

JOURNAL OF ANIMAL SCIENCE

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J Anim Sci 2007. 85:172-180.
doi: 10.2527/jas.2005-742

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Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application

H. H. Stein, B. Sève, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange¹

Committee on Terminology to Report AA Bioavailability and Digestibility^{2,3}

ABSTRACT: In this review, the terminology that is used to describe the bioavailability and ileal digestibility of AA in pig feed ingredients is defined. Aspects of the methodology to establish bioavailability and ileal digestibility values also are discussed, and recommendations about the use of these values are provided. Two main factors can contribute to differences between bioavailability and ileal digestibility of AA. First, some AA, such as Lys, may be absorbed in chemical complexes that preclude their use for metabolism. Second, fermentation in the upper gut may result in a net loss or gain of AA to the animal. In addition, dietary effects on the efficiency of using bioavailable AA intake for tissue growth or milk production should be considered and may be attributed to endogenous AA losses in the hindgut and the metabolic costs associated with endogenous gut protein synthesis and losses. Ileal digestibility values may be expressed as apparent ileal digestibility (AID), standardized ileal digestibility (SID), or true ileal digestibility (TID). These terms are used to specify how ileal endogenous AA losses are reflected in digestibility values. Ileal endogenous AA losses may be sepa-

rated into basal losses, which are not influenced by feed ingredient composition, and specific losses, which are induced by feed ingredient characteristics such as levels and types of fiber and antinutritional factors. Values for AID are established when total ileal outflow of AA (i.e., the sum of endogenous losses and nondigested dietary AA) is related to dietary AA intake. A concern with the use of AID values is that these are not additive in mixtures of feed ingredients. This concern may be overcome by correcting AID values for defined basal endogenous losses of AA, which yields SID values. Furthermore, if the AID values are corrected for basal and specific endogenous losses, then values for TID are calculated. However, reliable procedures to routinely measure specific endogenous losses are not yet available. It is recommended that basal ileal endogenous losses of AA should be measured in digestibility experiments using a defined protein-free diet and that these losses are reported with observed AID and SID values. It is suggested that SID values should be used for feed formulation, at least until more information on TID values becomes available.

Key words: amino acid, apparent digestibility, endogenous loss, pig, standardized digestibility, true digestibility

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J. Anim. Sci. 2007. 85:172–180
doi:10.2527/jas.2005-742

INTRODUCTION

A careful assessment of the bioavailability of each of the dietary indispensable AA is critical for evaluat-

ing the nutritional value of feed ingredients for pigs and for estimating AA requirements of pigs. This assessment presents several challenges. Among these are choosing methods for estimating AA bioavailability that are accurate and easy to use in practice and that yield values that are additive in mixtures of feed ingredients. To improve the implementation of research findings, a consistent terminology should be used when reporting research results. In addition, there should be consistency between how AA bioavailability in ingredients is expressed and how the pig's AA requirements are expressed.

The terminology used to represent AA bioavailability and digestibility is defined, and methodology to assess aspects of digestibility is briefly described in this review. It is anticipated that the universal adoption of the proposed terminology and methodology will

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²The committee on terminology to report AA availability and digestibility was appointed on the request of the late J. T. Yen, who for many years served as the chair of the international steering committee of the Symposia on Digestive Physiology in Pigs. Yen wanted to bring clarity to the manner in which experimental results were presented to use research results in animal production effectively. de Lange was appointed chair of the committee on terminology.

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Received December 21, 2005.

Accepted August 30, 2006.

facilitate the development and exchange of information concerning AA bioavailability and digestibility in feed ingredients for pigs and possibly other species.

