PHYSICALLY EFFECTIVE NDF AND ITS USE IN FORMULATING DAIRY RATIONS

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INTRODUCTION

The effects of amount and source of forage on milk fat production are well established (Van Soest, 1963; Donefer, 1973). In a review on low milk fat production, Van Soest (1963) reported that many experiments consistently confirmed the original observation by Powell (1939) that high-concentrate, low-forage diets resulted in milk fat depression. Van Soest (1963) indicated that the effects of grinding roughage on milk fat depression were less consistent. He hypothesized that the variable responses appeared to be related to the degree of fineness of the roughage. Thus, the ideas that forages are needed by dairy cows and that the physical form (particle size) of the forage is important have been accepted for some time.

McCullough (1973) suggested that optimal rations could be formulated for dairy cows by keeping the forage to concentrate ratio (**F:C**) between 40:60 and 60:40. Mertens (1987, 1992) developed a system that uses NDF concentration of the forage and energy requirement of the cow to determine the F:C ratio that maximizes forage in the ration. When most of the fiber in dairy rations comes from long or coarsely chopped forages, NDF can also be used to formulate rations with minimum fiber. However, NDF is less effective in formulating minimum fiber rations when finely chopped forages or ground nonforage fiber sources (byproduct feeds) are used.

The advent of least-cost ration formulation programs in the 1960's stimulated interest in developing a quantitative method for ensuring that the minimum forage requirement of dairy cows was met. It was often observed that, if concentrates were less expensive sources of nutrients than forages, these computer programs would formulate dairy rations that contained little or no forage. Although ruminants such as feedlot steers can survive and be productive for short periods (90 to 120 days) when fed diets low in fiber, the long term health and productivity of lactating cows depends on the consumption of forage to stimulate normal ruminal function and maintain milk fat percentage. Initial attempts to describe the effectiveness of feeds in meeting the forage requirement were based on hay equivalents (Gleaves et al., 1973). Fiber concentration was also used with a minimum requirement to ensure that the forage needs of dairy cows were met and the NRC (1989) currently uses this

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approach. However, chemically measured fiber did not always meet the "fiber" requirement. Some physical forms (finely ground) of fiber were not "effective" in maintaining milk fat percentage leading to the concept of effective fiber.

EFFECTIVENESS, FIBROUSNESS, AND ROUGHAGE VALUE

Although it was clear that some sources or physical forms of fiber were not effective in meeting the needs of dairy cows, there was limited data available to derive "effectiveness" factors for various feeds. Nutritional experience was used to estimate the effectiveness of various fiber sources for maintaining milk fat production relative to fiber in a reference feed. Gleaves et al. (1973) and Milligan et al. (1973) used hay equivalents to measure the effectiveness of various sources. Harris (1984) was one of the first to develop effective fiber values for feeds by adjusting crude fiber values to reflect the feed's ability to maintain milk fat percentage relative to cottonseed hulls. More recently Clark and Armentano (1993) and Swain and Armentano (1994) established effective fiber values relative to neutral detergent fiber (**NDF**) in alfalfa silage. Although the criteria for determining effective fiber was milk fat percentage, it was accepted that both the chemical and physical properties of fiber were important in determining effectiveness.

Concurrent with the development of the concept of effective fiber was the realization that the physical properties of feeds affected digestibility, passage, and ruminal function (Martz and Belyea, 1986; Sutherland, 1987). Rather than develop a laboratory method such as particle size distribution to describe physical properties, Balch (1971) proposed that chewing activity per unit of dry matter (**DM**) could be a biological measure of a feed's physical properties which he called fibrousness characteristic. Sudweeks et al. (1979, 1981) standardized the procedure under which chewing activity was measured and defined a roughage value index (**RVI**) for a variety of feeds as the minutes of total chewing time per kilogram of DM. In addition, they proposed that a minimum RVI of 30 min. of chewing/kg of DM was needed in dairy rations to maintain milk fat percentage.

Norgaard (1986) also used chewing activity measured under standardized conditions to assess the physical structure of feeds for dairy cows. His physical structure system (Table 1) is based on type of feed (physical structure group) and particle size (degree of grinding or chopping). Feeds in physical structure group 1 (grains, concentrates, and pelleted feeds) were assigned a standard chewing time of 4 or 10 min/kg of DM depending on the degree of grinding. Feeds in physical structure group 2 (forages and nonforage fiber sources) were given a chewing time of 300 min/kg of crude fiber intake multiplied by a degree of chopping factor. Norgaard (1986) also estimated the minimum physical structure for dairy rations to be 30 min of chewing activity per kg of DM.

