Defining ruminal and total-tract starch degradation for adult dairy cattle using in vivo data

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ABSTRACT

Literature was searched for studies performed in adult dairy cattle that simultaneously measured starch degradability in the rumen (RSDeg) and starch digestion in the total tract to compute postruminal starch digestion (PRSDig). Forty-one studies with 161 dietary treatments were used to form the data set. Of these diets, the major starch source was corn for 83 diets, small grain for 58 diets, and sorghum for 8 diets. Corn RSDeg was more variable than other sources. As measured in vivo across all starch sources, the percent RSDeg was influenced only by the amount of starch consumed, with the amount of degradation being approximately 75% at low starch intakes and decreasing to about 60% when 4 kg or more of starch were consumed. Small grain starch had greater RSDeg than corn or sorghum starch, which were approximately equal. The PRSDig of corn and small grain starches were approximately equal, but sorghum was about 15% less. Across all diets, models derived from the Cornell Net Carbohydrate Protein System predicted percentage of total-tract digestibility of starch very accurately, but overpredicted RSDeg and, as a result, underpredicted percent PRSDig. Calculation of RSDeg using a French model predicted the mean RSDeg with greater accuracy but less precisely. The relative differences in RSDeg percent among starch sources was correctly predicted by these models. A model using a revised rate of digestion as a way of combining effects of starch type and processing was developed, which predicted corn starch RSDeg and PRSDig with greater accuracy than nutrition models but only slightly better than using the mean observed degradation or the French calculation. Inaccuracies in prediction of RSDeg may be due mainly to processing effects and particle sizes, but these were not well reported in literature studies and were difficult to estimate. More accurate assessment of RSDeg and PRSDig will

require better and more consistent reporting of grain processing. Based on this study, the French calculation is the most accurate of the models examined, although adjustments will be required to improve accuracy.

Key words: ruminal starch degradation, postrumen digestion, total-tract starch digestion

INTRODUCTION

Dairy cattle consume large amounts of starch (20–40% of diet DM) as a way to increase energy consumption in support of high milk production. Accurate prediction of the amount of ruminal starch degradability (**RSDeg**) is critical for accurate prediction of ruminal microbial protein production as well as the amount and types of VFA presented for absorption (Stern and Hoover, 1979). At present, most ruminant nutrition models that predict RSDeg use a version of the equation suggested by Ørskov and McDonald (1979), where the $RSDeg = \text{weight of immediately disappearing fraction} + \text{weight of potentially degradable fraction} \times [kd/(kd + kp)]$, where kd = rate of digestion and kp = rate of passage, and kd and kp are expressed as percentage per hour. Rate of digestion for individual starch sources is defined by in situ incubations using Dacron bags. Methodology for in situ starch determinations, including bag pore size, grind size, and incubation times, have been rigorously defined (Nocek, 1988). Although this methodology provides reproducible kd numbers, it has been noted that estimates of RSDeg produced by the in situ technique do not closely match in vivo estimates (Mills et al., 1999).

Starch digestion in cattle and the many factors that affect it have been reviewed (Nocek and Tamminga, 1991; Mills et al., 1999; Firkins et al., 2001; Owens, 2005). Nocek and Tamminga (1991) published estimates of RSDeg based on the kd from in situ studies, including data from all ruminant species, and suggested that this was reasonably well correlated to in vivo starch degradability ($R^2 = 0.65$). These authors also concluded that the variability of RSDeg was high and that the amount of starch consumed had little effect on

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degradability. Firkins et al. (2001) summarized in vivo RSDeg in dairy cattle, as well as the effect that processing methods had on both total-tract starch digestion (**TT**) and milk production response to high-starch feeds. However, Firkins et al. (2001) estimated starch degradation and content from NFC data, which may have led to inaccurate prediction of chemically defined starch. These authors reported that postruminal starch digestion (**PRSDig**) was negatively affected by dietary NDF content and DMI and concluded that more rigorous processing increased both RSDeg and PRSDig. Nocek and Tamminga (1991) and Firkins et al. (2001) all concluded that as the percent of starch undegraded in the rumen increased, a greater percent of starch digestion occurred in the small intestine, resulting in little overall difference in total-tract digestion. Offner et al. (2003) also reported starch degradation based on in situ data, but only from experiments where it was determined in bovine species. In later studies Offner and Sauvant (2004) confirmed the previously reported effects of processing and intake. They also determined that RSDeg determined in situ were approximately 20 to 40% higher than those measured in vivo and offered regressions for calculating in vivo RSDeg from in situ values. Reynolds (2006) suggested that PRSDig is energetically more efficient than RSDeg, but that this efficiency occurs at the expense of microbial protein formation. For high-producing or early lactation cows where DMI is limited, he suggested that a diet with low RSDeg may have production advantages because of greater overall energy availability. Models based on the Cornell Net Carbohydrate Protein System (CNCPS) have been developed to predict both RSDeg and PRSDig (Sniffen et al., 1992; Tytlutki et al., 2008) and have been incorporated into dairy ration software [Cornell-Penn-Miner (**CPM**) Dairy version 3.0.10, Cornell University (Ithaca, NY), University of Pennsylvania (Philadelphia), The William H. Miner Agricultural Research Institute (Chazy, NY), and the University of Maryland (College Park) cooperating; software by Agricultural Modeling and Training Systems (**AMTS**) LLC, Cortland, NY]. However, to our knowledge, predicted amounts of RSDeg and PRSDig from these models have not been compared with data measured in vivo.

Therefore, the objectives of this study were (1) to identify factors affecting RSDeg and PRSDig for various feedstuffs using in vivo studies; (2) to compare in vivo observations of RSDeg and PRSDig in published studies with model estimates provided by CPM, AMTS, and a model suggested by Offner and Sauvant (2004); and (3) to investigate other methods of predicting RSDeg and PRSDig, comparing these with in vivo observations.

MATERIALS AND METHODS

Data Sources

The Google Scholar and Agricola electronic databases were scanned to identify studies where RSDeg and PRSDig had been measured simultaneously in lactating cattle fitted with both ruminal and duodenal cannulas and using marker techniques. Starch content was determined by different methods (Aman and Hesselman, 1984; Karkalas, 1985; Herrera-Saldana et al., 1990; Faisant et al., 1995), but each involved solubilization of starch and measurement of released glucose. Studies reporting digestibility of NFC or water-soluble carbohydrate without reporting a pure starch fraction were not used. Likewise, studies that reported dietary RSDeg determined only by in situ methods were not used because starch was not chemically defined. Mean dietary composition from each diet in each study was entered into the database at the reported treatment mean DM consumption. When nutrient composition of ingredients was reported in the study, this data was recorded in the database. When only the total dietary composition was provided, nutrient values (other than for starch) were taken from the National Research Council (NRC, 2001) and were used as a starting point, but were adjusted to agree with the reported dietary percentage of NDF, CP, RDP, RUP, neutral detergent-insoluble crude protein (**NDICP**), acid detergent-insoluble crude protein (**ADICP**), and lignin, as well as fat and ash, all on a DM basis. Individual feeds were not varied by more than 15% of the default value. If starch content of an ingredient was not reported, starch data from the CPM v.3.0.10 feed library was used for this ingredient. These values were also adjusted to agree with starch levels reported in the total diet. In almost all studies, the starch content of major sources was reported. Therefore, starch values from CPM were used only for ingredients contributing minor amounts of starch to the diet. The other default values were taken from the NRC because this is the most widely accepted database and most published diets would be evaluated with these values. Similarly, unknown starch values were taken from CPM because it contains a widely recognized starch database. Because different models were evaluated, the goal was to standardize data entered into the models, so that methods of calculating RSDeg were compared without the confounding influence of different database starch contents.

