Development of a System to Predict Feed Protein Flow to the Small Intestine of Cattle*

H. G. Bateman, II,¹ J. H. Clark,² and M. R. Murphy²

¹Department of Dairy Science, Louisiana State University Agricultural Center, Baton Rouge 70803

²Department of Animal Sciences, University of Illinois, Urbana 61801

ABSTRACT

A data set constructed from research trials published between 1979 and 1998 was used to derive equations to adjust published tabular values for the rumen-undegradable protein (RUP) content of feeds to better predict the passage of nonammonia nonmicrobial N (NANMN) to the small intestine of lactating dairy cows. Both linear and nonlinear forms of equations were considered for making adjustments. Iterative processes were used to estimate equation parameters. A logistic equation was developed and considered to be the most optimal for adjustment of published tabular RUP contents of feeds. The equation is a function of dietary dry matter intake (DMI) and includes terms for tabular RUP and nonprotein N contents of individual feeds. The equation has a standard error of prediction of 69.29 g of NANMN/d per cow and a root mean square prediction error of 104.63 g of NANMN/d per cow. Independent evaluation of the equation indicated that the concept of variable RUP content for feeds based on DMI is correct. Further refinements may be needed as other data become available to quantify the effects of additional factors on the RUP value of feeds.

(**Key words:** protein, degradability, model, dairy cow)

Abbreviation key: MCPI = maintenance CP intake, MEI = maintenance energy intake, MPIAF = MCPI adjustment factor, MSPE = mean square prediction error, NANMN = nonammonia nonmicrobial N, RDTP = ruminally degradable true protein, RMSPE = root mean square prediction error, SEY = standard error of prediction.

INTRODUCTION

Numerous factors have been suggested to affect passage of microbial and feed protein to the small intestine

of ruminants including feed intake; forage-to-concentrate ratio in the diet; source, quality, and amount of carbohydrate and CP in the diet; ruminal pH; associative effects of feeds; frequency of feeding; forage and grain processing; forage conservation methods; micro-nutrient supply; feeding buffers, salts, and ionophores; and environmental conditions (Clark and Davis, 1983; NRC, 1985; Sniffen and Robinson, 1987; Clark et al., 1992). Because many variables affect degradability of protein in the rumen, RUP content of a given feed is not constant in all feeding situations. The many factors that affect degradation of feed protein in the rumen currently make it impossible to predict passage of feed protein to the small intestine with sufficient accuracy.

Santos et al. (1998) reviewed published literature where protein sources considered high in RUP content replaced soybean meal and concluded that increasing the RUP content of diets fed to lactating cows does not consistently improve lactational performance. Santos et al. (1998) also indicated that this may have resulted from 1) decreased microbial CP synthesis in the rumen, 2) poor AA profile of RUP, 3) low intestinal digestibility of RUP, or 4) the RUP content of control diets being adequate to maximize lactational performance. Bateman et al. (2001a) reported that prediction models underestimated the mean passage of feed CP to the small intestine of dairy cows. The underestimation of feed protein passage to the small intestine of dairy cows eating large amounts of feed was attributed to an overestimation of degradability of individual feed proteins.

Clark et al. (1992) reported a linear relationship between OM intake and passage of nonammonia nonmicrobial N (NANMN) to the small intestine of dairy cows. Santos et al. (1998) reported that there were no differences in DM or N intakes when soybean meal was replaced by protein sources reported to be high in RUP content. Therefore, it is likely that the RUP content of feeds increases as DMI increases.

The objectives of this work were 1) to evaluate some tabular values for the RUP content of feeds (NRC, 1985, 1989, 1996) for their ability to predict feed protein flow to the small intestine of lactating dairy cows and 2) to develop an equation that could be used to modify

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Corresponding author: H. G. Bateman, II; e-mail: hbateman@agcenter.lsu.edu.

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tabulated RUP values to better predict feed protein flow to the small intestine of lactating dairy cows.

MATERIALS AND METHODS

Model Development

A data set was constructed from research trials published between 1979 and 1998 (Appendix Table 1). The data set consisted of 150 treatment means from 35 research papers. The data set was supplemented with 8 treatment means from 2 unpublished trials from the University of Illinois. All were Latin square designs that measured passage of total, microbial, and NANMN to the small intestine of cattle. All trials were conducted using duodenally cannulated cattle. All treatment means were assumed to have been measured without bias, which might or might not have been correct.

Dry matter intake was reported in all studies. Diet composition was either reported or could be calculated for all studies. When CP content of individual feeds was reported, those values were used to calculate CP intake; otherwise, values in Table 1 were used to calculate CP intake. The CP compositions of feeds in Table 1 are those reported by NRC (2001). The NPN values (Table 1) were supplied by W. Weiss (personal communication, 1998) and represent a compilation of data from commercial laboratories, literature data, *Nutrient Requirements of Beef Cattle* (NRC, 1996), and unpublished data provided by university researchers. Tabulated values for RUP were from published sources (NRC, 1985, 1989, 1996). When published values conflicted for feeds, the more recent value was used for further analysis. Published RUP values were supplemented with data compiled from literature when feeds were encountered that had no published values. Tabulated values for forages were grouped in ways similar to those in the dairy NRC (2001). The RUP intake was calculated by multiplying CP intake from each N-containing feed in the diet by the RUP percentage of that feed and then summing intakes of RUP from all feeds in a diet. The calculated RUP intake was assumed to be equal to passage of RUP to the small intestine and was compared with passage of NANMN to the small intestine after dividing estimated passage of RUP by 6.25.