Sauvant et al. (1990) defined the fibrosity index of a feed as the minutes of chewing activity elicited per kg of DM and evaluated its potential as a tool in

Table 1. Using the Danish physical structure evaluation system to estimate standard chewing times of feeds fed to dairy cows (Norgaard, 1986).

	Degree of grinding		Degree of chopping (F[a])		
Characteristic	finely ground	coarsely ground	fine F = .25	coarse F = .75	none or slight F = 1.0
Physical structure group	1	1	2	2	2
Typical feedstuffs	concentrate molasses	rolled barley dried grass cubes	beet pulp	finely chopped grass silage	long hay long straw beets fresh grass
Average particle size, mm	<1	1-5	5-10	10-50	>50
Standard chewing time, (min/kg DM)	4	10	calculated[b]	calculated[b]	calculated[b]

[a]Weighting factor for the effect of chopping.
[b]Standard chewing time = F X 3 X % crude fiber which assumes 300 min of chewing/kg of crude fiber for unchopped feeds.

formulating dairy rations. They observed that the fibrosity index was highly correlated with the crude fiber concentration in feeds, but also noted that it was related to the level of feed intake. As dry matter intake (**DMI**) increased the fibrosity index of a feed or diet decreased. They concluded that fibrosity index provided only an indication of ration adequacy and was not an additive feed unit that could be used to formulate rations. Chewing activity (sum of eating and ruminating time) is affected by breed (Welch et al., 1970), size or age (Bae et al, 1983), and DM intake (Sauvant et al., 1990) of the animal; fiber concentration and particle size of the feed (Jaster et al., 1983, Mertens, 1986); and perhaps the method for measuring chewing activity (automated or visual monitoring, time not monitored during milking, etc.). As recognized by Sauvant et al. (1990) chewing activity/kg of DM is a variable that is not constant, therefore, it is difficult to use chewing activity directly to formulate rations (even when attempts are made to standardize measurements).

Mertens (1986) observed that chewing activity was related to NDF (chemical characteristic) and particle size (physical property). Because the term roughage implies both a feed texture and fiber value, he proposed the term roughage value unit (**RVU**) for defining the effectiveness of feeds in stimulating chewing activity. Although his system was related to chewing activity and effective fiber, it differed from these concepts in one important aspect, RVU were based on a clearly defined reference or standard. The maximum RVU for a feed is 100, which represents a hypothetical feed containing 100% NDF in a physical form that stimulates maximum chewing activity/kg of NDF, e.g., a long grass hay containing 100% NDF. In this system, a feed's RVU would be directly proportional to its NDF concentration multiplied by a roughage value adjustment factor (0 to 1) that is based on the feed's particle size. In effect, roughage value adjustments are discount factors for reducing the value of NDF in meeting the fiber requirement for minimum chewing activity.

Mertens (1992) standardized the effectiveness values of Harris (1984), Gleaves et al. (1973), Milligan et al. (1981) and others so they would be based on a common scale using long grass hay as the reference and developed roughage value adjustment factors that could be multiplied times NDF to obtain RVU for feeds. Because this system was conceptually based on chewing activity, but obtained adjustment factors from estimates of fiber effectiveness in maintaining milk fat percentage, it was a hybrid of the two concepts.

EFFECTIVE AND PHYSICALLY EFFECTIVE NDF

Although the concepts are related, the effectiveness of fiber in maintaining milk fat percentage is different from the effectiveness of fiber in stimulating chewing activity. To clarify these concepts two new terms were developed by a group of scientists (Allen, 1997; Armentano and Pereira, 1997; Grant, 1997; and Firkins, 1997) participating in a symposium sponsored by the American Society of Dairy Science and were presented by Mertens (1997). Effective NDF (**eNDF**) is related to the total ability of a feed to replace roughage so that the percentage of fat in milk is effectively maintained. Physically effective NDF (**peNDF**) is related to the physical properties of fiber (primarily particle size) that stimulates chewing activity and establishes the biphasic stratification of ruminal contents (floating mat of large particles on a pool of liquid and small particles). The peNDF will always be less that NDF, whereas eNDF can be less than or greater than the NDF concentration in a feed (Figure 1).