Determination of RSDeg and PRSDig Regressions

The DM amount of each ingredient in the ration was multiplied by the percentage of starch contained as

determined on a DM basis to determine the starch contributed by each feed. Within each ration, the weight of starch in individual ration components was then summed, and this was taken as the observed weight of starch consumed. The weight of starch reported in the study to be degraded in the rumen was divided by the DMI and multiplied by 100 to calculate a percent RSDeg as

$$\text{RSDeg} = \text{weight of starch degraded in rumen (DM)} / \text{weight of starch consumed (DM)} \times 100. \quad [1]$$

The amount of starch degraded in the rumen was then subtracted from the amount of starch reported to be digested in the total tract. This difference was taken as the amount of starch digested postruminally, which was then divided by the weight of starch consumed to determine the PRSDig as

$$\text{PRSDig} = \text{weight digested postruminally (DM)} / \text{weight of starch consumed (DM)} \times 100. \quad [2]$$

Dietary factors evaluated for possible effects on RSDeg and PRSDig were DM of ingredient, NDF, lignin, CP, RDP, RUP, NDICP, ADICP, NFC, starch, sugar, ash, and crude fat, all on percentage of DM basis, as well as the amount of each of these nutrients consumed. Also evaluated were cow factors such as BW, milk production, milk fat percentage, milk CP percentage, DIM, DMI, percentage of diet that was forage, percentage of NDF that was forage NDF, as well as rumen pH when it was reported. Regressions for determining significant correlations to RSDeg and PRSDig were performed in SAS (version 8; SAS Institute Inc., Cary, NC) using stepwise elimination. Regressions were also performed using the same inputs for starch sources within processing effects using PROC REG with stepwise elimination. For the regression graph of the effect of starch intake, the significant regression equation for kilograms of RSDeg was used to predict the kilograms of starch degraded, and that degraded starch amount converted to percentage of starch degraded.

Model Inputs

Diet and ingredient compositions determined as described above were entered into the CPM Dairy model with feed selection matching identified processing effects to the extent possible. The following model outputs were recorded: DMI, starch as percentage of diet DM, and kilograms of starch fermented in the rumen. For CPM, predicted PRSDig was calculated as total starch

consumed less the model-predicted starch degraded in the rumen multiplied by the model-calculated postruminal starch digestibility:

$$\text{PRSDig}_{\text{CPM}} = (\text{starch consumed} - \text{rumen-degraded starch}) \times \text{postruminal starch digestion (\%)}. \quad [3]$$

The CPM rations were uploaded into the AMTS model of the Cornell Net Carbohydrate Protein System and similar outputs recorded. Model degradation rates (kd) and intestinal digestion coefficients were not modified from default values in either program.

The model designated **OFF** was calculated from Offner and Sauvant (2004) with the kd of various feed-stuffs taken from Offner et al. (2003) and applied to the following equations to predict RSDeg:

$$\text{RSDeg} = 0.439 + 0.68 \times \text{effective degradability}, \quad [4]$$

where

$$\text{effective degradability} = \sum \pi_i \times \text{ED}_i \quad [5]$$

and $\pi_i \times \text{ED}_i$ = the effective starch degradability of each ingredient as determined by the Ørskov and McDonald (1979) formula described previously and with kp calculated for forage and concentrate (Offner and Sauvant, 2004) as

$$\text{kp}_{\text{forage}} = 0.021 + 0.007 \times \text{DMI, percentage of BW}, \quad [6]$$

$$\text{kp}_{\text{concentrate}} = 0.018 + 0.014 \times \text{DMI, percentage of BW}. \quad [7]$$

Because Offner et al. (2003) did not report starch kd data for all feeds in the data set, the following substitutions for kd were used: the corn silage kd value was used for barley silage; the soybean meal kd was used for canola meal; alfalfa kd was used for grasses, and the kd value for peas was used for whole linseeds. Data were calculated assuming no immediately degradable fraction (Offner and Sauvant, 2004). Data recorded included starch intake, starch degraded in the rumen, and starch digested in the total tract. The RSDeg and PRSDig were recorded as described earlier.

The accuracy of model predictions was tested against observed TT, RSDeg, and PRSDig by various methods including regression of observed values on predicted values, specifying coefficient of determination, intercept, and slope parameters as described by Pacheco et al. (2006). Also used were the mean square prediction error (**MSPE**), root mean square error (**RMSE**) as

percent of observed mean, and the decomposition of the MSPE into mean bias, regression error, and random error, as described by Bibby and Toutenburg (1977). All statistics were performed with version 8 of SAS.

Development of Alternative Models

In an attempt to improve on existing prediction of TT, RSDeg, and PRSDig, alternative methods for calculating these values were developed. A mean value for these estimates was calculated. Also, 2 different attempts were made to develop alternative kd values, as well as estimates derived from simple regression of total-tract digestibility, both across and within starch sources. These approaches are described in detail below.

Development of Simple Mean Model

Simple means of RSDeg and PRSDig for individual ingredients were calculated from in vivo data using the following technique. After observed RSDeg and PRSDig had been adjusted for the effects of study (St-Pierre, 2001), individual RSDeg and PRSDig of each feed were estimated by assuming that starch in other dietary ingredients was either totally digested or alternatively, not digested at all. This made possible the calculation of the highest possible starch degradation (i.e., the starch in other ingredients was indigestible, and all of the reported digested starch must come from the ingredient under consideration) and the lowest possible starch digestion (i.e., the starch in the other dietary ingredients was totally digestible, and only the last portion of the digested starch was contributed by the ingredient under consideration). A sample calculation is included in Appendix 1. At least 1 ingredient had to represent more than 50% of the total starch consumed for a diet to be evaluated by this technique. Additionally, all calculations were constrained so that the highest amount of starch degraded or digested was 99.9%, and the lowest amount was 0.1%. Two starch degradability and digestibility values were recorded for each ingredient in each ration of each study as the minimum and the maximum possible. The average of these values was calculated as the RSDeg and PRSDig for each feed. Finally, a mean of all ingredients of 1 type was calculated with the standard error reported as the standard error of the mean. These calculated means of RSDeg and PRSDig were applied to each ration, and these rations (simple mean, **SM**, model) were analyzed by the statistical methods described above.

Development of the Revised kd Model

Rates of passage were determined for OFF by the method described in Offner and Sauvant (2004), Cha-

lupa et al. (1991), Seo et al. (2006), and NRC (2001) to select an appropriate kp for development of a revised kd (**rkd**) model for use in the Ørskov and McDonald (1979) equation. After examination, the OFF kp was selected to calculate a revised kd for each feed in each ration by the rearrangement of the Ørskov and McDonald (1979) formula as

$$kd = R - kp/(S - R), \quad [8]$$

where S = starch amount, R = the amount of starch degraded, and kp was calculated as above. Starch digested for each feed was as determined by the simple mean method described previously. A second ingredient kd was determined as the percent of starch digestion reported for each ration multiplied by the starch content of each ingredient. Then, the individual kd values were grouped by feed, and the means of these calculations were designated as the rkd for each feed. An RSDeg was calculated in all rations using the mean rkd by the equation of Ørskov and McDonald (1979). A revised PRSDig was calculated for each feed by subtracting the revised RSDeg for each feed from the TT as predicted by the mean method described above. This model was also analyzed by the same statistical methods for models described before.