AA BIOAVAILABILITY

Bioavailability of dietary AA is defined as the proportion of ingested dietary AA that is absorbed in a chemical form that renders these AA potentially suitable for metabolism or protein synthesis (Batterham, 1992; Lewis and Bayley, 1995). Unfortunately, there is no direct measure of AA bioavailability. Traditionally, estimates of bioavailability of AA have been obtained using slope-ratio assays as described by Batterham (1992). In this assay, graded AA intake levels are created by varying the dietary inclusion level of a particular feed ingredient. The response, such as whole body protein deposition (Batterham, 1992) or AA oxidation (Moehn et al., 2005), of animals fed the test ingredient is related to the AA intake, and the slope of the regression line is compared with that from animals fed a defined reference protein source. The ratio of the slope of the test feed ingredient to the slope of the reference protein represents the relative bioavailability of the AA in question. All diets used in this assay must be first-limiting in this AA, and all dietary levels of the AA need to be below the animals' requirements needed to maximize the biological responses. When using this assay, it is assumed that the animals' response to graded AA intake levels is linear and not influenced by the dietary nutrient balance. A potential advantage of these assays is that metabolic costs to the animal that are induced by feeding a particular ingredient and that are associated with digestion and absorption (see next section) are reflected in this measure of availability. As a consequence, values obtained with this assay underestimate bioavailability as defined above, although the assay may provide estimates of availability for productive functions. The major disadvantages are that these assays are tedious and costly. In addition, the determined availabilities represent relative values only, generally have a high standard error of determination, are unique to the experimental conditions, and are unlikely to be additive in mixtures of feed ingredients (Gabert et al., 2001). Therefore, other methods, such as AA digestibility, are more suitable for estimating AA bioavailability than the slope-ratio assay. Traditionally, measures of in-vivo digestibility have been used to estimate AA bioavailability (Sauer and Ozimek, 1986).

AA DIGESTIBILITY AS A MEASURE OF AA BIOAVAILABILITY

Amino acid digestibility reflects enzymatic hydrolysis and microbial fermentation of ingested proteins and peptides and absorption of AA and peptides from the gastrointestinal lumen (Fuller, 2003). Digestion, fermentation, and absorption involve nutrients that

are of dietary origin or from endogenous secretions into the digestive tract. Because AA are absorbed only from the small intestine, and because of the effect of hindgut fermentation on AA metabolism, ileal digestibility is a more accurate estimate of AA bioavailability than total tract digestibility (Sauer and Ozimek, 1986).

Observed digestibility values should be expressed as apparent, standardized, or true AA digestibility values, depending on how endogenous gut AA losses are considered in the measure of digestibility. All measures of AA digestibility are based on the disappearance of AA from the digestive tract, and these measures do not reflect the net breakdown or synthesis of AA in the intestinal lumen or the form in which AA are absorbed. The latter is a concern when microbial fermentation in the gut lumen contributes to net AA breakdown or synthesis, or when feed ingredients contain absorbable chemical complexes that include AA. Especially in heat-treated feed ingredients, some AA, such as lysine, may be present in chemical forms, like Maillard reaction products, that may be absorbed but preclude utilization for protein synthesis (Carpenter, 1960; Moughan and Rutherfurd, 1996). In this case, the calculated digestibility overestimates AA bioavailability. Microbial fermentation in the lumen of the upper gut may contribute to the synthesis and the catabolism of AA, which may also lead to discrepancies between ileal digestibility and bioavailability (Fuller, 2003).

In addition to AA bioavailability, dietary effects on the efficiency of utilizing available AA intake for tissue growth or milk production should be considered. These effects include the metabolic costs associated with synthesis and recycling of endogenous gut AA losses, largely due to increases in AA catabolism (Tamminga et al., 1995; Hess, 1999; Lahaye et al., 2004) and the endogenous AA losses into the hindgut (Zhu et al., 2003). For example, Hess (1999) established that the reduction in whole body N retention was 1.9 times the increase in ileal endogenous N losses in growing pigs fed diets varying in content of antinutritional factors. Endogenous AA that are secreted into the hindgut are obviously not reflected in the measure of ileal digestibility but contribute directly to the pigs' available AA requirements. In particular, in pigs fed a threonine-limiting diet, inducing additional endogenous AA losses into the hindgut has been shown to reduce whole-body protein deposition (Zhu et al., 2003).