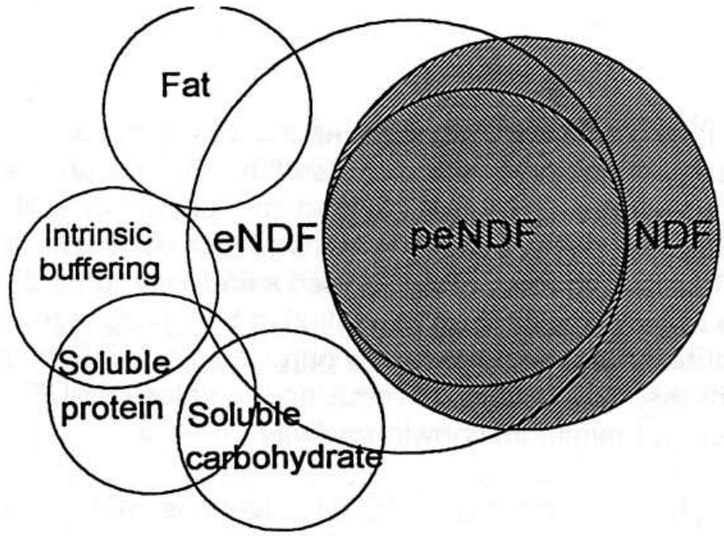

Figure 1. Illustration of the relationships among NDF, physically effective NDF, and effective NDF.

The animal response associated with eNDF is milk fat depression. Thus, eNDF is related to the original concept of effective fiber (Gleaves et al., 1973; Milligan et al., 1981; Harris, 1984; Clark and Armentano, 1993; Swain and Armentano, 1994). Effectiveness of NDF in maintaining milk fat production can vary from less than zero when a feed has a detrimental effect on milk fat synthesis that is greater than the stimulating effects of its NDF (e.g., molasses, purified starches) to greater than 1 when a feed maintains fat percentage more effectively than it maintains chewing activity. Although the base for measuring effectiveness is NDF concentration in the feed, the concept that effectiveness values can be greater than 1 or less than 0 indicates that other factors in feeds that stimulate or depress milk fat production will influence eNDF values. As illustrated in figure 1, eNDF includes all of the effects associated with peNDF but also includes characteristics of the feed associated with intrinsic buffering or acid neutralizing capacity, fat concentration and composition, soluble protein or carbohydrate concentrations, and ratios and amounts of VFA that affect milk fat synthesis.

The animal response associated with peNDF is chewing activity. The peNDF of a feed is the product of its NDF concentration and its physical effectiveness factor (**pef**). The pef varies from 0 when NDF in the feed stimulates no chewing to 1 when NDF promotes maximum chewing activity. Because it is related to fiber concentration, particle size, and reduction in particle size, peNDF is related to the stratification of ruminal contents which is a critical factor in the selective retention of large particles in the rumen, the stimulation of rumination and ruminal motility, and the dynamics of ruminal fermentation and passage. Salivary buffer secretion is an important factor in maintaining ruminal pH at optimal levels; therefore, peNDF is related to animal health and milk fat depression via its relationship to buffer secretion and ruminal pH.

Conceptually, peNDF is related to fibrousness characteristic (Balch, 1971), roughage value index (Sudweeks et al., 1979, 1981), physical structure (Norgaard, 1986), and fibrosity index (Sauvant et al., 1990) because all are related to chewing activity. However, peNDF differs from these concepts because it is a feed attribute that is based on a fixed scale and reference value (identical to the concept of RVU proposed by Mertens, 1986) rather than being a biological response (min. of chewing/kg of DM) that varies with the conditions under which it is measured. The peNDF provides a more consistent measure of effective fiber than chewing activity because it is based on two fundamental properties of feeds: fiber and particle size, and is independent of animal factors.

Because peNDF relates only to the physical properties of fiber, it is a more restricted term and concept than eNDF which represents all characteristics of a feed that help to maintain milk fat synthesis. New milk pricing systems may make the concern about milk fat percentage less important in the future. It may become more important to minimize stress on the animal associated with low fiber diets. Although low milk fat percentage is an indicator of inadequate diets, lameness can be observed in herds with no milk fat depression suggesting that milk fat depression may not be the best indicator of ruminal function or animal health. Thus, eNDF may be a less sensitive indicator than peNDF of the effectiveness of fiber in preventing intake depression, borderline acidosis, lameness, or displaced abomasum in dairy cows. The remaining discussion will focus on the measurement and use of peNDF to formulate rations for dairy cows.