Investigations into Other Approaches

Other approaches to produce better estimates of RSDeg and PRSDig were attempted. These included regression of RSDeg from the observed TT digestion, both across and within starch type with and without processing factors included. Also attempted was regression from the amount of starch consumed and a revised kd based on the average RSDeg and PRSDig reported in each study.

RESULTS AND DISCUSSION

Effects on Observed Results

Forty-one studies and 161 dietary treatment means were identified that met the established criteria. References for these studies are included in Appendix 2, and simple descriptive statistics including dietary factors are presented in Table 1. In these diets, corn made up the major starch source in 82 diets, small grain was the major source in 58 diets, whereas sorghum was the major starch source in 8 diets. Corn starch sources included corn grain of various processing methods, corn silage, and feed grade corn starch. Small-grain starch sources were both barley and wheat grains processed in various ways, whereas sorghum was entirely sorghum

Table 1. Descriptive statistics for diets used in evaluation of ruminal starch degradation and total-tract starch digestion

Variable	n	Mean	±SE	Minimum	Maximum
BW, kg	161	617	54	410	690
DIM	158	138	52	28	274
Milk, kg/d	140	29.2	6.5	13.0	42.5
Milk fat, %	140	3.60	0.40	2.67	4.61
Crude milk protein, %	140	3.14	0.20	2.62	3.86
DMI, kg/d	161	20.3	3.2	9.1	26.8
Forage, ¹ % of DM	161	47.0	11.0	23.0	90.0
Rumen pH	121	6.13	0.28	5.60	6.90
CP, % of DM	161	17.5	2.3	11.6	26.2
NDF, % of DM	161	32.3	6.8	20.7	65.3
Sugar, % of DM ²	161	4.3	2.4	1.2	12.9
Crude fat, % of DM	161	4.05	1.34	1.30	7.37
Starch, % of DM	161	25.2	8.0	0.7	39.7
Starch, kg/d consumed	161	5.17	1.9	0.13	9.14
Starch, kg reported degradable in rumen	161	3.141	1.368	0.01	6.432
Starch, kg reported digestible in total tract	161	1.650	1.255	0.03	4.841

¹Estimated assuming that corn silage was 100% forage.

²Estimated from values in CPM version 3.0.10 (Cornell University, Ithaca, NY).

grain, either steam flaked or ground. Mean observed RSDeg, PRSDig and TT for these feed classes are presented in Table 2.

Across all feeds, correlation between starch consumed and kilograms of RSDeg, kilograms of PRSDig, and kilograms of TT was high (Table 3), although no significant regression was observed for percentage of these factors. The relationship of RSDeg and intake is summarized across all diets in the regression plot in Figure 1. Across all diets, RSDeg was high (~75%) at low starch intakes, and it appeared to plateau at about 60% for starch consumption over 4 kg per day. Contrary to the reports of Firkins et al. (2001) and Offner et al. (2003), this in vivo data provided no indication of an effect of DMI on percentage or amount of RSDeg. In fact, 2 studies looked at this directly and in detail (Doreau et al., 1990; Volden, 1999). That is, they fed the same diet to the same cows at different stages of lactation when DMI was different. The mean RSDeg of low-intake cows (11.9 ± 3.0 kg/d) was $84.0 \pm 8.9\%$ compared with higher-intake cows (17.7 ± 0.3 kg/d), which was $85.0 \pm 8.4\%$, a nonsignificant difference. In the present study, no effect of dietary constituents across all feeds, including NDF and RDP, on RSDeg or PRSDig, and no cow effects such as BW were found,

which is different than reported by Firkins et al. (2001). For corn starch sources, sugar as percent DM was a significant factor for percent PRSDig and kilograms of PRSDig. For small grains, percent forage in the diet was also a significant factor, although the overall coefficient of determination was low. No significant regression equations for sorghum were identified, although the numbers of diets were few. Regression analyses were performed for individual starch sources and processing types where identified. For high-moisture corn, steam-processed corn, corn silage, all small grains, and sorghum, DMI did not enter into a significant equation. Only in the cases of cracked corn ($n = 3$ diets) and ground corn ($n = 46$ diets) was a term for DMI or DMI as percentage of BW significant for RSDeg (data not shown). For this data set, it appears that the amount of starch consumed is the only meaningful modifier of RSDeg. The lack of a large DMI effect on either RSDeg or PRSDig, coupled with the observations cited for the studies of Doreau et al. (1990) and Volden (1999), suggest that the rate of passage per se did not have a large effect on RSDeg as measured in vivo. This agrees in principle with the study by Hall (2004).

In this study, the standard error of TT between corn and small grains was not greatly different (Table 3),

Table 2. Observed mean percent starch digestion and degradation in studies used to evaluate starch utilization

Feed type	n	Total tract		Rumen		Postrumen	
		Mean	±SE	Mean	±SE	Mean	±SE
All	161	92.8	7.4	61.8	20.6	30.9	19.2
Corn	82	92.3	6.2	54.6	18.5	37.7	17.7
Small grain	58	94.6	5.4	76.4	15.4	18.2	13.0
Sorghum	8	80.4	17.7	54.0	17.5	26.3	12.7

Figure 1. Regression plot across all diets for effect of amount of starch consumed on percent ruminal starch degradation from equation: starch degraded = $0.0357 + 0.6000$ kg of starch consumed, ($R^2 = 0.87$) and these amounts converted to percentage of starch consumed. Color version available in the online PDF.

which was contrary to the study of Firkins et al. (2001). Across all diets, after correcting for the effects of study, mean percent RSDeg was $61.8 \pm 20.6\%$, mean percent PRSDig was $30.9 \pm 19.2\%$, and mean percent TT was $92.8 \pm 7.4\%$. The smaller standard errors for TT compared with RSDeg and PRSDig suggest that the combi-

nation of starch degradation and digestion is relatively constant for a given feed, although the location may shift between rumen and postrumen. This also suggests that different levels of processing of the grain source may provide a partial explanation for the variability of RSDeg. These observations are in agreement with

Table 3. Significant regression equation for ruminal degradation (RSDeg), postruminal digestion (PRSDig), and total-tract starch digestion (TT) for various feed types, both as percent and by weight

Starch type	Equation	R ²
All feeds	% RSDeg = NSE ¹	
	% PRSDig = NSE	
	% TT = NSE	
	kg of RSDeg = $0.1092 + (0.5956 \times \text{kg of starch consumed})$	0.84
	kg of PRSDig = $-0.070 + (0.321 \times \text{kg of starch consumed})$	0.70
Corn grain	kg of TT = $-0.0695 + (0.3211 \times \text{kg of starch consumed})$	0.69
	% RSDeg = $55.34 + (1.40 \times \text{sugar \% DM})$	0.10
	% PRSDig = $32.48 - (1.632 \times \text{sugar, \% DM}) + (1.11 \times \text{crude fat, \% DM})$	0.14
	% TT = NSE	
	kg of RSDeg = $0.3405 + (0.5455 \times \text{kg of starch consumed})$	0.73
Small grain	kg of PRSDig = $0.319 + (0.313 \times \text{kg of starch consumed}) - (0.081 \times \text{sugar, \% DM})$	0.64
	kg of TT = $-0.3184 + (0.3712 \times \text{kg of starch consumed})$	0.64
	% RSDeg = $61.406 + (0.153 \times \text{starch \% DM})$	0.05
	% PRSDig = NSE	
	% TT = $99.25 - (0.1145 \times \text{forage \% DM})$	0.15
Sorghum grain	kg of RSDeg = $-0.1125 + (0.6790 \times \text{kg of starch consumed})$	0.94
	kg of PRSDig = $0.161 + (0.250 \times \text{kg of starch consumed})$	0.78
	kg of TT = $0.1613 + (0.2496 \times \text{kg of starch consumed})$	0.79
	% RSDeg = NSE	
	% PRSDig = NSE	
	% TT = NSE	
	kg of RSDeg = NSE	
	kg of PRSDig = NSE	
	kg of TT = NSE	

¹NSE = no significant equation.

