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Additivity of values for apparent and standardized ileal digestibility of amino acids in mixed diets fed to growing pigs[1]

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ABSTRACT: The objective of this experiment was to determine whether the digestibility of CP and AA in a mixed diet fed to growing pigs is better predicted when based on standardized ileal digestibility coefficients (SID) or apparent ileal digestibility coefficients (AID). Eight growing pigs (initial BW = 92.1 ± 3.19 kg) were surgically equipped with a T-cannula in the distal ileum and arranged in an 8 × 8 Latin square design with eight diets and eight periods. Three of the diets contained corn, soybean meal (SBM), or canola meal (CM) as the sole source of CP and AA. Four mixed diets also were formulated using corn and soybean meal (CS); corn and canola meal (CCM); soybean meal and canola meal (SCM); or corn, soybean meal, and canola meal (CSCM). A N-free diet was used to measure the basal ileal endogenous losses (IAA_{end}) of CP and AA. Pigs were fed each of the eight diets during one 7-d period, and ileal digesta were collected during two 10-h periods on d 6 and 7. The AID values were calculated for CP and AA in all diets, except the N-free diet. By correcting the AID for IAA_{end}, the SID for CP and AA in each of the seven protein-containing diets were calculated. As expected, the AID for CP and the majority of AA were greater in SBM than in corn and CM ($P < 0.05$); however, the SID for CP and most AA did not differ between corn and SBM. For the majority of the AA, SID were less ($P < 0.05$) in CM than in the other two ingredients. Using the AID and the SID that were measured for CP and AA in corn, SBM, and CM, the AID and the SID in the four mixed diets were predicted and compared with the measured values for these diets. For the three mixed diets containing corn, the measured AID for CP and most AA were greater ($P < 0.05$) than the predicted AID, but with a few exceptions, no differences between predicted and measured values for SID were observed. For the diet based on SCM, there were no differences between predicted and measured values regardless of the procedure used, except for the AID of Ser. The results of this experiment demonstrate that the digestibility coefficients for a mixed diet containing low-protein feed ingredients, such as corn, are more accurately predicted using SID than AID.

Key Words: Additivity, Amino Acids, Apparent Ileal Digestibility, Pigs, Standardized Ileal Digestibility

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Introduction

Apparent ileal digestibility coefficients (**AID**) for CP and AA have been determined for most commonly used feed ingredients (Jondreville et al., 1995; NRC, 1998; Rademacher et al., 2001). In mixed diets, the proportional quantities of digestible AA from each feed ingredient are added, and the sum represents the quantity of digestible AA in the diet because additivity of the digestible contents of each AA in individual feed ingredients is assumed when these ingredients are mixed together. Nontheless, it has been reported that the AID for most AA in mixed diets are numerically greater than the values calculated from the digestibility coefficients for the individual ingredients (Imbeah et al., 1988; Furuya and Kaji, 1991; Fan et al., 1993). Therefore, the assumption of additivity for AID has been questioned (Boisen and Moughan, 1996b; Mosenthin et al., 2000). The reason for the lack of additivity of AID is an underestimation of the AID in low-protein feed ingredients (i.e., cereal grains). This underestimation is caused by a relatively greater contribution of endogenous AA and CP in the ileal digesta collected from pigs fed low-protein diets compared with pigs fed diets containing greater concentrations of CP and AA (Rademacher et al., 2001). By correcting the AID for the basal ileal endogenous losses of CP and AA, standardized ileal digestibility coefficients (**SID**) are calculated (Stein et

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al., 2001; Jansman et al., 2002). Because the values for SID are independent of basal ileal endogenous losses, it has been suggested that digestibility coefficients based on SID are more additive in mixed diets compared with values based on AID (Mosenthin et al., 2000; Rademacher et al., 2001). Therefore, the objective of the current experiment was to test the hypothesis that the AA digestibility coefficients in mixed low-protein diets fed to growing pigs can be predicted more accurately when calculations are based on SID rather than on AID.

Materials and Methods

Animals and Experimental Design

Eight growing barrows (initial BW = 92.1 ± 3.19 kg) originating from the matings of Hampshire × Duroc boars to Landrace × Yorkshire × Duroc sows were used in this experiment. Each pig was surgically equipped with a T-cannula in the distal ileum using procedures adapted from Stein et al. (1998). Pigs were housed individually in 1.2-m × 1.8-m pens. Room temperature was maintained at 20°C throughout the experiment. An 8 × 8 Latin square design was used, with eight periods and eight animals. Each experimental period lasted 7 d. The experiment was approved by the Animal Care and Use Committee at South Dakota State University.

