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Ideal amino acid profiles as a basis for feed protein evaluation

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Abstract

The most important single factor affecting the efficiency of protein utilization is the profile of digestible essential amino acids entering the small intestine. Assuming a constant ideal amino acid profile of absorbed protein the requirements of all amino acids can be calculated when the requirement of one individual amino acid has been determined. In non-ruminants, the supply will be greatly influenced by the diet, but less so in ruminants due to the rumen microbial degradation of feed protein and synthesis of microbial protein with high biological value. However, the high-producing dairy cow requires a significant amount of rumen escape protein. Thus, the profile of the undegraded feed protein could influence the profile of the amino acids entering the small intestine to a point at which individual amino acids become limiting. For non-ruminants, lysine is usually the first limiting amino acid in feedstuffs. This has led to the general practice of expressing the requirements for all other essential amino acids relative to lysine. Alternatively, the amino acid requirements can be expressed relative to N. Then, dietary N required for synthesis of other N-compounds is also included. Moreover, the requirements of all amino acids can be calculated when the N requirement has been determined. However, this method cannot be used for ruminants, because the N requirement of rumen microbes may be higher than the requirement of the animal. In the future, computerised animal models based on scientifically correct feed evaluation systems offer the opportunity for securing optimal feeding of farm animals in relation to their ideal amino acid profile for all different purposes of production.

Keywords: Pig; Dairy cow; Amino acids; Ideal protein; Protein evaluation

1. Introduction

The nutritional value of individual dietary protein sources for ruminants and non-ruminants differs markedly because of differences in anatomy and digestive processes. Thus, the significant synthesis of amino acids in the microbial fermentation processes in the rumen may reduce the importance of the dietary protein quality for ruminants significantly. This has been demonstrated by feeding urea as the only N-source to dairy cows which were still able to produce milk with normal amino acid composition (Virtanen, 1966). Consequently, alternative ap-

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proaches are required to evaluate the quality of dietary protein.

Common to both animal types, however, is a fundamental demand that feed proteins must be digestible, though the amino acid requirements of high-producing dairy cows put constraints on the desired rate of protein hydrolysis by the rumen microbes.

Most naturally occuring proteins are inherently highly digestible. However, in some feeds digestibility is impaired by a compact protein structure or the presence of protease inhibitors, lectins, tannins and other anti-nutritional constituents. Controlled heating can counteract many of these effects but excessive heating or inappropriate chemical treatment of feeds during processing can reduce digestibility by adversely modifying physical structure and chemical make-up. The availability of lysine and other amino acids is particularly sensitive to processing conditions due to the formation of Maillard products and other amino acid complexes or products at elevated temperatures (Boisen, 1998). On the other hand, for ruminant feeds, considerable efforts have been focussed on the possibility of reducing the availability of dietary protein for the microflora in the rumen by chemical and physical treatments and still preserving a high amino acid digestibility in the small intestine.

The aim of this paper is to discuss the opportunity for using the ideal amino acid profile as a fundamental basis for evaluation of the protein in feed for farm animals. The paper focuses on the growing pig as a representative of non-ruminants and on the high-producing dairy cow as a representative of ruminants. Current estimates of ideal protein for these two categories of farm animals and options for future improvements in its use in feed evaluation will also be discussed.

2. Essential and non-essential amino acids

Proteins are composed of 20 different amino acids, of which nine cannot be synthesized by most animal species. Therefore, a continuous supply of these nine amino acids plus sufficient nitrogen for synthesizing the other amino acids are essential for maintenance and production (growth). The nine essential amino acids are: Lysine, methionine, threonine, tryptophan, isoleucine, leucine, histidine, phenylalanine and valine.

Arginine is also an essential amino acid for many animal species, e.g. birds and fish. However, mammals, e.g. pigs and ruminants, synthesize arginine in the urea cycle where urea is produced from surplus nitrogen. On the other hand, most arginine produced in the urea cycle is broken down and some animals (e.g. young pigs) need a dietary supply (Fuller, 1994). Therefore, arginine is considered to be a semi-essential amino acid. However, in all common diets arginine seems to be in a considerable surplus as discussed later.

Cystine and tyrosine are also considered as semi-essential amino acids as they can only be synthesized by animals from methionine and phenylalanine, respectively. Therefore, the amino acid requirements have to include the sum of methionine + cystine (sulphur amino acids) and phenylalanine + tyrosine (aromatic amino acids), respectively. In addition, fulfilling the requirements of the sum alone may not be sufficient because methionine and phenylalanine cannot be synthesized from cysteine and tyrosine, respectively.