Table 4. Comparisons of existing models for starch digestion on a percentage basis across all sources in adult dairy cows

Site	Parameter ¹	Observed	Model ²		
			AMTS	CPM	OFF
Total tract	Mean	92.8	96.0	96.3	92.9
	±SE	7.4	2.2	2.6	3.5
	Linear regression		$y = -75.3 + 1.75x$	$y = -37.1 + 1.35x$	$y = 0.1 + 0.99x$
	R ²		0.83	0.78	0.72
	MSPE		9.09	11.95	14.95
	RMSE, % mean		3.24	3.72	4.17
	MSPE decomposition				
	Mean bias, %		18.8	22.0	3.1
	Regression error, %		1.9	0.4	4.4
	Random error, %		79.3	77.6	92.5
Rumen	Mean	61.8	81.2	82.4	64.9
	±SE	20.6	6.6	6.9	8.1
	Linear regression		$y = 8.7 + 0.65x$	$y = 27.7 + 0.41x$	$y = -27.9 + 1.38x$
	R ²		0.77	0.76	0.83
	MSPE		95.55	100.91	70.76
	RMSE, % mean		15.8	16.2	13.8
	MSPE decomposition				
	Mean bias, %		51.1	53.8	3.2
	Regression error, %		0.2	0.1	7.4
	Random error, %		48.7	46.1	89.4
Postrumen	Mean	30.9	14.8	14.0	27.8
	±SE	19.2	4.8	5.1	5.3
	Linear regression		$y = 32.2 - 0.08x$	$y = 37.5 - 0.46x$	$y = -4.4 + 1.27x$
	R ²		0.79	0.80	0.81
	MSPE		76.09	71.66	67.12
	RMSE, % mean		28.2	27.4	26.5
	MSPE decomposition				
	Mean bias, %		43.4	45.2	3.1
	Regression error, %		0.0	0.1	4.4
	Random error, %		56.6	54.7	92.5

¹MSPE = mean square prediction error; RMSE = root mean square error.

²AMTS = Agricultural Modeling and Training Systems LLC (Cortland, NY); CPM = Cornell-Penn-Miner Dairy version 3.0.10 [Cornell University (Ithaca, NY), University of Pennsylvania (Philadelphia), The William H. Miner Agricultural Research Institute (Chazy, NY), and the University of Maryland (College Park) cooperating]; OFF = calculated from Offner and Sauvant (2004).

those of other authors (Nocek and Tamminga, 1991; Firkins et al., 2001). A slight but significant positive association was observed in the present data set between the percent of RSDeg and the percent of TT [$84.68 + (0.131 \times \text{RSDeg})$, $R^2 = 0.13$], in agreement with Theurer et al. (1999), although the correlation was greater in their study. Regression of starch types with associated processing factors generally produced equations with high coefficients of determination. However, the numbers of samples were small and when evaluated, often produced RSDeg of greater than 100%. Therefore, they were considered inaccurate and are not reported.

Predictions by Existing Models

Predictions of RSDeg, PRSDig, and TT derived from AMTS, CPM, and OFF were compared with observed values (Tables 4–7). For ease of description when discussing model accuracy, we have arbitrarily used a distinction in which mean prediction within 5% of the observed was considered very accurate, within 10% was

accurate, within 15% was acceptable, and above 15% was not a useful prediction.

Across all diets on a percent basis, these 3 models predicted mean TT very accurately and had similar means and MSPE, although a difference in the source of error was found. The OFF model displayed a regression equation with an intercept closer to 0 and a slope closer to 1 than the other models, indicating a more robust model of TT. Although the MSPE was slightly larger, OFF also displayed less mean bias and regression bias with considerably more random error than AMTS or CPM. In terms of RSDeg, AMTS and CPM predictions were not useful, overpredicting by greater than 20%, whereas OFF estimated very accurately within 5% of observed values. Most of the error in the AMTS and CPM predictions of RSDeg resulted from mean bias. For all models, developed regression equations for RSDeg had large intercepts and poor slope agreement as well as high RMSE as percentage of observed mean. This indicates that there may be room to improve prediction of RSDeg. Similarly, the predictions of PRSDig

Table 5. Comparisons of existing models for starch digestion on a percentage basis in diets for adult dairy cows with corn grain (n = 82) as the major starch source

Site	Parameter ¹	Observed	Model ²		
			AMTS	CPM	OFF
Total tract	Mean	92.3	95.8	96.1	91.5
	±SE	6.2	2.3	2.5	3.2
	Linear regression		$y = -55.5 + 1.54x$	$y = -35.0 + 1.32x$	$y = -27.4 + 1.31x$
	R ²		0.82	0.76	0.74
	MSPE		6.74	8.85	9.95
	RMSE, % mean		2.8	3.2	3.4
	MSPE decomposition				
	Mean bias, %		27.1	30.8	1.4
	Regression error, %		0.0	0.0	10.5
	Random error, %		72.9	69.2	88.1
Rumen	Mean	54.6	79.9	80.5	70.1
	±SE	18.5	5.9	5.7	13.1
	Linear regression		$y = 27.2 + 0.36x$	$y = 19.9 + 0.45x$	$y = 11.6 + 0.72x$
	R ²		0.85	0.85	0.87
	MSPE		50.75	50.57	43.93
	RMSE, % mean		13.0	13.0	12.1
	MSPE decomposition				
	Mean bias, %		66.0	67.9	16.9
	Regression error, %		0.6	0.1	0.0
	Random error, %		33.4	32.0	83.1
Postrumen	Mean	37.7	15.9	15.6	29.4
	±SE	17.7	4.1	3.6	4.8
	Linear regression		$y = 43.7 - 0.49x$	$y = 45.0 - 0.58x$	$y = 33.4 + 0.09x$
	R ²		0.90	0.90	0.89
	MSPE		30.16	30.09	33.24
	RMSE, % mean		14.6	14.5	15.3
	MSPE decomposition				
	Mean bias, %		61.0	38.2	1.4
	Regression error, %		0.3	35.9	10.5
	Random error, %		38.7	25.9	88.1

¹MSPE = mean square prediction error; RMSE = root mean square error.

²AMTS = Agricultural Modeling and Training Systems LLC (Cortland, NY); CPM = Cornell-Penn-Miner Dairy version 3.0.10 [Cornell University (Ithaca, NY), University of Pennsylvania (Philadelphia), The William H. Miner Agricultural Research Institute (Chazy, NY), and the University of Maryland (College Park) cooperating]; OFF = calculated from Offner and Sauvant (2004).

by the AMTS and CPM models were not useful, underpredicting the observed mean by 15%, due to the overprediction of RSDeg. The OFF predicted PRSDig very accurately. The MSPE decomposition for the OFF model displayed much greater random error and less mean bias, although regression equations, coefficients of determination, and MSPE were similar among all 3 models.