Diets, Feeding, and Sample Collection

Eight diets were prepared (Tables 1 and 2). Three diets contained corn, soybean meal (**SBM**), or canola meal (**CM**), respectively, as the sole source of CP and AA. Two diets were prepared by mixing corn with either SBM or CM. One diet contained both SBM and CM, whereas another diet was prepared by mixing corn, SBM, and CM. A N-free diet also was included in the experiment. All diets were formulated (as-fed basis) to contain 0.5% P and 0.6% Ca. With the exception of the corn-based diet and the N-free diet, all diets also were formulated to contain 19% CP. Chromic oxide (0.25%) was included in all diets as an inert marker. Vitamins, salt, and minerals were included at levels that met or exceeded the estimated requirements for growing pigs (NRC, 1998).

Pigs were provided a daily quantity of feed that supplied three times the estimated maintenance requirement for energy (i.e., 106 kcal ME/kg$^{0.75}$; NRC, 1998). Pig BW was recorded at the beginning of each experimental period, and the quantity of feed supplied during the following period was calculated based on this weight. The daily feed allowance was divided into two equal meals that were fed at 0800 and 1800. Water was available from drinking nipples at all times. The initial 5 d of each period were considered an adaptation period to the diet. Ileal digesta were collected for 10 h on d 6 and d 7 in plastic bags as described previously (Stein et al., 1999a). Bags were removed whenever they were filled with digesta, or at least once every 30 min, and immediately stored at –20°C to prevent microbial degradation of the AA in the digesta.

Chemical Analyses

At the conclusion of the experiment, ileal samples were thawed and pooled within animal and diet. A subsample was used for chemical analyses. Digesta samples were lyophilized, and all samples were finely ground before analysis. All analyses were performed in duplicate. Diets and digesta were analyzed for their contents of DM (procedure 4.1.06; AOAC, 1998) and CP (Thiex et al., 2002). Chromium was analyzed according to Williams et al. (1962). Amino acid concentrations in diets and digesta samples were quantified on a Beckman 6300 Amino Acid Analyzer (Beckman Instruments Corp., Palo Alto, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Samples were hydrolyzed for 24 h at 110°C with 6 *N* HCl before analysis. Methionine and cysteine were determined as methionine sulfone and cysteic acid after cold performic acid oxidation before hydrolysis. Tryptophan was determined after hydrolysis with NaOH for 22 h at 110°C.

Calculations and Statistical Analyses

The AID and SID were calculated for CP and AA in all protein-containing diets following published procedures (Stein et al., 1999a, 2001). The basal ileal endogenous losses of CP and AA were calculated based on the flow of CP and AA to the distal ileum in pigs fed the N-free diet as previously described (Stein et al., 1999b).

The AID for AA in corn, SBM, and CM that were measured from the diets containing each of these feed ingredients as the sole source of CP and AA were used to calculate the predicted AID for CP and all AA in the four mixed diets according to the following equation (adapted from Hansen et al., 1991):

$$\mathrm{AIDp} = ([\mathrm{AA_C} \times \mathrm{AID_C}] + [\mathrm{AA_{SBM}} \times \mathrm{AID_{SBM}}] + [\mathrm{AA_{CM}} \times \mathrm{AID_{CM}}])/(\mathrm{AA_C} + \mathrm{AA_{SBM}} + \mathrm{AA_{CM}})$$

where AIDp is the predicted AID for an AA (%) in a mixed diet; AA_C, AA_{SBM}, and AA_{CM} are the concentrations of that AA in the mixed diet originating from corn, SBM, and CM, respectively (g/kg); and AID_C, AID_{SBM}, and AID_{CM} are the measured AID (%) for that AA in corn, SBM, and CM, respectively. The AID for CP in the mixed diets were predicted using the same equation.

The predicted SID for CP and all AA in the mixed diets were calculated using a similar equation:

$$\mathrm{SIDp} = ([\mathrm{AA_C} \times \mathrm{SID_C}] + [\mathrm{AA_{SBM}} \times \mathrm{SID_{SBM}}] + [\mathrm{AA_{CM}} \times \mathrm{SID_{CM}}])/(\mathrm{AA_C} + \mathrm{AA_{SBM}} + \mathrm{AA_{CM}})$$

where SIDp is the predicted SID for an AA (%) in a mixed diet; AA_C, AA_{SBM}, and AA_{CM} are the concentra-

Table 1. Composition of experimental diets, as fed-basis

Ingredient	Diet: Corn	SBM[a]	CM[a]	CS[a]	CCM[a]	SCM[a]	CSCM[a]	N-free
	(%)							
Corn	89.05	—	—	63.8	56.85	—	60.75	—
Soybean meal	—	37.5	—	25.65	—	18.75	14.5	—
Canola meal	—	—	46.25	—	33.25	23.0	14.5	—
Cornstarch	—	51.75	44.0	—	—	48.0	—	78.4
Soybean oil	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Dextrose	5.0	5.0	5.0	5.0	5.0	5.0	5.0	10.0
Solka floc[b]	—	—	—	—	—	—	—	5.0
Limestone	0.7	0.5	0.7	0.85	1.0	0.6	0.9	—
Dicalcium phosphate	1.4	1.4	0.2	0.85	0.05	0.8	0.5	2.75
Chromic oxide	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Salt	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Vitamin premix[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Micromineral premix[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

[a]SBM = soybean meal, CM = canola meal, CS = corn-soybean meal diet, CCM = corn-canola meal diet, SCM = soybean meal-canola meal diet, CSCM = corn-soybean meal-canola meal diet.

