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Metabolizable methionine and lysine requirements of growing cattle[1]

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ABSTRACT: Two growth studies were conducted to determine the Met and Lys requirements of growing cattle. In each 84-d trial, steer calves were fed individually diets containing 44% sorghum silage, 44% corn cobs, and 12% supplement (DM basis) at an equal percentage of BW. In Trial 1, 95 crossbred steers (251 kg) were supplemented with urea or meat and bone meal (MBM). Incremental amounts of rumen-protected Met were added to MBM to provide 0, .45, .9, 1.35, 3, and 6 g/d metabolizable Met. In Trial 2, 60 steers (210 kg) were supplemented with urea or corn gluten meal (CGM). Incremental amounts of rumen-protected Lys were added to CGM to provide 0, 1, 2, 3, 4, 5, 6, 8, and 10 g/d metabolizable Lys. Supplementation with MBM and CGM increased the supply of metabolizable protein to the animal. Steers fed MBM plus 0 Met gained 49 g/d more than steers fed urea, whereas steers fed CGM plus 0 Lys gained 150 g/d more than steers fed urea. Supplementation of rumen-protected Met and Lys improved ADG in steers fed MBM and CGM, respectively ($P < .10$). Nonlinear analysis, comparing gain vs supplemental Met and Lys intake, predicted supplemental Met and Lys requirements of 2.9 and .9 g/d, respectively. This amount of additional Met promoted .13 kg/d gain greater than MBM alone, and this amount of additional Lys promoted .10 kg/d gain greater than the CGM alone. Metabolizable Met and Lys requirements were predicted from Level 1 of NRC (1996) calculated metabolizable protein supply, amino acid analysis of abomasal contents, and the maximum response to supplemental AA. Steers gaining .39 kg/d required 11.6 g/d Met or 3.1% of the metabolizable protein requirement, whereas steers gaining .56 kg/d required 22.5 g/d Lys or 5.7% of the metabolizable protein requirement.

Key Words: Beef Cattle, Amino Acid, Methionine, Metabolism, Lysine, Requirements

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Introduction

Forage diets for growing calves are often deficient in metabolizable protein (Wilkerson et al., 1993). To meet the animal's metabolizable protein requirement and increase ADG, escape protein sources are generally supplemented (Goedeken et al., 1990a; Gibb et al., 1992b; Klemesrud et al., 1997b). However, sources of escape protein vary markedly in amino acid content, influencing the supply of metabolizable amino acids available for the animal (Merchen and Titgemeyer, 1992).

Balancing escape protein supplements to meet the animal's metabolizable amino acid requirements may improve ADG and efficiency of protein utilization (gain per unit of supplemental protein). Klemesrud et al. (1997a) reported meat and bone meal (**MBM**) to be a good source of escape protein although deficient in Met. Supplementation of ruminally protected Met increased ADG and protein efficiency in steers fed MBM. Corn gluten meal (**CGM**), also a good source of escape protein (Nakamura et al., 1994) and an excellent source of sulfur amino acids, is a poor source of Lys (Merchen and Titgemeyer, 1992).

Wilkerson et al. (1993) summarized a number of calf growth trials and estimated the metabolizable protein requirements of growing calves based on regression of daily gain against calculated metabolizable protein flow. The coefficient of variation for amino acids across all supplements was used in determining the amino acid requirements (Goedeken et al., 1990b). Ainslie et al. (1993) reported similar work with Holstein calves, with comparable values for metabolizable protein requirements. Estimates of amino acid requirements, however, were based on the amino acid composition of gain.

This research was conducted to determine the metabolizable Met and Lys requirements of growing cattle based on ADG response to supplemental rumen-protected Met and Lys.