Two forms of equations (linear and nonlinear) were developed to adjust RUP values of individual feeds as a function of DMI. To develop these equations, maintenance energy intake (**MEI**) for lactating cows was set equal to 6 kg of DM/d, and maintenance CP intake (**MCPI**) was set equal to 2.5 kg of DM/d when the DMI contained 1.72 Mcal of NE_L/kg and 17% CP. These quantities of DM were adequate to supply the energy and protein for maintenance of a 650-kg cow (NRC, 1989).

Equations were developed that adjusted published RUP values (Table 1) to maximize the coefficient of multiple determination when the observed passage of NANMN was regressed against the predicted passage of NANMN. Equations were parameterized by an iterative process using the solver in Microsoft Excel 2002. After providing initial estimates for coefficients in all equations based on a visual estimation from plots of measured and predicted passage of RUP, iterations were conducted to maximize the coefficient of multiple determination (R^2). Iterations were constrained by forcing the slope to equal unity while the intercept equaled zero for the prediction line. Equations were considered to adequately adjust RUP values when the slope of the regression of predicted and measured values did not differ from unity, and the intercept of this regression did not differ from zero (Graybill and Iyer, 1994). All regression lines were considered significant when a Student's *t*-test indicated that their slope differed from zero with a probability of $P < 0.05$. Bias in prediction was determined when the slope of the regression line between the prediction residuals (measured – predicted values) and the predicted values differed from zero with a probability of $P < 0.05$.

Model Evaluation

A second data set was constructed from research trials published between 1998 and 2003 (Appendix Table 2). These data represented 52 treatment means from 12 research papers that were from trials similar to those used for model development. The data set was supplemented with 4 treatment means from one unpublished trial from the University of Illinois. Again, all treatment means were assumed to have been measured without bias, which might or might not have been correct.

Dry matter intake and diet composition were either available for all trials or could be calculated. When CP contents of feeds were reported, those values were used to calculate CP intake; otherwise, values in Table 1 were used to calculate CP intake. The NPN values were from Table 1. Tabulated values for RUP contents of feeds were from Table 1. The calculations used for estimating flow of RUP were similar to those used in model development. The calculated RUP intake was assumed to equal the passage of RUP to the duodenum and was compared with passage of NANMN to the duodenum after dividing estimated passage of RUP by 6.25.

A 2-tailed Student's *t*-test was used to compare mean predicted and measured passage of NANMN to the duodenum (Snedecor and Cochran, 1989). Subtracting the predicted passage of NANMN from the measured passage of NANMN generated residuals of prediction for the individual observations. These residuals were sta-

Table 1. The CP, NPN, and tabulated RUP content of selected feedstuffs.

Feed name and description	CP ¹	NPN ²	RUP Tabulated ³
	(% of DM)	(% of CP)	
Alfalfa meal, 17% CP	19.2	3	59
Bakery by-products			
By-product meal	12.5	11	20
Bread, waste	15	11	20
Cereal by-product	9.1	11	20
Cookie by-product	9.7	11	20
Barley			
Grain	12.4	2	27
Malt sprouts	20.1	40	36
Silage, headed	12	59	23
Sugar beet pulp, dried	10	25	45
Blood meal	95.5	0	75
Brewers grains			
Dried	29.2	1	50
Wet	28.4	1	40
Canola			
Seed	20.5	21	20
Meal, mechanically extracted	37.8	14	28
Chocolate by-product	11.9	11	20
Citrus pulp, dried	6.9	26	30
Corn			
Cobs	3	3	50
Distillers grains with solubles	29.7	10	52
Gluten feed, dried	23.8	12	22
Gluten meal, dried	65	3	59
Grain, cracked, dried	9.1	3	55
Grain, cracked, high moisture	9.2	32	50
Grain and cob, dry, ground	8.6	3	55
Grain and cob, high moisture, ground	8.4	32	50
Hominy	11.9	14	35
Silage, immature	9.7	53	31
Silage, normal	8.8	36	31
Silage, mature	8.5	36	31
Cotton seeds			
Whole seeds, with lint	23.5	1	27
Seed hulls	6.2		50
Seed meal, solvent, 41.9% CP	44.9	1	43
Feathers meal with other parts, hydrolyzed	85	8	76
Fish by-products			
Anchovy, meal, mechanically extracted	71.2	10	60
Menhaden, meal, mechanically extracted	68.5	10	60
Grasses, cool season			
Pasture, intensively managed	26.5	12	20
Hay, all samples	10.6	18	35
Hay, immature	18	18	19
Hay, mid maturity	13.3	18	26
Hay, mature	10.8	18	38
Silage, all samples	12.8	59	22
Silage, immature	16.8	59	19
Silage, mid maturity	16.8	59	20
Silage, mature	12.7	59	24
Grass-legume mixtures			
Predominantly grass (17 to 22% hemicellulose)			
Hay, immature	18.4	20	18
Hay, mid maturity	17.4	20	24
Hay, mature	13.3	20	35
Silage, immature	18	59	18
Silage, mid maturity	17.6	59	19
Silage, mature	15.4	59	24

Continued

Table 1 (Continued). The CP, NPN, and tabulated RUP content of selected feedstuffs.