Based on the above considerations, clear distinctions between ileal digestibility, bioavailability, and dietary effects on utilization of available AA intake for production are warranted. The impact of the chemical form in which AA are absorbed (Moughan, 2003); the impact of enteric fermentation, especially in the upper gut (Fuller, 2003); and the dietary factors that influence the efficiency of utilizing available AA intake for production (Sève and Hess, 2000) deserve to be explored further.

APPARENT ILEAL DIGESTIBILITY

The apparent ileal digestibility (**AID**) of AA is defined as the net disappearance of ingested dietary AA from the digestive tract proximal to the distal ileum. Values for AID are calculated from the flow and composition of digesta at the distal ileum of pigs and by relating the total ileal outflow of AA to the dietary intake according to Eq. [1]:

$$\text{AID, \%} = [(\text{AA intake} - \text{Ileal AA outflow}) / \text{AA intake}] \times 100. \quad [1]$$

The word apparent is used to emphasize that nondigested dietary AA and AA of endogenous origin that were secreted into the gastrointestinal tract and not reabsorbed proximal to the distal ileum contribute to the total ileal outflow of AA.

Several methods may be used for measuring ileal outflow. Advantages and disadvantages of these methods are discussed in detail elsewhere (Laplace et al., 1994; Hodgkinson and Moughan, 2000; Sauer et al., 2000). Various surgical procedures are available to accommodate routine sampling of ileal digesta in pigs. Among those procedures, the insertion of a T-cannula at the distal ileum may be preferred because it is the least invasive procedure and does not involve the removal of parts of the lower digestive tract. However, in this procedure, contrary to ileorectal anastomosis, which allows quantitative collection of ileal digesta, only a portion of the ileal digesta outflow is collected. Therefore, the inclusion of an indigestible marker in the diet is needed, and additional assumptions about the adequacy of using indigestible markers are required, in particular in regard to obtaining representative digesta samples and marker recovery (Jagger et al., 1992; Yin and McCracken, 1996). Chromic oxide and titanium dioxide are the 2 most commonly used markers. It has been reported that only 71 to 85% of the dietary chromium is recovered at the end of the small intestine (Mroz et al., 1996). In contrast, Thomsen and Wiseman (1998) reported a 100% recovery of titanium dioxide over the entire intestinal tract, and Jagger et al. (1992) showed that the problems with low recoveries of chromium could be overcome by increasing the dosage to 5 g per kg of diet. At this dosage, the calculated ileal digestibility coefficients for AA were similar if calculated based on chromic oxide, titanium dioxide, or lignin. It also has been suggested that the marker recovery is influenced by the type of diet being fed with lower recoveries observed if high-fiber diets are used (Yin et al., 1997). Because ileal digestibility values for AA are calculated based on the assumption of full marker recovery, this is clearly an area that needs careful consideration.

If markers are used to calculate digestibility values, then the marker concentrations in feed and digesta are used to calculate AID according to Eq. [2]:

$$\text{AID, \%} = [1 - (\text{AA}_{\text{digesta}} / \text{AA}_{\text{diet}}) \times (\text{M}_{\text{diet}} / \text{M}_{\text{digesta}})] \times 100, \quad [2]$$

where $\text{AA}_{\text{digesta}}$ and AA_{diet} represent the AA concentrations (g/kg) in digesta and diet DM, respectively, and M_{diet} and $\text{M}_{\text{digesta}}$ represent the marker concentrations (g/kg) in diet and digesta DM, respectively.