[b]Fiber Sales Corp., Urbana, OH.

[c]Provided the following quantities of vitamins per kilogram of complete diet: vitamin A, 10,032 IU as vitamin A acetate; vitamin D_3, 992 IU as D-activated animal sterol; vitamin E, 88 IU as α-tocopherol acetate; vitamin K_3, 1.52 mg as menadione dimethylpyrimidinol bisulphite; thiamin, 1.5 mg as thiamine mononitrate; riboflavin, 10 mg; pyridoxine, 4.0 mg as pyridoxine hydrochloride; vitamin B_{12}, 0.05 mg; D-pantothenic acid, 25 mg as calcium pantothenate; niacin, 60 mg; folic acid, 1.5 mg; and biotin, 0.4 mg.

[d]Provided the following quantities of microminerals per kilogram of complete diet: Cu, 25 mg as copper sulfate; Fe, 120 mg as iron sulfate; I, 0.30 mg as potassium iodate; Mn, 25 mg as manganese sulfate; Se, 0.30 mg as sodium selenite; and Zn, 125 mg as zinc oxide.

Table 2. Analyzed nutrient composition of diets, as-fed basis

Item	Diet: Corn	SBM[a]	CM[a]	CS[a]	CCM[a]	SCM[a]	CSCM[a]	N-free
DM, %	92.16	93.26	92.99	92.58	92.74	93.09	92.85	91.95
ME, kcal/kg[b]	3,461	3,670	3,389	3,413	3,237	3,531	3,337	3,702
Ca, %[b]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
P, %[b]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CP, %	8.77	18.19	18.74	19.36	19.79	19.50	19.47	0.37
Indispensable AA, %								
Arg	0.34	1.13	0.97	1.08	0.95	0.97	0.99	0.01
His	0.22	0.44	0.48	0.48	0.49	0.43	0.48	0.01
Ile	0.27	0.72	0.68	0.71	0.70	0.68	0.72	0.01
Leu	0.91	1.27	1.24	1.59	1.53	1.20	1.53	0.03
Lys	0.26	1.02	0.92	0.90	0.83	0.91	0.87	0.01
Met	0.17	0.22	0.35	0.30	0.35	0.28	0.31	—
Phe	0.38	0.82	0.70	0.87	0.79	0.72	0.80	0.01
Thr	0.28	0.64	0.72	0.68	0.70	0.65	0.69	0.01
Trp	0.05	0.22	0.21	0.19	0.20	0.23	0.17	—
Val	0.35	0.76	0.85	0.81	0.90	0.81	0.88	0.01
Dispensable AA, %								
Ala	0.55	0.71	0.79	0.92	0.94	0.72	0.94	0.02
Asp	0.55	1.82	1.27	1.72	1.26	1.51	1.55	0.02
Cys	0.19	0.27	0.44	0.33	0.43	0.34	0.38	0.01
Glu	1.40	2.96	3.05	3.18	3.15	2.87	3.15	0.03
Gly	0.31	0.67	0.85	0.70	0.81	0.73	0.76	0.01
Pro	0.61	0.81	1.00	1.07	1.18	0.89	1.15	0.01
Ser	0.36	0.76	0.65	0.80	0.68	0.66	0.73	0.01
Tyr	0.31	0.52	0.46	0.61	0.56	0.47	0.55	0.01
Total AA	7.75	16.00	15.96	17.29	16.85	15.24	16.80	0.25

[a]SBM = soybean meal, CM = canola meal, CS = corn-soybean meal diet, CCM = corn-canola meal diet, SCM = soybean meal-canola meal diet, and CSCM = corn-soybean meal-canola meal diet.

[b]These values were calculated rather than analyzed (NRC, 1998).

tion of that AA in the mixed diet originating from corn, SBM, and CM, respectively (g/kg); and SID_C, SID_{SBM}, and SID_{CM} are the measured SID (%) for that AA in corn, SBM, and CM, respectively. The SID for CP in the mixed diets were predicted using the same equation.

In the calculations of predicted values for AID and SID in the mixed diets, the values for each ingredient that were obtained from the same pig were used. This procedure was used because there were no significant effects of period in the experiment.