Materials and Methods

Growth Trials. Two calf growth trials were conducted to determine the metabolizable Met and Lys require-

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Table 1. Composition of diets fed to growing steers, Trial 1

Ingredient	Supplemental amino acid treatment		
	Urea control	Meat and bone meal[a]	Meat and bone meal + Met[a]
	%, DM basis		
Sorghum silage	44	44	44
Ground corn cobs	44	44	44
Dry supplement			
Meat and bone meal	—	6.17	6.17
Soybean hulls	8.59	4.16	4.08
Urea	1.88	1.07	1.07
Dicalcium phosphate	.93	—	—
Salt	.3	.3	.3
Trace mineral premix[b]	.05	.05	.05
Vitamin premix[c]	.03	.03	.03
Selenium premix[d]	.02	.02	.02
Smartamine M[e]	—	—	.08

[a]Supplements mixed at feeding to provide incremental amounts of rumen-protected Met (0, .45, .90, 1.35, 3, or 6 g/d of supplemental Met).
[b]Contains 10% Mg, 6% Zn, 2% Mn, 4% Fe, .5% Cu, .3% I, and .05% Co.
[c]15,000 IU of vitamin A, 3,000 IU of vitamin D, and 3.75 IU vitamin E per gram of premix.
[d]Premix contains .06% Se.
[e]Contains 70% Met (Rhône-Poulenc Animal Nutrition, Atlanta, GA).

Table 2. Composition of diets fed to growing steers, Trial 2

Ingredient	Supplemental amino acid treatment		
	Urea control	Corn gluten meal[a]	Corn gluten meal + Lys[a]
	%, DM basis		
Sorghum silage	44	44	44
Ground corn cobs	44	44	44
Dry supplement			
Corn gluten meal	—	4.08	4.15
Finely ground corn	8.59	5.24	4.83
Urea	1.94	1.12	1.12
Dicalcium phosphate	.87	.82	.82
Salt	.3	.3	.3
Ammonium sulfate	.2	.2	.2
Trace mineral premix[b]	.05	.05	.05
Vitamin premix[c]	.03	.03	.03
Selenium premix[d]	.02	.02	.02
Limestone	—	.02	.02
Smartamine M[e]	—	.1	—
Smartamine ML[f]	—	—	.46

[a]Supplements mixed at feeding to provide incremental amounts of rumen-protected Lys (0, 1, 2, 3, 4, 5, 6, 8, or 10 g/d of supplemental Lys).
[b]Contains 10% Mg, 6% Zn, 2% Mn, 4% Fe, .5% Cu, .3% I, and .05% Co.
[c]15,000 IU of vitamin A, 3,000 IU of vitamin D, and 3.75 IU vitamin E per gram of premix.
[d]Premix contains .06% Se.
[e]Contains 70% Met (Rhône-Poulenc Animal Nutrition, Atlanta, GA).
[f]Contains 15% Met and 50% Lys (Rhône-Poulenc Animal Nutrition).

ments of growing cattle based on ADG response. Trial 1 used 95 medium-framed crossbred beef steers (251 ± 37 kg) assigned randomly to treatments, which consisted of either a urea supplement or MBM supplement plus incremental amounts of rumen-protected Met (Smartamine M; Rhône-Poulenc Animal Nutrition, Atlanta, GA; Table 1). The amounts of Met from rumen-protected Met were 0, .45, .90, 1.35, 3, or 6 g/d. Trial 2 used 60 medium-framed crossbred beef steers (210 ± 24 kg) assigned randomly to treatments that consisted of either a urea supplement or CGM supplement plus incremental amounts of rumen-protected Lys (Smartamine ML; Rhône-Poulenc Animal Nutrition; Table 2). The amounts of Lys from rumen-protected Lys were 0, 1, 2, 3, 4, 5, 6, 8, or 10 g/d. These Smartamine products contain Met alone or Lys and Met encapsulated in a pH-sensitive coating (poly-2-vinyl-pyridine-co-styrene) that is stable at a ruminal pH of 5.4, but it loses its integrity when it enters the abomasum (Polan et al., 1991).

Steers for each trial were fed individually, at an equal percentage of BW, once daily with Calan electronic gates (American Calan, Northwood, NH). Diets consisted of 44% sorghum silage (7.1% CP, 68% TDN), 44% corn cobs (2.3% CP, 48% TDN), and 12% supplement (DM basis) balanced to 60% TDN and 11% CP. The quantity of DM fed was computed as a percentage of BW and was adjusted as needed to minimize orts while maintaining intake near ad libitum. Average DMI was 1.93 and 2.15% of BW for Trials 1 and 2, respectively.

Body weight data were collected, before feeding, every 28 d, and amounts of feed offered were recalculated based on current weights. Weights were measured on three consecutive days at the beginning, at d 56, and at the end of each 84-d trial. Steers were implanted with estradiol-17β at the beginning of each study.

