Measuring fiber and its effectiveness in ruminant diets

David R. Mertens
US Dairy Forage Research Center
USDA-ARS, Madison, WI

INTRODUCTION

It appears that ruminants such as cattle and sheep evolved as forage consumers. Plant cell walls, which we measure as fiber, cannot be digested by animals, but must be fermented by microorganisms. Fermentative digestion of fiber is slow and incomplete, and ruminants have developed many attributes that result in efficient digestion. They swallow large particles of forage and selectively retain them in the rumen to allow adequate time for fermentation. They regurgitate and rechew the large particles (rumination) to enhance digestion and allow passage through the digestive tract. During chewing, they produce salivary buffers that help maintain the pH in the rumen. Ideally, roughages should be an integral part of the diet of ruminants to take advantage of their unique digestive capability. However, there are nutritional, operational, and economic reasons for limiting the forage or roughage content in some ruminant rations.

To attain higher levels production, animals need higher energy densities in their rations. Because forages or roughages are lower in digestibility and available energy than grains and other concentrates, it is often desirable, nutritionally, to reduce fiber to minimum levels in the diet. In addition, roughages tend to be more variable in nutrient content, which also makes it difficult to use them in rations with consistent results. Economically, grains and concentrate feeds often are less expensive sources of nutrients than forages. Operationally, roughages create difficulties and additional expense in processing (chopping or grinding), in uniformly mixing and delivering rations, and in obtaining consistent intakes without sorting. Thus, there are many practical reasons for minimizing forage in rations of dairy cows and feedlot cattle. Although cattle can be productive for short periods (< 180 days) when fed high grain diets, their performance may be compromised. The need for maintaining the long-term (multiple years) health and productivity of dairy cows led to the development of minimum fiber or effective fiber requirements for ruminants. However, it appears that these concepts may also be adapted to meet the fiber needs of feedlot cattle under conditions of maximum performance.

Although it is a small portion of feedlot rations, the total quantity of roughage that is fed daily in feedlot operations can be quite large. Given the nutritional, economic and operational considerations in including roughages in feedlot rations, it is important to determine an effective system for equating the roughage value or effective fiber of alternative fiber sources and to establish appropriate guidelines for minimum fiber recommendations for feedlot cattle. My objectives in this paper will be to discuss fiber measurement and the factors that influence its effectiveness in maintaining ruminant performance. Most of the seminal research on this topic has been done with dairy cows, but the principles learned and the methods of applying these principles may have direct applicability to meeting the needs of feedlot cattle.

MEASURING FIBER IN FEEDS FOR RUMINANTS

In animal feeding, fiber is a term used to define a nutritional, not a chemical or plant anatomical concept. From the beginning, fiber methods were developed to measure the feed components that represented the indigestible ballast in feeds (crude fiber - **CF**). Some nutritionists define fiber as the any component in a feed that is not digested by mammalian enzymes. Some of these components are soluble under mild extraction procedures and thus result in "soluble" and "insoluble" fiber. Most constituents of soluble fiber (pectin, fructans, beta-glucans) are readily fermented in the rumen and may even be readily fermented in the large intestine of monogastric animals. Although they may have unique nutritional properties, "soluble" fiber may contribute little to our understanding about the limitations that fiber plays in the digestion and intake in ruminants. Thus, I prefer a more restrictive definition of fiber as the "indigestible and slowly digesting, or incompletely available, fractions of feeds that occupies space in the gastrointestinal tract" (Mertens, 1989), which defines fiber as insoluble components. Nutritionally, fiber has both physical and chemical attributes that are related to the mechanical processes of digestion (chewing and passage) and to enzymatic degradation associated with fermentation.

Fiber methods isolate different chemical constituents in feeds (Table 1). The fiber with the smallest magnitude is CF because the strong acid and alkali in this method leaves a residue that is mostly cellulose with variable amounts of lignin and hemicellulose. Acid detergent fiber (**ADF**) is next largest in magnitude because it recovers most, if not all, of the polymeric lignin and cellulose in feeds, with some contamination from pectin, hemicellulose, tannin-protein complexes, and ash. Of the three routine fiber methods only neutral detergent fiber (**NDF**) isolates all of the insoluble fiber components in plants (hemicellulose, cellulose, and lignin) with some protein contamination. In animal byproduct feeds, NDF isolates the nitrogenous material that is indigestible or slowly digesting and thus meets the requirements of the nutritional definition of fiber. Because ADF does not contain hemicellulose it is not an accurate estimate of fiber in feeds. It was developed as a preparatory step for the determination of lignin (Van Soest, 1963a, b) and was never intended to be a measure of fiber in feeds.

The development of the NDF method was a significant advancement for the nutritional characterization of feeds (Mertens, 1993). Van Soest (1964, 1967) recognized that an inadequate understanding of the meaning and use of fiber prevented the development of methods to replace CF. The principle on which the NDF method was founded was that feeds should be divided into a readily digestible fraction what should be solubilized by the new fiber method and into an incompletely digestible fraction that would be isolated as fiber (Van Soest and Moore, 1965). Van Soest and Wine (1967) developed the NDF method to match the nutritional definition of fiber and solubilize those components in feed that are readily available. Ideally we would like to have chemical methods measure fractions that have constant availability across all feeds, so called "ideal nutritive entities." Thus, if we know the amount of these chemical fractions we automatically know their availability to the animal. Although NDF is not an ideal nutritive entity because its digestibility varies with lignin concentration and other factors, neutral detergent solubles (**NDS**) have ideal nutritive properties because they are almost completely digestible (95-98%), with the exception of the slowly digesting starch in some grains, and have relatively constant endogenous losses (11-15% of dry matter intake).

