Relationships between Starch and Physically Effective and Undegraded Fiber in Lactating Dairy Cows

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Introduction

For several years we have been working at the Institute on how to integrate measures of fiber (un)degradability and particle size in an effort to better predict dry matter intake (DMI) and energy-corrected milk (ECM) production (Grant et al., 2018). To-date, we have focused mainly on physically effective neutral detergent fiber (peNDF) and undegradable NDF at 240 hours of in vitro fermentation (uNDF240). The resulting value – termed physically effective uNDF240 (peuNDF240) - can be calculated simply as the physical effectiveness factor (pef) multiplied by uNDF240, or perhaps more accurately over a wide range of diets, as a direct in vitro measure of uNDF240 on the pef fraction of particles (more about this topic later). The pef is measured by sieving the total mixed ration (TMR) sample: either using a 1.18-mm sieve when dry, vertical sieving (Mertens, 1997) or using a 4.0-mm sieve when horizontally sieving as-fed samples on the farm. At least for corn silage and haycrop silage-based TMR, using the Penn State Particle Separator with a 4.0-mm sieve yields similar pef values as the standard dry sieving method with a 1.18-mm sieve (Schuling et al., 2015).

The objectives of this paper are to briefly review the progress to-date on integrating pef and uNDF240 to better predict DMI and ECM, and to present the lactation results from a recently completed study that investigated the interaction between dietary peuNDF240 and rumen fermentable starch (RFS).

Physically Effective Undegradable NDF

Miller et al. (2020) assembled a 5-study database from experiments using high-producing Holstein dairy cows at Miner Institute conducted between 2014 and 2019 to assess the relationship between uNDF240 and peuNDF240 with DMI and ECM. Details are provided in the abstract and the accompanying presentation from the 2020 American Dairy Science Association (ADSA) virtual annual conference (https://virtual2020.adsa.org/). Within this database, the range in dietary uNDF240 was 5.5 to 11.5% of ration dry matter (DM) and the range in peuNDF240 was 4.0 to 7.3 % of DM. This range in NDF undegradability spans what is commonly fed in the US with values of 10.0 to 11.5% more likely to limit DMI and values closer to 5 to 6% increasing the risk for subacute ruminal acidosis.

The relationship between uNDF240 and DMI (lb/d) was moderate ($y = -0.84x + 68.18$, $R^2 = 0.32$), but the relationship between peuNDF240 and DMI was stronger ($y = -2.16x + 72.42$, $R^2 = 0.60$). In particular, combining pef and uNDF240 allowed a better prediction of DMI when higher uNDF240 diets were more finely chopped. Our research to-date suggests that when forage fiber digestibility is lower than desired, a finer forage particle size will enhance DMI and ECM production. The improved lactational performance appears to be associated with less eating time and a more desirable rumen fermentation and fiber turnover for cows fed higher uNDF240 diet with finer chop length.

The relationship between uNDF240 and ECM (lb/d) was strong ($y = -2.26x + 126.38$, $R^2 = 0.58$), but similar to DMI, the relationship between peuNDF240 and ECM (lb/d) was even stronger than that observed for uNDF240 ($y = -4.92x + 133.14$, $R^2 = 0.78$). A field study reported by Geiser and Goeser (2019) using 55 commercial dairy farms where corn silage comprised 36.8 ± 7.9% of the ration DM found that a one-unit increase in uNDF240 of the corn silage was associated with a 0.59 lb/d decrease in DMI and a 1.30 lb/d reduction in ECM. In the Institute data base, we observed a reduction of 0.84 lb/d of DMI and 2.3 lb/d of ECM with each one-unit increase in ration uNDF240 with high-producing cows (Miller et al., 2020). So, there is general agreement between our Institute database and this field study which gives us confidence that these relationships are consistent and can be useful in the field.

We need to note that the diets in this database were primarily based on corn silage and haycrop silage with some chopped hay and straw. Importantly, there were no pure alfalfa diets, diets with larger amounts of non-forage fiber sources, or pasture. In the future, we intend to define the relationships between uNDF240, peuNDF240, and DMI and ECM for a wider range of diets and management scenarios. Nonetheless, there appears to be value in integrating two measures of fiber - uNDF240 and pef – when formulating rations.