The remaining eight amino acids, including alanine, aspartic acid, asparagine, glutamic acid, glutamine, serine, glycine and proline, can all be synthesized from metabolites produced during the oxidation of glucose. Although several papers in the literature report a beneficial effect of supplying some of these amino acids in the diet (Heger et al., 1987; Chung and Baker, 1992; Kirchgessner et al., 1995), their amount in common diets is generally sufficient.

An overview of the synthetic pathways of non-essential and semi-essential amino acids are indicated, together with the essential amino acids for the pig in Fig. 1. The amino acids are further grouped according to their chemically reactive (or functional) side chains.

3. The ideal protein concept

The amino acid requirements of farm animals are influenced by many different factors including: (1) population, i.e. weight, daily gain, sex and genotype; (2) environment and (3) health status (Moughan, 1989; Fuller, 1991,1994). However, most changes in

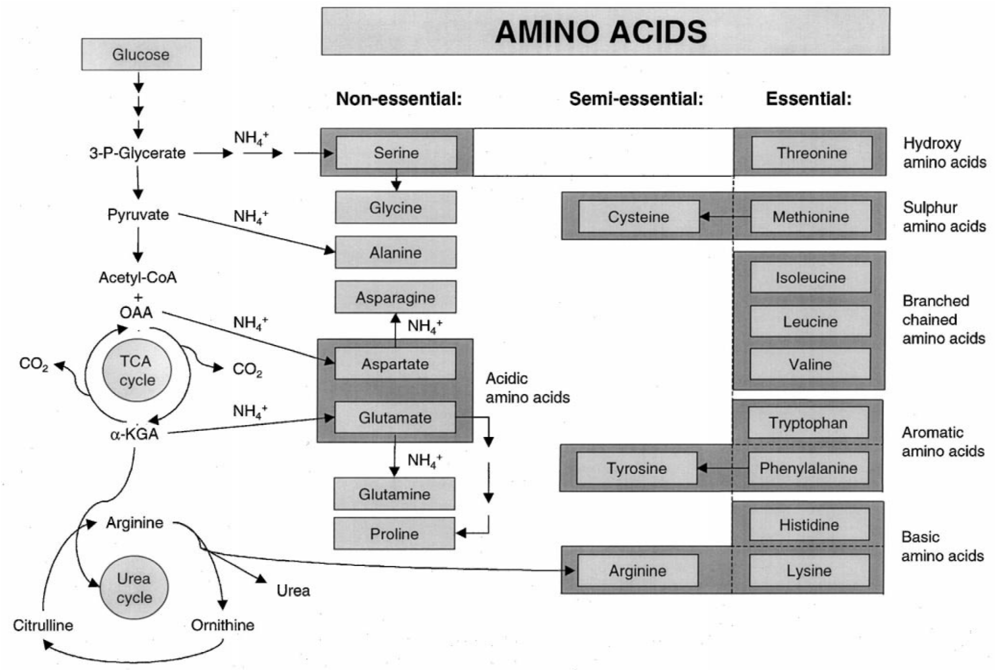

Fig. 1. Essential, semi-essential and non-essential amino acids for the growing pig grouped in relation to their functional groups. The synthetic routes for the semi-essential and non-essential amino acids are also indicated.

amino acid requirements do not lead to changes in the relative proportion of the different amino acids. Therefore, the actual changes can almost exclusively be considered to refer to the amount of balanced protein, or 'ideal protein' for the animal. In ideal protein each essential amino acid is equally limiting for performance (i.e. maintenance and production, e.g. growth) in the actual feeding situation, and there is a minimal surplus of N. Consequently, the application of an ideal protein profile in diet formulation is also a valuable tool for minimizing N excretion from farm animal production without any losses in performance (Boisen, 1993). The ideal protein is usually defined as:

> The perfect ratio among the essential amino acids required for maintenance and production.

Assuming a constant ideal amino acid profile the requirements of all essential amino acids can be calculated when the requirement of one individual amino acid has been determined. Commonly, the amino acid profile has been expressed relative to lysine. The argument for using lysine has been that lysine is usually the first limiting amino acid in the diet and is not used for the synthesis of other N-compounds. The above definition was introduced for the growing pig by ARC (1981).

The definition was extended to include an optimal ratio between essential and non-essential amino acids (Wang and Fuller, 1989). However, because the amount of non-essential amino acids is influenced by the composition of these, a correct definition should rather include the requirement for non-essential amino acid-N or simply the requirement for total N (Boisen, 1997). Consequently, the profile of essential amino acids should preferably be given relative to N or relative to crude protein ($N \times 6.25$). The ideal protein can alternatively be defined as:

> The perfect ratio among individual essential amino acids and N required for optimal performance.

From this definition it also follows that with a constant composition of the ideal protein the requirements for all essential amino acids can be calculated when the N requirement (ideal protein-N) has been determined.