PHYSIOLOGICAL RESPONSES TO FIBER

As less forage and fiber is included in the ration, the animal responds in a way that ultimately results in low ruminal pH and altered ruminal fermentation. When fiber is reduced to an absolute minimum (<10% NDF) and there are abrupt dietary changes (due to management or to animal responses to stresses) acute lactic acidosis can occur and result in laminitis and even death. However, prolonged sub acute acidosis is often related to health problems including rumen and liver abscesses, lameness, and possibly displaced abomasums. Although these disease responses are costly, they can be diagnosed easily leading to corrective actions. The digestive and metabolic responses of cows associated with borderline acidosis are much more difficult to detect.

As effective fiber is reduced in the diet, a cascade of events (Table 2) typically occurs. Less effective fiber results in less chewing by the animal (some linked causally, others simply occurring simultaneously). Because animals secrete more saliva when chewing than when resting, less chewing results in less salivary buffer secretion into the rumen. Decreased salivary buffer secretion (combined with greater volatile fatty acid (**VFA**) production) results in decreased ruminal pH. As pH drops, ruminal microbial populations change. The end products of fermentation shift from acetate to propionate and the acetate:propionate ratio (**A:P**) is reduced. Reduction in the A:P is associated with milk fat depression and shunting of nutrients toward fattening.

Although it is reasonable to conclude that reduced saliva production is a major factor in lower ruminal pH, there are concomitant changes in the ration when fiber is decreased that result in higher VFA production. In general, the proportions of crude protein (**CP**), fat or ether extract (**EE**), and ash are relatively constant in rations for dairy cows. Thus, the tradeoff in rations is between fiber and neutral detergent soluble or nonfibrous carbohydrates (**NFC** = 100 - NDF - CP - EE - Ash). The NFC include starch and sugars (the true nonstructural carbohydrates - **NSC**); beta-glucans, fructans, and pectins (so called soluble fiber); and organic acids. Organic acids are not readily fermented and do not contribute to microbial protein production. With the exception of coarsely cracked, dry corn and sorghum starches (that have digestion rates more similar to NDF than to sugar), the carbohydrates in NFC are rapidly and completely digested. When slowly fermenting NDF is replaced with rapidly fermenting NFC, more VFA are produced in the rumen which, when combined with decreased salivary buffer secretion, results in lower ruminal pH.

Table 2. Typical effects of varying forage and fiber proportions in rations on the physiological responses of dairy cows.

Variable	% Long grass hay in the diet					
	100	80	60	40	20	0
NDF, %	70	59	48	36	25	14
peNDF, %	70	57	44	32	18	6
Chewing time, min/d	1080	1040	970	820	520	320
Saliva secretion, l/d	200	196	189	174	143	123
Salivary bicarbonate, kg/d	2.5	2.4	2.3	2.2	1.8	1.5
Ruminal pH	6.8	6.7	6.5	6.2	5.8	5.0
Ruminal VFA, mM	85	95	105	115	125	135
Ruminal acetate, molar %	70	66	61	55	48	40
Ruminal propionate, molar %	15	18	22	27	33	40
A:P ratio	4.7	3.7	2.8	2.0	1.4	1.0
Milk fat, %	3.7	3.6	3.5	3.4	3.0	1.0

When milk fat depression and low ruminal pH are caused by lowering the F:C, it is impossible to determine if the effects are due to low fiber or high neutral detergent soluble carbohydrates or NFC in the ration. Although both play a role, research with finely chopped or ground forages suggest that it is the lack of effective fiber that is often responsible for borderline acidosis and milk fat depression. Earlier work cited by Van Soest (1963) and more recent work by Sudweeks et al. (1981), Woodford et al. (1986, 1988), and Grant et al. (1990a, 1990b) demonstrated that ruminal pH was lowered and milk fat was depressed when the forage in the ration was finely chopped or ground without changing the amounts or proportions of NFC. This suggests that it may be more crucial to monitor effective fiber during ration formulation than the proportion of NFC.