Interactions between Physically Effective uNDF240 and Rumen Fermentable Starch

Our most recent work has evaluated the relationship between dietary peuNDF240 and RFS (Smith et al., 2020). Initial studies were focused mainly on the middle to upper range of dietary uNDF240 concentrations to determine at what point DMI was constrained and how manipulating particle size affected DMI at a given uNDF240 content (Grant et al., 2018). In contrast, the study by Smith et al. (2020) was designed to determine the interaction between dietary starch (specifically RFS) and uNDF240 for diets that were on the lower end of the uNDF240 range commonly observed in the field. Consequently, the research focus shifted from gut fill and DMI constraints to maintenance of adequate dietary fiber and minimizing the risk of subacute rumen acidosis.

The negative associative effect of starch on rumen fiber degradation and peNDF requirements is well known. Mertens and Loften (1980) were the first to observe that too much starch resulted in lengthened lag times prior to NDF degradation in vitro. Subsequent work showed that, as rumen starch fermentability increased, the negative effect on the lag and fractional rate of NDF degradation increased and lower rumen pH amplified this negative effect of starch (Grant and Mertens, 1992; Grant, 1994). However, we still need to understand how dietary starch content and RFS influence rumen NDF turnover in diets that differ in their fiber characteristics such as uNDF240, peuNDF240, and fast- and slow-degrading NDF (measured using 30-, 120-, and 240-h in vitro fermentations).

Details of the study by Smith et al. (2020) are available in the abstract and at the ADSA annual conference web site. Briefly, 16 lactating Holstein cows (8 ruminally fistulated) that were approximately 85 ± 15 days in milk were enrolled, blocked by parity, days in milk, and milk production and were used in a replicated 4 x 4 Latin Square design. The study had 28-d periods (18 d of adaptation, 10 d of collection). A factorial arrangement of four diets was used to evaluate the effect of dietary peuNDF240 content, dietary RFS content, and their interaction. Table 1 lists the primary dietary ingredients that were used in the study. Differences in dietary uNDF240 or peuNDF240 content were obtained by using a brown midrib (lower peuNDF240 diets) versus a conventional corn silage hybrid (higher peuNDF240 diets). The two dietary RFS concentrations were obtained primarily by varying the content of finely ground corn meal together with the starch in the corn silages. The corn meal contained 62% of DM ≤ 0.60 mm when dry sieved with a pef = 0.10.

Table 1. Ingredient composition of diets with varying concentrations of physically effective 240-h undegraded neutral detergent fiber (peuNDF240) and ruminal fermentable starch (RFS).

	Diets			
	Low peuNDF240		High peuNDF240	
Ingredients, % of DM	Low RFS	High RFS	Low RFS	High RFS
Conventional corn silage	-	-	47.60	47.60
Brown midrib corn silage	47.60	47.60	-	-
Timothy hay, chopped	7.94	7.94	7.94	7.94
Wheat straw, chopped	1.59	1.59	1.59	1.59
Corn meal	2.78	7.94	3.57	8.73
Beet pulp pellets	7.14	5.16	6.35	4.37
Concentrate mix	32.95	29.77	32.95	29.77

Table 2 summarizes the chemical composition of the four treatment diets. Unexpectedly, the two corn silage hybrids did not differ as much as anticipated in their uNDF240 content as they were fed out during the trial: 8.6% of DM for conventional versus 6.7% of DM for the brown midrib corn silage (although initial samples used in ration formulation had indicated 11.8% and 5.6% of DM for conventional and brown midrib, respectively). Consequently, the dietary uNDF240 concentration averaged 6.85% of ration DM for the lower uNDF240 diets and 7.20% of DM for the higher uNDF240 diets; in other words, the uNDF240 content was quite similar across all diets. Similarly, the peuNDF240 values (pef x uNDF240) were similar and ranged from 3.88 to 4.16% of ration DM. For all diets, the uNDF240 and the peuNDF240 values were on the lower end of the range in our 5-study data base.