Blood was drawn by jugular venipuncture from all steers before feeding on d 56 of each study. Blood was placed on ice until it was centrifuged at 5,000 × g for 20 min. Three milliliters of plasma from each calf was deproteinized with 90 mg of sulfosalicylic acid and analyzed for plasma amino acids (AOAC, 1984) using ion-exchange chromatography with HPLC equipment (Waters, Milford, MA).

For each trial, animal gain was first analyzed as a completely randomized design using the GLM procedure of SAS (1985). Steer was the experimental unit. The model included protein source and protected amino acid (**AA**) amount; the residual was the error term. F-Test-protected least significant differences (SAS, 1985) were used to determine response to the protein source and verify that there was a response to the protected AA. Then daily gain was plotted for each trial using the slope-ratio technique (Klopfenstein et al., 1985) with supplemental amino acid level as the independent variable.

The GLM procedure of SAS (1985) and least significant differences (SAS, 1985) were used to determine the mean plasma concentrations of amino acids for each treatment. Linear and quadratic contrasts were also

conducted for non-urea treatments to detect responses of plasma amino acids to increasing amounts of amino acid supplementation. Coefficients for unequal spacing were applied. The NLIN procedure of SAS (1985) was used to find the breakpoint in plasma concentration of Met and Lys with no initial response to supplemental Met or Lys followed by a positive slope. Such a response is characteristic of a limiting amino acid (Gibb et al., 1992a). Essential amino acids with an initial negative response followed by a plateau were also analyzed for a breakpoint. Such a pattern may identify amino acids that became limiting.

Metabolism Trial. The amino acid composition of the protein present at the abomasum was determined in a separate metabolism trial. Four steers were fed the urea control diet from the growing trials for 14 d preceding slaughter. Immediately following slaughter, the abomasum was isolated and the contents of the abomasum were collected. These contents were freeze-dried, ground (1-mm screen), and analyzed for N content with the macro-Kjeldahl method (AOAC, 1984). To determine amino acid composition, samples were hydrolyzed in 6 *N* HCl, and amino acid contents of hydrolyzates were determined with ion-exchange chromatography (AOAC, 1984). Separate samples were oxidized with performic acid for analysis of Cys and Met (AOAC, 1984). All analyses were conducted in duplicate.

In Situ Study. Escape protein, true protein digestibility, and amino acid composition of the MBM was determined using procedures similar to those used by Goedeken et al. (1990a) for CGM. Escape protein was determined by placing a 4-g sample into each of four Dacron bags (10 × 20 cm; 50-μm pore size; Du Pont, Wilmington, DE). Each bag was sealed by wrapping the top around a #8 rubber stopper and secured with a #18 rubber band. The bag was then folded over the rubber band and a second rubber band was added. Sample bags were placed in a 36- × 42-cm polyester bag made of mesh material and closed with a nylon zipper. To facilitate hydration, bags were soaked in 39°C water for 20 min before ruminal incubation. Bags were then placed in the liquid phase of the ruminal ventral sac of a cannulated crossbred steer (534 kg) maintained on a grass hay diet (Wilkerson et al., 1995).

Following 12 h of ruminal incubation (Goedeken et al., 1990a), bags were removed from the rumen and washed by hand until rinse water was clear (Wilkerson et al., 1995). Total N (AOAC, 1984) was determined before and after ruminal incubation to estimate the amount of ruminal escape protein. Residue remaining after ruminal incubation was composited and analyzed for amino acid composition. Residue was hydrolyzed in 6 *N* HCl, and amino acid content of hydrolysates was determined with ion-exchange chromatography (AOAC, 1984). Separate samples were oxidized with performic acid for analysis of Cys and Met (AOAC, 1984).

Digestion Study. Fourteen crossbred wether lambs (37 ± 2 kg) housed in individual metabolism crates were fed a basal diet (Table 3) containing ensiled corn cobs and alfalfa pellets. The basal diet was fed to lambs at 1.8% of BW (DM basis) throughout the trial. This maintenance diet was balanced to provide a minimum of 10% CP, 52% TDN, .42% Ca, and .18% P. Urea was included in the basal diet at 1.48% to ensure that rumen NH_3 was not limiting digestion by ruminal microbes. The urea provided 44% of the basal dietary CP.

