A Tale of Two Fibers: Physically Effective and Undegradable Neutral Detergent Fiber and Their Interaction with Starch

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Abstract

Measurement of dietary particle size (physically effective neutral detergent fiber; **peNDF**) and fiber indigestibility (undegradable NDF at 240 hr of in vitro fermentation; **uNDF240**) improves the prediction of dry matter intake (**DMI**) and milk production from NDF. Consequently, exploring potential relationships between peNDF and uNDF240 is important. Combining peNDF and uNDF240 into one term - physically effective uNDF240 (**peuNDF240**) – appears to be useful when interpreting and predicting feed intake and milk response to diets based on corn and haycrop silages. When forage fiber undegradability is greater than desired, a finer chop length boosts feed intake to levels similar to lower uNDF240 rations. However, finely chopping low uNDF240 forages and rations should be avoided. Feeding even moderately high rumen fermentable starch (**RFS**; approximately 19% of ration DM) depresses milk fat percentage and 3.5% fat-corrected milk (**FCM**) production when diets contain relatively low content of uNDF240 and peuNDF240 (approximately 7 and 4% of ration DM, respectively). High producing cows are sensitive to starch and its rumen fermentability, and we need to consider the interaction between RFS and uNDF240 or peuNDF240. The concept of integrating physical effectiveness factor (i.e., particle size) with uNDF240 is promising, but research with legumes, pastures, and non-forage sources of fiber is needed to test the relationship between peuNDF240 and feed intake across a wide range of diet types.

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Nutritionists have long realized that neutral detergent fiber (**NDF**) content alone does not explain all the observed variation in DMI and milk yield as forage source and concentration in the diet vary. Incorporating measures of fiber degradability and particle size improves our ability to predict feed intake and productive responses.

Waldo et al. (1972) recognized that NDF needed to be fractionated into digestible and indigestible pools for calculation of fractional degradation rates. The recognition that there is an indigestible portion of fiber led to research that improved our understanding of the degradability of fiber in ruminant diets and the beginning of dynamic models of fiber degradation and turnover. Research has focused on a three-pool model of ruminal NDF degradation: uNDF240 (as a laboratory measure of indigestible NDF) plus a fast- and slow-fermenting pool of NDF (Mertens, 1977; Raffrenato and Van Amburgh, 2010; Cotanch et al., 2014).

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To date, more research has focused on defining biologically relevant fiber degradation pools than particle size pools within the rumen, although both degradation and particle size characteristics of a fiber particle are important for explaining ruminal fiber turnover (Mertens, 2011). In a classic paper, Mertens (1997) laid out a comprehensive system for integrating NDF content and particle size, based on the 1.18-mm dry sieved fraction of particles, known as peNDF. Although the peNDF system is based solely on particle size as a measure of physical form, it explains a substantial amount of the variation in chewing activity, ruminal pH, and milk fat elicited among forage sources.

For the past several years, we have focused on the relationship between undegradable and physically effective NDF at the Institute and have conducted a series of studies designed to assess the relationship between dietary uNDF240 and particle size measured as peNDF. The potential relationship between peNDF and uNDF240 is an important topic among nutritionists with several practical feeding questions being asked in the field:

- What are the separate and combined effects of peNDF and uNDF240 in diets fed to lactating cows?
- Can we adjust for a lack of dietary peNDF by adding more uNDF240 in the diet?
- Similarly, if forage uNDF240 is higher than desired, can we at least partially compensate by chopping the forage finer to maintain feed intake?
- How do starch and RFS interact with ration uNDF240 and peuNDF240?

The answer to these questions is likely affected by the source of fiber, forage or non-forage, since they differ dramatically in fiber degradation pools and particle size. Some nutritionists have questioned the importance of particle size in feeding dairy cattle as we better understand fiber fractions (i.e., fast, slow, and uNDF240) and their rates of degradation. This is a complicated question, but the short answer is – yes – particle size is important. However, it may be for reasons that we haven't always appreciated, such as its effect on eating behavior more so than rumination.