Because the cows responded to dietary fiber characteristics (see Tables 3 and 4), and yet the measured uNDF240 and calculated peuNDF240 (pef x uNDF240) values did not differ markedly, we decided to directly measure the uNDF240 concentration (using an in vitro fermentation) in the fraction of each diet that was retained on the ≥1.18-mm sieve and the fraction that passed through this sieve. Interestingly, the uNDF240 was not uniformly distributed across the two size fractions as had been the case in some previous research (Grant et al., 2018). The directly assayed peuNDF240 averaged 6.2 and 8.3% of ration DM for the lower peuNDF240 and higher peuNDF240 diets, respectively. This range in directly measured peuNDF240 helps to explain the animal responses in Table 3 and 4. However, it does call into question the validity of simply calculating peuNDF240 as pef x uNDF240 in all dietary scenarios. In many instances, this simple approach appears to work well, but we need to be aware that, if the uNDF240 is not uniformly distributed across the particle size fractions, then the calculated number may not be appropriate. In addition, we need to be specific about how the peuNDF240 is measured. In this article, we will use the terms *calculated* or *assayed* peuNDF240.

The dietary starch content averaged 20.7 and 24.7% of DM for the high and low RFS diets, respectively. Starch degradability did not differ much across diets, but the RFS content averaged 16.8 and 19.1% of ration DM for the lower and higher RFS diets, respectively. It is important to put these starch measures into context. Although the diets differed by 4 units in starch percentage, the starch and RFS contents were moderate to low compared with many commonly fed diets in much of the US. The fact that the higher RFS diets were only moderately high is important to consider when interpreting the animal responses where negative effects on milk fat percentage were observed with relatively low RFS concentrations (see Table 4). Assessment of the interaction between RFS and fiber may be especially important with lower fiber diets with increased risk of subacute rumen acidosis ($pH < 5.8$; Stone, 2004).

Finally, a post-hoc analysis of the intake of dietary carbohydrate fractions was performed using Cornell Net Carbohydrate Protein System (CNCPS) biology (NDS Professional, CNCPS biology v. 6.5, Reggio Emilia, IT) with Kurt Cotanch (Barn Swallow Consulting, LLC, Underhill, VT). This analysis used the ingredient compositional measures and animal measures from the study. Intake of uNDF240 was 2.2, 2.2, 2.5, and 2.4 kg/d for the lower peuNDF240/lower RFS, lower peuNDF240/higher RFS, higher peuNDF240/lower RFS, and higher peuNDF240/higher RFS diets, respectively. In the same dietary order, the intake of RFS was 5.0, 5.6, 5.0, and 5.5 kg/d. The ratio of dietary RFS:uNDF240 was 2.42, 2.82, 2.32, and 2.68 which may potentially have usefulness as a benchmark for milk fat depression (see discussion for Table 4).

Table 2. Composition of diets with varying concentrations of physically effective undegraded neutral detergent fiber after 240-h fermentation (peuNDF240) and rumen fermentable starch (RFS).

	Diets			
	Low peuNDF240		High peuNDF240	
Item	Low RFS	High RFS	Low RFS	High RFS
Dry matter (DM), %	55.3	55.3	54.4	54.2
Crude protein (CP), % of DM	16.1	15.3	16.0	15.2
Soluble protein, % of CP	40.6	39.8	43.4	42.5
aNDFom[1], % of DM	33.1	32.4	33.3	32.6
Lignin, % of DM	3.21	3.1	3.5	3.42
Starch, % of DM	20.7	24.6	20.8	24.7
Starch degradability[2], % of starch	80.5	78.1	81.4	77.0
Rumen fermentable starch, % of DM[3]	16.7	19.2	16.9	19.0
Sugar, % of DM	3.9	4.5	4.7	4.5
Ether extract, % of DM	3.83	3.76	3.81	3.75
uNDF30om, % of DM	13.5	15.2	15.1	15.5
uNDF120om, % of DM	7.5	7.6	8.5	8.5
uNDF240om, % of DM	6.9	6.8	7.3	7.1
pef[4]	0.60	0.57	0.57	0.57
Calculated peuNDF240 (pef x uNDF240), % of DM	4.14	3.88	4.16	4.05
Assayed peuNDF240om, % of DM[5]	6.35	6.07	8.60	8.00

[1] Amylase- and sodium sulfite-treated neutral detergent fiber, ash corrected.

[2] The 7-h starch degradability value was measured on the entire total mixed ration.

[3] Rumen fermentable starch: starch content multiplied by starch degradability.

[4] Physical effectiveness factor: measured by dry sieving with the 1.18-mm sieve (Mertens, 1997).