Table 3. Basal diet for the digestion trial with lambs

Ingredient	%, DM
Ensiled corn cobs	72.70
Alfalfa pellets	15.00
Ground corn	10.00
Urea	1.48
Dicalcium phosphate	.26
Salt	.30
Ammonium sulfate	.17
Trace mineral premix[a]	.04
Vitamin premix[b]	.03
Selenium premix[c]	.02

[a]Contains 10% Mg, 6% Zn, 2% Mn, 4% Fe, .5% Cu, .3% I, and .05% Co.
[b]15,000 IU of vitamin A, 3,000 IU of vitamin D, and 3.75 IU vitamin E per gram of premix.
[c]Premix contains .06% Se.

The trial consisted of a 14-d adaptation period and a 7-d fecal collection period. Lambs were assigned randomly to receive either MBM or an unsupplemented control. Meat and bone meal was fed at 3.75% of the basal diet DMI as units of additional CP. Therefore, diets containing MBM provided 13.75% CP, whereas the unsupplemented control diet provided 10% CP. Meat and bone meal was individually weighed and hand-mixed into the basal diet at time of feeding.

Lambs were weighed before the trial to enable feeding diets on an equal percentage of BW. Lambs were fitted with fecal collection bags to allow for total fecal collection. Feces were collected daily and weighed, and a 10% subsample was taken. Subsamples were composited by lamb for the 7-d collection period. Feed, feces, and orts were oven-dried (60°C) and analyzed for DM and CP (AOAC, 1984). True protein digestion was calculated by difference in apparent N digestibilities from the unsupplemented urea control as outlined by Blasi et al. (1991).

Total metabolizable protein flow for steers at maximum gain in each of the growing trials was predicted using Level I of the NRC model (1996) for ruminant protein metabolism using the steers' average midtrial BW and DM intake. Metabolizable protein contribution from the supplemental protein source was calculated as (CP × % escape) − (CP × (1 − digestibility)]. Flow of metabolizable amino acids from the supplemental protein source were estimated based on the amino acid profile of the residue escaping ruminal degradation in the in situ study. Metabolizable protein contribution from the basal diet and the microbial contribution were calculated by difference (total metabolizable protein −

Table 4. Daily gain and dry matter intake of steers fed urea supplement or meat and bone meal supplement with incremental amounts of rumen-protected methionine, Trial 1

	Treatment							
		Meat and bone meal + Met, g/d						
Item	Urea	0	.45	.9	1.35	3	6	SEM
Number of animals	17	16	10	10	16	16	10	—
Daily DMI, % of BW	1.9	1.9	1.9	1.9	1.9	1.9	1.9	—
Daily gain, kg[a]	.22	.27	.27	.32	.33	.39	.38	.04

[a]NLIN analysis: slope = .04 (± .013) kg gain/g Met; maximum gain = .39 (± .038) kg/d (.12 kg/d greater than the meat and bone meal control); breakpoint = 2.9 g/d Met (.12/.04).

supplemental metabolizable protein). Metabolizable amino acids from the basal diet and microbial contribution were estimated based on the amino acid profile of abomasal contents.

Results and Discussion

Growth Trials. Daily gain of steers fed MBM + 0 Met was not greater ($P = .27$) than for steers fed the urea supplement (Table 4). Level 1 of the NRC (1996) predicted animals fed the urea supplement to be deficient in metabolizable protein, whereas added MBM met the animals' metabolizable protein requirement. The additional metabolizable protein from MBM should have increased ADG, unless the first-limiting amino acid in microbial protein was not provided by MBM. Methionine and Lys have been reported to be the limiting amino acids in microbial protein (Nimrick et al., 1970; Williams and Smith, 1974). Even though MBM is a good source of Lys, it is deficient in Met (Klemesrud et al., 1997a). Insufficient Met from MBM may be responsible for the lack of an ADG response over the urea control.

Addition of rumen-protected Met to MBM improved ADG ($P < .05$; Table 4), indicating that MBM provided adequate amounts of metabolizable amino acids with the exception of Met. Improvements in ADG and protein efficiency from the addition of rumen-protected Met to MBM have also been reported by Klemesrud et al. (1997a). Additionally, the improved ADG is further evidence that the rumen-protected Met source was available postruminally (Polan et al., 1991).