Data were analyzed using the Mixed procedure of SAS (SAS Inst., Inc., Cary, NC). The pig was the experimental unit for all analyses. An analysis of variance was used to compare the AID and SID for CP and AA in corn, SBM, and CM. Diet was the main effect, and pig and period were random effects. Means were separated using an LSD test, and an α level of 0.05 was used to assess significant differences among means. Within each of the four mixed diets, the difference between measured and predicted values for AID and SID was estimated using the LSMeans option in the Mixed procedure. The confidence intervals for the differences were estimated with an α level of 0.05. If the confidence interval for the mean difference did not include zero, the difference between measured and predicted values was considered significant.

Results

All pigs remained healthy throughout the experiment and readily consumed their designated diets. No feed refusals were registered for any of the diets.

The AID and SID for CP and AA in corn, SBM, and CM are presented in Table 3. The AID for CP and all AA except Leu, Met, Phe, Ala, Cys, Glu, and Tyr were greater in SBM than in corn ($P < 0.04$). The AID for CP and all AA except Met, Trp, Ala, Cys, Glu, and Gly also were greater in SBM than in CM ($P < 0.05$); however, except for Leu, Lys, Phe, Thr, Trp, Gly, Ser, and Tyr, there were no differences in AID between corn and CM. The SID for CP and all AA except Leu, Lys, and Ala did not differ between corn and SBM, but the SID for CP and all AA except Trp, Ala, Cys, Glu, and Gly were greater ($P < 0.05$) in SBM than in CM. The SID for CP and all AA except Lys, Trp, and Glu also were greater in corn than in CM ($P < 0.05$).

The measured and predicted values for AID and SID for CP and AA in the corn-SBM-based diet are presented in Table 4. The differences between the measured and the predicted AID differed ($P < 0.05$) from zero for CP and all AA except His, Ile, Leu, Lys, Met, Phe, Ala, Glu, and Ser. In contrast, for SID, there was no difference between the predicted and the measured value for CP or for any of the AA.

Differences ($P < 0.05$) between the measured and the predicted AID for the corn-CM-based diet were found for CP and all AA except His, Lys, Met, Trp, Ala, Cys, Gly, Ser, and Tyr (Table 5). The differences were between 1.6 and 6 percentage units for the indispensable AA. The measured SID also were greater ($P < 0.05$) than the predicted SID for CP, Arg, Ile, and Val, but for all other AA, no differences between measured and predicted values for SID were observed.

The measured values for both AID and SID for CP in the SBM-CM-based diet (**SCM**) were greater ($P < 0.05$) than the predicted values (Table 6); however, for all AA except Ser, no differences between measured and predicted values for AID were detected. Similarly, there were no differences between the measured and predicted values for SID for any of the AA.

For CP and all indispensable AA except His, Leu, Met, and Trp, and for the mean of the indispensable AA, greater ($P < 0.05$) values for AID were measured than predicted in the corn-SBM-CM-based diet (Table 7). Similarly, the measured values for Ala, Asp, Glu, Gly, the mean of the dispensable AA, and the mean of all AA also were greater ($P < 0.05$) than the predicted values. In contrast, except for Trp, no differences between the measured and predicted values for SID were observed for this diet.

Discussion

The AID and SID of CP and AA that were measured in the current experiment for corn, SBM, and CM were within the range of reported values for these feed ingredients (NRC, 1998; Stein et al., 2001; Pedersen and Boisen, 2002). Similarly, the quantities of basal ileal endogenous losses that were measured in the present experiment are within the range of values previously reported (Boisen and Moughan, 1996a; Stein et al., 1999b; Jansman et al., 2002).

The measured AID for CP and AA were significantly greater than the calculated values in 41 of 66 observations in the three mixed diets that contained corn. This observation is likely a result of the fact that the corn diet contained <9% CP, whereas all other diets contained 18 to 20% CP. In diets with low concentrations of CP, the CP and AA of endogenous origin contribute relatively more to the total flow of CP and AA at the distal ileum compared with diets with greater concentrations of CP (Donkoh and Moughan, 1994; Fan et al., 1994). This, in turn, results in a lower calculated value for AID in diets containing low concentrations of CP and AA than for diets containing greater concentrations of CP and AA. Therefore, if AID obtained in diets containing a low concentration of CP are used to predict the AID in a mixed diet containing greater concentrations of CP and AA, the AID in the mixed diet may be underestimated (Boisen and Moughan, 1996b; Mosenthin et al., 2000; Jansman et al., 2002). The results from the present experiment support this hypothesis. It should be noted, however, that the problems related to measuring AID in low-protein feed ingredients may be overcome by estimating the AID using the difference method or a regression procedure rather than the direct method that was used in the current experiment (van Leeuwen et al., 1987; Fan and Sauer, 1995).