[5] Physically effective undegraded neutral detergent fiber after 240 h of in vitro fermentation, ash corrected. The uNDF240om from composited diet that was retained on ≥1.18-mm sieve. This value is sensitive to differences in uNDF240om distribution across dietary particle size fractions.

Table 3 summarizes the intake responses to the diets. There were no interactions between dietary peuNDF240 and RFS on DMI or intake of starch and uNDF240.There was no effect of either peuNDF240 or RFS on DMI in kg/d, but the higher peuNDF diets did slightly reduce DMI as a percentage of BW similarly for both RFS concentrations. The higher RFS diets reduced the intake of aNDFom which reflected the small differences between the diets in aNDFom content (Table 2). As expected, the higher RFS diets increased starch intake by approximately 18 to 20%. Likewise, the higher peuNDF240 diets increased uNDF240 intake by 9 to 14%; the content of dietary RFS also affected uNDF240 intake although the effect was very small.

Table 4 summarizes the milk and milk component responses to the diets. The higher peuNDF240 diets reduced milk yield by approximately 1.2 kg/d compared with the lower peuNDF240 diets. The daily yield of 3.5% fat-corrected milk (FCM) and ECM were both reduced by greater RFS content. Although there was no significant interaction between dietary peuNDF240 and RFS, the higher RFS reduced 3.5% FCM by 2.3 kg/d for the lower peuNDF diets versus only 0.7 kg/d for the higher peuNDF diets. It appears that the negative associative effect of RFS on FCM yield was more pronounced with the lower peuNDF240 diet. Again, it is important to remember that the uNDF240 and peuNDF240 (pef x uNDF240) values for all diets were at the lower range (approximately 7 and 4% of ration DM, respectively).

Table 3. Dry matter intake (DMI) and carbohydrate intake responses to experimental diets.

Variable	Diets				*P*-value[1]	
	Low peuNDF240		High peuNDF240			
	Low RFS	High RFS	Low RFS	High RFS	peuNDF	Starch
DMI, kg/d	29.7	29.4	29.4	29.2	0.27	0.40
DMI, % of BW/d	4.31	4.28	4.24	4.20	0.04	0.41
aNDFom[2] intake, kg/d	9.9	9.5	9.8	9.6	0.75	0.03
aNDFom intake, % of BW/d	1.44	1.39	1.42	1.37	0.37	0.03
Starch intake, kg/d	6.1	7.2	6.0	7.2	0.74	<0.0001
Starch intake, % of BW/d	0.88	1.06	0.87	1.04	0.35	<0.0001
uNDF240om intake, kg/d	2.25	2.16	2.45	2.40	<0.0001	0.008
uNDF240om intake, % of BW/d	0.322	0.315	0.354	0.345	<0.0001	0.0078

[1] There was no significant ($P > 0.10$) interaction between peuNDF240 and rumen fermentable starch.

[2] Amylase- and sodium sulfite-treated neutral detergent fiber, ash corrected.

Milk fat percentage was greater for the higher peuNDF240 than the lower peuNDF240 diets (Table 4). Similarly, milk fat percentage and daily output were depressed by the higher RFS versus the lower RFS diets. There was no significant interaction between peuNDF240 and RFS, although it is useful to note that numerically the highest milk fat percentage was for cows fed the higher peuNDF/lower RFS diet and the lowest milk fat percentage was with cows fed the lower peuNDF240/higher RFS diet. A negative associative effect existed between peuNDF240 and RFS that expressed itself in reduced milk fat. Overall, milk fat percentage was lower for all diets in this study compared with the typical milk fat percentage for the Institute dairy herd of approximately 4.0%. This general depression in milk fat likely reflected the lower uNDF240 and calculated peuNDF240 for all diets.

Table 4. Milk and milk component responses to experimental diets.