Maximal gain was .39 kg/d, or .12 kg/d more than the MBM control using NLIN. The breakpoint for this maximal gain was achieved by the addition of 2.9 g Met. Added Met in excess of 2.9 g did not improve ADG, suggesting that the requirement for Met was satisfied at this amount. Based on the amino acid composition of gain (Ainslie et al., 1993), 2.9 g of added Met should promote an additional gain of .15 kg/d, which is similar to the .12 kg/d observed.

Daily gain of steers fed CGM + 0 Lys was greater than that of steers fed the urea supplement ($P < .05$; Table 5). Level 1 of the NRC (1996) predicted animals fed the urea supplement to be deficient in metabolizable protein, whereas added CGM met the animals' metabolizable protein requirement. Although the requirement for metabolizable protein was satisfied, addition of rumen-protected Lys to CGM improved ADG ($P < .05$; Table 5), indicating that CGM provides adequate amounts of metabolizable amino acids with the exception of Lys. Improved responses in N retention to postruminal infusions of Lys suggested that Lys is probably the first-limiting amino acid when corn protein is fed (Burris et al., 1976; Titgemeyer et al., 1988).

Maximal gain was .56 kg/d, or .10 kg/d more than the CGM control using NLIN. The breakpoint for this maximal gain was achieved by the addition of .9 g/d Lys. Added Lys in excess of .9 g/d did not improve ADG, suggesting that the requirement for Lys was satisfied

Table 5. Daily gain and dry matter intake of steers fed urea supplement or corn gluten meal supplement with incremental amounts of rumen-protected lysine, Trial 2

	Treatment										
		Corn gluten meal + Lys, g/d									
Item	Urea	0	1	2	3	4	5	6	8	10	SEM
Number of animals	10	10	5	5	5	5	5	5	5	5	—
Daily DMI, % of BW	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	—
Daily gain, kg[a]	.31[b]	.46[c]	.55	.60	.57	.52	.52	.61	.56	.51	.05

[a]NLIN analysis: slope = .11 (± .063) kg gain/g Lys; maximum gain = .56 (± .016) kg/d (.10 kg/d greater than the corn gluten meal control); breakpoint = .9 g Lys/d (.10/.11).
[b,c]Treatments differ ($P < .05$).

Table 6. Plasma amino acid responses to incremental amounts of dietary rumen-protected methionine, Trial 1[a]

	Treatment									
		Meat and bone meal + Met, g/d								
Amino acid	Urea	0	.45	.9	1.35	3	6	SEM	Lin[b]	Quad[b]
Methionine	.23	.24	.24	.23	.25	.35	.34	.04	.004	—
Lysine	1.25	1.30	1.21	1.21	1.18	1.20	1.17	.07	—	—
Histidine	.61	.60	.53	.56	.59	.57	.68	.04	.012	—
Phenylalanine	.66	.74	.73	.70	.70	.72	.74	.04	—	—
Threonine	.54	.50	.41	.41	.49	.47	.40	.05	—	—
Leucine	1.27	1.34	1.30	1.23	1.23	1.32	1.10	.09	—	—
Isoleucine	1.17	1.17	1.19	1.13	1.11	1.09	1.00	.04	.002	—
Valine	2.01	2.10	2.05	2.10	2.00	1.92	1.69	.08	.001	—
Arginine	1.81	1.96	2.25	2.56	2.36	2.33	1.95	.25	—	.044
Tryptophan	.39	.39	.38	.38	.35	.37	.31	.02	.009	—

[a]Least squares mean concentrations (mg/100 mL).
[b]Probability values for significant linear or quadratic effects ($P < .05$).

at this amount. Based on the amino acid composition of gain (Ainslie et al., 1993), .9 g/d of added Lys should promote an additional gain of .02 kg/d, which is different from the .10 kg/d we observed.