Table 3. Apparent (AID) and standardized (SID) ileal digestibility coefficients (%) of CP and AA in corn, soybean meal (SBM), and canola meal (CM) by growing pigs[a,b,c]

	AID					SID				
Item	Corn	SBM[d]	CM[d]	SEM	$P <$	Corn	SBM[d]	CM[d]	SEM	$P <$
CP	71.9[x]	82.1[y]	73.2[x]	1.43	0.001	86.8[x]	90.4[x]	81.2[y]	1.43	0.001
Indispensable AA										
Arg	83.4[x]	92.4[y]	84.8[x]	0.82	0.001	95.2[x]	95.9[x]	89.0[y]	0.82	0.001
His	84.4[x]	88.8[y]	83.4[x]	0.88	0.001	92.2[x]	92.7[x]	86.9[y]	0.88	0.001
Ile	74.6[x]	83.0[y]	75.7[x]	1.25	0.001	88.4[x]	88.3[x]	81.3[y]	1.25	0.001
Leu	86.3[x]	84.1[x]	78.1[y]	0.97	0.001	92.8[x]	88.9[y]	82.9[z]	0.97	0.001
Lys	69.0[x]	87.7[y]	78.1[z]	1.32	0.001	85.5[x]	91.9[y]	82.8[x]	1.32	0.001
Met	85.2	86.0	84.2	0.90	0.42	91.2[x]	90.7[x]	87.2[y]	0.90	0.01
Phe	83.2[x]	85.0[x]	78.5[y]	1.27	0.005	92.4[x]	89.3[x]	83.5[y]	1.27	0.001
Thr	66.9[x]	79.5[y]	72.7[z]	1.57	0.001	84.8[x]	87.4[x]	79.8[y]	1.57	0.008
Trp	67.9[x]	86.8[y]	86.4[y]	1.59	0.001	87.0	91.2	91.0	1.59	0.13
Val	73.9[x]	80.6[y]	74.2[x]	1.28	0.002	87.5[x]	86.9[x]	79.8[y]	1.28	0.001
Dispensable AA										
Ala	78.6	77.4	75.4	1.17	0.17	89.6[x]	86.0[y]	83.1[y]	1.17	0.003
Asp	72.8[x]	83.2[y]	72.5[x]	1.43	0.001	88.2[x]	87.9[x]	79.2[y]	1.43	0.001
Cys	77.3	78.6	78.9	1.26	0.64	90.2[x]	87.8[xy]	84.5[y]	1.26	0.02
Glu	84.2	86.7	84.4	1.09	0.23	92.0	90.4	88.1	1.09	0.06
Gly	61.0[x]	73.0[y]	71.9[y]	1.77	0.001	92.2[x]	87.7[xy]	83.4[y]	1.77	0.008
Pro	71.2[x]	79.4[y]	72.1[x]	2.33	0.04	108.5[x]	107.8[x]	95.0[y]	2.33	0.001
Ser	78.8[x]	85.5[y]	74.4[z]	1.25	0.001	91.2[x]	91.4[x]	81.4[y]	1.25	0.001
Tyr	82.1[x]	83.9[x]	76.6[y]	1.17	0.001	92.2[x]	90.0[x]	83.4[y]	1.17	0.001
All AA	78.5[x]	84.1[y]	78.1[x]	1.09	0.001	92.5[x]	90.8[y]	84.9[z]	1.09	0.001

[a]Data are least squares means of eight observations per treatment.

[b]AID values were calculated as (1 − [{CP or AA in digesta/CP or AA in feed} × {Cr in feed/Cr in digesta}]) × 100%.

[c]SID were calculated as (AID + [endogenous loss/intake]) × 100. Endogenous losses were calculated from the flow of CP and AA to the distal ileum after feeding the N-free diet. These losses were determined as (g/kg DMI): CP, 14.1; Arg, 0.45; His, 0.19; Ile, 0.42; Leu, 0.66; Lys, 0.49; Met, 0.12; Phe, 0.39; Thr, 0.55; Trp, 0.10; Val, 0.53; Ala, 0.67; Asp, 0.93; Cys, 0.28; Glu, 1.21; Gly, 1.06; Pro, 2.47; Ser, 0.49; and Tyr, 0.35.

[d]SBM = soybean meal; CM = canola meal.

[x,y,z]Means within a row and a procedure that do not have a common superscript differ, $P < 0.05$.