4. Current estimates of ideal protein for farm animals

4.1. The growing pig

The proposal for an ideal amino acid profile for the growing pig given by ARC (1981) was based on earlier studies of the requirements for the individual essential amino acids. However, these requirements have commonly been determined by measuring the effect on performance when different amounts of supplementary amino acids are added to a basal diet consisting of natural ingredients. Consequently, the determined requirements of amino acids are influenced by the accuracy of the determined values of digestible (available) amino acids in question in the basal diet (Sauer and Ozimek, 1986; Moughan et al., 1987).

4.1.1. Available dietary amino acids in the small intestine

Estimates of amino acid requirements and the resulting ideal amino acid profile rely on several experimental factors.

Firstly, they depend on chemical analyses. In particular the sulphur amino acids, methionine and cystine, are very susceptible to degradation during the preceding acid hydrolysis and may be underestimated leading to an overestimation of the requirement.

Secondly, they depend on the technique and calculation of the digestibility (availability) of the amino acids. Amino acids are only digested in the small intestine and their digestibility needs to be determined at the terminal ileum (by fistulation or slaughter technique) because of microbial metabolism in the hindgut.

Measurements of ileal digestibility of amino acids are significantly influenced by endogenous protein losses, and values of apparent digestibility are therefore related only to the specific protein level, or more correctly, to the specific concentrations of the individual amino acids in the experimental diet (Boisen and Moughan, 1996a). In the literature, many studies of ideal protein profile in common diets have been based on apparent digestible amino acids (e.g. Wang and Fuller, 1990; Lenis et al., 1993; Tuitoek et al., 1997). However, values of apparent digestibility may underestimate the digestibility of low-protein sources (e.g. cereals) and in particular the relatively lowest amino acids (e.g lysine in cereal proteins and sulphur amino acids in legume proteins).

New approaches for determining ileal digestibility of amino acids in pig feedstuffs and feed mixtures have recently been described (Boisen and Moughan, 1996b), and it was concluded that true ileal digestibility of amino acids determined under standardized conditions should generally be used in feed evaluation. Values for true (standardized) digestible amino acids in single feedstuffs are, in contrast to values of apparent digestible amino acids, not influenced by protein level and are therefore additive in feed mixtures (Boisen, 1998). Furthermore, values of true (standardized) digestible amino acids can be considered to correspond to the determined amino acid requirements which cover both maintenance and protein accretion in the growing pig as determined by Fuller and coworkers (Wang and Fuller, 1989; Fuller et al., 1989).

From the discussion above, it follows that in cereal-based diets values of apparently digestible lysine may generally underestimate the relative amount of digestible lysine in the final diets, and consequently overestimate the contribution of most of the other amino acids in the assumed ideal protein in the experimental diet.

4.1.2. Ideal amino acid profile

Although the concept of ideal protein has been used commonly during the last two decades a precise amino acid pattern for growing pigs has not yet been finally documented. Therefore, several different patterns are used. Table 1 summarizes some ideal proteins given in the literature. The table demonstrates considerable differences between the different proposals.

As discussed above, the amino acid pattern given relative to N (1 kg crude protein corresponding to 160 g N) appears to be more informative due to the inclusion of dietary N required for synthesis of other

Table 1
Amino acid profile (relative to lysine) of ideal protein for growing pigs[a]

	A	B	C	D	E	F	G	H
Lysine	100	100	100	100	100	100	100	100
Met + Cys	50	60	55	63	59	60	60	50
Threonine	60	60	64	72	75	65	64	66
Tryptophan	15	18	16	18	19	18	19	18
Isoleucine	55	60	61	60	61	60	54	50
Leucine	100	72	80	110	110	100	100	100
Valine	70	–	64	75	75	68	70	70
Histidine	33	26	29	–	32	32	36	33
Phe + Tyr	96	100	88	120	122	95	95	100
Arginine	–	–	42	–	–	42	31	–

[a] A: ARC (1981); B: INRA (1984); C: NRC (1988); D: Wang and Fuller (1989); E: Fuller et al. (1989); F: Chung and Baker (1992); G: Rhone–Poulenc (1993); H: Cole and Van Lunen (1994).

N-compounds than essential amino acids. Furthermore, the accuracy of the pattern does not rely on a correct estimate of the available amount of one particular amino acid, which is particularly a problem with lysine. Not only in relation to the above discussion on apparently digestible lysine but also in relation to many processed foods, which may contain lower amounts of available lysine than assumed. Besides, specific values for both methionine and phenylalanine (rather than simply sulphur amino acids and aromatic amino acids) need to be given for a complete ideal protein.