Addition of rumen-protected Met to MBM resulted in an increase in plasma Met concentration ($P < .05$; Table 6). Nonlinear analysis predicted a breakpoint in plasma Met concentration between 1.35 and 3 g/d of added rumen-protected Met. Such a response is characteristic of a limiting amino acid (Gibb et al., 1992a). This breakpoint indicates where the Met requirement is satisfied, and it corresponds to the requirement determined using ADG as the response criteria. The amino acids Ile, Val, and Trp exhibited decreases in plasma concentration ($P < .05$; Table 6), suggesting that one or more of these amino acids may become next-limiting. However, the initial negative responses were not followed by a plateau, which would indicate that the amino acids did not become limiting.

Addition of rumen-protected Lys to CGM resulted in a quadratic response in plasma Lys concentration ($P < .05$; Table 7) with an initial increase in concentration followed by a decrease. Nonlinear analysis predicted a breakpoint in plasma Lys concentration at 1 g of added rumen-protected Lys in which there was no initial response to supplemental Lys followed by a positive slope. This breakpoint indicates where the Lys requirement is met and corresponds to the requirement determined using ADG as the response criterion. The amino acid Met exhibited a decrease in plasma concentration ($P < .05$; Table 7), suggesting it may become next-limiting. However, the initial negative response is not followed by a plateau, which would indicate that the amino acid did not become limiting.

Metabolism Trial. Amino acid composition of protein present in the abomasum was determined (Table 8). These values represent the amino acid composition of the microbial protein, as well as the dietary protein from the basal diet that escapes ruminal degradation. Whereas the microbial protein supply is a function of the dietary TDN supply (Burroughs et al., 1974), its amino acid composition is similar among different cat-

Table 7. Plasma amino acid responses to incremental amounts of dietary rumen-protected lysine, Trial 2[a]

	Treatment												
		Corn gluten meal + Lys, g/d											
Item	Urea	0	1	2	3	4	5	6	8	10	SEM	Lin[b]	Quad[b]
Methionine	.22[c]	.40	.38	.33	.39	.31	.37	.34	.31	.27	.03	.003	—
Lysine	1.03[c]	.72	.72	.73	.82	.78	1.00	.87	.85	.76	.08	—	.034
Histidine	.51	.47	.41	.45	.52	.42	.57	.53	.46	.48	.05	—	—
Phenylalanine	.64[c]	.92	.94	.89	.98	.83	1.01	.93	.96	.89	.05	—	—
Threonine	.56	.65	.76	.59	.86	.53	.82	.69	.67	.55	.09	—	—
Leucine	1.42[c]	1.96	2.07	2.04	2.14	2.01	2.38	2.19	2.10	2.05	.13	—	—
Isoleucine	1.21[c]	1.05	1.07	1.07	1.16	1.06	1.10	1.16	1.12	1.06	.06	—	—
Valine	1.99	1.81	1.85	1.82	1.97	1.77	2.19	1.98	1.89	1.78	.13	—	—
Arginine	1.08	1.19	1.25	1.24	1.24	1.15	1.14	1.35	1.13	1.24	.09	—	—
Tryptophan	.19[c]	.22	.25	.15	.25	.16	.23	.21	.26	.23	.04	—	—

[a]Least squares mean concentrations (mg/100 mL).
[b]Probability values for significant linear or quadratic effects ($P < .05$).
[c]Urea vs corn gluten meal with 0 added Lys, $P < .05$.

Table 8. Amino acid composition of abomasal protein

Amino acid	% of crude protein (DM basis)[a]
Methionine	2.19 ± .11
Lysine	5.86 ± .70
Histidine	1.85 ± .38
Phenylalanine	4.56 ± .83
Threonine	4.80 ± .57
Leucine	8.63 ± 1.28
Isoleucine	4.44 ± .70
Valine	5.30 ± .83
Arginine	4.64 ± .79
Cystine	2.07 ± .62

[a]Mean ± SD.

tle and different diets (Burris et al., 1973; Storm et al., 1983). The metabolizable protein and amino acid supply from the basal diet, however, is a function of the escape protein value of the feedstuffs in the basal diet as well as their amino acid content.

In Situ and Digestion Studies. The MBM contained 44.5% CP (DM basis), of which 61.8% escaped ruminal degradation (Table 9). True protein digestibility of the MBM and its amino acid composition are similar to previously reported values for MBM of similar CP and ash content (Klemesrud et al., 1997a). The CGM contained 71.3% CP (DM basis), of which 80.4% escaped ruminal degradation (Table 9). Stern et al. (1997) reported problems with measuring degradability of CGM protein. Cozzi et al. (1993) studied degradation of CGM in situ with and without added fiber. Their escape protein values ranged from 69.4 to 87.5 depending on added fiber and assumed rate of passage. Our value falls with that range. The CGM was highly digestible and contained an amino acid array similar to that reported by NRC (1996).