A primary concern with the use of AID in diet formulation and interpretation of experimental data is the lack of additivity of AID in mixtures of feed ingredients (Nyachoti et al., 1997b; Jansman et al., 2002; Stein et al., 2005; Table 1). The lack of additivity of values for AID can be attributed largely to the effect of diet AA level on AID values (Furuya and Kaji, 1991; Donkoh and Moughan, 1994; Fan et al., 1994; Figure 1) and the relative contribution of endogenous AA to total AA in ileal outflow (Figure 2). Starting at low dietary AA levels, increasing the dietary inclusion level of protein-containing feed ingredients will reduce the relative contribution of endogenous AA to total AA in ileal outflow. As a result, AID of AA increases in a nonlinear manner with dietary AA level. The lack of additivity of AID values is a concern when feed ingredients with low AA levels, such as cereal grains, are included in the diet (Jansman et al., 2002; Stein et al., 2005). When establishing AID values for AA in high-protein containing test feed ingredients, the impact of dietary AA level on AID may be overcome by determining AID of AA in a diet in which the test feed ingredient is combined with N-free feed ingredients. By subtracting endogenous AA losses that are induced by the N-free feed ingredients from total ileal AA outflow, the AID of AA in the test feed ingredient per se may be derived (Boisen and Moughan, 1996). This approach has been used to establish AID for AA in high-protein containing feed ingredients (CVB, 2003; INRA-AFZ-INAPG, 2004) but requires estimates of ileal endogenous AA losses that are induced by the N-free feed ingredients. The latter is addressed in further detail in subsequent sections in this review.

ILEAL ENDOGENOUS AA LOSSES

Ileal endogenous AA losses (IAA_{end}) represent AA that are present in endogenously synthesized proteins secreted into the intestinal lumen of the pig that have not been digested and reabsorbed before reaching the distal ileum (Tamminga et al., 1995; Hodgkinson and Moughan, 2000). Mucoproteins, sloughed cells, serum albumin, digestive enzymes, amides, and ingested hair contribute to the IAA_{end} (Nyachoti et al., 1997a). Bacterial protein, although strictly not endogenous protein, is often included in the measurement of ileal endogenous protein. In pigs fed practical diets, IAA_{end} can vary considerably and may contribute more than 50% to total ileal AA outflow (Souffrant, 1991).

The IAA_{end} may be divided into 2 main components: basal and specific losses (Sève and Henry, 1996; Nya-

Table 1. Measured and predicted values for apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of selected AA in corn and soybean meal-based diets¹

Item	AID				SID			
	Measured	Predicted	Difference	SE	Measured	Predicted	Difference	SE
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	90.8	-0.8	1.2
Thr	78.5	74.7	3.8 ^a	1.4	86.2	86.2	0.0	1.4
Trp	85.7	82.4	3.3 ^a	1.7	90.6	89.5	1.1	2.0

^aMeasured and predicted values differ, $P < 0.05$.

¹Derived from Stein et al. (2005). Measured values for AID and SID were determined in a diet containing 63.8% corn and 25.65% soybean meal. Predicted values were calculated for a similar diet and from digestibility values determined in diets containing corn (89.05%) or soybean meal (25.65%) as the only protein source.

choti et al., 1997a; Jansman et al., 2002). The basal losses (previously also referred to as nonspecific or diet-independent losses) represent the minimum quantities of AA inevitably lost by the animal. These losses are considered to be related to the physical flow of feed DM through the digestive tract or the animals' metabolic state, and in this sense are not influenced by dietary composition (Figure 2).

According to Butts et al. (1993b), Hess and Sève (1999), and Moter and Stein (2004), basal IAA_{end}, expressed as grams per kilogram of DMI, decrease with increased DMI. Moreover, observations made by Furuya and Kaji (1992) and Hess and Sève (1999) indicate that basal IAA_{end} per kg of DMI decrease with increased BW, and the effect of BW is largest at low DMI. However, if animals are fed to appetite, IAA_{end} per kilogram of DMI are similar in gestating sows and growing pigs at 112 kg of BW (Stein et al., 1999). These observations suggest that the effects of DMI and of the animals' metabolic state on basal IAA_{end} need to be

considered carefully and explored further. Until more information becomes available, basal IAA_{end} are best established at levels of feed intake that are close to the voluntary feed intake of the animals and expressed in proportion to DMI (Boisen and Moughan, 1996; Jansman et al., 2002).

The specific endogenous losses (previously also referred to as extra or diet-dependent losses) are influenced by diet ingredient composition. The specific losses are those losses above the basal losses that are induced by specific feed ingredient characteristics, such as contents and types of fiber and antinutritional factors (Schulze et al., 1995). When feeding highly digestible purified proteins (i.e., casein or egg protein), the specific endogenous losses are minimal. In contrast, if feed ingredients containing fibers or antinutritional factors are fed, specific losses may contribute more than 50% of the total IAA_{end} (Souffrant, 1991; Moughan, 2003).