Table 2 shows some of the patterns recalculated from given values of N and from the values in Table 1. These are compared with the composition in sow's milk, which has been found to be very consistent (Boisen et al., 1988) and were suggested to have been developed during the evolution to have an ideal pattern for suckling pigs. Most values are comparable except those for sulphur amino acids (met + cys) and threonine which have a relatively higher requirement than their contents in sow's milk. These amino acids are characteristically very high in the endogenous protein loss from the digestion processes in the gut of growing pigs (Boisen and Moughan, 1996a). After weaning, due to the dietary change from highly digestible nutrients in the milk to more and more fiber-rich diets, endogenous protein losses increase and contribute considerably to the total amino acid maintenance requirements of the growing pig. Consequently, growing pigs have higher requirements for sulphur amino amino acids and threonine than suckling pigs. On the other hand, the pattern in sow's milk for the other essential amino acids appear to be a reasonable estimate for growing pigs. Furthermore, due to the deposition of a predominant portion of the requirements for amino acids (about 80%), the amino acid pattern of deposited protein in the growing pig is also similar to that of milk protein (Table 2).

Several amino acid patterns for maintenance have been suggested. The maintenance requirement for N can be measured at N-equilibrium (no gain or loss of N). However, this is much more difficult to determine directly for amino acids because at N-

Table 2
Amino acid composition (g/160 g N) of ideal protein for growing pigs[a]

	A	B	C	D	E	F	G	H	Factor
Lysine	70	81	65	59	81	71	69	70	0.438
Methionine	18	–	–	16	25	18	19	18	0.113
Met + Cys	35	45	41	35	49	31	29	36	0.225
Threonine	42	52	47	44	53	39	38	45	0.281
Tryptophan	10	13	12	11	15	12	–	12	0.075
Isoleucine	38	49	39	36	49	41	40	40	0.250
Leucine	70	65	72	65	81	81	77	80	0.500
Valine	49	52	49	44	55	54	51	52	0.325
Histidine	23	23	–	–	26	25	32	25	0.156
Phenylalanine	34	–	–	35	41	39	37	40	0.250
Phe + Tyr	67	71	78	72	77	81	65	80	0.500

[a] A: ARC (1981); B: NRC (1988); C: Wang and Fuller (1989); D: Fuller et al. (1989); E: Chung and Baker (1992); F: Sowś milk (Boisen et al., 1988); G: Deposited from 20 to 90 kg live weight (Jørgensen et al., 1988); H: Proposed standard composition (Boisen, 1997); Factor: conversion factors from N requirement to individual amino acid requirements.

equilibrium redistribution of tissue protein will occur. Thus, cutaneous tissues including hair will continue to grow (Fuller, 1994) and from the digestion processes losses of endogenous protein will also continue. To compensate for this, muscle protein will be degraded (De Lange et al., 1989). As the pattern of muscle protein is considerably lower in sulphur amino acids and threonine than protein in hair and endogenous losses, a relative surplus of all other essential amino acids becomes available. Consequently, the experimentally determined requirements for these amino acids may be more or less underestimated (Boisen, 1997).

It follows that present knowledge of the specific requirements for amino acids for maintenance is rather limited, although it is generally assumed that the relative requirements for maintenance increase during growth. On the other hand, maintenance requirements relative to total requirements seem to be relatively low, except for sulphur amino acids, threonine and tryptophan (Moughan, 1995). Furthermore, the efficiency of utilization of available dietary amino acids for accretion and how this may change during growth is unclear. Therefore, it is suggested that, for practical feed evaluation, the ideal protein pattern for growing pigs is considered constant from 20 kg to slaughter at 100 kg live weight. Based on this a general ideal protein for growing pigs is suggested (Table 2). In the table is also given the conversion factors from N to the individual amino acids. From these factors the requirements for all amino acids can be calculated from measurements of N requirements.

4.1.3. Protein quality of feeds

When the ideal protein has been established, detailed information about the protein quality of single feedstuffs and complete diets can be obtained from calculations of the contribution of each individual amino acid to the ideal pattern (Table 3). The table demonstrates the well-known fact that cereals are generally low in lysine and threonine, and maize also in tryptophan, while legumes are low in sulphur amino acids. These amino acids are also considered to be the first limiting amino acids in pig diets and can all be obtained commercially as industrial amino acids. Of these, methionine is produced synthetically and consists of a 50:50 mixture of the D- and L-forms (D,L-methionine), while the other amino acids are microbially produced and are 100% L-form.