Feed name and description	CP ¹	NPN ²	RUP Tabulated ³
	(% of DM)	(% of CP)	
Mixed grass and legume (12 to 15% hemicellulose)			
Hay, immature	19.7	22	17
Hay, mid maturity	18.4	22	22
Hay, mature	18.2	22	33
Silage, immature	20.3	60	17
Silage, mid maturity	19.1	60	19
Silage, mature	17.4	60	24
Predominantly legume (10 to 13.5% hemicellulose)			
Hay, immature	20.5	24	17
Hay, mid maturity	19.1	24	21
Hay, mature	17.2	24	31
Silage, immature	20	60	17
Silage, mid maturity	19	60	19
Silage, mature	18.3	60	23
Legumes, forage			
Pasture, intensively managed	26.5	15	13
Hay, all samples	20.2	27	19
Hay, immature	22.8	27	16
Hay, mid maturity	20.8	27	19
Hay, mature	17.8	27	28
Silage, all samples	20	60	23
Silage, immature	23.2	60	16
Silage, mid maturity	21.8	60	18
Silage, mature	20.3	60	23
Linseed meal, solvent	32.6	5	23
Meat			
Meal, rendered	57.6	3	56
Meat and bone, rendered	54.2	3	56
Molasses			
Beet sugar	8.5		20
Sugarcane	5.8		20
Oats			
Grain, rolled	13.2	1	17
Hay, headed	9.1	27	20
Silage, headed	12.9	55	23
Peanut meal, solvent	51.8	2	30
Rice bran	15.5		25
Sorghum			
Grain, dry rolled	11.6	4	57
Silage	9.1	27	29
Soybean			
Hulls	13.9	13	25
Meal, expellers, 45% CP	46.3	5	47
Meal, solvent, 44% CP	49.9	3	35
Meal, solvent, 48% CP	53.8	3	35
Seeds, whole	39.2	25	26
Seeds, whole roasted	43	25	62
Silage, early maturity	17.4	60	23
Sunflower meal, solvent	28.4	3	26
Tomato pomace	19.3	7	62
Wheat			
Bran	17.3	2	20
Grain	14.2	2	23
Hay, headed	9.4	45	23
Middlings	18.5	2	21
Silage, early head	12	64	20
Straw	4.8		40

¹Adapted from NRC (2001).²Supplied by W. Weiss (personal communication, 1998).³Derived from NRC (1985, 1989, and 1996) and supplemented with literature data.

Table 2. Mean, maximum, minimum, and standard error of the mean for DMI, N intake, and measured flow of nonammonia nonmicrobial N (NANMN) to the small intestine from published data.¹

	Mean	SE	Minimum	Maximum
DMI, kg/d	17	0.45	3	27
N intake, g/d	470	14	80	855
NANMN, g/d	217	10	16	465

¹Derived from research papers cited in Appendix Table 1.

tistically analyzed using the mean square prediction error (**MSPE**) according to procedures outlined by Theil (1966). This analysis allows the MSPE to be subdivided into proportions of 1) error of predicting the mean (mean bias); 2) systematic errors in the prediction function, which can be corrected through a linear adjustment (slope bias); and 3) error in prediction because of random variance around the line of perfect prediction (dispersion). Mean bias was calculated as (mean predicted – mean observed)². Slope bias was calculated as R^2 for regression of predicted and observed values $\times$ (MSPE – mean bias). Dispersion was calculated as MSPE – mean bias – slope bias.

RESULTS AND DISCUSSION

A summary of the univariate statistics for the data set used to develop the equations is shown in Table 2. A wide range of diets and DMI were included in the data set (see references in Appendix Table 1).

The relationship between predicted passage of NANMN using tabulated values for the RUP contents of feeds and measured passage of NANMN to the duodenum from the data set is presented in Figure 1. There

Figure 1. Relationship between measured ($\blacktriangle$) or residual ($\bullet$) (measured – predicted) passage of nonammonia nonmicrobial N (NANMN) and predicted NANMN at the duodenum of dairy cows using tabular values for the RUP content of feeds to predict the passage of NANMN. Measured NANMN = $1.29 \pm 0.074 \times$ predicted NANMN + 6.78 ± 13.36 ($P < 0.01$); $R^2 = 0.6605$; root mean square prediction error = 89.34 g of NANMN/d. Residual NANMN = $0.287 \pm 0.074 \times$ predicted NANMN + 6.93 ± 13.36 ($P < 0.01$); $R^2 = 0.0879$.

was a positive linear relationship between measured and predicted passage of NANMN to the duodenum. Furthermore, a linear bias was indicated by the regression of residuals (measured – predicted) for NANMN and predicted passage of NANMN to the duodenum. Using tabular values to predict flow of NANMN at the small intestine produced a root mean square prediction error (**RMSPE**) of 89.34 g of NANMN/d (Theil, 1966) and a standard error of prediction (**SEY**) of 43.07 g of NANMN/d. Distribution of the errors contained in the MSPE analysis is presented in Table 3. These data indicate that tabulated values for the RUP contents of feeds did not accurately predict the measured passage of RUP to the duodenum of cattle and are in agreement with previous evaluations from our laboratory (Bateman et al., 2001a,b).