The differences between the measured and the predicted AID in the SCM-based diet were much smaller than in the three diets containing corn. This result is likely because both the SBM- and the CM-based diets contained nearly 20% CP. Therefore, there was no underestimation of the AID in the two ingredients that were subsequently used to predict the AID for the mixed SCM diet. The current data, therefore, demonstrate that if AID are measured for CP and AA in individual feed ingredients using diets with a relatively high concentration of CP and AA, then the AID in a mixed diet can be precisely predicted from these values. It has been reported that the AID for CM measured using the direct procedure are identical to values calculated using the difference method or the regression procedure (Fan and Sauer, 1995), which indicates that the AID for CM are not underestimated if measured using the direct procedure. The data from the current experiment also indicate that the AID for CM that were measured using the direct procedure were not underestimated, and thus support the data of Fan and Sauer (1995).

Results from experiments in which the additivity of AID was measured were reported previously by Imbeah et al. (1988), Furuya and Kaji (1991), and Fan et al. (1993). A total of seven mixed diets was used in these experiments. Greater values for AID were measured than predicted for CP and most AA in these diets; however, most differences between measured and predicted values were not significant. The reason why the differences between the measured and predicted values for AID in mixed diets containing corn in the present experiment were significant is likely because there were more replications and lower SE than in the previous experiments. Fewer low-protein cereal grains were included in the mixed diets used by Imbeah et al. (1988), Furuya and Kaji (1991), and Fan et al. (1993) compared with the diets used in the present experiment; therefore, the effect of the low-protein ingredient was greater in the present experiment. Using a barley-CM-based diet, Nyachoti et al. (1997) reported greater measured AID for five AA compared with the predicted values. However, for the remaining 10 AA, no significant differences between predicted and measured values were observed. However, the difference in the CP concentration between the barley-based diet and the barley-CM-based diet was only three percentage units, which is likely the reason why not all of the measured values were greater than the predicted values.

Differences between the measured and calculated values for SID in the four mixed diets used in the current experiment were numerically smaller than the differences for AID; this was true for 81 of 88 total observa-

Table 4. Measured and predicted values for apparent (AID) and standardized (SID) ileal digestibility coefficients (%) for CP and AA in a corn-soybean meal-based diet[a]

	AID				SID			
Item	Measured	Predicted	Difference	SE	Measured	Predicted	Difference	SE
CP	80.7	77.5	3.2*	1.2	87.8	87.8	0.0	1.2
Indispensable AA								
Arg	91.0	89.9	1.1*	0.5	94.9	95.7	–0.8	0.7
His	87.5	86.9	0.6	0.8	91.3	92.5	–1.2	1.2
Ile	81.9	80.2	1.7	1.0	87.5	88.4	–0.9	1.4
Leu	85.0	84.7	0.3	0.9	89.1	90.7	–1.6	1.2
Lys	83.8	83.5	0.3	0.9	88.9	90.8	–1.9	1.6
Met	86.4	85.2	1.2	0.9	90.1	90.9	–0.8	1.2
Phe	85.2	84.2	1.0	1.0	89.4	90.4	–0.9	1.3
Thr	78.5	74.7	3.8*	1.4	86.2	86.2	0.0	1.4
Trp	85.7	82.4	3.3*	1.7	90.6	89.5	1.1	2.0
Val	79.9	77.7	2.2*	0.9	86.0	86.8	–0.8	1.4
Mean	84.5	82.4	2.1*	0.9	89.4	89.5	–0.1	1.1
Dispensable AA								
Ala	78.9	77.1	1.8	1.0	85.9	87.3	–1.4	1.3
Asp	82.8	79.9	2.9*	1.2	88.0	87.6	0.4	1.4
Cys	79.9	77.4	2.5*	1.3	87.6	88.5	–0.9	2.7
Glu	87.1	85.1	2.0	1.3	90.8	90.6	0.2	1.2
Gly	74.3	67.8	6.5*	1.9	89.1	89.2	–0.1	3.6
Pro	80.5	73.2	7.3*	3.3	104.2	109.1	–4.9	8.4
Ser	84.7	83.0	1.6	1.2	90.6	91.6	–1.0	1.1
Tyr	85.1	83.0	2.1*	1.0	90.5	91.0	–0.5	1.3
Mean	81.7	78.5	3.2*	1.2	89.5	90.1	–0.6	1.3
All AA	83.8	81.6	2.2*	1.0	90.4	91.4	–1.0	1.0

[a]Data are least squares means of eight observations per treatment.
*Measured and calculated values differ, $P < 0.05$.