USING CHEWING ACTIVITY TO ESTIMATE peNDF

Welch and Smith (1970) observed that NDF was highly correlated with rumination time in cattle and Mertens summarized the work of several researchers and demonstrated that NDF is also related to total chewing activity. Of the routine fiber methods available, NDF is the best measure of the total fiber content of a feed. Thus, NDF can serve as the basis for determining effective fiber. Numerous researchers (Welch and Smith, 1970; Balch, 1971; Sudweeks et al., 1981; Mertens, 1986; Norgaard, 1986; Sauvant et al., 1990; de Boever et al., 1990) have shown that chewing activity is a characteristic that reflects the chemical and physical properties of feeds. Mertens (1997) used chewing activity to develop the physical effectiveness factors that are needed to calculate peNDF from NDF.

Mertens (1997) summarized the chewing activity data from 45 published experiments. Mertens (1986) concluded that two variables (NDF intake and physical form) were the major characteristics of feeds that affect chewing activity. Thus, NDF intake from each source and physical form were determined for each of the 274 combinations of cows and treatments. A physical form classification scheme was designed to provide a uniform system for describing the particle size information provided by the various researchers. Feeds were assigned to a physical form class based on the descriptions of the feed provided by the authors. If no particle size information was provided, feeds were assigned to the median class for that feed.

The kilograms of daily NDF intake from each feed and physical form was regressed on the daily total minutes of chewing. A zero intercept linear model was used under the assumption that no chewing activity would occur if no feed was consumed. The regression coefficients in these equations represented the minutes of chewing activity per kilogram of NDF from each source and physical form. Long grass hay resulted in 150 min. of chewing/kg of NDF and was chosen as the standard (pef = 1.00) for calculating the pef for all other NDF sources.

The pef were determined by dividing the observed total chewing time by 150 min/kg of NDF and regressing this variable against the kilograms of NDF intake from each source. Many of these factors had standard errors of 0.05 or less; however there were inconsistencies in the pattern of the pef within and among

Table 3. Physical effectiveness factors (pef) per kg of neutral detergent fiber from various sources and physical forms.

Classification	Grass hay	Grass silage	Corn silage	Alfalfa hay	Alfalfa silage	Concen-trates	By-products
Long	1.00			0.95			
Coarse chopped	0.95	0.95	0.90	0.90	0.85		
Medium chopped	0.90	0.90	0.85	0.85	0.80		
Fine chopped		0.85	0.80	0.70	0.70		
Rolled HM corn						0.80	
Rolled barley						0.70	
Rolled or Coarse ground						0.60	
Medium ground	0.40			0.40		0.40	0.40
Ground/pelleted						0.30	

NDF sources. To rectify inconsistencies, pef were smoothed within each NDF source to obtain a logical progression of factors in relation to physical form. For example, the regression coefficients for pef of corn silage were 1.09, .93, and .93, respectively for coarse, medium and fine chopping. These factors were smoothed to obtain 1.00, .95, and .90 for coarse, medium and fine chopped corn silage, respectively. Then the pef were standardized to obtain a consistent pattern within a physical form classification across all NDF sources (Table 3). To evaluate the accuracy of standardized pef, they were used to predict daily chewing activity. After obvious outliers and experimental differences were removed, the $r^2 = 0.76$ between observed and predicted chewing activity and the pooled standard error of all pef estimates was 0.10.

The peNDF of a feed is the product of its NDF concentration and its pef. To estimate a peNDF for a feed: (1) determine the NDF of the feed by laboratory analysis, (2) obtain the pef for its feed class from Table 3 and (3) multiply the measured NDF times the pef (peNDF = NDF X pef). This approach was used to calculate the peNDF of several of the feeds (Table 4) provided in the NRC (1989). There was no chewing activity for cottonseed hulls in the database compiled by Mertens (1997). Based on the particle size and density of cottonseed hulls, it was estimated that the pef would be about 0.90 when some long hay (equivalent to 1.6 kg of NDF/day) was fed in the ration. Cottonseed hulls are probably less effective as a fiber source when they provide the only unground fiber source in the ration.

Table 4. Physically effective NDF of selected feeds.