Table 1. Conceptual partitioning of feeds into chemical and nutritional fractions.

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CHEMICAL FRACTIONS:
Moisture | -- Dry Matter --- |
     | Ash | -- Organic Matter --- |
        | Lipid | Protein | --------------- Carbohydrates, Organic Acids, and Complex Polymers --------------- |
               | Sugars | Starches | Org. Acids[a] | Pectins[b] | Hemicellulose | Lignins+[c] | Cellulose |

NUTRITIONAL FRACTIONS -- Incompletely Digested:
                                          | --------------------- Cell Walls ---------------------|
                                              | -------- Neutral Detergent Fiber -------|
                                                    | Acid Detergent Fiber[d] |
                                                         | Crude Fiber |

NUTRITIONAL FRACTIONS -- Readily Digested:
                        | ----------------------- Nitrogen-Free Extract[e] ------------------------ |
       | --------------------- Neutral Detergent Solubles ---------------------- |
                | --------------------- NFC[f] --------------------- |
                  | -- TNC or NSC[g] -- |
                      | Starches |

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[a] Organic acids, including the volatile fatty acids in silages and other fermented feeds.
[b] Includes other soluble fiber such as beta-glucans and fructans.
[c] Polymeric lignins and phenolic acid complexes (some of which may be soluble).
[d] Some phenolic complexes and lignins with low molecular weight may be solubilized by acid detergent, especially in grasses.
[e] Nitrogen free extract was supposed to represent the readily available carbohydrate in feeds, but does not because it contains some lignins, phenolics, and hemicellulose, especially in forages.
[f] Nonfibrous carbohydrates determined by difference (100 - Ash - Lipid - Protein - Neutral Detergent Fiber)
[g] Total nonstructural carbohydrates (Smith, 1969) or nonstructural carbohydrates determined analytically.

      Variation in dry matter digestibility (**DMD**) is related primarily to the concentration and digestibility of NDF in feeds and a simple summative equation can be used to estimate digestibility (Table 2):

     DMD = .98*NDS + Dc*NDF - 12.9; where Dc = the variable digestion coefficient of NDF and 12.9 = average endogenous loss of DM by the animal. Goering and Van Soest (1970) reported equations that can be used to estimate the digestion coefficient of NDF from the ratio of lignin to ADF. The summative approach has been modified by Conrad et al. (1984) and Weiss (1993) who: 1) fractionated NDS into crude protein (**CP**), ether extract (**EE**), and nonfibrous carbohydrates (**NFC**) and 2) related the digestibility coefficient of NDF to lignin (**L**) using a complex surface law function. The most recent equation derived by Weiss (1993) is:

     $TDN_{1X} = (e^{-.012*ADIN})*CP + .98*NFC + .94*2.7*(EE-1)$
$+ .75*(NDF_{CP} - L)(1 - (L/NDF_{CP})^{2/3}) - 7$; where TDN_{1X} is total digestible nutrients at one times maintenance level of intake, ADIN is acid detergent insoluble nitrogen expressed as a percentage of total nitrogen, NDF_{CP} is NDF corrected for CP content, and 7 is the endogenous loss of TDN. Although complex, this equation indicates that the primary components affecting digestibility are NDF and lignin concentration.

Table 2. Using the summative equation to estimate digestibility of feeds.

Component	Corn	Alfalfa	Grass
Neutral detergent fiber (% NDF)	10.0	40.0	63.0
Fraction of NDF digested (Dc)	.90	.46	.62
Digestible NDF (= Dc X % NDF)	9.0	18.4	39.1
Neutral detergent solubles (% NDS)	90.0	60.0	37.0
Digestible NDS (= .98 X NDS)	88.2	58.8	36.3
True DM digestibility (%)	97.2	77.2	75.4
Endogenous fecal DM excretion	-12.9	-12.9	-12.9
Apparent DM digestibility (%)	84.3	64.3	62.5

There are high correlations among fiber methods within a feed type and, therefore some nutritionists argue that it does not matter which fiber is chosen to develop feeding recommendations. However, such feeding recommendations would only apply to a restricted set of feeds and diets. Only NDF measures the differences within and among feed types and has the potential for developing a system of general feeding recommendations across all feeds.

The NDF method has the reputation for being more difficult and variable than methods for ADF or CF. The most important and controllable source of variation in NDF among laboratories is due to differences in method and to poor laboratory technique. Both 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, cause values to be different among laboratories, and give the mistaken impression that NDF cannot be measured accurately or precisely. Poor laboratory technique compounds these problems by increasing filtration difficulties and decreasing the effectiveness of washing fiber residues.

The original NDF method (Van Soest and Wine, 1967; Goering and Van Soest, 1970) used a boiling detergent solution with sodium sulfite to remove protein and EDTA to chelate calcium and remove pectin. However, this procedure 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 assist in the removal of starch. They also eliminated the use of sodium sulfite because it might remove phenolic compounds thought to be lignin. Although the NDR method solved many of the problems associated with measuring fiber in starchy feeds, it did not eliminate all of the filtration difficulties or provide specific laboratory techniques that were needed to establish NDF as an accurate, routine method.