The potential for improving protein quality (ideal protein ratio) by amino acid supplementation can be exemplified by a simple mixture of barley and

Table 3
Protein quality of common protein sources in pig feeds calculated from the amino acid pattern relative to that of ideal protein

	Cereals			Oilseed by-products[a]			Others		
	Barley	Wheat	Maize	SBM	RSM	SFM	Wheat bran	Pea	Fish meal
Lysine	53[c]	38[c]	42[c]	89	77[c]	49[c]	56[c]	98	108
Methionine	87	81	118	78[c]	111	122	89	54[c]	155
Met + Cys	104	91	118	87	120	103	98	69	105
Threonine	72	59	75	87	92	76	67	81	87
Tryptophan	94	97	63	113	107	10	124	98	96
Isoleucine	91	86	92	114	98	103	78	102	107
Leucine	85	81	150	96	87	79	75	87	91
Valine	97	77	88	91	91	89	87	88	92
Histidine	84	88	112	84	104	92	96	97	76[c]
Phenylalanine	132	115	122	129	98	113	103	86	90
Phe + Tyr	102	94	110	110	85	87	89	96	77
Arginine	147	138	144	221	182	244	197	265	165
IP ratio[b]	53	38	42	78	77	49	56	54	76

[a] SBM: soybean meal; RSM: rapeseed meal; SFM: sunflower meal.
[b] Ideal protein-N relative to total N.
[c] First limiting amino acid.

Table 4
Protein quality (composition of standardized digestible amino acids relative to the ideal amino acid pattern) of feeds for growing pigs

	Barley	Soybean meal (SBM)	Barley/SBM diet (87:10)	Barley/SBM + supplemented AA[a]
Lysine	47[c]	94	63[c]	88
Methionine	74	81[c]	76	88
Met + Cys	88	82	86	92
Threonine	65	86	72	88
Tryptophan	98	119	105	105
Isoleucine	100	111	104	104
Leucine	83	95	87	87[c]
Valine	93	98	95	95
Histidine	80	107	88	88
Phenylalanine	129	123	127	127
Phe + Tyr	103	107	104	104
IP ratio[b]	47	81	63	87

[a] Supplementation per kg feed: 0.23 g lysine, 0.03 g methionine and 0.09 g threonine.
[b] Ideal protein-N relative to total N.
[c] First limiting amino acid.

soyabean meal (Table 4). The ratio of ideal protein-N to total N can be increased from 63 to 87% by supplementing with lysine, threonine and methionine. The potentials and limitations for improving the protein quality of pig diets by amino acid supplementation is further illustrated in Fig. 2. Although the composition of the diets in Table 4 and Fig. 2 are identical, the data for digestible amino acids are from different sources. In Fig. 2 the third limiting amino acid is histidine and not methionine as in Table 4. This also illustrates that the order of limiting amino acids may change. Consequently, when using fixed values the calculated order of limiting amino acids may not always be correct for the actual feed.

In more complex diets the protein quality may be improved to more than 90% by supplementation with the first limiting amino acid. However, in general it

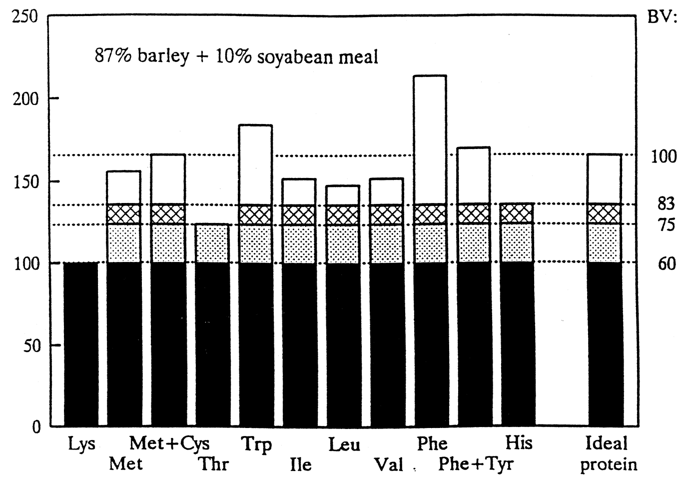

Fig. 2. Amino acid composition relative to ideal protein of a barley/soyabean meal pig diet. The figure illustrates the potentials and limitations for improving the protein quality of pig diets by amino acid supplementation (Boisen, 1993). Left axis: Amino acid contribution to ideal protein relative to lysine in unsupplemented diet; right axis: Theoretical biological value (BV) of dietary protein. The increase in BV after supplementation of lysine and threonine, respectively, is indicated. The figure is based on other data than those given in Table 4. For further information see text.

can be concluded that after supplementation of the first two to three limiting amino acids, most of the other essential amino acids may become limiting. Therefore, for proper amino acid supplementation of diets, exact knowledge of the available dietary essential amino acids, relative to their requirements, is necessary. However, compared to the first limiting amino acid, the requirements for the other essential amino acids have been much less studied (NRC, 1998).