Feed ingredient	Physical form	NDF	pef	peNDF
Alfalfa, dehydrated	Pelleted	45	0.40	18.0
Alfalfa hay, early bloom	Long	42	0.95	39.9
Alfalfa hay, early bloom	Medium chopped	42	0.85	35.7
Alfalfa silage, early bloom	Finely chopped	42	0.70	29.4
Bahiagrass, late vegetative	Long	73	1.00	73.0
Barley grain	Rolled	19	0.70	13.3
Bermudagrass, 15-28 days	Coarsely chopped	74	0.95	70.3
Brewer's grains		42	0.40	16.9
Corn grain	Medium ground	10	0.40	4.0
Corn hominy		55	0.40	22.0
Corn distiller's grains		43	0.40	17.2
Corn silage, well-eared	Coarse chopped	40	0.90	36.0
Corn silage, well-eared	Fine chopped	40	0.80	32.0
Cottonseed hulls		90	0.90[a]	81.0
Cottonseed meal		26	0.40	10.4
Sorghum silage	Coarsely chopped	65	0.95	61.8
Soybean meal, 44% CP		15	0.40	6.0
Soybean hulls		67	0.40	26.8

[a]Estimated based on particle size and density when long hay is fed.

PROPOSED LABORATORY MEASUREMENT OF peNDF

Both fiber concentration and physical form are important in determining peNDF. Neutral detergent fiber measures the important chemical characteristics of fiber for ruminants, but it does not measure the physical properties, such as particle size, that affect the effectiveness of fiber in meeting the cow's minimum requirements.

MEASUREMENT OF NDF

The NDF method has the reputation for being more difficult and variable than other fiber methods. The largest sources of variation in NDF among laboratories is due to differences in method and to poor laboratory technique. Both of these problems can be minimized by following a standard NDF method exactly. Although the concept of fiber is based on nutritional criteria, the chemical measurement of fiber is defined by the laboratory method that is used. Modifications of the NDF method affect the "fiber" being measured, causes values to be different among laboratories, and gives the mistaken impression that NDF cannot be measured accurately.

The original NDF method (Van Soest and Wine, 1967; Goering and Van Soest, 1970) did not adequately remove starch from concentrates or silages that contained grains. Robertson and Van Soest (1980) and Van Soest et al. (1991) developed the neutral detergent residue (**NDR**) method which uses a heat-stable and detergent-stable amylase to remove starch. They also eliminated the use of sodium sulfite because it might remove phenolic compounds thought to be lignin. Sodium sulfite was included in the original method to reduce the protein contamination of NDF. Although the NDR method solved many problems with measuring fiber in starchy feeds, it did not eliminate all of the difficulties that were needed to establish NDF as an accurate, routine method.

We developed a method for NDF that will measure fiber in all types of feeds. This method has been published in the Forage Analyses Procedure Manual of the National Forage Testing Association (Undersander et al., 1993) and is currently being tested to obtain Official Method status from the Association of Official Analytical Chemists. Our amylase-treated NDF (**aNDF**) procedure differs from the original NDF method (Van Soest and Wine, 1967) because it uses a heat-stable amylase and differs from the NDR method of Robertson and Van Soest (1980) because it uses sodium sulfite to remove protein contamination.

Unfortunately, the results from all three methods (NDF, NDR, and aNDF) are often called "NDF" even though the results of the three methods can be quite different (Table 5). Therefore, it is important to know which "NDF" is being reported and to understand that some of the discrepancies among laboratories in NDF results may be due to differences in methods. Although the differences can be small for forages, when feeds are heated (such as distillers or brewers grains) the use of sodium sulfite becomes crucial for the removal of protein that is denatured or bound with carbohydrates in Maillard products. Because sulfite removes protein contamination, aNDF will give substantially lower values for fiber in dried feeds than the NDR method and will result in more accurate estimates of fiber.

Table 5. Values obtained using various methods to measure NDF (Hintz et al., 1996).

Feed description	NDF[a]	NDR[b]	aNDF[c]	aNDF/NDR
	(------------	% of DM	------------)	(%)
Wheat straw[d]	83.9	86.0	82.8	96.3
Timothy[d]	67.2	68.0	65.1	95.7
Alfalfa hay[d]	47.2	50.4	46.3	91.9
Alfalfa hay		45.5	44.3	97.4
Alfalfa silage		43.6	42.2	96.8
Corn silage[d]	55.9	55.0	52.6	95.6
Ladino clover		31.9	30.3	95.0
Brewer's grains		52.3	40.9	78.2
Distiller's grains		38.6	27.9	72.3
Soybean meal		18.5	12.4	67.0
Corn grain		11.4	10.1	88.6
Citrus pulp		21.3	20.2	94.8

[a] Neutral detergent fiber - original method with sulfite, but no amylase (Van Soest and Wine, 1967).
[b] Neutral detergent residue - no sulfite, but with amylase (Robertson and Van Soest, 1980).
[c] amylase-treated neutral detergent fiber - with sulfite and amylase (Undersander et al., 1993).
[d] R.B. Robertson (personal communication, 1988).