Table 5. Measured and predicted values for apparent (AID) and standardized (SID) ileal digestibility coefficients (%) for CP and AA in a corn-canola meal-based diet[a]

	AID				SID			
Item	Measured	Predicted	Difference	SE	Measured	Predicted	Difference	SE
CP	77.5	72.2	5.3*	1.7	84.1	81.4	2.7*	1.4
Indispensable AA								
Arg	88.6	84.2	4.6*	1.1	92.7	89.9	2.8*	1.2
His	85.1	83.5	1.6	1.6	88.2	87.7	0.5	1.5
Ile	80.9	75.1	5.8*	1.7	85.9	82.3	3.6*	1.8
Leu	83.9	81.0	2.9*	1.3	87.3	85.8	1.5	1.3
Lys	79.0	76.0	3.0	2.1	83.8	82.6	1.2	2.2
Met	85.8	84.2	1.6	1.0	88.5	87.8	0.7	1.2
Phe	84.2	79.7	4.5*	1.7	88.2	85.6	2.6	1.6
Thr	74.8	70.8	4.0*	2.1	81.7	80.2	1.5	2.0
Trp	86.3	83.3	3.0	1.8	91.3	90.7	0.6	1.7
Val	79.6	73.6	6.0*	1.9	84.5	80.8	3.7*	1.8
Mean	82.8	78.7	4.1*	1.5	87.2	84.8	2.4	1.4
Dispensable AA								
Ala	78.8	76.4	2.4	1.6	84.9	84.8	0.1	1.6
Asp	76.9	72.3	4.6*	2.1	83.1	80.7	2.4	2.0
Cys	78.5	78.2	0.3	2.2	83.5	84.9	–1.4	2.2
Glu	86.5	84.1	2.3*	1.2	89.6	88.4	1.2	1.2
Gly	72.8	69.1	3.7	3.4	84.6	85.2	–0.6	3.7
Pro	78.3	72.7	5.6*	2.0	98.6	102.0	–3.4	5.6
Ser	78.1	75.2	2.9	1.9	84.4	83.6	0.8	1.7
Tyr	82.3	78.6	3.7	1.6	87.4	85.9	1.5	1.5
Mean	79.0	75.6	3.4*	1.8	86.4	85.8	0.6	1.9
All AA	81.6	78.0	3.6*	1.5	87.7	86.5	1.1	1.6

[a]Data are least squares means of eight observations per treatment.
*Measured and calculated values differ, $P < 0.05$.

Table 6. Measured and predicted values for apparent (AID) and standardized (SID) ileal digestibility coefficients (%) for CP and AA in a soybean meal-canola meal-based diet[a]

	AID				SID			
Item	Measured	Predicted	Difference	SE	Measured	Predicted	Difference	SE
CP	78.3	76.2	2.1*	1.7	85.2	83.4	1.8*	0.8
Indispensable AA								
Arg	86.7	88.2	–1.5	0.9	90.9	92.1	–1.2	1.0
His	84.5	85.1	–0.6	1.4	88.6	89.0	–0.4	1.8
Ile	78.2	78.6	–0.4	1.7	84.0	84.3	–0.3	2.2
Leu	79.2	80.1	–0.9	1.8	84.4	85.2	–0.8	2.3
Lys	80.7	82.6	–1.9	1.8	85.6	87.2	–1.6	2.5
Met	83.9	84.1	–0.2	1.4	87.7	87.9	–0.2	1.7
Phe	79.7	80.9	–1.2	2.1	84.9	85.8	–0.9	2.5
Thr	73.4	74.6	–1.2	1.9	81.5	82.3	–0.8	2.2
Trp	86.4	86.1	0.3	1.5	90.9	91.0	0.1	2.0
Val	76.2	76.1	0.1	1.7	82.4	82.4	0.0	2.1
Mean	80.9	81.7	–0.8	1.5	86.2	86.8	–0.6	1.8
Dispensable AA								
Ala	74.2	75.3	–1.1	2.1	83.0	83.7	–0.7	2.6
Asp	77.0	77.7	–0.7	1.9	82.9	83.3	–0.4	2.2
Cys	77.2	77.3	–0.1	1.5	84.9	84.7	0.2	2.6
Glu	83.7	84.4	–0.7	1.6	87.7	88.3	–0.6	1.7
Gly	70.2	70.8	–0.6	2.3	83.0	83.1	–0.1	3.0
Pro	73.8	74.8	–1.0	3.0	97.2	97.8	–0.6	7.2
Ser	76.7	79.1	–2.4*	1.2	83.9	85.8	–1.9	1.6
Tyr	78.4	79.3	–0.9	2.1	85.2	85.8	–0.6	2.4
Mean	76.4	77.4	–1.0	1.7	84.6	85.3	–0.7	1.7
All AA	79.2	80.2	–1.0	1.6	86.2	86.9	–0.7	1.7

[a]Data are least squares means of eight observations per treatment.
*Measured and calculated values differ, $P < 0.05$.