My laboratory developed a NDF method that can be used on all feeds and is both repeatable within laboratories and reproducible among laboratories. This method has been

published in the Forage Analyses Procedure Manual of the National Forage Testing Association (Undersander et al., 1993) and is being evaluated by the Association of Official Analytical Chemists for recognition as an Official Method. Our amylase-treated NDF (**aNDF**) procedure differs from the original NDF method (Van Soest and Wine, 1967) because it uses 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 values can be quite different (Table 3). 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 heated feeds than the NDR method and will result in more accurate estimates of fiber. Likewise, removal of starch by the use of amylase is crucial for the accurate determination of NDF in grains.

Table 3. 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 silage		43.6	42.2	96.8
Corn silage[d]	55.9	55.0	52.6	95.6
Citrus pulp		21.3	20.2	94.8
Corn grain		11.4	10.1	88.6
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

[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)

Given that it is possible to measure fiber accurately in all types of feeds by using the aNDF method (or the original NDF method for feeds with little starch), it is unclear why there are still difficulties in measuring fiber values for concentrates. Fiber values are provided in Table 4 to give reference values for common feeds. Sometimes low test weights of grains can yield lower than normal starch concentration, which has the effect of increasing fiber values. But NDF values

for concentrates are still reported that are unreasonably high, even in research publications. If starch or total nonstructural carbohydrates (**TNC**) are measured, they can be used to validate NDF results by comparing starch or TNC concentration to the calculated nonfibrous carbohydrates (**NFC**) value. If starch or TNC are greater than NFC, it is an indication that NDF results are too high. Values that differ more than 10% from the NDF listed in table 4 should be suspected, but recognize that occasional atypical values do occur.

Table 4. Chemical composition of selected feeds.

Feedstuff	CP[a]	EE[b]	Ash	NFC[c]	TNC[d]	Starch	CF[e]	ADF[f]	NDF[g]
Alfalfa pellets, 3/8"	17.2	2.4	10.6	22.3	20.1	4.5	29.8	36.0	47.5
Alfalfa hay, mid bloom	17.2	2.1	9.1	24.1	21.7	2.6	29.8	36.0	47.5
Alfalfa hay, full bloom	14.3	1.5	8.9	23.2	20.9	2.0	33.7	40.0	52.1
Cool season grass, early veg.	16.5	3.8	8.5	15.8	9.1	2.1	24.8	30.0	55.5
Cool season grass, late veg.	11.5	2.6	7.1	13.6	7.4	1.6	30.5	36.8	65.3
Warm season grass, early veg	13.7	2.4	6.9	8.2	6.1	2.3	28.3	32.9	68.9
Warm season grass, late veg	9.4	1.9	7.3	8.0	5.3	2.6	32.0	38.7	73.3
Sorghum sudan, early veg.	15.0	3.9	10.5	11.6	8.8	2.6	28.0	34.0	59.0
Sorghum sudan, headed	7.0	2.8	9.6	10.6	8.1	2.4	34.0	42.0	70.0
Small grain silage	11.3	3.3	7.7	21.3	20.2	17.0	27.0	34.7	56.5
Corn silage, well-eared	8.0	3.1	3.8	42.1	39.5	35.6	20.0	24.0	41.0
Corn silage, average	8.4	3.0	4.2	36.4	30.7	27.7	23.0	28.0	46.0
Corn silage, few ears	8.6	3.0	4.6	30.8	27.4	24.7	26.0	31.0	51.0
Corn stover	5.9	2.1	7.0	15.0	14.3	12.8	33.0	42.0	70.0
Sorghum sil., (grain).	9.4	3.0	7.0	27.6	26.8	24.1	26.0	32.8	53.0
Sorghum sil., (forage) soft dough	7.2	2.2	5.1	20.3	15.4	4.6	26.3	34.4	65.2
Sorghum sil., (forage) milk stage	7.7	2.3	4.7	12.5	9.5	2.8	32.6	38.6	72.8
Barley straw	4.4	1.9	7.5	13.7					72.5
Wheat straw	3.6	1.8	7.8	6.8	2.0	1.0	42.0	50.0	80.0
Barley grain, heavy	13.5	2.1	2.4	63.0	62.2	59.7	4.5	6.0	19.0
Barley grain, light	12.5	2.3	2.5	54.7	53.6	52.0	6.5	9.0	28.0
Corn and cob (ear corn)	9.0	3.7	1.9	59.4	58.8	57.6	9.4	11.0	26.0
Corn, high moist. ear, 1/2 cob	9.0	3.7	1.9	67.4	66.7	65.4	5.0	6.0	18.0
Corn, high moist. ear, 1/2 cob	9.0	3.7	1.9	67.4	66.7	65.4	5.0	6.0	18.0
Corn dry grain, light	11.0	3.7	1.9	71.4					12.0
Corn dry grain, normal	10.0	4.3	1.6	74.1	73.4	72.0	2.6	3.0	10.0
Corn, high moisture	10.0	4.3	1.6	74.1	73.4	71.9	2.6	3.0	10.0
Oats grain	13.3	5.2	3.4	48.1	46.7	44.0	12.0	15.0	32.0

Table 4. Continued.