Tyrrell and Moe (1975) reported that the digestibility of a specific feed is not constant but changes with intake. An approximate 4 percentage unit decrease in total digestible nutrient content of a diet has been reported for each multiple that energy intake increases above that required for maintenance (Moe and Tyrrell, 1976). This reduction in total digestible nutrient content of a diet is a result of the depression in the digestibility of the diet as energy intake (and presumably DMI) increases. It is unlikely that the entire depression of digestibility occurs postruminally without any depression of ruminal fermentation. If ruminal fermentation was depressed, a larger percentage of the CP from the feed would pass intact to the small intestine. Therefore, an equation (not shown) was developed to apply a 4 percentage unit decrease in ruminal degradability of protein for each multiple increase in MEI above maintenance to all feeds, and the relationship between predicted and measured passage of NANMN to the duodenum of cows in the data set were compared. Dry matter intake for maintenance was set to 6 kg/d for this analysis and was based on a dietary energy content of 1.72 Mcal of NE_I /kg of DM, which supplied 10.32 Mcal of NE_I /d and is equal to the maintenance energy requirement of a 650-kg mature lactating cow (NRC, 1989). Under practical feeding situations, it is unlikely that diets with energy content similar to this would be fed at the low levels needed for maintenance. However, an energy content of 1.72 Mcal of NE_I /kg of DM also was used when calculating the DMI requirements for

Table 3. Precision of predictions for flow of nonammonia nonmicrobial N (NANMN) to the small intestine of cattle by various models as measured by the mean square prediction error (MSPE) criterion.

Prediction ¹	RMSPE ² (g/d)	Percentage of MSPE attributable to		
		Mean bias	Slope bias	Dispersion
		(%)		
Tabulated values	89.34	36.87	41.70	21.43
4% linear reduction	70.00	5.04	62.36	32.60
Eq. 1 adjustment	99.35	0.00	27.11	72.89
Eq. 5 adjustment	104.63	56.69	28.14	15.18
Eq. 5 evaluation	82.71	47.32	28.38	24.30

¹Values correspond to the following: Tabulated values = prediction of NANMN for the data set in Appendix Table 1 using values from Table 1; 4% linear reduction = prediction of NANMN for the data set in Appendix Table 1 after reducing values in Table 1 by 4% for each multiple of maintenance energy intake (6 kg DMI) above maintenance; eq. 1 adjustment = prediction of NANMN for the data set in Appendix Table 1 using eq. 1 ($RUP_{adj1} = 100 - ([RDTP \times MPIAF] + NPN)$); eq. 5 adjustment = prediction of NANMN for the data

set in Appendix Table 1 using eq. 5 $\left[RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}} \right]$; and eq. 5 evaluation = prediction of NANMN

for the data set in Appendix Table 2 using eq. 5.

²RMSPE = Root mean square prediction error.

cows producing >40 kg of milk/d (NRC, 1989) and was similar to the energy concentration of most of the diets represented in the model development database (Appendix Table 1).

The relationship between observed or residual passage of NANMN to the duodenum and predicted passage of NANMN to the duodenum after increasing RUP values by 4 percentage units for each multiple increase in MEI above maintenance is shown in Figure 2. De-

Figure 2. Relationship between measured (▲) or residual (●) (measured – predicted) passage of nonammonia nonmicrobial N (NANMN) and predicted NANMN at the duodenum of dairy cows after increasing tabular values for the RUP content of feeds by 4 percentage units per multiple increase in maintenance energy intake to predict the passage of NANMN. Measured NANMN = $0.976 \pm 0.056 \times \text{predicted NANMN} + 20.74 \pm 12.73$ ($P < 0.01$); $R^2 = 0.6567$; root mean square prediction error = 70.00 g of NANMN/d. Residual NANMN = $-0.025 \pm 0.056 \times \text{predicted NANMN} + 20.71 \pm 12.73$ ($P > 0.6$); $R^2 = 0.0012$.

creasing the RUP content of feeds by 4 percentage units per multiple of maintenance energy intake resulted in a RMSPE of 70.00 g of NANMN/d (Table 3) and a SEY of 57.01 g of NANMN/d. The decrease in the slope of the regression between predicted and measured passage of NANMN compared with that of Figure 1, along with the decrease in the RMSPE, indicates that increasing the RUP content of feeds by 4 percentage units for each multiple increase in MEI above maintenance improved the accuracy of prediction of passage of NANMN to the duodenum compared with the tabular values. This adjustment removed most of the mean bias, but a significant slope bias remained. Because increasing RUP as a function of MEI improved the accuracy of prediction of NANMN passage to the duodenum, but did not eliminate all bias of prediction, additional adjustment equations were required.

When the ruminal availabilities of N and energy are not adequately balanced in the rumen, an uncoupling of fermentation may occur (Hespell and Bryant, 1979; Stern and Hoover, 1979). For diets containing 17% CP, only 2.5 kg of DM are needed to supply the CP requirement for maintenance of mature cows. As with the situation for energy, it is unlikely that a small amount of feed would be offered with a high content of CP. However, the level of CP chosen was similar to that of the diets represented in the model development data set (Appendix Table 1). Because a smaller amount of DM can be used to supply the maintenance requirement for protein than the maintenance requirement for energy, the potential must exist for the change in RUP to be different per unit of MEI than per unit of MCPI. Therefore, a 4 percentage unit increase in RUP values for

each multiple increase in MCPI above maintenance was used to estimate NANMN passage to the duodenum. Changing the adjustment to the equation from an energy basis to a CP basis improved the accuracy of predicting the mean passage of NANMN to the duodenum but had no effect on bias of prediction (data not shown).