Measurement of Basal and Specific Ileal Endogenous AA Losses

Conventional methods to quantify IAA_{end} include feeding a protein-free diet, feeding a highly digestible purified diet, the peptide alimentation technique, and the regression technique. All of these methods provide estimates of basal IAA_{end} only and have previously been discussed (Fuller, 1991; Jansman et al., 2002; Moughan, 2003). The main concern with feeding pigs intact highly digestible proteins is that assumptions have to be made about the true digestibility of the ingested protein. This concern can be overcome by feeding peptides derived from partly hydrolyzed proteins and by physically separating endogenous gut proteins from the nondigested dietary peptides (Butts et al., 1993a). However, based on potential stimulating effects of feeding large amounts of peptides to pigs on endogenous protein secretions, the peptide alimentation technique may yield higher estimates of basal IAA_{end} than feeding synthetic AA or intact and highly digestible protein (Butts et al., 1993a; Jansman et al., 2002; Yin et al., 2004). Studies remain to be conducted to compare directly the impact of feeding hydrolyzed protein and intact protein from the same source on

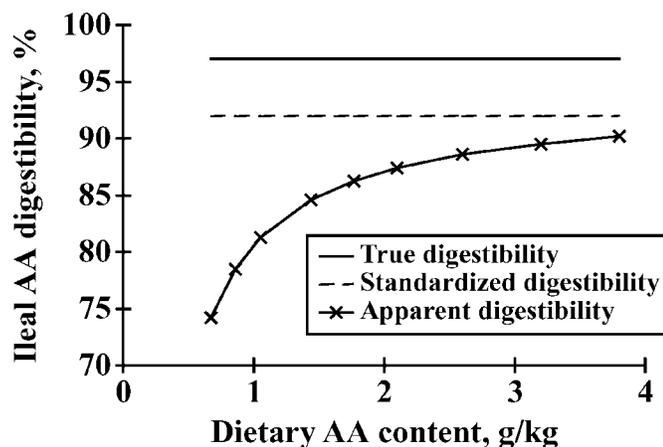


Figure 1. Influence of the dietary AA content on the measured values of apparent, standardized, and true ileal AA digestibility [adapted from Krawielitzki et al. (1977) and Fan et al. (1994)]. Changes in dietary AA content are the result of varying the inclusion level of a protein containing a feed ingredient that induces specific ileal endogenous AA losses.

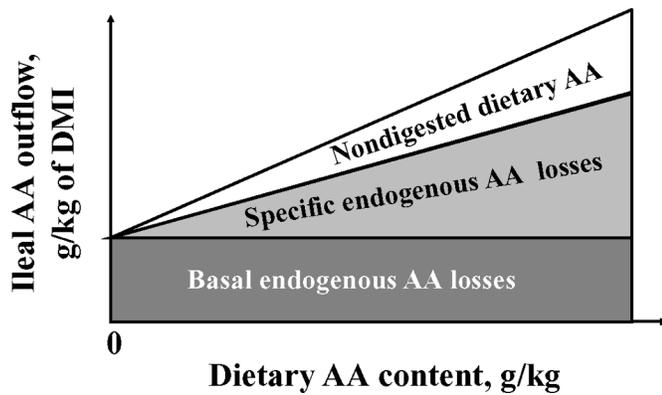


Figure 2. Partitioning of AA in ileal digesta from pigs as influenced by dietary AA content [adapted from Krawielitzki et al. (1977) and Fan et al. (1994)]. Changes in dietary AA content are the result of varying the inclusion level of a protein containing a feed ingredient that induces specific ileal endogenous AA losses.