Feedstuff	CP[a]	EE[b]	Ash	NFC[c]	TNC[d]	Starch	CF[e]	ADF[f]	NDF[g]
Sorghum grain (milo)	11.5	3.4	2.0	71.1	68.6	67.2	3.0	6.0	12.0
Wheat grain, hard red	13.0	1.8	1.9	70.3	69.6	68.0	2.9	4.0	13.0
Beet pulp	9.7	0.6	7.5	40.9	29.1	0.4	16.0	21.5	41.3
Brewers grains, dried	28.0	7.0	4.8	13.2	12.0	3.8	14.9	23.0	41.0
Canola rapeseed meal	40.0	2.8	7.4	23.8	14.1	13.5	10.4	17.0	26.0
Citrus pulp	7.2	3.8	6.6	60.4	27.2	0.2	13.0	17.5	22.0
Corn cobs	3.2	0.7	2.8	7.3	5.2	1.0	33.2	40.0	86.0
Corn distillers grains w/ solubles	29.0	10.3	5.0	17.7	14.1	2.4	9.9	19.0	28.0
Corn distillers grains w/o solubles	25.0	9.4	3.0	18.6	17.0	2.4	12.1	18.0	34.0
Corn gluten meal	67.2	2.6	1.4	18.8	16.2	15.6	2.0	3.0	10.0
Corn gluten feed	21.0	4.0	6.5	30.5	26.0	23.3	8.0	10.0	38.0
Corn hominy feed	11.2	6.5	2.6	56.7	52.0	31.0	5.2	6.0	23.0
Cottonseed, whole, w/o lint	25.0	23.0	4.5	8.5	4.2	0.8	18.0	29.0	39.0
Cottonseed, whole, w/ lint	23.0	20.0	4.8	3.2	1.6	0.3	26.0	34.0	49.0
Cottonseed hulls	4.4	1.7	2.8	2.1	1.9	1.0	48.0	70.0	89.0
Cottonseed meal, solv. extr.	46.5	1.5	7.0	15.0	7.5	1.5	14.1	20.0	30.0
Linseed meal, solv. extr.	38.8	1.7	6.5	28.0	26.8	4.0	10.1	19.0	25.0
Molasses, liquid	5.8	0.1	13.1	78.0	77.2	0.0	2.0	2.0	3.0
Molasses, dried on hulls	10.3	0.9	13.3	25.5	25.2	0.0	6.7	35.0	50.0
Peanut meal, mech. extr.	51.0	5.6	5.2	21.2	14.8	4.8	9.0	13.0	17.0
Peanut hulls, coarse	7.8	1.7	4.6	11.9	6.0	1.0	60.0	65.0	74.0
Peanut hulls, pelleted	7.8	1.7	4.6	11.9	6.0	1.0	60.0	65.0	74.0
Rice bran	14.1	15.3	12.0	25.6	25.3	22.8	13.0	19.0	33.0
Rice mill feed	7.0	5.7	15.0	12.3	10.0	6.0	32.0	48.0	60.0
Soybean hulls, fine grind	15.0	2.4	5.0	13.6	13.2	5.3	36.0	46.0	64.0
Soybean meal 44%CP	49.9	1.5	7.3	27.3	13.7	2.7	7.0	10.0	14.0
Soybean meal 48%CP	55.1	1.0	6.5	27.4	13.7	2.7	5.0	7.0	10.0
Soybean seeds, roasted	40.8	19.0	5.7	22.5	9.0	1.5	5.0	8.0	12.0
Sunflower meal w/o hulls	49.0	3.1	7.5	13.4	11.0	4.0	14.0	20.0	27.0
Sunflower meal with hulls	30.0	1.7	6.7	19.6	15.0	6.0	25.0	30.0	42.0
Wheat bran	17.1	4.4	6.9	29.6	27.0	18.0	9.0	12.0	42.0
Wheat middlings	18.0	4.5	5.2	35.8	34.4	29.0	8.9	13.2	36.5
Wheat shorts	18.6	5.2	4.9	38.3	35.0	23.8	7.7	10.0	33.0

[a] Crude protein.
[b] Ether extract or crude fat.
[c] Nonfiber carbohydrates or neutral detergent soluble carbohydrates (= 100 - CP - EE - ash - NDF)
[d] Total nonstructural carbohydrates measured analytically.
[e] Crude fiber.
[f] Acid detergent fiber.
[g] Neutral detergent fiber (various methods).

Although aNDF measures the important chemical characteristics of fiber for ruminants, it does not measure the physical properties, such as particle size, that influence the effectiveness of

fiber in meeting ruminant minimum requirements. When most of the fiber in rations is from long or coarsely chopped forages, NDF concentration can be used to formulate rations to meet minimum fiber needs. However, NDF is less effective in formulating minimum fiber rations when finely chopped forages or ground nonforage fiber sources (byproduct feeds) are used.

FIBROUSNESS, FIBROSITY INDEX, ROUGHAGE VALUE AND PHYSICAL STRUCTURE

The importance of the physical properties of rations is well established. Balch (1971) proposed that chewing activity per unit of dry matter (**DM**) could be a biological measure of a feed's physical properties that he called fibrousness characteristic. Sudweeks et al. (1979, 1981) developed the concept of roughage value index (**RVI**), which was based on the minutes of total chewing time per kilogram of DM. They standardized the procedure under which chewing activity was measured by steers and established the RVI for a variety of feeds and defined a minimum RVI for dairy rations.

Norgaard (1986) also used chewing activity measured under standardized conditions to assess the physical structure of feeds for dairy cows. His system 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 for fine or coarse grinding, respectively. Feeds in physical structure group 2 (forages and nonforage fiber sources) were given a chewing time of 300 min/kg of CF intake multiplied by a degree of chopping factor (fine = .25, coarse = .75, and long = 1.00). Sauvant et al. (1990) also observed a relationship between CF and chewing activity (min per kg of DM) which they called fibrosity index. 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. The major limitation of these systems is the use of chewing time as a feed attribute. The variability of chewing activity per kilogram of DM that is related to animal differences (even when attempts are made to standardize measurements) limits its usefulness as a feed attribute.