For corn-based diets, the mean TT was again very accurately predicted by the 3 models and displayed similar trends as noted for TT across all starch sources (Table 5). However, estimates of RSDeg by these models were not useful, with OFF overpredicting the observed mean RSDeg by 15% and AMTS and CPM overpredicting by greater than 25%. The RMSE as percentage of mean and MSPE were similar among models predicting RSDeg in corn-based diets. For RSDeg of this diet type, the OFF model displayed less mean bias with an intercept and slope of the linear regression displaying more acceptable values than AMTS and CPM. Neither AMTS nor CPM made useful predictions of PRSDig, although OFF predicted accurately. For PRSDig, OFF

displayed a larger MSPE, but it had a much larger random error. Some of the inaccuracy in prediction of RSDeg and PRSDig by OFF for corn-based diets may be due to differences in processing methods, which were not well reflected in the kd of the Offner et al. (2003) data set. This is also true of the AMTS and CPM models to a lesser extent because although processing of grains were added when present in the study, these effects were not commonly reported.

As was true for all starch sources and corn starch sources, the mean TT of small grains was very accurately predicted by all 3 models compared with mean observed values (Table 6). The OFF model displayed a more acceptable decomposition of MSPE for small grain starches. The RMSE as percentage of mean and MSPE were similar between model predictions. However, the linear regression displayed an intercept closer to 0 and a slope closer to unity for the AMTS model. The regression models for CPM and OFF are far from these values, but the coefficient of determination values are not greatly different. Unlike the RSDeg for all feeds and corn-based diets, the 3 models predicted RSDeg of

Table 6. Comparisons of existing models for starch digestion on a percentage basis in diets for adult dairy cows with small grain (n = 58) as the major starch source

Site	Parameter ¹	Observed	Model ²		
			AMTS	CPM	OFF
Total tract	Mean	94.6	96.9	97.1	95.6
	±SE	5.4	0.9	2.0	2.3
	Linear regression		$y = -16.3 + 1.13x$	$y = 84.0 + 0.10x$	$y = 101.07 - 0.08x$
	R ²		0.74	0.72	0.72
	MSPE		7.25	7.90	7.83
	RMSE, % mean		2.8	3.0	3.0
	MSPE decomposition				
	Mean bias, %		15.7	16.7	0.9
	Regression error, %		0.4	7.2	7.8
	Random error, %		83.9	46.1	91.3
Rumen	Mean	76.4	85.4	86.7	85.4
	±SE	15.4	3.2	3.0	8.1
	Linear regression		$y = 64.6 + 0.11x$	$y = 26.5 + 0.55x$	$y = 45.3 + 0.41x$
	R ²		0.90	0.90	0.90
	MSPE		22.52	22.18	22.96
	RMSE, % mean		6.2	6.2	6.3
	MSPE decomposition				
	Mean bias, %		26.3	33.5	21.4
	Regression error, %		0.2	1.0	18.6
	Random error, %		73.5	65.5	60.0
Postrumen	Mean	18.21	11.5	10.5	24.3
	±SE	13.0	2.8	2.7	4.2
	Linear regression		$y = 22.2 - 0.19x$	$y = 16.6 + 0.33x$	$y = 15.9 + 0.17x$
	R ²		0.90	0.90	0.90
	MSPE		15.53	15.54	15.84
	RMSE, % mean		21.6	21.6	21.9
	MSPE decomposition				
	Mean bias, %		21.7	21.4	0.9
	Regression error, %		0.1	18.6	7.8
	Random error, %		78.2	60.0	91.3

¹MSPE = mean square prediction error; RMSE = root mean square error.

²AMTS = Agricultural Modeling and Training Systems LLC (Cortland, NY); CPM = Cornell-Penn-Miner Dairy version 3.0.10 [Cornell University (Ithaca, NY), University of Pennsylvania (Philadelphia), The William H. Miner Agricultural Research Institute (Chazy, NY), and the University of Maryland (College Park) cooperating]; OFF = calculated from Offner and Sauvant (2004).

small grains accurately compared with observed mean values and very close to each other, overpredicting RS-Deg for small grains by approximately 10%. Although the MSPE was very similar among the models, the OFF model exhibited a larger percent of regression error than the other models. All models displayed regression equations that had intercepts significantly larger than 0 (26.5 to 64.6), yet all displayed coefficients of determination of 0.90. The overprediction of RS-Deg resulted in underprediction of PRSDig for small grains by 6.7, 7.7, and 8.0% for AMTS, CPM, and OFF, respectively. Values for other types of model evaluations were similar, with the exception of the decomposition of MSPE, which displayed a larger mean bias for AMTS and CPM, a larger random error for OFF, and a larger regression error for the CPM model. For sorghum sources, TT was overpredicted by all 3 models, acceptably by AMTS and CPM, and accurately by OFF (Table 7). All linear regressions had exceptionally large negative intercepts (−133.7, −134.9, and −601.2) and comparatively large slopes (2.28, 2.28, and 7.57)

for AMTS, CPM, and OFF, respectively. All 3 models also displayed a large mean bias and relatively small random error in decomposition of TT MSPE for sorghum. The AMTS and CPM models considerably overpredicted RS-Deg for sorghum sources. The OFF model predicted sorghum RS-Deg accurately but displayed more regression error. Although TT and RS-Deg were overpredicted for sorghum, the result was very accurate predictions of PRSDig for AMTS and CPM and an accurate prediction for OFF. Linear regression equations for PRSDig of sorghum display more desirable intercept and slope parameters, although the coefficients of determination of all equations were rather lower than the coefficients of determination of other sorghum fractions or for PRSDig of other starch sources. The starch data from sorghum may need to be discounted because of the few diets included in this analysis.

Standardization of model evaluation is always a difficult process (Tedeschi, 2006). In the present context, the RS-Deg and PRSDig may be used to predict energy and energy substrates for ration balancing. This, in turn,

Table 7. Comparisons of existing models for starch digestion on a percentage basis in diets for adult dairy cows with sorghum grain (n = 8) as the major starch source

Site	Parameter ¹	Observed	Model ²		
			AMTS	CPM	OFF
Total tract	Mean	80.4	93.2	93.5	89.9
	±SE	17.7	3.7	3.7	1.2
	Linear regression		$y = -133.7 + 2.28x$	$y = -134.9 + 2.28x$	$y = -601.2 + 7.57x$
	R ²		0.97	0.96	0.94
	MSPE		5.95	6.85	12.43
	RMSE, % mean		3.0	3.3	3.1
	MSPE decomposition				
	Mean bias, %		45.1	46.2	25.6
	Regression error, %		21.3	20.3	5.7
	Random error, %		33.6	33.5	68.7
Rumen	Mean	54.0	68.6	69.9	56.8
	±SE	17.5	8.9	8.9	2.6
	Linear regression		$y = -46.4 + 1.47x$	$y = -52.4 + 1.54x$	$y = -233.2 + 5.08x$
	R ²		0.73	0.82	0.76
	MSPE		51.92	33.64	45.98
	RMSE, % mean		13.3	10.7	12.6
	MSPE decomposition				
	Mean bias, %		62.2	67.7	3.5
	Regression error, %		5.0	5.8	28.7
	Random error, %		32.8	26.5	67.8
Postrumen	Mean	26.3	24.6	23.6	33.0
	±SE	12.7	5.2	5.3	1.6
	Linear regression		$y = 5.6 + 0.73x$	$y = 0.65 + 0.96x$	$y = -82.5 + 3.20x$
	R ²		0.59	0.68	0.68
	MSPE		41.47	31.34	32.45
	RMSE, % mean		24.5	21.4	21.7
	MSPE decomposition				
	Mean bias, %		1.9	4.6	25.6
	Regression error, %		11.4	2.5	5.7
	Random error, %		86.7	92.9	68.7

¹MSPE = mean square prediction error; RMSE = root mean square error.