IAA_{end} . Based on these and practical considerations, feeding a protein-free diet may be preferred over the other methods, even though it leads to an overestimation of endogenous ileal losses of proline and glycine (de Lange et al., 1989a; Leterme et al., 1996) and may lead to an underestimation of basal endogenous losses overall. It may be argued that feeding pigs a diet containing highly purified and digestible proteins is a more physiological approach to estimate basal IAA_{end} as compared with feeding a protein-free diet. In addition, the AA composition of basal endogenous ileal protein losses is influenced by the animals' physiological state (de Lange et al., 1989b; Butts et al., 1993a; Leterme et al., 1996). These considerations should be explored further. However, based on an extensive review of the available literature, Jansman et al. (2002) concluded that estimates of basal IAA_{end} derived from pigs fed protein-free diets are similar or only slightly lower compared with feeding highly digestible proteins. Furthermore, values obtained with feeding pigs protein-free diets are consistent with those obtained with the regression method (Mariscal-Landin et al., 1995; Jansman et al., 2002).

The ingredient composition of the protein-free diet may influence estimates of basal losses as well (Taverner et al., 1981; de Lange et al., 1989a; Mariscal-Landin et al., 1995). Therefore, it is suggested that a standard protein-free diet be used to obtain estimates of basal IAA_{end} (Table 2). It should be noted that even when experimental conditions, such as diet ingredient composition, digesta sampling, and analytical procedures, are closely controlled, differences in basal IAA_{end} may be observed among laboratories (Sève et al., 2001), which may be associated with between-laboratory variation in housing conditions, intestinal health of pigs, or pig genotype. For this reason, basal IAA_{end} should be measured routinely in studies aimed

Table 2. Suggested composition (% , as-fed basis) of N-free diets to allow estimation of basal ileal endogenous AA losses

Ingredient, %	Category of pigs	
	Nursery	Growing-finishing
Cornstarch	54.5	79.1
Dextrose	15.0	10.0
Lactose	20.0	—
Vegetable oil	3.0	3.0
Synthetic fiber	3.0	4.0
Limestone	0.5	0.5
Monocalcium phosphate	2.4	1.9
Indigestible marker	0.4	0.4
Salt	0.5	0.4
Vitamin premix ¹	0.05	0.05
Micromineral premix ¹	0.15	0.15
Potassium carbonate	0.4	0.4
Magnesium oxide	0.1	0.1
Total	100.0	100.0

¹The vitamin and micromineral premixes should provide the final diet with concentrations of vitamins and microminerals that meet the minimum requirements according to the NRC (1998).

at evaluating ileal AA digestibility. The latter also implies that the variable basal IAA_{end} should be considered as a component of the pigs' AA requirements (Sève et al., 2001). An alternative view is that the basal IAA_{end} are constant among groups of pigs and that a mean value for the basal IAA_{end} can be used for adjustments of AID for basal IAA_{end} and for the estimation of AA requirements of pigs (Jansman et al., 2002).

If a protein-free diet is used, the basal IAA_{end} are usually measured using an indigestible marker according to Eq. [3]:

$$IAA_{end} = AA_{digesta} \times (M_{diet}/M_{digesta}), \quad [3]$$

where IAA_{end} is the basal endogenous loss of an AA in grams per kilogram of DMI, $AA_{digesta}$ is the concentration of that AA in the ileal digesta (g/kg of DM), and M_{diet} and $M_{digesta}$ are the marker concentrations in diet and digesta, respectively (g/kg of DM).

No routine procedures are available for determining specific IAA_{end} in pigs. However, it is possible to calculate the specific IAA_{end} by estimating the total (specific plus basal) IAA_{end} and then subtract the basal IAA_{end} from total IAA_{end} . Procedures used to estimate total IAA_{end} include the homoarginine technique (Hagemeister and Ebersdobler, 1985; Rutherford and Moughan, 1990) and the isotope tracer dilution technique (Krawielitzki et al., 1977; Simon et al., 1987; de Lange et al., 1990). Each of these methods has some important limitations and requires assumptions that may be questioned (Nyachoti et al., 1997a; Leterme et al., 1998). Moreover, these procedures are laborious, costly, and require specialized equipment. As a consequence, total IAA_{end} are not routinely measured for feed ingredient evaluation. However, accurate mea-

surements of total IAA_{end} are expected to improve the understanding of AA digestion and utilization.