The metabolizable protein requirement for a 269-kg steer (average midtrial BW, Trial 1) gaining .39 kg/d (maximum gain) is 375 g/d (NRC, 1996; Table 10). Meat and bone meal supplied 57 g/d of metabolizable protein, and the rumen-protected Met supplied 2.9 g/d. The remaining 315 g, calculated by difference, must have been provided by microbial protein and dietary escape protein from the basal diet. Based on the amino acid composition of abomasal contents and MBM, the amount of Met supplied to maximize ADG was 11.6 g/d, or 3.1% of the metabolizable protein requirement (Table 10).

The estimated Met requirement of 3.1% of MP is greater than the requirement reported by the NRC (1996). However, a summary of very similar growth trials predicted a Met requirement of 3.0% of metabolizable protein for cattle gaining up to .89 kg/d (Wilkerson et al., 1993). Whereas the NRC (1996) Met requirement is based on the composition of muscle and whole empty-body contents (Ainslie et al., 1993), our requirement of 3.1% and that of Wilkerson et al. (1993) are based on amino acid supply to the animal and ADG response. Additionally, amino acid requirements for maintenance may be different from amino acid requirements for gain. For cattle at low rates of gain, the maintenance requirement is a greater proportion of the total. The greater the gain, the closer the amino acid requirements should approach the composition of body tissue.

Total sulfur AA (**TSAA**) were calculated to be 5.3% of MP, and Cys supplied 42% of the TSAA. If Cys can supply 50% of the TSAA (Klemesrud et al., 2000), then the Met requirement would be 2.65% of MP if Cys was supplied at 2.65% of MP or higher.

The metabolizable protein requirement for a 233-kg steer (average midtrial BW, Trial 2) gaining .56 kg/d (maximum gain) is 397 g/d (NRC, 1996; Table 11). The corn gluten meal supplied 110 g of metabolizable protein, whereas the rumen-protected Met and Lys supplied 2.7 g. The remaining 284 g, calculated by difference, must have been provided by microbial protein and dietary escape protein from the basal diet. Based on the amino acid composition of abomasal contents and CGM, the amount of Lys supplied to maximize ADG was 22.5 g/d, or 5.7% of its metabolizable protein requirement (Table 11).

Based on our data, the estimated Lys requirement of 5.7% of MP is less than the requirement reported by the NRC (1996), possibly for the same reasons previously discussed. In both trials, all other amino acids seemed to be present in excess of the NRC requirement (1996), with the exception of His. However, plasma concentrations of His do not suggest that it became limiting. Our results would suggest that the NRC (1996) requirement for His is an overestimate and that the actual requirement is 2.1%, or less, of the metabolizable protein.

During periods of rapid growth, microbial protein production is not sufficient to meet the animal's protein requirements (Klopfenstein et al., 1985). The value of an escape protein source then becomes its ability to complement microbial amino acid production to meet an animal's amino acid requirements. Accurate deter-

Table 9. Crude protein, escape protein, digestibility, and amino acid content[a] of protein sources

Item	Meat and bone meal	Corn gluten meal[b]
CP, % DM	44.5	71.3
Escape protein, % CP	61.8	80.4
Digestibility, % CP[c]	78.6	96.5
Methionine, % CP	1.0	2.7
Lysine, % CP	3.7	1.8
Histidine, % CP	1.0	1.9
Phenylalanine, % CP	2.6	6.6
Threonine, % CP	2.4	3.7
Leucine, % CP	4.5	16.5
Isoleucine, % CP	2.1	4.2
Valine, % CP	3.2	4.5
Arginine, % CP	6.2	4.3
Cystine, % CP	.8	2.1

[a]Expressed as a ratio to CP remaining after 12-h incubation in situ.
[b]Based on Goedeken et al. (1990a).
[c]Based on lamb digestibility trial.