To correct the linear bias, an adjustment factor based on MCPI was developed. Iteration was used to determine the optimal unit change per multiple of MCPI and the MCPI that equates to tabulated RUP values. Iterations were evaluated by comparing the resulting variation around the regression of predicted and measured passage of NANMN to the duodenum. Also, NPN content of the diet was not included in measurements of passage of feed CP (NANMN) to the duodenum because it is degraded to NH_3 in the rumen. Therefore, an adjustment was made to the equation to correct for NPN content of the feed. The following equation was developed for adjusting the RUP contents of feeds, expressed as a percentage of CP, per multiple of MCPI above maintenance.

$$\text{RUP}_{\text{adj1}} = 100 - ([\text{RDTP} \times \text{MPIAF}] + \text{NPN}) \quad [1]$$

where RUP_{adj1} is the adjusted percentage of RUP in CP of a feed used to predict passage of CP to the duodenum, **RDTP** is the percentage of ruminally degradable true protein in a feed, **MPIAF** is an adjustment factor for MCPI of cows, and NPN is expressed as a percentage of CP and is considered to be ruminally degradable. Ruminally degradable true protein was calculated as

$$\text{RDTP} = 100 - \text{RUP}_{\text{tab}} - \text{NPN} \quad [2]$$

where RUP_{tab} is the percentage of RUP for an individual feed reported in Table 1. The adjustment factor for MCPI was calculated as

$$\text{MPIAF} = 1 - \{0.13 \times [(\text{DMI}/2.5) - 9.56]\} \quad [3]$$

where DMI is the measured or expected DMI for the cows and is expressed in kg/d, the 2.5 represents the kg of DM needed to meet the CP requirement for maintenance of a 650-kg mature cow when the diet contains 17% CP, and the 0.13 and 9.56 are constants determined using an iterative process to adjust the unit change per multiple increase in MCPI to correct the linear bias.

An evaluation of predicted and measured passage of NANMN to the duodenum of dairy cows based on adjustments using eq. 1 previously presented is presented in Figure 3. When applying the adjustment of eq. 1 to individual feeds, both slope and mean bias were lowered (Table 3). Equation 1 has a SEY of 52.01 g

Figure 3. Relationship between measured (▲) or residual (●) (measured – predicted) passage of nonammonia nonmicrobial N (NANMN) and predicted NANMN at the duodenum of dairy cows after increasing tabular values for the RUP content of feeds using a linear function of maintenance protein intake to predict the passage of NANMN. Measured NANMN = $1.00 \pm 0.131 \times \text{predicted NANMN} - 0.01 \pm 29.88$ ($P < 0.01$); $R^2 = 0.2711$; root mean square prediction error = 99.35 g of NANMN/d. Residual NANMN = $0.00 \pm 0.13 \times \text{predicted NANMN} + 0.009 \pm 29.88$ ($P > 0.9$); $R^2 = 0.0000$.

of NANMN/d and a RMSPE of 99.35 g of NANMN/d. However, at low DMI, eq. 1 will predict negative RUP values for some feeds, and at high DMI, eq. 1 will predict RUP values for some feeds in excess of 100% of CP. Also, the multiple coefficient of determination (R^2) between measured values and values predicted using eq. 1 was only 0.27. This suggests that a linear adjustment based on maintenance protein intake was inadequate for adjusting tabulated RUP values of feeds and that the actual relationship between the RUP content of feeds and feed intake may be nonlinear.

A nonlinear adjustment equation was considered to prevent adjusted RUP values from going outside the biologically possible range of 0 to 100% of CP. A sigmoidal (logistic) curve was chosen to represent the RUP content of a feed as DMI was increased. At low DMI, fractional passage rate from the rumen is relatively low, and the majority of protein in feed is degraded in the rumen. As DMI increases, fractional passage rate increases so that both the quantity and proportion of feed protein escaping degradation and reaching the duodenum increases. At high DMI, there is only a small increase in the proportion of CP that escapes ruminal degradation, and a plateau is reached in measured RUP values.

The specific form of the sigmoidal curve chosen to describe the change in RUP values was

$$y = \frac{a}{1 + e^{-\left(\frac{\text{DMI} - c}{b}\right)}} \quad [4]$$

where y is the apparent percentage of RUP in a feed adjusted to a given DMI, a represents the upper asymptote or highest possible RUP value for a feed, DMI is the observed (or expected) DMI in kilograms, b is a constant used to describe the range in DMI over which the majority of change in RUP values occurs, and c is a constant equal to the DMI at the inflection point of the RUP curve (Koops and Grossman, 1991).

Tabular values (Table 1) for the percentage of RUP in feeds were largely determined in vitro or in animals consuming between 1 and 3× their maintenance energy requirement (6 to 18 kg of DMI). Therefore, a series of c values was generated that resulted in RUP values equal to tabular values. For this process, a was set to 100, b to 7, and DMI to 12. The upper asymptote of the equation (a) was set to 100 because that would represent complete passage of CP in a feed, b was set to 7 to represent approximately 4× the standard deviation for DMI (Koops and Grossman, 1991), and DMI was set to 12 to represent 2× the maintenance energy requirement of lactating cows. While holding these parameters constant, c was estimated for various values of y . This process was then repeated after changing DMI to 15, which represented the DMI needed to supply approximately 2.5× the maintenance energy requirement for lactating cows. Linear relationships were observed between the values for c and y , which had identical slopes but differed in the intercept by the same amount as the change in DMI. Therefore, c was described as a linear function of RUP_{tab} with the intercept of this function being an indicator of the inflection point of the RUP adjustment curve.