Undegradable and Physically Effective Fiber

To begin addressing the questions above, we conducted a study (Smith et al., 2018a; 2018b) to assess the effect of feeding lower (8.9% of ration DM) and higher (11.5% of ration DM) uNDF240 content in diets with either lower or higher peNDF (19 to 20 versus ~22% of ration DM). The diets contained approximately 35% corn silage, 1.6% chopped wheat straw, and chopped timothy hay with either a lower physical effectiveness factor (**pef**; fraction of particles retained on ≥1.18-mm screen with dry sieving; 0.24) or a higher pef (0.58). Note that for diets based on corn silage and haycrop silage, pef measured using the 4-mm sieve of the Penn State Particle Separator on an as-is sample is similar to that measured using dry vertical sieving and a 1.18-mm sieve (Schuling et al., 2015).

A Haybuster (DuraTech Industries International, Inc., Jamestown, ND) with its hammer mill chopping action was used to achieve the two particle sizes of grass hay. Additionally, for the lower forage diets, we partially replaced the timothy hay with nearly pelleted beet pulp to help adjust the fiber fractions (i.e., reduce the uNDF240 content). The lower uNDF240 diets contained about 47% forage, whereas the higher uNDF240 diets contained about 60% forage on a DM basis (Table 1).

Combining particle size and undegradability: physically effective uNDF240

To better define the relationship between physical effectiveness and uNDF240 among these 4 diets, we calculated physically effective uNDF240 (peuNDF240 = pef x uNDF240). It is important to stress that we view peuNDF240 more as a useful nutritional concept than as a ration formulation target. We also understand the potential limitations of a value that is derived as the product of 2 other measures; the sampling and analytical variation inherent in each individual measure becomes combined in the single measure. Nonetheless, it is useful to observe how cows respond to diets differing markedly in peuNDF240.

In Table 1, we see that this value ranged substantially from 5.4% of DM for the low uNDF240-low peNDF diet to 7.1% of DM for the high uNDF240-high peNDF diet. And by design, the two intermediate diets contained 5.9% of ration DM as peuNDF240. A key assumption underpinning our focus on a peuNDF value is that uNDF240 is uniformly distributed across the particle size fractions, particularly above and below the 1.18-mm screen when a sample has been dry sieved. Current research at the Miner Institute Forage Laboratory indicates that uNDF240 is relatively evenly distributed above and below the 1.18-mm screen for the diets fed in this study. This assumption is being tested in other types of diets. Similar to peNDF, it can be calculated simply as pef x NDF or as the direct measure of NDF on particles retained on the 1.18-mm screen and greater. Thus, we will need to measure and compare the peuNDF240 values obtained with both approaches as diets based on different fiber sources are assessed. In fact, in our work assessing the interaction between RFS and peuNDF240 (next section), we found that uNDF240 was not uniformly distributed in the ration particles retained above and below the 1.18-mm sieve.

When feeding these 4 diets, we expected the bookend diets to elicit predictable responses in DMI based on their substantial differences in uNDF240 and particle size (Harper and McNeill, 2015). We considered them as "bookends" because these diets represented a range in particle size and undegradability that would reasonably be observed in the field for these types of diets. And most importantly, we tested whether the 2 intermediate diets would elicit similar responses in DMI given their similar calculated peuNDF content.

Lactation responses to differing dietary physically effective uNDF240

The high uNDF240-high peNDF diet limited DMI compared with the lower uNDF240 diets (Table 2). When lower uNDF240 diets were fed, the peNDF did not affect DMI. But, a shorter chop length for the higher uNDF240 diet boosted DMI by 5.5 lb/d. As a result, intake of NDF and uNDF240 was greatest for cows fed the high uNDF240 diet with smaller particle size. As expected, uNDF240 intake was greater for cows fed the higher versus lower uNDF240 diets. But, the most striking response was the 6.9 lb/d intake of uNDF240 for cows fed the high uNDF240 diet with hay that had been more finely chopped. The intake of peNDF was driven first by the uNDF240 content of the diet, and then by particle size within each level of uNDF240 (Table 2).