	Diets				*P*-value[1]	
	Low peuNDF240		High peuNDF240			
Variable	Low RFS	High RFS	Low RFS	High RFS	peuNDF	Starch
Milk, kg/d	53.1	52.0	51.2	51.5	0.01	0.35
3.5% FCM[2], kg/d	53.8	51.5	52.9	52.2	0.85	0.01
ECM[3], kg/d	53.4	51.5	52.5	51.9	0.56	0.02
Fat, %	3.59	3.48	3.74	3.60	0.05	0.06
Fat, kg/d	1.90	1.79	1.90	1.84	0.41	0.01
True protein, %	2.83	2.87	2.85	2.86	0.61	0.12
True protein, kg/d	1.50	1.48	1.45	1.47	0.02	0.94
Lactose (anhydrous), %	4.57	4.57	4.59	4.61	0.04	0.58
Lactose (anhydrous), kg/d	2.43	2.38	2.35	2.37	0.09	0.60
Urea nitrogen, mg/dL	12.0	10.1	12.4	10.5	0.08	<0.0001
De novo FA[4], g/100 g milk	0.80	0.76	0.81	0.80	0.15	0.26
Mixed origin FA, g/100 g milk	1.34	1.31	1.43	1.38	0.008	0.13
Preformed FA, g/100 g milk	1.31	1.26	1.34	1.29	0.17	0.02
De novo and mixed origin FA, g/100 milk	2.14	2.07	2.24	2.18	0.03	0.17
Unsaturation, double bonds/FA	0.288	0.294	0.281	0.280	0.005	0.43
3.5% FCM/DMI, kg/kg	1.81	1.75	1.81	1.79	0.41	0.06

[1] There was no significant (*P* > 0.10) interaction between peuNDF240 and rumen fermentable starch.

[2] Fat-corrected milk.

[3] Energy-corrected milk.

[4] Fatty acids.

Although milk fat yield was unaffected by peuNDF240 content, the yield of true protein was reduced slightly with higher peuNDF240 (Table 4). Milk urea nitrogen content tended to be increased by higher peuNDF240 and RFS substantially reduced milk urea nitrogen at either concentration of peuNDF240. These responses reflect greater efficiency of nitrogen use for cows fed the lower peuNDF240 and particularly the positive effect of moderately greater RFS on rumen nitrogen efficiency.

Mixed origin and mixed + de novo fatty acids were reduced by lower peuNDF240 diets versus higher peuNDF240. Likewise, the unsaturated fatty acids were increased for cows fed the low peuNDF240 diets. Numerically, cows fed the lower peuNDF240/higher RFS diet that produced milk with the lowest milk fat percentage also had the least mixed + de novo fatty acids and highest unsaturated milk fatty acids. Overall, these changes in milk fatty acid composition track with the changes in milk fat percentage and indicate the onset of trans fatty acid-induced milk fat depression (Barbano et al., 2018). As a bottom line measure of herd performance, efficiency of FCM production (3.5% FCM/DMI) was lower for cows fed the higher RFS diets and it was least numerically for cows fed the lower peuNDF240/higher RFS diet. As a final “food for thought”: in the post hoc analysis with CNCPS biology, it appeared that a RFS:uNDF240 ratio >2.8 might be a useful indicator for diets that have greater risk of milk fat depression. This idea requires further research to validate, but it seems to fit this data set.

Take Home Messages

As this research story unfolds, we plan to better define the interactions between RFS and fiber particle size and degradability to provide target values and benchmarks to use when formulating rations. To-date, take home messages of this research include:

- There is value in integrating forage particle size and uNDF240, and useful relationships exist between uNDF240 and peuNDF240 with DMI and ECM for high producing dairy cows.
- For corn silage-based diets, when uNDF240 exceeds 10 to 11% of ration DM, DMI may decrease; consider a finer chop length.
- uNDF240 less than 7% of ration DM may increase the risk of subacute rumen acidosis; maintain peNDF at least 19 to 20% of ration DM. Don’t chop low uNDF240 forage too fine: cows still need effective NDF.
- peuNDF240 (pef x uNDF240) is a work-in-progress, but a range of 4.5 to 6% of ration DM seems to be a target for high producing cows fed corn silage-based diets.
- Associative effects among RFS, uNDF240, and peNDF are important. When peuNDF240 is approximately 4 to 6% of ration DM for corn silage-based diets (depending on how measured), and uNDF240 is <7.0% of ration DM, then negative effects of RFS on milk fat at only 19 to 20% of ration DM may occur.

- If dietary uNDF240 is not uniformly distributed across particle sizes, then direct measurement of uNDF240 in pef particle fraction may be a better approach. It will be critical not to confuse the two methods for measuring peuNDF240. Stay tuned.

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