The AA in the ileal digesta may be partitioned into 3 fractions: undigested dietary AA, basal IAA_{end}, and specific IAA_{end} (Figure 2). It has been shown that the total AA outflow at the distal ileum increases linearly with the dietary inclusion level of a protein-containing ingredient (Donkoh and Moughan, 1994; Fan et al., 1994; Figure 2). This increase is due mainly to an increased ileal outflow of undigested dietary AA. If the protein-containing feed ingredient induces specific IAA_{end}, then the quantity of specific IAA_{end} will also increase (Figure 2). Whether the quantity of undigested dietary AA and specific IAA_{end} increase linearly with the dietary inclusion level of protein-containing ingredients that induce specific IAA_{end} remains to be confirmed. However, the general relationships presented in Figure 2 are consistent with those in Figure 1 and with observations obtained with the ¹⁵N isotope dilution technique in rats that were fed varying levels of different protein-containing ingredients (Krawielitzki et al., 1977).

TRUE ILEAL AA DIGESTIBILITY

The true ileal AA digestibility (**TID**) reflects the proportion of the dietary AA that disappears from the digestive tract proximal to the distal ileum. In this case, only the undigested dietary AA and not the IAA_{end} in the ileal AA outflow are related to AA intake. The TID are calculated the same way as the AID with the exception that the total IAA_{end} of AA are subtracted from the ileal outflow of AA according to Eq. 4:

$$\text{TID, \%} = \{[\text{AA intake} - (\text{ileal AA outflow} - \text{total IAA}_{\text{end}})] / \text{AA intake}\} \times 100. \quad [4]$$

If the AID of AA have already been calculated, then the TID may more easily be estimated according to Eq. [5]:

$$\text{TID, \%} = \text{AID} + [(\text{total IAA}_{\text{end}} / \text{AA}_{\text{diet}}) \times 100]. \quad [5]$$

Previously, TID has been referred to as real ileal digestibility (Krawielitzki et al., 1977; de Lange et al., 1990; Souffrant, 1991). However, in an effort to maintain consistency among different nutrients and species, the term true ileal digestibility is preferred over real digestibility. Within this context, a clear differentiation should be made between TID and ileal digestibility of AA that have been corrected for basal IAA_{end} only. This differentiation is addressed in the next section.

When pig diets are formulated based on the TID of AA, diet effects on IAA_{end} in the upper and lower gut should be reflected explicitly in the pigs' AA requirements. As a result, the pigs' TID AA requirements will vary with feed ingredient composition when feed

ingredients are used that induce specific IAA_{end} losses. This approach also allows the metabolic costs associated with synthesis and recycling of endogenous gut AA losses to be represented explicitly. A major limitation to the use of TID and total IAA_{end} for routine pig feed formulation is that insufficient information is available on these values for the wide range of pig feed ingredients that are commonly included in commercial pig diets.

STANDARDIZED ILEAL AA DIGESTIBILITY

As an alternative to TID, standardized ileal digestibility (**SID**) may be calculated (Jondreville et al., 1995; Mosenthin et al., 2000; Jansman et al., 2002). Using this approach, only basal IAA_{end} are subtracted from the ileal outflow of AA according to Eq. [6]:

$$\text{SID, \%} = \{[\text{AA intake} - (\text{ileal AA outflow} - \text{basal IAA}_{\text{end}})] / \text{AA intake}\} \times 100. \quad [6]$$

If AID values have already been calculated, then SID may be estimated according to Eq. [7]:

$$\text{SID, \%} = \text{AID} + [(\text{basal IAA}_{\text{end}} / \text{AA}_{\text{diet}}) \times 100]. \quad [7]$$

Equation 7 is equivalent to Eq. 5 with the exception that the basal rather than the total IAA_{end} are considered in the calculations. As mentioned earlier, different estimates of basal IAA_{end} have been obtained and basal IAA_{end} can vary among groups of pigs. Therefore, estimates of basal IAA_{end} that are used to derive SID values should be specified when reporting SID values.