The intake of peuNDF (calculated as the product of pef and uNDF240) was affected considerably by the bookend diets: 3.2 versus 3.8 lb/day for the low-low versus high-high uNDF240-peNDF diets, respectively. And most interestingly, we observed that the 2 intermediate diets resulted in similar peuNDF intake; we were able to elicit the same peuNDF240 intake by the cow whether she consumed lower dietary uNDF240 chopped more coarsely or higher dietary uNDF240, but with a finer particle size.

Lactation performance followed the responses observed in DMI among the diets (Table 2). Energy-corrected milk production tracked with peuNDF240 intake (Table 2). Production of ECM was lowest for cows fed the high-high uNDF240-peNDF diet and greatest for the low-low diet (Table 2). Tracking with DMI, the ECM yield was similar and intermediate for the low-high and high-low uNDF240-peNDF diets.

Mean ruminal pH followed the same pattern of response as DMI and ECM yield (Table 2). Interestingly, total volatile fatty acid (**VFA**) concentration followed the same pattern as DMI, ECM yield, and mean ruminal pH with cows that consumed similar peuNDF240 having similar total ruminal VFA concentrations (Table 2). We measured ruminal pool size and turnover, and observed that the pool size of NDF tended to be greater for cows fed higher uNDF240 diets, and that the pool size of uNDF240 was greater for cows fed these same diets. Ruminal turnover rate of NDF tended to be slower for cows fed the higher uNDF240 diets with the high-high uNDF240-peNDF diet having the slowest ruminal turnover of fiber (rumen pool size and turnover data not shown). Overall, the differences among diets in ruminal pool size and turnover were small, but it appeared that higher uNDF240 diets increased the amount of uNDF240 in the rumen and slowed the turnover of NDF. The higher ruminal NDF turnover for cows fed the finely chopped high uNDF240 diet helped to explain the observed increase in DMI.

Chewing and particle size reduction

Dietary uNDF240 and peNDF had a greater impact on eating than ruminating time (Table 2). The observation that dietary fiber characteristics may have a substantial effect on chewing during eating and time spent eating has been observed in multiple studies. A recent review reported that higher forage content, greater dietary NDF or peNDF content, and lower NDF degradability may all increase time spent eating for a wide range of forages (Grant and Ferraretto, 2018). The cows in our study ranged 45 min/day in eating time depending on the diet (Table 2). In fact, cows on the high-high uNDF240-peNDF diet spent 45 min/day longer eating, yet consumed nearly 6.6 lb/day less DM than cows fed the low-low uNDF240-peNDF diet. However, finely chopping the hay in the high uNDF240 diet reduced eating time by about 20 min/day and brought it closer to the lower uNDF240 diets. A practical management question is whether cows have sufficient time to spend at the bunk eating with greater dietary uNDF240 that is too coarsely chopped. In an overcrowded feed-bunk environment, the constraint on feeding time could be even more deleterious to the DMI achievable by the cow.

Eating activity was more affected than rumination by differing particle size and uNDF240, likely because cows tend to chew a bolus of feed to a relatively uniform particle size prior to swallowing. Grant and Ferraretto (2018) summarized research that showed that particle length over a wide range of feeds was reduced during ingestive chewing to approximately 10 to 11 mm (Schadt et al., 2012). This process of chewing to some uniform particle size prior to swallowing seems to reflect the situation with silage and hay-based diets but is probably not true for cows grazing pastures where long particles have been observed in omasal samples (Van Amburgh, 2019, personal communication).

Similarly, in our current study, we confirmed that cows consuming all 4 diets swallowed boli of total mixed ration with a mean particle size of approximately 7 to 8 mm (data not shown), regardless of uNDF240 or peNDF content of the diet. The actual particle size values for the swallowed bolus differed between our study and the study by Schadt et al. (2012) due to different methods for measuring particle size (wet sieving in our study versus direct measurement of length in Schadt et al., 2012). But the main point is that there was a *6-fold reduction in the largest particles* for the high uNDF240-high peNDF diet prior to swallowing while eating. That takes time that the cow may not have depending on the feeding environment.

If future research confirms the results of these initial studies, it suggests that when forage fiber degradability 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 ruminal fermentation and fiber turnover for cows fed the higher uNDF240 diet with lower peNDF.