EFFECTIVE FIBER, ROUGHAGE VALUE UNITS AND EFFECTIVE AND PHYSICALLY EFFECTIVE NDF

The effects of the amount and source of fiber on milk fat production have been known for a long time (Van Soest, 1963; Donefer, 1973). The concept of effective fiber was developed by nutritionists to formulate rations that would maintain milk fat percentage in dairy cows. Effectiveness of the fiber in a specific feed for maintaining milk fat production was estimated relative to fiber in a standard or reference feed. Effective fiber values were based on several standards such as cottonseed hulls, (Harris, 1984), hay (Gleaves et al., 1973; Milligan et al., 1981), or alfalfa silage (Clark and Armentano, 1993; Swain and Armentano, 1994), which made it difficult to use these systems over the full range of feeds fed to ruminants.

Roughages are coarse, bulky feeds that are high in fiber. The unique aspect of the term roughage is that it implies texture, a physical property of feeds. If a high fiber feed is ground, it loses its roughage property. Biologically, roughages are coarse, high-fiber feeds that stimulate or require chewing, and also influence rate of passage and the biphasic nature of the rumen.

Mertens (1986) proposed a roughage value unit (**RVU**) system for measuring the effectiveness of feeds in stimulating chewing activity that was based on a chemical measure of fiber (NDF) and a physical measure of particle size. A standard or reference value with an RVU of 100 was defined as a hypothetical feed containing 100% NDF with all particles large enough to stimulate chewing (a long grass hay containing 100% NDF). Mertens (1992) standardized the effectiveness values of Harris (1984), Gleaves et al. (1973), Milligan et al. (1981), Clark and Armentano (1993), and Swain and Armentano (1994) 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 (table 4).

Although (Mertens (1986) related roughage value to the effectiveness of fiber in stimulating chewing activity, the traditional definition of effective fiber was related to the ability of fiber to maintain milk fat production or animal health (Gleaves et al., 1973; Milligan et al., 1981; Harris, 1984; Clark and Armentano, 1993; Swain and Armentano, 1994). To clarify these concepts Mertens (1997) proposed definitions for both effective NDF (**eNDF**) and physically effective NDF (**peNDF**). The peNDF of a feed is related to the physical properties of its 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 eNDF is related to the sum total ability of a feed to replace roughage so that the percentage of fat in milk is effectively maintained. Because peNDF relates only to the physical properties of fiber, it is a more restricted term and concept than eNDF. 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).
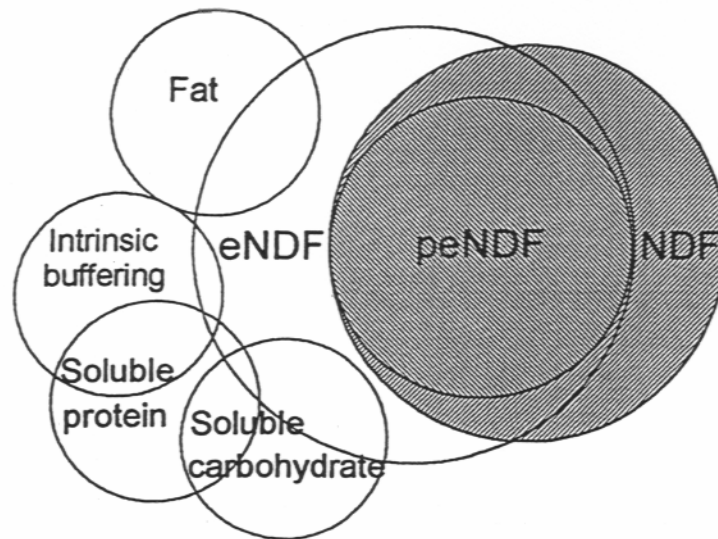

Figure 1. Illustration of the relationships among NDF, physically effective NDF, and effective NDF.

The animal response associated with 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 a 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 an important 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., 1991) 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 (0 to 1) and reference value (long grass hay) rather than being a biological response (chewing min/DM) that varies with the conditions under which it is measured. As indicated by Sauvant et al. (1991), chewing activity is a variable that is not constant or additive for feeds in a ration. Chewing activity varies with breed (Welch et al., 1970), animal size (Bae et al., 1983), and level of intake (Sauvant et al., 1991) as well as fiber concentration and particle size (Jaster et al., 1983, Mertens, 1986).

Variations due to animal and experimental differences are minimized because pef are fractions in which the animal effects in the numerator and denominator cancel (pef = [min. of chewing per kg of NDF in the test feed] / [min of chewing per kg of NDF in long grass hay]). Thus, pef is a proportional change in expected chewing response that should be relatively consistent among ruminants. It is well known that lactating cows at high levels of intake do not chew the same amount per kilogram of intake as steers. However, we would expect that changes in NDF content and physical form of a feed or ration would result in similar proportional changes in chewing between these animals. Because peNDF is a constant for a feed and is additive in feed formulation systems, variation due to the animal is attributed to the peNDF requirements and not arbitrarily partitioned between feed characteristics and animal requirements. This implies that the requirement for peNDF would be different between dairy cows and feedlot cattle, but an accurate peNDF for each feed represents the proportional response of each animal type to the ration they consume.