MEASURING PHYSICAL EFFECTIVENESS FACTORS

Mertens (1986) proposed that only fiber particles that are large enough to be retained in the rumen and to require chewing should be related to roughage value (or peNDF). To measure peNDF, it is crucial to determine the size of particles that are retained in the rumen and ruminated. Dixon and Milligan (1981) reported that particles retained on sieves with apertures >3.2 mm pass out of the rumen slowly and require additional chewing. Poppi et al. (1985) concluded that particles retained on a 1.18-mm sieve have a high resistance to passage in both cattle and sheep. Cardoza (1985) measured the particles size of feces from dairy cows and observed that <5% of the particles were retained on 3.35-mm sieves (vertical shaking). His results also suggested that particles passing through a 1.18-mm sieve readily pass out of the rumen and provide little stimulus for chewing.

Mertens (1986, 1997) proposed a simple laboratory method of combining chemical and physical laboratory methods to estimate peNDF. A feed would be measured for NDF chemically and the proportion of DM retained on a 1.18-mm sieve would be measured using vertical shaking. It is assumed that DM passing through the 1.18-mm sieve would stimulate no chewing activity; therefore the pef of a feed would be equal to the proportion of DM retained on a 1.18-mm sieve (vertical shaking). Using this system, the peNDF would be determined as shown in table 6. The primary limitation to laboratory assessment of peNDF is that methods for measuring particle size have not been standardized.

Table 6. Estimating the physically effective NDF (peNDF) of feeds using chemical (NDF) and physical (DM retention) measurements in the laboratory (adapted from Mertens, 1986).

Feed	pef[a]	DM retained on 1.18-mm sieve[b]	X	NDF	=	peNDF
Standard	1.00	1.00		100		100.0
Grass hay, long	1.00	0.98		65		63.7
Legume hay, long	0.95	0.92		50		46.0
Legume silage, coarse chop	0.85	0.82		50		41.0
Legume silage, fine chop	0.70	0.67		50		33.5
Corn silage	0.85	0.81		51		41.5
Brewers grains	0.40	0.18		46		8.3
Corn, ground	0.40	0.48		9		4.3
Soybean meal	0.40	0.23		14		3.2
Soybean hulls	0.40	0.03		67		2.0
Rice mill feed	0.40	0.005		56		0.3

[a]Standardized physical effectiveness factors based on chewing activity (from table 3).
[b]Vertical shaking motion was used to separate particles.

Although particle size separation has promise as a laboratory method for estimating pef, the method used to measure particle size distribution can have a substantial impact on results. Depending on the method, Murphy and Zhu (1997) reported that the proportion of forage retained on a 1.18-mm sieve ranged from 0.75 to 0.90 which would have a substantial impact on the estimation of peNDF. They observed that the range in the proportion of concentrate DM retained on a 1.18-mm sieve was similar; 0.45 to 0.65. The methods they compared used horizontal motion to separate the particles. Shakers that use a vertical displacement motion would be expected to obtain lower proportional retentions on a 1.18-mm sieve. Research using a vertical shaker (Mertens et al., 1984) indicated that this method tended to separate particles by their minimum cross-sectional dimension. Long particles tend to bounce on end and pass through sieve openings lengthwise. Mertens et al. (1984) reported that the ratio of length to width of particles retained on sieves that were vertically shaken was about

10:1 for alfalfa and bermudagrass hay and 4:1 for corn silage. This suggests that to achieve the same particle size distributions, apertures for horizontally shaken sieves would need to be 4 to 10 times larger than those for vertical shakers.

Lammers et al. (1996) described a simple, 2-sieve system that is manually shaken using horizontal displacement (Penn State separator). They reported that the 19 and 8-mm sieves retained 0.80, 0.65, 0.45 of the particles for corn silage and 0.85, 0.70, and 0.45 of the particles for hay crop silages that were longest, average, or shortest chopped, respectively. Extrapolating the distribution plots of Lammers et al. (1996) suggests that using their method with smallest sieve apertures of 4 mm and 6 mm would yield retained proportions that correspond to pef measured by chewing activity (Table 3) for corn silage and hay crop silage, respectively. Thus, using the total proportion of material retained on the two sieves of the Penn State separator will slightly underestimate the pef observed by Mertens (1997) that were based on chewing activity.