Physically Effective, Undegradable NDF and Feed Intake and Milk Responses:

A Summary of Five Experiments

We have combined data from 5 experiments conducted at the Institute to explore the relationship between dietary uNDF240 and peuNDF, DMI, and ECM yield (Miller et al., 2020b). The basic dietary formulations for these 5 studies were:

- Study 1: the study just described (see Table 1; Smith et al. 2018a; 2018b).

- Study 2: approximately 50 or 65% forage in the ration DM, with 13% haycrop silage (mixed mostly grass), and between 36 and 55% corn silage (either brown midrib 3 or conventional) in ration DM (Cotanch et al., 2014).

- Study 3: approximately 42 to 60% corn silage (brown midrib 3 or conventional) and 2 to 7% wheat straw (finely or coarsely chopped) in ration DM (Miller et al., 2017).

- Study 4: approximately 55% corn silage (brown midrib 3, conventional, or a brown midrib 3 with floury starch genetics; Coons et al., 2019).

- Study 5: approximately 57% brown midrib 3 or conventional corn silage with chopped wheat straw (Miller et al., 2020a).

Details of the dietary composition may be found in the references for each study. All of the diets fed in these experiments were based mainly on corn silage, contained some combination of haycrop silage and chopped straw, and in Study 1 (the current study), 2 of the diets also contained substantial pelleted beet pulp to formulate the lower uNDF240, lower forage diet. In addition, all the studies used high producing Holstein cows.

Figures 1 and 2 illustrate the relationships that we observed when we combined the data from these 5 studies. For these types of diets, both uNDF240 and especially peuNDF240 appear to be usefully related with DMI and ECM production. Within this database, the range in dietary uNDF240 was 5.5 to 11.5% of ration 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 7% increasing the risk for subacute ruminal acidosis.

The relationship between uNDF240 and DMI (lb/day) 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. The relationship between uNDF240 and ECM (lb/day) was relatively strong (y = -2.26x + 126.38, R^2 = 0.58); but similar to DMI, the relationship between peuNDF240 and ECM (lb/day) 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 (measured using near infrared reflectance) of the corn silage was associated with a 0.59 lb/day decrease in DMI and a 1.30 lb/day reduction in ECM. In the Institute database, we observed a reduction of 0.84 lb/day of DMI and 2.3 lb/day of ECM with each one-unit increase in ration uNDF240 with high-producing cows (Miller et al., 2020a,b). So, there is 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. In the future, we intend to define the relationships between uNDF240, peuNDF240, and DMI and milk yield for a wider range of diets and management scenarios on commercial dairy farms.

At the moment, it is important to restrict these inferences to similar diets (corn silage with hay, haycrop silage, and fibrous byproducts) because more research is required with varying forage types and sources of uNDF (forage versus non-forage) to determine the robustness of the relationships shown in Figures 1 and 2. In particular, legumes such as alfalfa contain more lignin and uNDF240, but have faster NDF digestion rates than grasses, and we might expect different relationships between dietary uNDF240 and DMI for legume- versus grass-based rations. In fact, research has shown that very high levels of uNDF240 intake may be achieved when lactating cows are fed finely chopped alfalfa hay (Fustini et al., 2017), even though alfalfa contains more uNDF240 than grasses (Palmonari et al., 2014; Cotanch et al., 2014).

Interactions Between Physically Effective uNDF240 and Rumen Fermentable Starch

Our most recent work has evaluated the relationship between dietary peuNDF240, uNDF240, and RFS (Smith et al., 2020a). 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. (2020a) 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 (i.e., 6 to 7% of ration DM). 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 and potentially milk fat depression.

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-hr in vitro fermentations).

Details of the study by Smith et al. (2020a) are available in the abstract and at the ADSA annual conference web site. A factorial arrangement of 4 diets was used to evaluate the effect of dietary peuNDF240 content, dietary RFS content, and their interaction. Table 3 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 2 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 4 summarizes the chemical composition of the 4 treatment diets. Unexpectedly, the 2 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. Importantly, for all diets, the uNDF240 and the peuNDF240 values were on the lower end of the range in our 5-study data base and responses in DMI and ECM generally tracked with the relationships in the database.