Iteration was used to determine values for the intercept of the linear relationship between c and RUP_{tab} , and b in the nonlinear curve that maximized the R^2 for the regression of predicted and measured NANMN to the duodenum under the condition that the slope of this regression did not differ from unity, whereas the intercept did not differ from zero. The parameters estimated from the iterations were part of the nonlinear equation. However, the constraints used in generating them were based on the linear regression between measured and predicted data. Because NPN in feeds must be excluded from the predictions for them to be comparable with observed flows of NANMN, the upper asymptote of the nonlinear function (a) was set to 100 minus the NPN for each feed, where NPN was expressed as a percentage of CP. This process resulted in the following equation being accepted for predicting an adjusted RUP as a percentage of the CP in a feed at a specific DMI:

$$RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}} \quad [5]$$

Figure 4. Relationship between measured (▲) or residual (●) (measured – predicted) passage of nonammonia nonmicrobial N (NANMN) and predicted NANMN at the duodenum of dairy cows after increasing tabular values for the RUP content of feeds using a nonlinear function of maintenance protein intake to predict the passage of NANMN. Measured NANMN = $1.01 \pm 0.060 \times$ predicted NANMN + 76.91 ± 10.03 ($P < 0.01$; $R^2 = 0.6496$; root mean square prediction error = 104.63 g of NANMN/d. Residual NANMN = $0.01 \pm 0.060 \times$ predicted NANMN + 76.89 ± 10.03 ($P > 0.8$; $R^2 = 0.0003$).

where $c = 27.36 - 0.1253 \times RUP_{tab}$.

Equation 5 eliminated both linear and mean bias from the prediction of NANMN passage to the duodenum (Figure 4) and maintained the RUP_{adj2} values in the biologically allowable range of 0 to 100% of the CP. Equation 5 had a SEY of 69.29 g of NANMN/d and a RMSPE of 104.63 g of NANMN/d (Table 3). Therefore, adjustments to the RUP content of feeds using eq. 5 were only slightly superior to those using eq. 1 and were slightly inferior to adjusting the RUP content of feeds by 4 percentage units for each multiple increase in maintenance energy intake in their ability to predict flow of NANMN at the small intestine. However, use of eq. 5 was concluded to be most optimal because its predictive ability was similar to the other approaches considered and it maintained predicted RUP values in the biologically valid range of 0 to 100% of CP.

The relationship between measured and predicted passage of NANMN to the duodenum for the data set used for evaluation of eq. 5 (Appendix Table 2) is presented in Figure 5. Use of eq. 5 to predict passage of NANMN to the duodenum in these experiments did not eliminate the bias of prediction. However, failure of the equation to remove all bias of prediction should not necessarily be considered evidence that the equation is incorrect. The data set used for evaluation purposes was somewhat limited in number and range of the observations (Appendix Table 2). The data set used for evaluation also contained data from steers consuming diets that were somewhat different than those repre-

Figure 5. Relationship between measured (▲) or residual (●) (measured – predicted) passage of nonammonia nonmicrobial N (NANMN) and predicted NANMN at the duodenum of dairy cows using the evaluation data set after increasing tabular values for the RUP content of feeds using eq. 5 to predict the passage of NANMN:

$$RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}. \text{ Measured NANMN} = 0.719 \pm 0.091 \times \text{pre-}$$

dicted NANMN + 82.89 ± 11.25 ($P < 0.01$); $R^2 = 0.5387$; root mean square prediction error = 47.32 g of NANMN/d. Residual NANMN = $0.28 \pm 0.091 \times \text{predicted NANMN} - 82.89 \pm 11.25$ ($P < 0.01$); $R^2 = 0.1518$.

sented in the data set used for model development. Additional observations should increase the power associated with the regression while simultaneously decreasing the impact of any one individual observation to skew the regression (Graybill and Iyer, 1994). Also, additional observations from lactating cows should lessen the impact of the steer data. The mean predicted flow of NANMN to the duodenum differed from the mean measured flow ($P < 0.01$), indicating that eq. 5 was not making satisfactory adjustments to tabulated RUP values for the evaluation data set. The evaluation data set produced a SEY of 56.30 g/d with a RMSPE of 82.71 g/d. The MSPE analysis (Theil, 1966) of the residuals from the evaluation of eq. 5 (Table 3) indicated that 47.32% of the error was attributable to inaccurate prediction of the mean passage of NANMN to the duodenum, 28.38% of the error was correctable through a linear function of the measured and predicted passages of NANMN at the duodenum, and the final 24.30% of the error was random variation. St Pierre (2003) suggested that any perceived bias should be evaluated in relation to reported measurement errors to determine its potential impact on the predictive ability of the model. It is likely that differences in the type of diets represented in the model evaluation and model development data sets were negatively impacting the apparent predictive ability of the model. As more data become available, it will be possible to determine whether there

Figure 6. Apparent RUP content of barley grain (■), corn grain (▲), high moisture corn grain (×), and sorghum grain (●) at differing multiples of maintenance energy intake as determined using eq. 5:

$$RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}.$$

are true errors or if the problems uncovered in this exercise are an artifact of the analysis related to abnormalities in the evaluation data set (Mayer and Butler, 1993; Carroll and Galindo, 1998; Oreskes, 1998; Carroll et al., 1999).