²AMTS = Agricultural Modeling and Training Systems LLC (Cortland, NY); CPM = Cornell-Penn-Miner Dairy version 3.0.10 [Cornell University (Ithaca, NY), University of Pennsylvania (Philadelphia), The William H. Miner Agricultural Research Institute (Chazy, NY), and the University of Maryland (College Park) cooperating]; OFF = calculated from Offner and Sauvant (2004).

implies that poorly estimated RSDeg and PRSDig, because of failure to predict the mean with a sufficiently low MSPE, may result in suboptimal ration balance. Poor accuracy in predicting the site of starch utilization would appear to have different metabolic consequences with respect to propionate and glucose production. Of these 3 models, OFF predicted the mean RSDeg with greater accuracy and greater precision, which suggests adjustment of this model has the greatest potential to more accurately predict RSDeg. It also appears that differences in RSDeg between AMTS and CPM were due to differences in predicted kp. With the exception of sorghum grains, AMTS and CPM overpredicted RSDeg and underpredicted PRSDig. However, most of this error was related to a mean bias, which may be corrected by adding a constant term as did Offner and Sauvant (2004). It should not be surprising that AMTS and CPM displayed similar predictions and parameter values, as they are both derived from the Cornell Net Protein Carbohydrate System.

SM Model

Because there appeared to be room for improvement in predicting RSDeg, an attempt was made to develop models that would better predict this data set using the terms of the Ørskov and McDonald (1979) equation. First, simple averages of RSDeg and TT were developed. This method has been shown to be accurate for predicting AA flows from RUP (Patton and Stevenson, 2000). Grain processing was included in this determination to the extent possible, and the means derived for individual feedstuffs are presented in Table 8. It is interesting to note that this method produced a mean observed RSDeg for all corn sources with the exception of high-moisture shelled corn that was reasonably consistent. Likewise, mean estimates of barley grain RSDeg were similar to each other, whether ground or steam rolled. The means for RSDeg and TT were close to those first proposed by Firkins et al. (2001) as well as Theurer et al. (1999) and Owens (2005), except for

RSDeg of high-moisture corn, which was estimated to be less in the current study than the others. The idea of using a mean value was appealing because of its simplicity and, as suggested by Owens (2005), factors other than inherent degradability and processing factors probably have less than a 2% effect on overall degradability.

However, problems arise using this method for determining *in vivo* digestibility of individual feeds, especially feeds that have low starch content or that are included at low levels. Often, the minimum possible degradation

for these feeds was 0.1%, and the maximum was 99.9% by definition. This resulted in a mean calculation of 50% RSDeg, which may not be very meaningful. Also, because the data set that was used to develop the SM values is almost exactly the same as the data set used to evaluate it, care must be exercised when discussing the relative merits of these values in relation to the other models evaluated (Gill, 1978). Across all diets, use of the simple means for starch degradation resulted in a model that predicted the mean RSDeg percent with improved accuracy and which had the smallest

Table 8. Simple means of percent starch ruminally degraded (RSDeg) and percent starch digested in total tract (TT) for various feeds fed to adult dairy cattle

Feed	Comparisons	RSDeg	±SE	TT	±SE
Alfalfa cubes	4	50.0	—	55.0	—
Alfalfa hay	38	50.0	0.2	62.3	16.5
Alfalfa silage	53	50.0	4.0	52.4	9.2
Barley grain, dry rolled	8	69.0	6.3	98.9	2.9
Barley grain, ground	14	68.7	4.2	96.7	1.6
Barley grain, steam rolled	25	69.2	7.7	95.2	2.5
Barley silage	15	50.1	0.3	81.1	16.9
Beet pulp	21	47.8	7.5	83.4	15.3
Brewers grains, dried	1	50.5	—	74.5	34.6
Canola meal	14	51.8	6.3	79.7	12.2
Corn distillers grain, dried	16	48.1	4.0	50.0	—
Corn gluten feed	4	50.0	—	87.5	8.7
Corn gluten meal	18	50.0	—	76.3	11.0
Corn grain, cracked	11	54.6	6.0	89.0	6.1
Corn grain, ground ¹	57	59.4	10.3	93.2	3.2
Corn grain, high moisture	8	68.8	11.3	94.3	6.9
Corn grain, steam flaked ²	18	60.5	12.5	95.7	4.3
Corn silage	60	50.5	13.7	87.7	2.7
Corn starch	4	82.7	21.5	98.5	1.7
Cottonseed meal	5	51.0	1.9	76.3	19.0
Cottonseed, whole w/lint	30	49.8	0.9	59.9	13.9
Grass hay	5	50.0	—	67.7	20.5
Grass silage	16	49.1	2.7	52.9	11.5
Hominy feed	1	45.3	—	98.5	—
Linseed, whole	2	50.0	—	95.0	—
Linseed meal	4	50.0	—	94.0	—
Mixed alfalfa-grass silage	4	49.1	—	52.9	8.8
Oats, ground	6	67.0	7.1	94.2	0.3
Palm kernel meal	4	50.0	—	77.0	0.5
Peas, ground	2	50.0	—	87.5	3.5
Ryegrass pasture	8	51.3	2.2	64.5	14.3
Sorghum grain, dry rolled	6	47.0	6.8	82.7	5.5
Sorghum grain, steam flaked	4	71.9	10.3	97.5	4.8
Soybean hulls	11	53.9	9.0	76.8	16.6
Soybean meal ³	99	50.4	6.6	84.8	17.8
Soybean meal, expeller	6	50.0	—	73.0	20.1
Soybeans, whole, roasted	1	50.0	—	85.0	—
Soybeans, whole, raw	2	50.0	—	85.0	10.0
Sunflower meal	4	50.0	—	67.9	19.3
Wheat bran	4	50.0	—	90.0	10.0
Wheat flour	4	68.7	1.0	96.4	0.5
Wheat germ meal	2	50.0	—	82.1	18.3
Wheat grain, ground	20	70.0	2.4	96.3	1.3
Wheat grain, steam rolled	3	74.4	2.4	96.9	0.1
Wheat straw	2	35.5	0.7	67.5	45.9

¹Includes all reported grinds.

²Includes corn reported as steam rolled.

³Includes both 44 and 48% soybean meals.

Table 9. Comparisons of simple mean and developed rkd model for sites of starch digestion on a percentage basis for diets of adult dairy cows