However, because the cows responded to dietary fiber characteristics (see Tables 5 and 6), 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 2 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 Tables 5 and 6. 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).

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 4.8, 4.8, 5.5, and 5.3 lb/day 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 11.0, 12.3, 11.0, and 12.1 lb/day. 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 6).

Table 5 summarizes the DM and carbohydrate 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 lb/day, 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 6 summarizes the milk and milk component responses to the diets. The higher peuNDF240 diets reduced milk yield by approximately 2.6 lb/day 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 5.1 lb/day for the lower peuNDF diets versus only 1.5 lb/day 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 commonly fed to lactating dairy cows (approximately 7 and 4% of ration DM, respectively).

Milk fat percentage was greater for the higher peuNDF240 than the lower peuNDF240 diets (Table 6). 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.

Although milk fat yield was unaffected by peuNDF240 content, the yield of true protein was reduced slightly with higher peuNDF240 (Table 6). 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 an 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.

Conclusions

As Charles Dickens wrote in his classic novel *Tale of Two Cities* "It was the best of times, it was the worst of times." When considering fiber, it seems that we can have the best of times when we are able to integrate 2 measures of fiber – uNDF240 and peNDF - when formulating rations (Grant, 2018). There is value in integrating forage particle size and uNDF240, and nutritionally useful relationships exist between uNDF240 and peuNDF240 with DMI and ECM for high producing dairy cows. To-date, take home messages of this research include:

- There is value in integrating forage particle size and uNDF240, and nutritionally 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 finely; cows still need adequate physically effective NDF.

- peuNDF240 (pef x uNDF240) is a work-in-progress, but a range of 4.5 to 6% (calculated peuNDF240) of ration DM seems to be a useful 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 approximately 7.0% of ration DM, then negative effects of RFS on milk fat may occur at only 19 to 20% of ration DM.

- If dietary uNDF240 is not uniformly distributed across particle sizes, then direct measurement of uNDF240 in pef particle fraction may be a better approach. On-going research will address this topic.

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Table 1. Ingredient and chemical composition of experimental diets (% of DM; Smith et al., 2018a,b).

	Low uNDF240[1]		High uNDF240	
	Low peNDF[2]	High peNDF	Low peNDF	High peNDF
Ingredients				
Corn silage	34.7	34.7	34.7	34.7
Wheat straw, chopped	1.6	1.6	1.6	1.6
Timothy hay, short chop	10.5	---	24.2	---
Timothy hay, long chop	---	10.5	---	24.2
Beet pulp, pelleted	12.9	12.9	0.4	0.4
Grain mix	40.3	40.3	39.1	39.1
Composition				
Forage	46.8	46.8	60.5	60.5
aNDFom[3]	33.1	33.3	35.7	36.1
uNDF240om	8.9	8.9	11.5	11.5
peNDFom	20.1	21.8	18.6	21.9
peuNDF240[4]	5.4	5.9	5.9	7.1

[1]Undigested NDF at 240 hr of in vitro fermentation.
[2]Physically effective NDF (measured as described by Mertens, 1997).
[3]Amylase-modified NDF on an organic matter (OM) basis.
[4]Physically effective uNDF240 (physical effectiveness factor x uNDF240).

Table 2. Responses of lactating Holstein cows fed diets differing in uNDF240[1] and peNDF[2] (Smith et al., 2018a,b).

	Low uNDF240		High uNDF240			
Measure	Low peNDF	High peNDF	Low peNDF	High peNDF	SE	*P*-value
DMI, lb/day	60.6[a]	60.1[a]	60.4[a]	54.9[b]	1.3	<0.01
NDF intake, lb/day	20.1[b]	19.9[b]	21.5[a]	19.8[b]	0.42	0.008
uNDF240om[3] intake, lb/day	5.31[c]	5.36[c]	6.86[a]	6.33[b]	0.11	<0.001
peNDFom intake, lb/day	12.26[b]	13.10[a]	11.18[c]	11.99[b]	0.24	<0.001
peuNDF240[4] intake, lb/day	3.24[c]	3.51[b]	3.55[b]	3.84[a]	0.07	<0.001
Energy-corrected milk, lb/day	103.6[a]	100.8[ab]	102.3[ab]	98.3[b]	1.9	0.03
Eating time, min/day	255[b]	263[b]	279[ab]	300[a]	12	<0.01
Ruminating time, min/day	523	527	532	545	16	0.36
24-hr mean rumen pH	6.11[b]	6.17[ab]	6.22[ab]	6.24[a]	0.05	0.03
Total VFA, mM	122.8[a]	120.6[ab]	118.3[ab]	112.3[b]	4.1	0.05