Table 10. Calculated metabolizable protein and amino acid flow, Trial 1[a]

Item	Amino acid source[b] Basal diet	Meat and bone meal	Met	Total[c]	% of MP	Requirement[d] % of MP
Metabolizable protein	315	57	2.9	375	—	
Methionine	8.1	.6	2.9	11.6	3.1	2.0
Lysine	21.7	2.1		23.8	6.4	6.4
Histidine	6.9	.6		7.5	2.0	2.5
Phenylalanine	16.9	1.5		18.4	4.9	3.5
Threonine	17.8	1.4		19.2	5.1	3.9
Leucine	32.0	2.6		34.6	9.2	6.7
Isoleucine	16.5	1.2		17.7	4.7	2.8
Valine	19.6	1.8		21.4	5.7	4.0
Arginine	17.2	3.5		20.7	5.5	3.3
Cystine	7.7	.5		8.2	2.2	—

[a]Expressed as grams/day of metabolizable protein and amino acids flowing to the small intestine for steers at maximum gain (.39 kg/d). Based on a 269-kg animal (average midtrial BW) consuming 1.9% of body weight.

[b]Contribution from basal diet, meat and bone meal (MBM) and rumen-protected Met. Metabolizable protein supplied by basal diet calculated as total – (MBM + Met). Metabolizable protein supplied by MBM calculated as (CP × escape) – [CP × (1 – digestibility)]. Contribution from Met at breakpoint for maximum gain (see Figure 1). Amino acids from the basal diet calculated as (metabolizable protein × amino acid composition [Table 8])/85% true protein. Amino acids from MBM calculated as metabolizable protein × amino acid composition (Table 9).

[c]Total metabolizable protein (MP) calculated from Level 1 of NRC (1996) model. Total individual amino acids equals the sum from each source.

[d]Requirement based on NRC (1996) expressed as a percentage of metabolizable protein (MP).

mination of amino acid requirements and diet formulation for amino acids can improve ADG and efficiency of protein utilization (Klemesrud et al., 1997b).

Implications

Addition of rumen-protected amino acids to diets adequate in metabolizable protein can improve ADG of growing steers if that amino acid is deficient in the metabolizable protein presented postruminally. By meeting the animal's requirement for amino acids without overfeeding them, efficiency of protein utilization can be maximized. The supply of amino acids from microbial protein and from dietary escape protein must be considered when evaluating the supply of metabolizable amino acids to the ruminant relative to the requirements.

Table 11. Calculated metabolizable protein and amino acid flow, Trial 2[a]

Item	Amino acid source[b] Basal diet	Corn gluten meal	Met and Lys	Total[c]	% of MP	Requirement[d] % of MP
Metabolizable protein	284	110	2.7	397	—	
Methionine	7.3	3.0	1.8	12.1	3.0	2.0
Lysine	19.6	2.0	.9	22.5	5.7	6.4
Histidine	6.2	2.1		8.3	2.1	2.5
Phenylalanine	15.3	7.3		22.6	5.7	3.5
Threonine	16.0	4.1		20.1	5.1	3.9
Leucine	28.8	18.2		47.0	11.8	6.7
Isoleucine	14.8	4.6		19.4	4.9	2.8
Valine	17.8	5.0		22.8	5.7	4.0
Arginine	15.5	4.7		20.2	5.1	3.3
Cystine	6.9	2.3		9.2	2.3	—

[a]Expressed as grams/day of metabolizable protein and amino acids flowing to the small intestine for steers at maximum gain (.56 kg/d). Based on a 233-kg animal (average midtrial BW) consuming 2.1% of body weight.

[b]Contribution from basal diet, corn gluten meal (CGM), and rumen-protected Met and Lys. Metabolizable protein supplied by basal diet calculated as Total – (CGM + Met and Lys). Metabolizable protein supplied by CGM calculated as (CP × escape) – [CP × (1 – digestibility)]. Contribution from Met and Lys at breakpoint for maximum gain (see Figure 2). Amino acids from the basal diet calculated as (metabolizable protein × amino acid composition [Table 8])/85% true protein. Amino acids from CGM calculated as metabolizable protein × amino acid composition (Table 9).

[c]Total metabolizable protein (MP) calculated from Level 1 of NRC (1996) model. Total individual amino acids equals the sum from each source.

[d]Requirement based on NRC (1996) expressed as a percentage of metabolizable protein (MP).

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