Starch type	Site	Parameter ¹	Model ²	
			SM	rkd
All	Total tract	Mean	91.8	91.8
		±SE	3.5	3.5
		Linear regression	$y = 10.2 + 0.90x$	$y = 10.2 + 0.90x$
		R ²	0.78	0.78
		MSPE	11.54	11.54
		RMSE, % mean	3.7	3.7
		MSPE decomposition	11.54	11.54
		Mean bias, %	2.10	2.10
		Regression error, %	0.80	0.80
		Random error, %	97.10	97.10
	Rumen	Mean	60.2	61.4
		±SE	6.6	6.5
		Linear regression	$y = -29.1 + 1.5x$	$y = -45.2 + 1.73x$
		R ²	0.92	0.90
		MSPE	35.32	42.96
		RMSE, % mean	9.6	10.6
		MSPE decomposition		
		Mean bias, %	0.7	0.1
		Regression error, %	0.3	11.2
		Random error, %	99.0	88.7
	Postrumen	Mean	31.6	30.3
		±SE	4.5	5.4
		Linear regression	$y = -16.8 + 1.52x$	$y = -5.5 + 1.21x$
		R ²	0.86	0.83
		MSPE	49.94	62.00
		RMSE, % mean	22.9	25.6
		MSPE decomposition		
		Mean bias, %	0.1	0.1
		Regression error, %	0.2	3.3
		Random error, %	99.7	96.6
Corn	Total tract	Mean	92.0	92.0
		±SE	3.0	3.0
		Linear regression	$y = 11.4 + 0.87x$	$y = 11.4 + 0.87x$
		R ²	0.70	0.70
		MSPE	11.21	11.21
		RMSE, % mean	3.6	3.6
		MSPE decomposition		
		Mean bias, %	0.2	0.2
		Regression error, %	5.7	5.7
		Random error, %	94.1	94.1
	Rumen	Mean	58.9	58.8
		±SE	6.5	4.9
		Linear regression	$y = -8.6 + 1.08x$	$y = -47.1 + 1.74x$
		R ²	0.91	0.88
		MSPE	28.32	38.48
		RMSE, % mean	9.8	0.1
		MSPE decomposition		
		Mean bias, %	5.4	5.4
		Regression error, %	1.1	0.4
		Random error, %	93.5	94.2
	Postrumen	Mean	33.1	33.2
		±SE	4.5	4.3
		Linear regression	$y = 11.8 + 0.74x$	$y = 27.2 + 0.26x$
		R ²	0.90	0.88
		MSPE	28.84	33.30
		RMSE, % mean	14.2	15.3
		MSPE decomposition		
		Mean bias, %	6.3	6.4

Continued

Table 9 (Continued). Comparisons of simple mean and developed rkd model for sites of starch digestion on a percentage basis for diets of adult dairy cows

Starch type	Site	Parameter ¹	Model ²	
			SM	rkd
Small grain	Total tract	Regression error, %	1.0	0.1
		Random error, %	92.7	93.5
		Mean	92.5	92.5
		±SE	2.9	2.9
		Linear regression	$y = 29.4 + 0.70x$	$y = 29.4 + 0.70x$
		R ²	0.79	0.79
		MSPE	5.94	5.94
		RMSE, % mean	2.6	2.6
		MSPE decomposition		
		Mean bias, %	11.5	11.5
		Regression error, %	11.3	11.3
		Random error, %	77.2	77.2
	Rumen	Mean	63.4	67.0
		±SE	4.6	4.8
		Linear regression	$y = 14.3 + 0.93x$	$y = 36.2 + 0.56x$
		R ²	0.92	0.90
		MSPE	16.96	22.53
		RMSE, % mean	5.4	6.2
		MSPE decomposition		
		Mean bias, %	38.2	31.5
		Regression error, %	9.4	6.9
		Random error, %	52.4	61.6
	Postrumen	Mean	29.9	25.6
		±SE	3.4	3.6
		Linear regression	$y = 25.1 - 0.18x$	$y = 21.2 - 0.05x$
		R ²	0.90	0.90
		MSPE	16.03	15.70
		RMSE, % mean	22.0	21.8
		MSPE decomposition		
		Mean bias, %	34.9	24.4
		Regression error, %	27.7	1.9
		Random error, %	37.4	73.7
Sorghum grain	Total tract	Mean	87.5	87.5
		±SE	7.4	7.4
		Linear regression	$y = -26.1 + 1.20x$	$y = -26.1 + 1.20x$
		R ²	0.97	0.97
		MSPE	5.20	5.20
		RMSE, % mean	2.8	2.8
		MSPE decomposition		
		Mean bias, %	26.3	26.3
		Regression error, %	20.2	20.2
		Random error, %	53.5	53.5
	Rumen	Mean	56.1	56.4
		±SE	12.4	12.3
		Linear regression	$y = -11.7 + 1.19x$	$y = -9.2 + 1.14x$
		R ²	0.83	0.82
		MSPE	31.74	35.30
		RMSE, % mean	10.4	11.0
		MSPE decomposition		
		Mean bias, %	24.7	5.7
		Regression error, %	29.5	2.4
		Random error, %	47.8	91.9
	Postrumen	Mean	31.4	31.0
		±SE	5.0	5.1
		Linear regression	$y = -4.4 + 0.89x$	$y = -0.4 + 0.77x$
		R ²	0.62	0.63
		MSPE	37.49	40.87

Continued

Table 9 (Continued). Comparisons of simple mean and developed rkd model for sites of starch digestion on a percentage basis for diets of adult dairy cows

Starch type	Site	Parameter ¹	Model ²	
			SM	rkd
		RMSE, % mean	23.3	24.6
		MSPE decomposition		
		Mean bias, %	14.1	11.6
		Regression error, %	8.5	12.0
		Random error, %	77.5	46.4

¹MSPE = mean square prediction error; RMSE = root mean square error.

²SM = simple mean model in which the calculated means of ruminal starch degradability (RSDeg) and postruminal starch digestion (PRSDig) were applied to each ration; rkd = revised rate of digestion model.

MSPE and highest percent random error (Table 9). Across all diets and with starch sources other than small grains, the SM model provided more accurate estimates of RSDeg when compared with observed means with smaller MSPE and higher random error in this decomposition. Unfortunately, the SM model greatly underpredicted RSDeg and PRSDig for small grains when compared with other models. Inspection of individual diets indicated that the problem was with the prediction of RSDeg of ground barley diets. The reason SM should predict so poorly for ground barley diets is not presently known, but it may be related to adjustment of study effects, which may have led to a bias. The accuracy of the SM model for corn starch sources seems to indicate that 2 starch fractions may exist in corn. One fraction is a readily fermentable fraction, and the other is a fraction resistant to rumen microbial action but readily digestible in the small intestine. Less evidence exists for similar fractions for small grains and sorghum, although greater sample numbers may reveal a similar situation for these starches.

Revised kd Model

Logically, the failure of OFF to sufficiently predict RSDeg must be from 1 of 3 sources: (1) the kd must be incorrect, (2) the kp must be badly estimated, or (3) some other factors must be operating. To study which of these factors was most likely the cause of this inaccuracy, the kp for each feed in each ration was calculated by the 4 methods cited: Seo et al. (2006) as used in AMTS, Chalupa et al. (1991) as used in CPM, and Offner and Sauvant (2004); the kp as calculated by NRC (2001) was included for comparison. Across all feeds and all diets, the kp for Seo et al. (2006), Chalupa et al. (1991), Offner and Sauvant (2004), and NRC (2001) for this data set was found to be 5.86, 5.60, 5.78, and 5.91% per hour, respectively. Because of these relatively small differences, it appeared that the estimation of kp was essentially correct in OFF and that it would

take substantially large differences in kp to correct the deficiencies of prediction of RSDeg. Further, given the scope of the data summarized, it appeared that kd for the in situ data of Offner et al. (2003) reflected closely the in situ starch degradability of various feeds when determined in cattle. Therefore, other factors must be responsible for this difference in RSDeg. One such factor that could influence the RSDeg difference might be the differences between commercially processed grain and that ground to the 2 to 5 mm recommended for the in situ starch determination (Nocek, 1988). The structure, moisture, and vitreousness of the starch source can also influence degradation kinetics (Mills et al., 1999), and these factors must be considered a possible source of deviation. Moreover, the protein matrix surrounding the starch granules (McAllister et al., 1993) and protozoal populations (Mendoza et al., 1993) have been shown to negatively affect RSDeg. When it was reported, grind size was sometimes reported as grams per liter or as mean particle size in millimeters. Because there does not appear to be a direct correlation between them, it is impossible to separate the effects of processing from effects of starch structure using this data set. For example, when determining simple means, we found that ground corn ($n = 57$) had a calculated mean degradability of 59.4%, but the standard error was $\pm 10.3\%$. Steam-flaked corn had a calculated mean degradability of $60.5 \pm 12.5\%$. This large amount of variation in these feeds suggests more difference than might be expected for consistent grain processing. Better reporting of grain processing, vitreousness, and particle size may lead to better estimates of in vivo RSDeg for different processing methods.