[abc]Means within a row with unlike superscripts differ ($P \leq 0.05$).
[1]Undigested NDF at 240 hr of in vitro fermentation.
[2]Physically effective NDF (measured as described by Mertens, 1997).
[3]Organic matter.
[4]Physically effective uNDF240 (physical effectiveness factor x uNDF240).

Table 3. Ingredient composition of diets with varying concentrations of physically effective 240-hr 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

(Smith et al., 2020a).

Table 4. Composition of diets with varying concentrations of physically effective undegraded neutral detergent fiber after 240-hr fermentation (peuNDF240) and rumen fermentable starch (RFS) (Smith et al., 2020a).

	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
aNDFom[1], % of DM	33.1	32.4	33.3	32.6
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-hr 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 hr 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 5. Dry matter intake (DMI) and carbohydrate intake responses to experimental diets (Smith et al., 2020a).

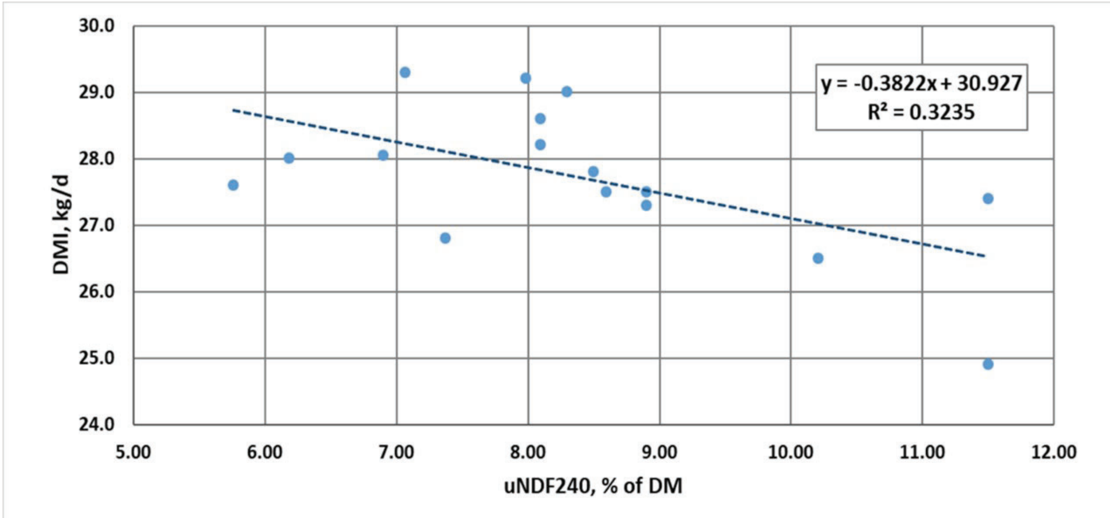
	Diets					
	Low peuNDF240		High peuNDF240		*P*-value[1]	
Variable	Low RFS	High RFS	Low RFS	High RFS	peuNDF	Starch
DMI, lb/day	65.3	64.7	64.7	64.2	0.27	0.40
DMI, % of BW	4.31	4.28	4.24	4.20	0.04	0.41
aNDFom[2] intake, lb/day	21.8	20.9	21.6	21.2	0.75	0.03
aNDFom intake, % of BW	1.44	1.39	1.42	1.37	0.37	0.03
Starch intake, lb/day	13.5	15.9	13.2	15.9	0.74	<0.0001
Starch intake, % of BW	0.88	1.06	0.87	1.04	0.35	<0.0001
uNDF240om intake, lb/day	4.96	4.76	5.40	5.29	<0.0001	0.008
uNDF240om intake, % of BW	0.322	0.315	0.354	0.345	<0.0001	0.0078

[1]No significant ($P > 0.10$) interaction between peuNDF240 and rumen fermentable starch.
[2]Amylase- and sodium sulfite-treated neutral detergent fiber, ash corrected.