Because only the basal IAA_{end} are subtracted from the total ileal AA outflow, values for SID are intermediate between values for AID and TID and independent of dietary AA level (Figure 1; Table 3). By correcting AID values for basal IAA_{end} to calculate SID values, some of the variation in observed AID values among different samples of the same ingredient is reduced, largely because effects of protein levels on ileal digestibility are eliminated. The SID values reflect TID and feed ingredient effects on specific IAA_{end}. In other words, a reduction in SID may be caused by a reduction in TID or by an increase in specific IAA_{end}. Unfortunately, the term TID has also been used to represent SID (e.g., NRC, 1998) leading to some confusion about the interpretation of ileal digestibility values.

When moving from AID to SID values in pig feed formulation, the basal IAA_{end} should be reflected in the pigs' AA requirements according to Eq. [8]:

$$\text{AA}_{\text{requirement, SID, g/kg of diet}} = \text{AA}_{\text{requirement, AID}} + \text{basal IAA}_{\text{end}} \quad [8]$$

where AA_{requirement, SID} and AA_{requirement, AID} represent AA requirements (g/kg of diet) based on SID and AID,

Table 3. Apparent ileal digestibility (AID), standardized ileal digestibility (SID), and true ileal digestibility (TID) of Lys and Thr in selected feed ingredients for pigs

	Wheat ¹	Barley ²	Peas ²	Faba beans ²	Canola meal ²	Sunflower meal ²	Soybean meal ²	Soybean meal ³
Lys								
AID	66.1	73.5	80.6	78.1	70.5	68.6	56.3	87.3
SID	75.8	79.3	82.5	79.8	72.1	71.1	57.5	92.0
TID	81.4	92.3	85.5	85.0	78.4	85.0	67.1	96.6
Thr								
AID	66.1	48.8	61.1	65.4	63.6	68.5	54.1	75.2
SID	77.6	63.2	65.4	69.0	65.8	72.8	56.1	88.0
TID	87.7	86.0	81.6	84.4	74.6	85.0	68.6	101.0

¹Data obtained with ¹⁵N-labeled feedstuffs (Hess, 1999).

²Data obtained with ¹⁵N-labeled feedstuffs. The soybean meal sample had high residual trypsin inhibitor activity (P. Leterme, W. Souffrant, and B. Sève; INRA–Centre de Recherches de Rennes, Saint Gilles, France; unpublished data from the AMINOPIG European project, 1997-2003).

³Data obtained with ¹⁵N-labeled pigs for a regular soybean meal sample (de Lange et al., 1990).

respectively, and basal IAA_{end} are expressed as gram per kilogram of diet and adjusted for diet DM content.

The main advantage of using SID compared with AID is that values for SID are more likely to be additive in mixed diets (Stein et al., 2005; Table 1). Therefore, by using SID for the interpretation of experimental observations or for practical feed formulation, some of the disadvantages and limitations of AID and TID are overcome. Estimates of SID have been generated for most pig feed ingredients (NRC, 1998; CVB, 2003; INRA-AFZ-INAPG, 2004).

IMPLICATIONS

The universal adoption of the terminology and methodology proposed in this review will facilitate accurate reporting and use of amino acid bioavailability and digestibility values in feed ingredients for pigs and possibly other species. It is suggested that standardized ileal amino acid digestibility values are used to report experimental results and for the formulation of pig diets, at least until more solid information becomes available about true ileal AA digestibility and feed ingredient-specific effects on endogenous gut amino acid losses. When reporting standardized ileal amino acid digestibility values, the values for basal ileal endogenous amino acid losses that were used to calculate the standardized ileal amino acid digestibility values should also be reported. Means to express amino acid bioavailability should be consistent with those used to express the pigs' amino acid requirements. The impact of the chemical form in which amino acid are absorbed, the metabolic cost associated with endogenous amino acid losses, endogenous amino acid losses into the hindgut, and the impact of enteric fermentation in the upper gut on amino acid bioavailability and utilization deserve to be explored further.

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