A revised kd to be used in the Ørskov and McDonald (1979) calculation was proposed to better blend the effects of processing and starch type in hopes of predicting RSDeg with greater accuracy. These calculations were performed assuming that the kp of Offner and Sauvant (2004) was approximately correct. This calculation was used because it is both intermediate between the

Table 10. Revised rates of digestion (kd, % per h) estimated for starch contained in various feeds fed to adult dairy cattle

Feed	Determinations	kd	±SE
Alfalfa cubes	4	4.4	—
Alfalfa hay	38	4.4	0.3
Alfalfa meal	6	4.6	0.2
Alfalfa silage	53	4.6	2.2
Barley grain, dry rolled	8	15.3	9.1
Barley grain, ground	14	15.8	2.2
Barley grain, steam rolled	25	15.3	0.9
Barley silage	15	4.5	0.2
Beet pulp	21	5.8	0.8
Brewers grains, dried	6	6.2	0.1
Canola meal	14	6.5	0.9
Corn distillers grain, dried	16	6.3	0.4
Corn gluten feed	4	7.0	1.6
Corn gluten meal	19	6.5	0.3
Corn grain, cracked	9	8.4	0.6
Corn grain, ground ¹	62	9.7	0.9
Corn grain, high moisture	8	15.5	1.4
Corn grain, steam flaked ²	18	9.7	0.9
Corn silage	60	4.6	0.3
Corn starch	4	30.3	2.4
Cottonseed meal	6	6.9	0.8
Cottonseed, whole with lint	30	4.7	0.4
Grass hay	5	4.3	0.1
Grass silage	20	3.9	0.4
Hominy feed	1	4.6	—
Linseed, whole	2	6.0	0.1
Linseed meal	4	5.6	1.6
Mixed alfalfa-grass silage	4	4.5	0.2
Oats, ground	6	11.5	2.8
Palm kernel meal	4	5.6	0.2
Peas, ground	2	5.6	0.3
Rapeseed meal	6	5.7	1.4
Ryegrass pasture	8	4.5	1.0
Sorghum grain, dry rolled	6	5.7	0.4
Sorghum grain, steam flaked	4	16.5	1.1
Soybean hulls	14	7.8	0.6
Soybean meal ³	109	6.5	0.7
Soybean meal, expeller	6	7.3	0.5
Soybeans, whole, roasted	1	6.2	—
Soybeans, whole, raw	2	6.9	0.1
Sunflower meal	4	5.8	0.1
Wheat bran	4	6.1	0.1
Wheat flour	4	14.7	0.2
Wheat germ meal	2	6.8	0.1
Wheat grain, ground	18	14.6	1.3
Wheat grain, steam rolled	2	11.9	1.8
Wheat straw	2	2.4	—

¹Includes all reported grinds.²Includes corn reported as steam rolled.³Includes both 44 and 48% soybean meals.

other kp estimates, and it is computationally simple. The revised kd values for individual ingredients are presented in Table 10. This model was evaluated as were the others, and analyses are presented in Table 9 also. The mean RSDeg and PRSDig estimations of rkd were similar to those of the SM method with larger MSPE and slope coefficients farther from 1. This similarity was primarily because the amounts of degraded and digested starch were taken from the MS model to back calculate the revised kd. Thus, the rkd model failed to evaluate RSDeg and PRSDig of small grains well and

overpredicted the TT of sorghum as well as overpredicted the amount of sorghum RSDeg. The rkd method should be evaluated as a method to enable the Ørskov and McDonald (1979) equation to predict the mean RSDeg, although refinement is required for prediction of RSDeg of small grain starches.

Discarded Models

Models of RSDeg based on regression of TT digestibility, both across and within feed type as well as from

regression models within feed type, produced prediction of low accuracy and precision, so they were discarded. Use of rkd predicted as a percentage of starch present for each ingredient all produced a model with low accuracy. In spite of the high correlation of RSDeg within processing type, when these same groups of diets, which were used to develop these equations, were subjected to the AMTS, CPM, OFF, SM, and rkd models, with the exception of ground corn and ground barley, predictions of mean RSDeg values were highly accurate, but the associated regression equations had extremely high intercepts with negative slopes. The negative slopes across all models indicated that the amount of data associated with processing effects was not sufficient for model evaluation.

CONCLUSIONS

Across all feeds, the OFF, SM, and rkd models predicted RSDeg and PRSDig more accurately than the AMTS and CPM models. The use of revised kd values in the equation of Ørskov and McDonald (1979) has the potential to improve the in vivo prediction of RSDeg. Further, it appears that more careful reporting of starch structure, particle size, and processing method when measuring in vivo RSDeg and TT will provide opportunities to not only better predict the amount and types of energy fuels, but may also result in more accurate prediction of rumen microbial protein.

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APPENDIX 1. LIST OF STUDIES USED TO DETERMINE RUMINAL STARCH DEGRADATION AND TOTAL-TRACT STARCH DIGESTION

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APPENDIX 2. CALCULATION OF SIMPLE MEAN RUMINAL STARCH DEGRADATION

As an example of simple mean RSDeg, consider the ration presented in Table A1 with a reported starch digestion of 60%. Of the 5.22 kg of starch in the diet, 3.132 kg are degraded:

$$5.22 \text{ kg} \times 0.60. \tag{A1}$$

The first assumption is that all feeds except the largest starch source are indigestible. Therefore, for this example, all 3.132 kg of degraded starch must come from the 4.900 kg of starch in corn grain. This means that the maximum possible degradation of corn grain is 63.9%:

$$\begin{aligned} &3.132 \text{ kg of starch degraded} / 4.90 \text{ kg of starch} \\ &\text{in corn grain} \times 100 = 63.9\%. \tag{A2} \end{aligned}$$

Table A1. Dairy cow ration with a reported starch digestion of 60%

Ingredient	DMI, kg	Starch, %	Total, kg
Alfalfa hay	10.0	2.0	0.20
Corn grain ground	7.0	70.0	4.90
Soybean meal	2.0	6.0	0.12
Wheat straw	2.0	0.0	0.00
Vitamin-mineral mix	1.6		0.00
Total	22.0		5.22

To find the minimum possible corn grain degradation, assume that all starch sources except the largest are 100% digestible. Thus the minimum of starch digestion for corn is

$$\begin{aligned} &3.132 \text{ kg of starch degraded} - (0.20 \text{ kg of alfalfa hay} \\ &\text{starch} + 0.12 \text{ kg of soybean meal starch}) = 2.812 \text{ kg} \\ &\text{of starch degraded from corn grain,} \tag{A3} \end{aligned}$$

$$\begin{aligned} &\text{Minimum percent of starch degradability} = \\ &2.812 \text{ kg of starch degraded} / 4.90 \text{ kg} \\ &\text{of corn starch} \times 100 = 57.4\%, \tag{A4} \end{aligned}$$

and the simple mean would be

$$(63.9\% + 57.4\%) / 2 = 60.6\%. \tag{A5}$$