Table 6. Milk and milk component responses to experimental diets.

	Diets					
	Low peuNDF240		High peuNDF240			
	Low	High	Low	High	*P*-value[1]	
Variable	RFS	RFS	RFS	RFS	peuNDF	Starch
Milk, lb/day	117.1	114.7	112.9	113.6	0.01	0.35
3.5% FCM[2], lb/day	118.6	113.6	116.6	115.1	0.85	0.01
ECM[3], lb/day	117.7	113.6	115.8	114.4	0.56	0.02
Fat, %	3.59	3.48	3.74	3.60	0.05	0.06
Fat, lb/day	4.19	3.95	4.19	4.06	0.41	0.01
True protein, %	2.83	2.87	2.85	2.86	0.61	0.12
True protein, lb/day	3.31	3.26	3.20	3.24	0.02	0.94
Urea nitrogen, mg/dL	12.0	10.1	12.4	10.5	0.08	<0.0001
Preformed FA[4], 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, lb/lb	1.81	1.75	1.81	1.79	0.41	0.06

[1]No significant ($P > 0.10$) interaction between peuNDF240 and rumen fermentable starch.
[2]Fat-corrected milk.
[3]Energy-corrected milk.
[4]Fatty acids.



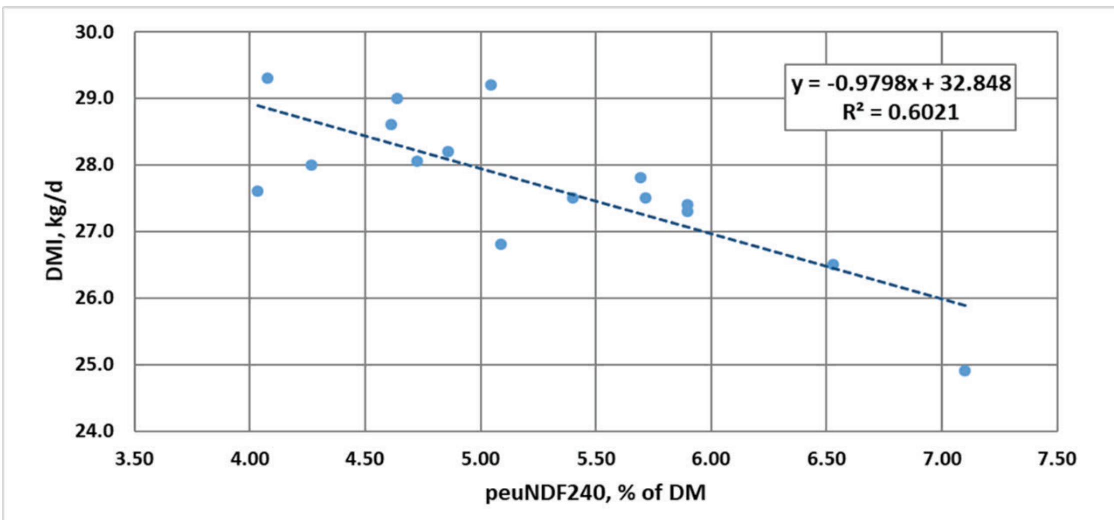


Figure 1. Relationship from 5 studies between dietary undigested neutral detergent fiber at 240 hr of in vitro fermentation (uNDF240) and physically effective uNDF240 (peuNDF240) and dry matter intake (DMI) for cows fed diets based primarily on corn silage, haycrop silage, and chopped wheat straw or grass hay (1 kg = 2.205 lb).