4.2. The dairy cow

For ruminants, the most important single factor affecting the efficiency of protein utilization is, as for monogastric animals, the profile of digestible essential amino acids entering the small intestine. However, the supply of amino acids for absorption in the small intestine of ruminants is a mixture of undegraded dietary protein and microbial protein produced in the rumen. To achieve an ideal protein at the duodenal level, it is necessary to balance the amino acid composition of the microbial protein produced in the rumen with feed protein which has escaped degradation in the rumen.

4.2.1. Amino acid outflow from the rumen

The major contribution to duodenal protein flow is microbial protein. A central question is therefore to what extent is it possible to influence the composition of the protein leaving the rumen. It has often been emphasized that the composition of duodenal protein is rather constant due to a high proportion of microbial protein which was earlier considered to be very constant (Purser and Buechler, 1966; Bergen et al., 1968). On the other hand, if the feed protein has a low degradability in the rumen and an amino acid composition different from the microbial protein, it may have an impact on the amino acid composition of the outflow from the rumen.

Comparisons of the amino acid composition of the feed with that of the duodenal protein from 33 different diets (Table 5) clearly show that metabolism in the rumen leads to a reduced variation in the concentrations of the individual amino acids. However, a considerable variation remains which may be caused by contributions from dietary amino acids. On the other hand, in a review of the literature Clark et al. (1992) found variations in the bacterial amino acid compositions of 441 samples collected after feeding 61 different diets, which were generally about the double those given in Table 5. Still, the mean amino acid composition was very close to that given in Table 5 and much of the higher variation can probably be ascribed to the different methods used for isolation and analysis. Table 5 shows that the amino acid composition of isolated rumen bacteria, as well as the variation of the individual amino

Table 5
Amino acid composition (g AAN/100 g AAN) in ruminant diets, isolated rumen bacteria, endogenous protein and duodenal content

	Feed[a]		Rumen bacteria[b]		Endogenous protein[c]		Duodenal content[a]	
	Mean	*CV*	Mean	*CV*	Mean	*CV*[d]	Mean	*CV*
Lysine	7.6	*16*	10.6	*7*	7.8		9.9	*7*
Methionine	1.3	*17*	1.6	*9*	0		1.3	*10*
Threonine	3.8	*11*	4.6	*6*	3.5		4.8	*5*
Isoleucine	3.6	*10*	4.6	*5*	2.7		4.4	*4*
Leucine	6.0	*13*	6.1	*5*	4.5		6.5	*5*
Valine	5.1	*11*	5.5	*5*	4.4		5.7	*4*
Histidine	4.8	*14*	3.4	*11*	5.3		4.1	*11*
Phenylalanine	2.9	*8*	3.2	*9*	1.5		3.2	*8*
Arginine	14.8	*27*	11.7	*8*	6.5		12.6	*11*

[a] Results for 33 different diets (Hvelplund and Madsen, 1989).
[b] Results from 49 samples collected after feeding 24 different diets (Hvelplund, 1986).
[c] Values for duodenal endogenous flow estimated by Larsen et al. (2000).
[d] Not determined CV: Coefficient of variation.

acids, is very close to that of the duodenal content. This indicates that the variation in the amino acid composition of duodenal contents is influenced by variations in the microbial population, as well as dietary protein.

In conclusion, these results demonstrate that there can be significant differences in the amino acid composition of microbial protein produced in the rumen. Therefore, it is important to identify the factors responsible for this variation when predicting the amino acid profile of the microbial protein produced after feeding different diets.

4.2.2. Available amino acids in the small intestine

The digestibility in the small intestine of individual amino acids from microbial protein produced by the rumen bacteria appears to be quite constant and has been determined to be about 85% for all amino acids, except for cystine, which was determined to be only about 75% (Storm et al., 1983; Hvelplund and Hesselholt, 1987). These results were obtained from sheep by infusion of microbial protein and correspond, therefore, to the true digestibility, as endogenous losses are not considered to influence the measurements.

The rumen degradability of protein as well as the intestinal digestibility of undegraded protein from different feedstuffs can be much more variable. In a recent study by Weisbjerg et al. (1996), which included 15 different concentrates, large differences in intestinal amino acid digestibilities were observed among different concentrates, with the highest for potato protein (Protamyl, 0.98) and the lowest for cottonseed cake (0.84). With respect to individual amino acids, glutamic acid and arginine had higher, and threonine and glycine lower, digestibilities compared to total amino acids, whereas the remainder of the individual amino acids were similar to total amino acids. In general, the digestibility of the amino acids, measured by the mobile nylon bag technique, may often be very similar to that determined for crude protein in concentrates (Weisbjerg et al., 1996) as well as in roughages (Skiba et al., 1996), although higher digestibility values have been reported for amino acids than for crude protein (Skorko-Sajko et al., 1994). As amino acid digestibility is the value required in modern protein evaluation systems, intestinal crude protein digestibility (measured with the mobile bag technique) is also assumed to represent individual amino acid digestibilities.