Figures 6, 7, 8, 9, 10, and 11 present apparent predicted RUP content of selected feeds at different levels of DMI. Apparent predicted RUP contents of cereal grains as intake increases from 0.5 to 5× maintenance energy intake (3 to 30 kg DMI) are presented in Figure 6. Similar information for oil seed meals is presented in Figure 7. Apparent predicted RUP contents of oil

Figure 7. Apparent RUP content of canola seed meal (◆), solvent-extracted soybean meal (▲), expeller-extracted soybean meal (×), and cottonseed meal (■) at differing multiples of maintenance energy intake as determined using eq. 5: $RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$.

Figure 8. Apparent RUP content of canola seed (◆), raw soybeans (▲), roasted soybeans (×), and whole cottonseed (■) at differing multiples of maintenance energy intake as determined using eq. 5:

$$RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$$

seeds at differing multiples of maintenance energy intake are presented in Figure 8, and similar data for forages are presented in Figure 9. Figure 10 presents the apparent predicted RUP content as estimated by eq. 5 for byproduct feeds, and Figure 11 is a similar representation for animal protein meals. All of the example feeds exhibited the expected sigmoidal shape to their apparent predicted RUP content curve. At low DMI, the majority of the CP in most feed is degraded, resulting in a low apparent RUP content of that feed. However, at high DMI, the majority of the CP in most

Figure 10. Apparent RUP content of beet pulp (◆), corn distillers grains with solubles (▲), soybean hulls (×), dried brewers grains (■), and wheat middlings (●) at differing multiples of maintenance energy intake as determined using eq. 5: $RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$

Figure 9. Apparent RUP content of corn silage (◆), grass silage (▲), legume hay (×), grass hay (■), and legume silage (●) at differing multiples of maintenance energy intake as determined using eq. 5:

$$RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$$

Figure 11. Apparent RUP content of blood meal (◆), fish meal (▲), and feather meal (■) at differing multiples of maintenance energy intake as determined using eq. 5: $RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$

feed is not degraded in the rumen but passes to the small intestine, resulting in a high apparent RUP content of that feed. At high DMI, a large amount of degradable CP is supplied from feeds that have large quantities of NPN, such as corn silage or legume forages, and smaller amounts of degradable CP are supplied from other feeds. The amount of RDP and RUP that is supplied from these feeds when diets with a typical forage content are fed to lactating dairy cows at high DMI appears adequate to support microbial protein synthesis and the predicted passage of RUP to the small intestine.

CONCLUSIONS

Current tabular values for the RUP content of feeds do not allow accurate prediction of NANMN passage to the duodenum of lactating dairy cows. Tabular values for RUP can be adjusted using either a linear or nonlinear function of DMI to better predict passage of NANMN. A nonlinear function relating RUP to DMI agreed better with the underlying biology of lactating dairy cows than did a linear function because estimated RUP values for individual feeds remained within the biologically possible range of 0 to 100% of CP. Both of the equations developed for adjusting tabular RUP values of feeds better predicted the passage of NANMN to the small intestine than did tabular values. The nonlinear equation was able to eliminate the bias in predicting flow of NANMN to the small intestine, but it was not able to completely remove the variation around the line of prediction. This is an indication that, although the concept of adjusting tabulated RUP values based on DMI is correct, other factors are also influencing the apparent RUP content of feeds. When more data for cows consuming larger amounts of DM become available, this equation should be reevaluated for its ability to properly adjust RUP values of feeds reported by NRC. Furthermore, as other data become available that quantify the effects of factors other than DMI on the apparent RUP values of feeds, they should also be incorporated into an adjustment equation to better predict passage of NANMN to the duodenum.

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APPENDIX

Table A1. Data set used to derive constants for prediction equations.

Reference	Measured NANMN ¹	Predicted NANMN ²	DMI
	(g/d)		(kg/d)
Aldrich et al. (1993)	274	258	25
	351	321	24.9
	315	339	26.7
	396	351	25.3
Cameron et al. (1991)	239	190	23.1
	239	186	23
	266	171	21.6
	254	158	21
Christensen et al. (1993)	374	303	21.3
	387	255	21
	365	265	20.7
	576	239	21.5
Christensen et al. (1996)	345	171	24.2
	296	185	22.6
	354	191	23.6
	334	247	22.7
Cunningham et al. (1993)	261	328	24.1
	272	307	23.5
	233	281	22.3
	258	286	22.7
	189	307	23.2
Cunningham et al. (1994)	144	94	17.8
	190	115	17.9
	234	139	18
	240	149	17.5
Holden (1994)	134	162	19.2
	184	116	16.3
Horner et al. (1988)	78	21	8.1
	83	23	8.4
	52	24	8.5
	70	23	8.5
Hvelplund and Madsen (1985)	168	92	13.5
	108	51	14.2
	86	22	7.1
	54	11	7.3
	131	41	12.7
	111	41	12.9
	65	9	6.4
	58	10	7.1
	140	35	14.1
	279	149	13.6
	359	142	13.5
	292	141	11
	97	39	13
	156	44	11.1
	92	32	10.6
	106	30	5.5
	26	5	14.2
Khorasani et al. (1996)	216	169	19.6
	118	141	18.6
	147	108	16.7
	181	114	17.2
Klasmeyer et al. (personal communication, 1998)	298	308	24.2
	446	261	24.1
	383	259	22.5
	460	222	23.8

*Continued***Table A1 (Continued).** Data set used to derive constants for prediction equations.