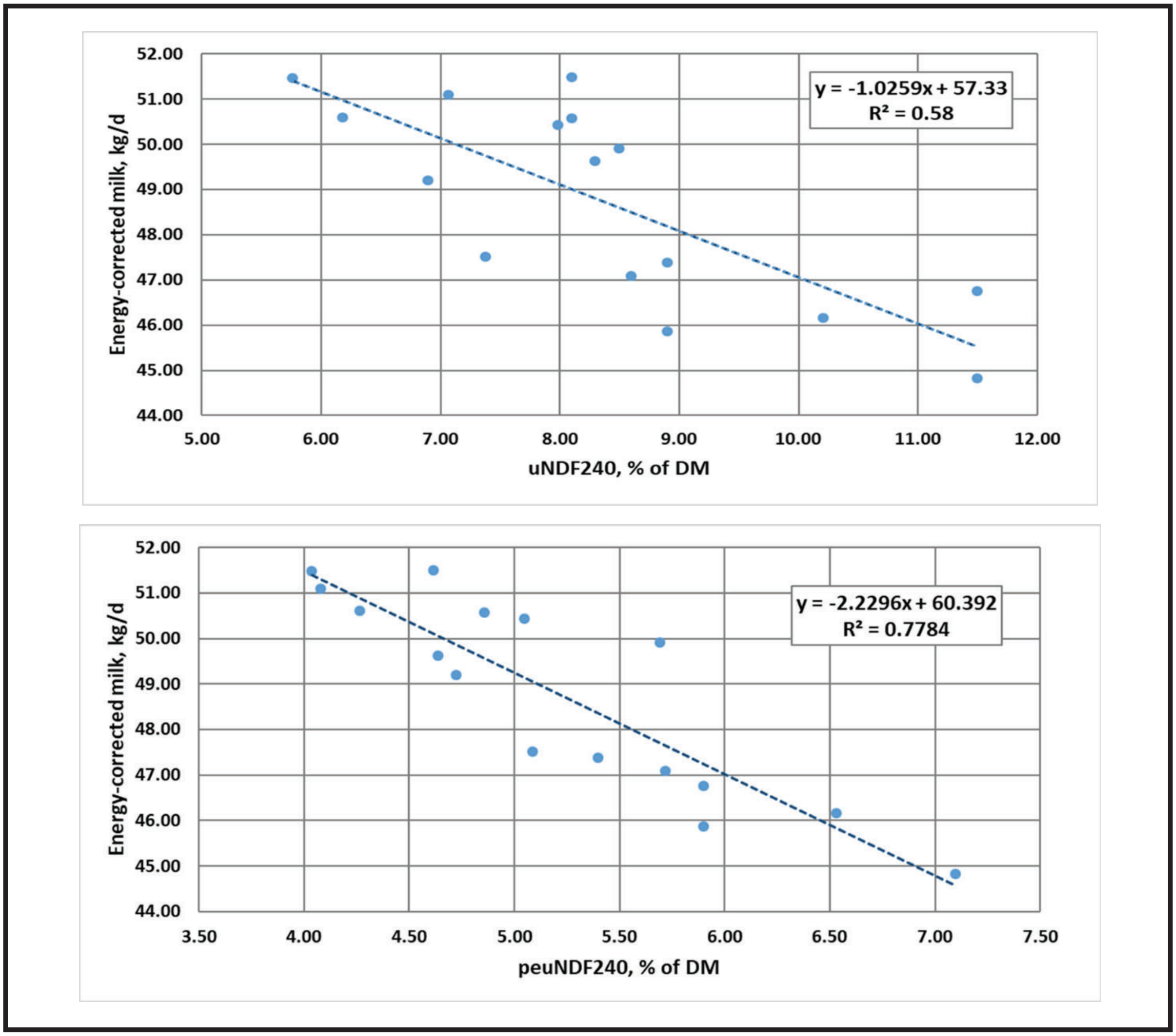


Figure 2. Relationship from 5 studies between dietary undigested neutral detergent fiber measured at 240 hr of in vitro fermentation (uNDF240) and physically effective uNDF240 (peuNDF240) and energy-corrected milk (ECM) yield for cows fed diets based on corn silage, haycrop silage, and chopped wheat straw and grass hay (1 kg = 2.205 lb).