efficiency is not changed if whey powder, lactose, or whey permeate is included in diets fed to weanling pigs (Mahan, 1992; Nessmith et al., 1997a; Naranjo et al., 2010). However, removal of ash from whey permeate increases the concentration of GE, DE, and ME.

Table 5. Energy values for whey powder, whey permeate, and low-ash whey permeate fed to weanling pigs[1]

	Ingredient[2]				
Item	Whey powder	Whey permeate	Low-ash whey permeate	SEM	*P*-value
As-fed basis					
DE, kcal/kg	3,494[a]	3,177[b]	3,626[a]	74	0.001
ME, kcal/kg	3,317[a]	3,009[b]	3,537[a]	77	<0.001
DM basis					
DE, kcal/kg	3,646[a]	3,253[b]	3,683[a]	76	<0.001
ME, kcal/kg	3,462[a]	3,081[b]	3,593[a]	80	<0.001

[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Each least squares mean represents 8 observations.

[2]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

Phosphorus Digestibility, Exp. 2

Pigs consumed their respective diets without problems, but total feed intake tended ($P = 0.08$) to be less in pigs fed the diet containing low-ash whey permeate than in pigs fed the other diets (Table 6). This was a result of a small amount of feed wastage for those pigs. As expected, P intake was greater ($P < 0.001$) for pigs fed the whey powder diet or the whey permeate diet than for pigs fed the low-ash whey permeate diet, which resulted in more ($P < 0.01$) P being excreted in the feces from these pigs. The intake of Ca was greater ($P < 0.001$) for pigs fed the whey powder diet than for pigs fed both permeate diets.

The ATTD of DM was greater (98.2 and 98.4 vs. 97.8%; $P < 0.01$) for the diets containing whey permeate or low-ash whey permeate compared with the whey powder diet. This observation is likely a result of the greater ash concentration in whey powder than in the 2 sources of whey permeate and indicates that ash has a reduced digestibility compared with other fractions in the DM, which in turn resulted in a greater ($P < 0.001$) fecal excretion of DM for pigs fed the whey powder diet compared with pigs fed the 2 whey permeate diets.

The basal endogenous losses of P were calculated at 153 mg per kg of DMI in pigs fed the P-free diet. This value is within the range of previously reported values for basal endogenous losses of P (Petersen and Stein, 2006; Widmer et al., 2007; Almeida and Stein, 2010) and indicates that there is relatively little variation in determined values for basal endogenous losses of P among experiments.

The ATTD of P in low-ash whey permeate was less ($P < 0.001$) than in whey powder and whey permeate (55.9 vs. 84.3 and 86.1%). However, when the ATTD values were corrected for the basal endogenous losses of P and values for the STTD of P were calculated, no differences among the 3 ingredients were observed (91.2, 93.1, and 91.8% for whey powder, whey permeate, and low-ash whey permeate, respectively). The reason for this difference between values for ATTD and values for STTD is most likely that the concentration of P in low-ash whey permeate is much less than in whey powder and whey permeate. The contribution of P of endogenous origin to the total fecal output of P is relatively greater when P intake is reduced (Fan et al., 2001), which results in a reduced calculated value for the ATTD of P in ingredients with a decreased concentration of P. However, because values for the STTD of P are corrected for the basal endogenous losses of P, this discrepancy is corrected when the STTD values are calculated. This principle is clearly illustrated for the low-ash whey permeate that was used in this experiment. It is, therefore, apparent that values for the STTD of P reflect the digestibility of P in a feed ingredient more correctly than values for ATTD of P. These principles are similar to the principles reported for AA because values for the standardized ileal digestibility of AA reflect the digestibility of AA in a feed ingredient more accurately than values for the apparent ileal digestibility of AA (Stein et al., 2005).

The value for the ATTD of P in whey powder determined in this experiment is in agreement with Sauvant et al. (2004), who reported that the ATTD of P in

Table 6. Digestibility of DM, Ca, and P in whey powder, whey permeate, and low-ash whey permeate by weanling pigs[1]

	Diet[2]				
Item	Whey powder	Whey permeate	Low-ash whey permeate	SEM	*P*-value
Feed intake					
Total feed intake, g	2,362	2,208	2,073	86	0.080
DMI, g	2,163	2,047	1,947	79	0.183
P intake, g	4.79[a]	4.46[a]	0.83[b]	0.13	<0.001
Ca intake, g	18.66[a]	9.28[b]	7.88[b]	0.46	<0.001
Fecal output					
Total dry feces, g	51.0[a]	38.9[b]	31.9[b]	2.8	<0.001
P in dry feces, %	1.47[a]	1.59[a]	1.14[b]	0.08	0.003
Ca in dry feces, %	5.49	4.32	5.50	0.96	0.612
DM output, g	48.0[a]	36.8[b]	30.1[b]	2.7	<0.001
P output, g	0.75[a]	0.63[a]	0.36[b]	0.06	<0.001
Ca output, g	2.68	1.70	1.81	0.38	0.161
Digestibility,[3] %					
ATTD of DM	97.8[b]	98.2[a]	98.4[a]	0.1	0.002
ATTD of P	84.3[a]	86.1[a]	55.9[b]	2.1	<0.001
ATTD of Ca	85.6	82.0	77.6	3.3	0.258
STTD of P	91.2	93.1	91.8	2.1	0.813

[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Each least squares means represents 8 observations.

[2]Whey powder was obtained from Associated Milk Producers Inc., New Ulm, MN; whey permeate (Perlac 850) and low-ash whey permeate (Variolac 960) were obtained from Arla Foods Amba, Viby, Denmark.

[3]Values for standardized total tract digestibility (STTD) were calculated by correcting apparent total tract digestibility (ATTD) values for the basal endogenous loss of P. The basal endogenous loss of P was determined in pigs fed the P-free diet at 153 ± 11.2 mg/kg of DMI.

sweet whey powder, as well as in acidic whey powder, is 90%. Likewise, the relative bioavailability of P in whey powder is 97% (NRC, 1998). Both of these values indicate that the P in whey powder is well digested by pigs, and the results of this experiment support those reports. It also appears that P in whey permeate is equally well digested.

The Ca in the 3 diets containing whey products originated from a combination of Ca contributed by limestone and Ca from the whey products. The ATTD of Ca was not different among the 3 diets, but all diets had relatively large values for the ATTD of Ca. The ATTD of Ca in calcium carbonate is close to 70% (Stein et al., 2011) and the fact that greater values for the ATTD of Ca were determined for the diets used in this experiment indicates that the digestibility of Ca in the 3 whey products is very high. However, because of the addition of limestone to all diets, it was not possible to calculate the actual digestibility of Ca in the 3 whey products.

In conclusion, data from this experiment indicated that the P in whey powder, whey permeate, and low-ash whey permeate is well digested by weanling pigs. It was also demonstrated that values for STTD of P describe the digestibility of P in ingredients with a decreased concentration of P more accurately than values for the ATTD of P.

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