Reference	Measured NANMN ¹	Predicted NANMN ²	DMI
	(g/d)		(kg/d)
Klasmeyer et al. (personal communication, 1998)	458	277	23
	465	270	23.7
	443	207	22.3
	344	183	22.4
Klasmeyer et al. (1991b)	335	263	25.1
	324	307	23.8
	343	247	23.4
	342	269	22.3
Klasmeyer et al. (1991a)	357	286	25.5
	372	250	24
	344	252	24.7
	314	225	23.3
Knowlton et al. (1998)	269	261	23.4
	349	261	23.4
	318	264	24.4
	333	246	23.7
Kung and Huber (1983)	204	143	17.7
	183	143	17.7
	222	170	18.5
	161	141	17.2
Lu et al. (1988)	160	53	13
	176	57	12.1
Lykos et al. (1997)	193	243	25.8
	199	242	25.9
	228	237	25.9
Mabjeesh et al. (1996)	208	126	17.6
	256	135	17.8
	224	144	18.6
	288	169	19.1
Mansfield and Stern (1994)	344	205	20.2
	368	250	20.8
	357	207	20.7
	373	190	19.1
McCarthy, Jr. et al. (1989)	373	239	23.3
	372	250	24.2
	307	152	20.5
	289	156	20.9
McNiven et al. (1995)	95	60	14
	124	57	13.6
	121	51	13.1
Møller (1985)	125	83	16
	178	130	16.3
	102	64	15.7
	156	113	16.2
	111	51	13.5
	165	77	13.4
	73	32	12.5
	136	65	13.5
Narasimhalu et al. (1989)	76	7	9.7
	85	10	11.2
Overton et al. (1995)	327	201	22.8
	271	179	22.1
	276	156	21.3
	239	117	19.5
	224	113	19.6

Continued

Table A1 (Continued). Data set used to derive constants for prediction equations.

Reference	Measured NANMN ¹	Predicted NANMN ²	DMI
	(g/d)		(kg/d)
Poore et al. (1993)	272	185	20.7
	210	183	20.7
	259	232	21.3
	216	213	20.7
Prange et al. (1984)	90	82	15.6
	95	93	16.2
Putnam et al. (1997)	376	138	18.1
	423	161	19.2
	388	165	18.3
	414	182	19
Robinson and Sniffen (1985)	119	131	18
	122	62	17.3
	137	125	17.7
Robinson et al. (1985)	33	13	6.4
	88	9	11.3
	120	88	15.8
	132	136	18.6
Rode et al. (1985)	157	62	14.3
	124	44	13.5
	194	60	14.3
	82	124	16.8
	91	131	17.7
	100	103	16.5
	91	59	14
Rooke et al. (1985)	16	3	3.3
	23	3	3.3
	39	9	6.2
	60	9	6.2
Shabi et al. (1998)	208	103	16.7
	272	112	16.4
	176	84	15.5
	240	109	16.1
Song and Kennelly (1989)	239	50	15.3
	242	59	15.8
	225	48	15.3
Stern et al. (1983)	208	86	17.6
	229	129	17.9
	299	167	17.8
	336	183	17
Tamminga et al. (1979)	66	15	8.2
	74	25	8.2
	64	34	8.2
	165	43	12.9
	200	72	12.9
	199	100	12.9
Tesfa (1993)	57	13	7.4
	56	14	7.9

¹NANMN = Nonammonia nonmicrobial N.

²Predicted values were derived using eq 5: $RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$

Table A2. Data set used to evaluate prediction equation 5.

Reference	Measured NANMN ¹	Predicted NANMN ²	DMI
	(g/d)		(kg/d)
Ahvenjarvi et al. (2002)	133	25	13.8
	121	63	17.5
	164	59	16.2
	149	94	18.1
Callison et al. (2001)	189	125	18.4
	224	131	18.7
	229	133	18.8
	203	119	18
	211	119	18
Choi et al. (2002)	133	61	13.8
	120	25	17.5
	163	57	16.2
	148	92	18.1
Crocker et al. (1998)	249	110	17.7
	266	136	19.1
	261	133	18.9
	276	119	18.1
Elizalde et al. (1999)	51	16	8.5
	30	26	6.6
	35	28	8.7
	59	28	9.2
	67	24	9.3
Hamali et al. (2001a)	70	15	7.9
	66	14	7.7
	42	12	7.8
	39	11	7.6
Hamali et al. (2001b)	54	10	6.5
	54	10	6.5
	53	11	6.8
Ipharraguerre et al. (2002)	250	210	22.1
	265	183	21.1
	285	195	21.7
	275	201	22
	273	172	20.9
Oba and Allen (2003)	138	255	20.8
	123	330	22.5
	164	226	19.7
	191	228	19.6
Oldick and Firkins (2000)	65	13	8.5
	61	13	8.5
	58	13	8.5
	57	13	8.5
O'Mara et al. (1998)	61	24	10.9
	89	26	11.1
	104	47	13.2
	119	53	13.3
Shabi et al. (personal communication, 2003)	191	211	22.5
	256	241	23.6
	280	236	23.3
	277	190	21.3
Volden (1999)	218	97	19.3
	191	97	19.3
	169	53	19.3
	129	19	9.8
	116	19	9.8
	97	3	9.8

¹NANMN = Nonammonia nonmicrobial N.

²Predicted values were derived using eq. 5: $RUP_{adj2} = \frac{100 - NPN}{1 + e^{-\left(\frac{DMI - c}{7.18}\right)}}$