Table 7. Measured and predicted values for apparent (AID) and standardized (SID) ileal digestibility coefficients (%) for CP and AA in a corn-soybean meal-canola meal-based diet[a]

	AID				SID			
Item	Measured	Predicted	Difference	SE	Measured	Predicted	Difference	SE
CP	79.8	76.4	3.4*	1.3	86.3	85.6	0.7	1.2
Indispensable AA								
Arg	89.8	87.8	2.0*	0.7	93.7	93.2	0.4	0.8
His	87.5	85.6	1.9	1.3	91.1	90.6	0.5	1.5
Ile	82.5	78.4	4.1*	1.3	87.6	86.0	1.6	1.6
Leu	85.2	83.4	1.8	1.4	89.2	89.0	0.2	1.6
Lys	83.4	80.9	2.5*	1.4	88.3	87.8	0.5	1.9
Met	86.6	85.3	1.3	1.0	89.9	89.8	0.1	1.3
Phe	85.2	82.4	2.8*	1.5	89.7	88.7	1.2	1.7
Thr	77.7	73.8	3.9*	1.7	85.0	84.3	0.7	1.7
Trp	81.9	83.5	–1.6	1.4	87.8	91.0	–3.2*	1.7
Val	81.7	76.6	5.1*	1.5	87.2	85.0	2.2	1.7
Mean	84.2	81.3	2.9*	1.2	88.9	88.0	0.9	1.4
Dispensable AA								
Ala	81.2	77.7	3.5*	1.4	87.6	86.9	0.7	1.5
Asp	82.5	77.9	4.6*	1.6	87.9	85.7	2.2	1.8
Cys	81.1	78.5	2.6	2.0	87.7	87.9	–0.2	2.7
Glu	88.0	85.0	3.0*	1.3	91.4	90.0	1.4	1.3
Gly	74.8	69.3	5.5*	2.2	85.9	85.1	0.8	2.2
Pro	74.5	74.5	0.0	8.3	91.1	99.8	–8.7	9.4
Ser	82.4	80.5	1.9	1.4	88.5	88.8	–0.3	1.4
Tyr	82.9	81.2	1.7	1.4	88.3	88.6	–0.3	1.6
Mean	80.9	78.0	2.9*	1.5	87.7	87.8	–0.1	1.3
All AA	83.4	80.6	2.8*	1.2	89.4	89.2	0.2	1.1

[a]Data are least squares means of eight observations per treatment.
*Measured and calculated values differ, $P < 0.05$.

tions in the four diets. Significant differences between measured and calculated values for SID were obtained only in eight of the 88 total observations. Therefore, the SID more accurately predicted the digestibility in the mixed diets than did AID.

The additivity of SID in mixed diets has previously been reported by Furuya and Kaji (1991). In that experiment, mixed diets based on SBM and barley, corn, or wheat were used to compare measured and predicted SID for CP and AA. With the exception of four observations in the barley-SBM-based diet, no significant differences between measured and predicted values for SID were obtained. Thus, the results of the current experiment agree with the data reported by Furuya and Kaji (1991).

The largest differences between calculated and measured values for SID were obtained for Pro. This is likely because the endogenous loss of Pro is overestimated if measured using a N-free diet (Sauer et al., 1977; Stein et al., 1999b), as was the case in the present experiment. In general, diets containing a low or unbalanced concentration of AA often elicit elevated ileal losses of Pro (Taverner et al., 1981; Pedersen et al., 2002). This, in turn, leads to an overestimation of the calculated SID for Pro. In the present experiment, the calculated SID for Pro were >100% for both corn and SBM and also for the corn-SBM- and corn-CM-based diets. Recently, SID in excess of 100% for Pro have been reported by Dilger et al. (2004) and Moter and Stein (2004). Because a digestibility coefficient cannot exceed 100%, these calculated values demonstrate that the endogenous losses of Pro are often overestimated when measured using a N-free diet.

In conclusion, the results of the current experiment support the hypothesis that digestibility coefficients based on SID are more additive in a mixed diet than are values based on AID. This was true if a cereal grain with a relatively low concentration of CP and AA (i.e., corn) was included in the diet and if the AID for this ingredient was measured using the direct method. In addition, results of the experiment also demonstrate that values based on AID were as additive as values based on SID when no low-protein ingredients were included in the mixed diet.

Implications

Digestibility coefficients for crude protein and amino acids in a mixed diet containing a low-protein feed ingredient were predicted more accurately from the digestibility coefficients obtained in the individual ingredients if the predictions were based on standardized ileal digestibility coefficients rather than apparent ileal digestibility coefficients. However, values based on apparent ileal digestibility coefficients were as additive as values based on standardized ileal digestibility coefficients if no low-protein ingredients were included in the mixed diet. Because most mixed diets used under commercial conditions contain at least one low-protein feed ingredient (i.e., a cereal grain), it is more accurate to use standardized than apparent ileal digestibility coefficients to predict the digestibility coefficients for crude protein and amino acids in mixed diets.

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