4.2.3. Protein quality of feeds

A general improvement of the protein quality when comparing the amino acid composition of duodenal flow and rumen bacteria with dietary protein was indicated in Table 5. In particular the contribution of lysine and threonine, which are often the first limiting amino acids in diets for mammals, were found to be considerably increased in the duodenal protein flow.

The ideal amino acid pattern for the dairy cow can be considered to be closely related to the composition of the cow's milk. The amino acid requirements for maintenance have not been determined directly for dairy cows. However, a tentative estimate can be obtained from a general value for mammals related to metabolic weight (Fuller, 1991). For a 500 kg cow producing 30 kg milk with 3.2% protein, the calculated amino acid requirements for maintenance by this method account, for most amino acids, for about 30% of the amino acids in the milk. The calculated total daily amino acid requirements are given in Table 6. An alternative calculation from the maintenance requirements suggested by Asplund (1994) for sheep would result in higher values.

The calculations were based on the following assumptions:

(i) the dietary intake meets the energy requirements for maintenance and production of 30 kg milk,
(ii) microbial production in the rumen is 125 g amino acid per kg fermented carbohydrates,
(iii) the amino acid composition of microbial protein corresponds to the one used in the Nordic protein evaluation system (Madsen et al., 1995),
(iv) all amino acids in microbial protein are 85% digestible,
(v) there are no changes in the body amino acid pool.

The calculated microbial protein supply with digestible essential amino acids is for all amino acids less than the amount required (Table 6).

Table 6
Estimates of the first limiting amino acid in different feedstuffs for fulfilling the amino acid requirements (g AA/day) of the dairy cow from ruminally undegraded feed protein

	Supply from ruminally undegraded protein								
	Requirements[a]	Microbial supply[b]	Deficit	Barley	Maize	SBM[c]	RSM[d]	Fishmeal	Mixture[e]
Lysine	99.7	81.8	17.9	17.9[f]	17.9[f]	26.6	21.5	28.7	17.9[f]
Methionine	31.4	25.4	6.0	8.7	13.1	6.0[f]	8.0	10.5	7.5
Threonine	68.4	58.6	9.8	16.9	21.5	16.7	17.5	16.1	13.5
Isoleucine	66.6	64.1	2.5	17.9	20.9	20.6	15.3	15.4	12.6
Leucine	113.1	85.1	28.0	34.8	74.0	33.4	28.0[f]	28.0[f]	28.9
Valine	75.9	68.5	7.4	25.6	32.2	20.6	20.4	18.9	17.0
Phenylalanine	59.4	56.4	3.0	25.2	28.6	21.4	15.6	14.4	14.4

[a] Maintenance + production of 30 kg milk with 3.2% protein (no changes in body protein mass).
[b] Predicted outflow from the rumen of digestible microbial amino acids when the dietary energy supply fulfils the requirements.
[c] Soybean meal.
[d] Rapeseed meal
[e] Composition,%: barley, 10; maize, 30; rapeseed meal, 30; fish meal, 20; grass, 10.
[f] First limiting amino acid.

The deficit in the requirements must therefore be met from undegraded dietary protein. Different feed proteins have different amino acid composition and digestibility and consequently different potential for supplying the cow with the amino acids that are in short supply. This is also illustrated in Table 6 where the amounts of supplementary digestible amino acids required to meet the requirements of the first limiting amino acid are calculated for different feeds. These calculations assume that the amino acid profile of the undegraded protein is the same as that of the intact protein. Furthermore, it is assumed that each individual amino acid is digested in the small intestine to the same extent although this may not always be the case as discussed earlier.

Table 6 illustrates that the first limiting amino acid differs among feeds. For rapeseed meal and fishmeal, leucine was first limiting. For grains, including barley, oats and maize the calculations showed that lysine was the first limiting amino acid. For soybean meal, methionine was identified as the first limiting amino acid.

In Table 7 an ideal amino acid profile is calculated on the basis of the requirements given in Table 6. The ideal profile is compared with values estimated for endogenous protein (Larsen et al., 2000) and directly determined values for duodenal flow resulting from 33 diets (Hvelplund, 1986). Based on the variation determined for each amino acid in the duodenal flow the percentage of diets in which the amino acid is relatively undersupplied is calculated (Table 7). Apparently, the most frequently limiting amino acid is leucine which is calculated to be undersupplied by 89% of the diets, while methionine, lysine and threonine were found to be undersupplied by 68, 34 and 15% of the diets, respectively. This finding is rather surprising, because leucine has, to the authors' knowledge, never been experimentally found to be the first limiting amino acid. On the other hand, Table 7 also demonstrates that the contributions of methionine and lysine to the duodenal flow are much more variable than that of leucine, indicating that the supply of the two former amino acids is much more influenced by diet composition than that of leucine. Most probably, methionine is the first limiting amino acid in diets in which soyabean meal is the main protein, whereas lysine is the first limiting amino acid when cereal protein predominates. Consequently, leucine would be expected to generally be the second limiting amino acid. This is in agreement with the finding of Fisher (1972).