The animal response associated with eNDF is milk fat depression. Thus, eNDF is related to the 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 < 0 when a feed depresses fat percentage in milk to >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 1.0 indicates that other factors in feeds that stimulate milk fat production influence the eNDF value. Conversely, it could be hypothesized that eNDF values could be 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). Because eNDF includes the effects of peNDF, it is expected that eNDF should have a larger value (and range of values) than peNDF for most feeds.

As illustrated in figure 1, eNDF includes the effects of peNDF that influences milk fat percentage, but also includes other characteristics of the feed that affect milk fat production, such as intrinsic buffering or acid neutralizing capacity, fat concentration and composition, soluble protein or carbohydrate concentrations, and ratios and amounts of VFA produced during

fermentation that induce metabolic changes. Armentano and Pereira (1997) described a slope ratio method for assessing eNDF that relates milk fat percentage to the intake of NDF from nonforage fiber sources. They assumed that concentrates had zero eNDF and plotted milk fat percentage against dietary NDF from alfalfa and nonforage fiber sources. They determined the effectiveness factor for NDF as the ratio of the slope of the test feed to that of the alfalfa silage reference. Their plots have nonzero intercepts, which accounts for baseline differences in cows among experiments.

DETERMINING peNDF USING CHEWING DATA

Fiber effectiveness is a nutritional concept that can be truly measured only by animal response. The biological assessment of peNDF and eNDF differ because the animal response is different. Using chewing activity to assign peNDF values to feeds in a unified, quantitative system involved several aspects. The first step in developing a unified system for assessing pef was to define a standard reference against which all feeds are compared. Mertens (1986) proposed that the hypothetical standard should result in the maximum amount of chewing activity per kilogram NDF. He suggested that the reference feed be a long grass hay that would be assigned a pef of 1.0. If the reference grass hay contained 100% NDF it would also have a peNDF of 100. Using the data from dairy cows eating 0.4 to 2.0 times maintenance, Mertens (1986) reported that chewing activity per kilogram of DM intake was highly correlated to percentage of NDF in the feed. Based on equations generated from this data, Mertens (1986) estimated that the hypothetical long grass hay with 100% NDF would require about 230 min. of chewing per kilogram of NDF by dairy cows with an average intake of 1.1 times maintenance.

Mertens (1986) also summarized data to demonstrate that particle size reduction of the feed by chopping or grinding reduced the chewing activity per kilogram of NDF intake (table 5). Chopping feeds through screens with 40-mm (1.5 in) openings reduced chewing activity to 80% of the unchopped feed. Chopping to a theoretical length of cut of 5 mm (1/4 in) decreased chewing to 70% of that observed when the forage was chopped using a 20 mm (3/4 in) theoretical length of cut. Grinding reduced chewing activity to 20 to 60% of that for long forage.

To estimate pef for NDF based on chewing activities of lactating cows consuming concentrates and nonforage fiber sources, Mertens (1997) summarized the data from 45 published experiments. The 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.

Table 5. The effect of particle size of forages on the chewing activity of cows (Mertens, 1997).

		Total chewing activity		
Feed		min/kg	Chewing	
Physical form	NDF	NDFI	reduction	Reference

Alfalfa hay				
long	54	134	100	Mertens, unpublished
chopped (38 mm, 1.5 in)[a]	54	109	82	
Bermudagrass hay				
long	72	149	100	Mertens, unpublished
chopped (38 mm, 1.5 in)[a]	72	118	79	
Alfalfa hay				
long	53	117	100	Sudweeks et al. (1979)
chopped (38 mm, 1.5 in)[a]	53	84	72	
Oat Straw				
long	84[b]	194	100	Campling & Freer (1966)
ground	75[b]	113	58	
Ryegrass				
long	65[b]	139	100	Freer & Campling (1965)
finely ground (1.2 mm, 1/8 in)[a]	64[b]	29	21	
Corn silage				
19 mm, 3/4 in TLC[c]	68	97	100	Sudweeks et al. (1979)
13 mm, 1/2 in TLC[c]	62	96	99	
6 mm, 1/4 in TLC[c]	60	66	68	
Alfalfa hay				
25 mm, 1 in TLC[c]	55	95	100	Santini et al. (1983)
5 mm, 3/16 in TLC[c]	45	66	69	

[a]Screen aperture diameter.
[b]NDF calculated from crude fiber concentration (Mertens, 1985b).
[c]Theoretical length of cut.

Kilograms of daily NDF intake from each feed and physical form were 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. In this data set, the mean chewing time for long grass hay was 150 min/kg of NDF. Long grass hay was chosen as the standard (pef = 1.0) for calculating the pef for all other NDF sources.

The pef were estimated 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. The regression coefficients from this analysis are a direct estimate of the pef for the NDF from each source and physical form relative to that for long grass hay. Most pef had standard errors of 0.05 or less with the exception of pef for byproduct feeds and concentrates. The NDF intakes from many sources were combined for byproduct feeds and concentrates, which resulted in a imprecise estimate of pef for these feeds. In addition, there were some inconsistencies in the pattern of the pef within and among NDF sources. To rectify inconsistencies, pef were smoothed within each NDF source to obtain a logical progression of factors in relation to physical form and they were standardized to obtain a consistent pef within a physical form classification across all NDF

sources. After obvious outliers and experimental differences were removed, the $r^2 = 0.76$ between observed and predicted chewing activity based on the standard pef. These pef are given in table 6 and also in table 9 where they are compared to other estimates of fiber effectiveness.