MEETING THE MINIMUM REQUIREMENT FOR peNDF

Cows selectively retain fiber in the rumen to allow adequate time for digestion by swallowing large particles while eating. These large particles form a floating mat in the rumen and provide the "scratch stimulus" that stimulates rumination activity. After several cycles of rumination or cud chewing, fibrous particles are reduced to a size that can escape the rumen. However, when minimal fiber rations are fed, there may be too little effective fiber to promote optimal ruminal fermentation and production.

MINIMUM peNDF REQUIREMENT

Mertens (1997) compared calculated peNDF in rations to milk fat percentage and ruminal pH of cows fed these rations as a way of estimating a recommended minimum peNDF. Approximately 19.7% peNDF was needed to maintain milk fat percentage of Holstein cows at 3.4% and 22.3% peNDF was needed to maintain an average ruminal pH of 6.0. Assuming a minimum peNDF of 21% in ration DM, the characteristics of dairy rations were determined using a variety of fiber sources (Table 6). When rations were formulated using corn silage, bermudagrass hay, or cottonseed hull with bermudagrass hay to meet the 21% peNDF minimum requirement, they contained only about 25% forage (corn silage is about 50% stalks) which is lower than most nutritionists would recommend. Although these rations should stimulate minimum recommended chewing times, they may contain more fermentable carbohydrate than is desirable. It seems reasonable that these rations would result in borderline ruminal pH (about 6.0) and moderate milk fat depression. Thus, rations formulated using 21% peNDF probably should not be fed to dairy cows for extended periods of time. When byproduct feeds were used with a minimum amount of bermudagrass hay (providing 3.5 lb. of long NDF/d), the amount of corn in the ration was reduced dramatically. It appears that the minimum peNDF requirement would work best when rations contain a combination of forages and byproduct feeds as illustrated by the average ration.

Table 6. Characteristics of rations formulated to contain a minimum of peNDF of 21% of the ration dry matter for a 600 kg dairy cow producing 30 kg of 4% fat-corrected milk/day (equivalent to 71 lb. of milk with 3.5% fat/day).

Ingredient	Corn silage	Bermuda-grass hay	CS hulls w/ BG hay	Byproducts w/ BG hay	Average fiber
Bermudagrass hay, %	0	25.2	11.6	12.0	12.2
Corn silage, %	51.9	0	0	0	13.0
Corn grain, %	28.6	61.3	59.9	29.3	44.8
Soybean meal, %	19.5	13.5	16.8	5.0	13.7
Cottonseed hulls, %	0	0	11.7	0	2.9
Byproducts[a], %	0	0	0	53.7	13.4
Characteristics					
Dry matter intake (kg/d)	18.5	18.4	18.6	18.0	18.4
NEL (mcal/kg DM)	1.75	1.76	1.74	1.80	1.76
Crude protein (%)	16.8	16.9	16.7	17.3	16.9
NDF (%)	26.0	26.4	27.6	40.5	30.1
NFC (%)	49.3	49.0	49.0	33.0	45.1

[a]25% corn hominy feed, 25% brewer's grains, 25% distiller's grains, and 25% soybean hulls.

CONCLUSIONS

Both the chemical and physical characteristics of dairy rations are important. Physically effective NDF attempts to take into account both the chemical and physical nature of fiber that influences the chewing activity of dairy cows. Although chewing activity is important in providing salivary buffers for controlling ruminal pH, it is also an indicator of the physical environment of the rumen (floating mat of large particles on a pool of liquid and small particles) that helps to establish an optimal ruminal fermentation. Chewing activity can be used to establish physical effectiveness factors for use in estimating peNDF. In addition, it may be possible to measure peNDF directly in the laboratory using NDF and particle size analyses. The current minimum peNDF recommendation is 21% of ration DM. This recommendation probably will result in borderline ruminal pH and mild milk fat depression when forages or cottonseed hulls are fed as the only fiber source, and these types of rations should not be fed for extended periods of time. Inclusion of moderate amounts of byproduct feeds in rations containing minimum peNDF results in more desirable diets.

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