The proportions of methionine and lysine in the ideal amino acid profile shown in Table 7 are somewhat lower than the values proposed by Rulquin et al. (1993). However, it should be noted that the values given in Table 7 are in % of total amino acids, whereas those given by Rulquin et al. (1993)

Table 7
Amino acid profile (g AA/100 g AA[a]) of ideal protein compared with those of endogenous protein and duodenal flow and calculated per cent of diets in which the amino acids in duodenal flow were relatively undersupplied when compared to the ideal protein

	Ideal protein[a,b]	Endogenous protein[c]	Duodenal flow[a,d]		Relative undersupply
			Mean	CV	(% of diets[e])
Lysine	6.7	6.0	6.9	7.4	34
Methionine	2.0	0	1.9	9.6	68
Threonine	5.2	4.4	5.4	4.4	15
Isoleucine	4.8	3.7	5.6	3.4	0
Leucine	8.6	6.3	8.1	4.3	89
Valine	5.3	5.5	6.4	3.6	0
Phenylalanine	4.4	2.6	5.0	7.7	5

[a] Tryptophan not included.
[b] Calculated from requirements for maintenance and milk production – see Table 6.
[c] Larsen et al. (2000).
[d] Results from 33 different diets (Hvelplund, 1986).
[e] Based on the duodenal flow given in the preceeding column.

are in % of protein. When this is taken into consideration the values given by Rulquin are lower for lysine but higher for methionine compared to those in Table 7.

These theoretical calculations indicate that different amino acids can limit milk production and, furthermore, they suggest which amino acid is the first limiting in different feeds. The calculations agree with experiments for estimating the amino acid requirements for milk production of dairy cows, which have shown that different amino acids are first limiting in different feeding situations, and also that lysine and methionine seem to be the most frequently limiting amino acids (Fisher, 1972; Seymour et al., 1990; Fraser et al., 1991; Schwab et al., 1992).

5. Options for future improvements in the use of ideal protein in feed evaluation

Current feed formulation and feed evaluation is generally based on average table values for the contents and digestibility of amino acids in the individual feedstuffs. However, new approaches for analysis of digestible amino acids based on rapid in vitro and in situ analysis techniques (Hvelplund et al., 1992; Boisen and Fernandez, 1995) appear to result in more correct estimates of the actual feed batches. Alternatively, physical analysis methods (e.g. NIRS) which are much more rapid and can be used on-line during feed production, after appropriate calibration and an automatic set-up. Generally, physical analysis methods may become realistic alternatives for the direct but more slow chemical methods in routine analyses of feed quality.

With a more precise knowledge of the nutritional value of the actual feed batches it may also be relevant to consider documented smaller differences and changes in the ideal protein composition. These may primarily be caused by animal factors, e.g. sex and age but also the health status may be relevant to correct for. Future feed evaluation for both ruminants and non-ruminants aims at developing dynamic whole animal models where new knowledge with respect to the ideal protein concept can be incorporated when available.

6. Conclusions

The ideal amino acid profile is a valuable tool for protein evaluation of feeds for farm animals. The ideal protein most investigated is that for growing pigs. However, even for this purpose a specific amino acid profile has not been finally documented or generally accepted.

The ideal amino acid pattern needs to be related to available dietary amino acids in the small intestine, i.e. standardized ('true') digestible amino acids. The opportunity to supply pig diets with industrial amino acid preparations covering the generally first limiting amino acids, i.e. lysine, methionine, threonine and tryptophan, has drawn more attention to the precise requirements for the other essential amino acids, because they may become limiting in amino acid-supplemented diets

For ruminants, the determination of the intestinal supply of amino acids, and consequently the requirements for these, is more complicated. Thus, several predictions of the processes in the digestive tract are required. These include: (i) microbial degradation of the dietary protein in the rumen, (ii) microbial net synthesis of protein in the rumen related to the specific feed, which mainly corresponds to the dietary supply of fermentable carbohydrates, and (iii) digestion in the small intestine (ileal amino acid digestibility) of undegraded dietary protein and microbial protein.

More research is needed for obtaining commonly accepted and more correct feed evaluation systems, including protein evaluation systems, for the different farm animals. The implementation of such systems, in which a more flexible ideal protein concept plays a central role, can generally improve feed utilization and thus reduce the vaste of nutrients. Furthermore, animal welfare and performance can be improved and environmental pollution from excreted surplus nitrogen minimized.

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