Table 6. Physical effectiveness factors (pef) of NDF for various sources and physical forms.

Classification	Dimension (inches[a])	Grass hay	Grass silage	Corn silage	Alfalfa hay	Alfalfa silage	Concen -trates	Byproducts
Long		1.00			.95			
Chopped								
Coarse	>2	0.95	0.95		0.90			
Medium-coarse	1-2	0.90	0.90			0.85		
Medium	.5-1	0.85	0.85	0.90	0.85	0.80		
Medium-fine	.25-.5			0.85	0.80			
Fine	<.25			0.80	0.70	0.70		
Ground								
Medium	>.25	0.40			0.40			
Fine/pelleted	<.25	0.30			0.30			
Rolled HM corn[b]							0.80	
Rolled barley							0.70	
Ground								
Cracked/coarse	>.5						0.60	
Medium	.25-.5						0.40	0.40
Fine/pelleted	<.25							
					0.30			

[a] Approximate dimensions of screen openings or theoretical lengths of cut.
[b] Rolled high moisture corn.

The pef in table 6 can be used to estimate peNDF for a specific feed by: 1) analyzing the feed to determine its NDF concentration, 2) determining its physical form classification, 3) obtaining the pef from table 6, and 4) multiplying NDF concentration by the pef (peNDF = NDF X pef). This approach was used to calculate the peNDF of several of the feeds (table 7). 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 in the ration. One of the desirable consequences of using NDF as the basis for describing the physical effectiveness of feeds in stimulating chewing activity and ruminal function is that differences in NDF concentration among specific batches of feed can be taken into account. This approach should account for the major differences in peNDF among feeds, but is limited by the correct selection of the appropriate physical form class in table 6.

Table 7. Calculated physically effective NDF concentrations of selected feeds.

Feed ingredient	Physical form	NDF	X	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 some long hay is included in the ration.

DETERMINING peNDF USING PHYSICAL MEASUREMENTS

Although effectiveness can be truly measured only by animal response, it is clear that this is not a feasible approach for determining peNDF values on specific lots or batches of feed. To provide an accurate and specific peNDF value for a particular feed, both NDF and pef must be determined using routine laboratory methods. Laboratory assessment of peNDF involves compromises, but these compromises should have minimal consequences if they are made based on biological principles and if the feed values and animal requirements for peNDF are consistent with one another.

Mertens (1986) proposed that only fiber particles that are large enough in size to be retained in the rumen and to require chewing should contribute to roughage value or peNDF. This suggests that measurement of chemically determined NDF and physical description of particle size could be used to estimate peNDF. To implement this concept, the size of the particles that are important in physical effectiveness must be determined. Dixon and Milligan (1981) reported passage rates of 0.0004, 0.010, 0.025, 0.041, 0.048 and 0.059/h for particles retained on sieves with apertures of 6.8, 4.9, 3.2, 2.0, 0.7, and 0.25 mm, respectively. Their results suggest 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, suggesting that they are selectively retained

and chewed. Cardoza (1985) measured the particles size of feces from cows fed 40 combinations of forage source and concentrate level to determine the threshold size for passage. He observed that <5% of the particles were retained on 3.35-mm sieves and that the median particle size in feces was retained on sieves with apertures of 0.4 to 2.0 mm (vertical shaking). His results suggest 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 method of combining chemical and physical laboratory measurements to estimate peNDF. A feed would be measured for NDF chemically and the proportion of DM of dried samples retained on a 1.18-mm sieve using vertical shaking would be measured. The pef would be assumed to equal the proportion of DM retained on a 1.18-mm sieve and the peNDF would be determined as shown in table 8. The primary limitation to laboratory assessment of peNDF is that methods for measuring particle size have not been standardized.

Although sieving 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 a 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 8-mm sieve retained 0.80, 0.65, and 0.45 of the particles for corn silage and 0.85, 0.70, and 0.45 of the particles for hay crop

Table 8. Estimating the physically effective NDF (peNDF) of feeds using chemical (NDF) and physical measurements (sieving) 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 6).
[b]Vertical shaking motion was used to separate particles.

silages that had longest, average, or shortest chop, respectively. Extrapolating the distribution plots of Lammers et al. (1996) suggests that using their method with sieve apertures of 4 mm and 6 mm would yield retained proportions that correspond to pef (Table 6) 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.

There are several difficulties in using the Penn State separator other than determining the correct sieve apertures that are related to peNDF. One is separation technique. It is difficult to standardize the method because shaking intensity, and perhaps duration, varies among individuals. Perhaps more important is the moisture of feeds and how it affects both separation and measurement. Particles tend to stick to one another when one or both are moist. This is especially true of ground concentrates sticking to moist silage particles. This causes a bias in the separation of undried materials because small particles stick to large moist ones and are measured as weight or proportion of large particles. However, even more important may be the weight of water in moist particles. For example, if a ration consists of corn silage, ground corn and soybean meal, all of the large particles will be corn silage that contains 60-70% water and all the small particles will be corn and soybean meal that contain only 10% water. Using undried weights retained on sieves will greatly over estimate effective fiber.

Laboratory assessment of peNDF using dried samples is limited by the assumption that fiber and DM distribution are similar among particle sizes. It is expected that larger particles would have more fiber than smaller ones. Thus, using particle distributions of DM probably underestimates physical effectiveness. This limitation could be overcome easily by directly determining peNDF as the NDF in particles retained on the 1.18-mm sieve (vertical shaking) as a percentage of total DM. Finally, the limitation that not all particles larger than 1.18-mm will result in the same amount of chewing could be overcome by using additional sieves with apertures greater than 1.18 mm and weighting the NDF retained on each sieve by the amount of chewing it should stimulate. More research is needed to relate chewing activity to particle size before the weighting factors for the particles on each sieve can be determined.

COMPARISON OF FIBER EFFECTIVENESS FACTORS

Various factors have been proposed for determining the effectiveness of NDF in maintaining ruminant health, ruminal function and productivity (table 9). Mertens (1985a, 1986) suggested that particles < 1.18-mm would not stimulate chewing or maintain ruminal function and reported the proportion of DM retained on sieves with openings of 1.18 mm and greater for several feeds (table 9). It appears that these data were used to develop effective NDF values (table 9) for the Net Carbohydrate and Protein System (NCPS). Although Mertens (1985a) was not cited

by Sniffen et al. (1992) as the source for the NCPS eNDF values, his work was noted in Fox et al. (1990). It appears that these same effectiveness factors are used in the Nutrient Requirements of Beef Cattle (NRC, 1996). Later, Mertens (1992) summarized all data that had been used to assign fiber effectiveness values for lactating cows and expressed them on a common scale as roughage value units. Most recently, Mertens (1997) derived physical effectiveness factors for NDF based on chewing activity by cows.

Table 9. Comparison of neutral detergent fiber effectiveness factors from various sources.

Feed ingredient	Texture	PS[a]	ef[b]	rvf[c]	ef[d]	pef[e]
Alfalfa, dehydrated	1/8" pellets	6	6	35	6	40
	3/8" pellets			60		40
Bermudagrass (Coastal)	1/8" pellet			45		30
Alfalfa hay	Long			95	92	95
	Coarse chop					90
	Medium chop					85
	Fine Chop					70
Alfalfa silage	Coarse chop	82	82	80	82	90
	Medium chop					85
	Fine Chop	67	67			70
Wheat silage	Medium chop			100	61	90
Oats silage	Medium chop			95	61	90
Barley silage	Medium chop			95	65	90
Grass hays	Long	98	98	100	98	100
	Coarse chop					95
	Medium chop					90
Corn silage, mature, well-eared	Medium chop		71	95	71	85
	fine chop		61			80

Table 9. Continued.

Feed ingredient	Texture	PS[a]	ef[b]	rvf[c]	ef[d]	pef[e]
Corn silage, average	Medium chop	81	81	95	81	85
	fine chop		71			80
Orchardgrass silage	Medium chop		88	100		90
	Fine chop		73			85
Sorghum sil., forage variety	Medium chop			95	81	85
Sorghum sudangrass hay	Long				98	100
Sorghum sudangrass silage	Medium chop			95	41	90
	Fine chop					85
Barley straw	Long				100	100
Wheat straw	Long			100	98	100

Feed ingredient	Texture	PS[a]	ef[b]	rvf[c]	ef[d]	pef[e]
Barley grain, heavy	Whole					
	Steam flaked					(90)
	Crimped. rolled	99				(80)
	Rolled					70
	Medium grind	34	34	40	34	40
	Fine grind					
Corn dry grain, normal	Whole	99	100		60	
	Steam flaked			20	48	(80)
	Cracked/coarse		60	40		60
	Medium grind	48	48		0	40
	Fine grind			20		30
Corn, high moisture	Whole	100	100	30	0	
	Medium rolled		70			80
	Fine rolled		48			
Corn and cob (ear corn)	Medium grind		56	35	56	40
Corn, high moist. ear, 1/2 cob	Rolled			50		80
	Medium grind			50		60
Oats grain	Whole	100				
	Rolled	76				(80)
	Medium grind		34	40	34	40
Sorghum grain (milo)	Steam flaked				34	(80)
	Rolled				34	60
	Medium grind			20	34	40
Wheat grain, hard red	Whole	100			0	
	crimp					(90)
	rolled					(60)
	Cracked/coarse					
	Medium grind		34	20	0	40
	Fine					
Barley malt sprouts				45	34	40

Table 9. Continued.

Feed ingredient	Texture	PS[a]	ef[b]	rvf[c]	ef[d]	pef[e]
Beet pulp	Whole		33	40	33	40
Beet pulp	Pelleted					30
Brewers grains, dried		18	18	35	18	40
Canola rapeseed meal		5		20	23	40
Citrus pulp	Whole	76				
Citrus pulp	Pelleted		23	45	33	30
Corn cobs	Medium grind	56	56	40		40
Corn distillers grains w/ solubles		4	4	30	4	40
Corn distillers grains w/o solubles				30		40
Corn gluten meal			36	20	36	40
Corn gluten feed		36	36	50	36	40

Feed	Description	a	b	c	d	e
Corn hominy feed		9	9	30		40
Cottonseed, whole, w/ lint	Whole		100	85	100	(90)
Cottonseed hulls	Whole, with long hay			80		(90)
	Whole, w/o long hay					(40)
Cottonseed hulls, pelleted				65		
Cottonseed meal, mech. extr.			36	30	36	40
Linseed meal, solv. extr.				20		40
Molasses, dried on hulls				30		40
Oat hulls				60		40
Peanut meal, mech. extr.			36	30	36	40
Peanut hulls, coarse				85		40
Peanut hulls, pelleted		12		25		30
Rice bran				50	0	40
Rice mill feed	Fine grind	1		10		30
Soybean hulls	Whole	99				40
Soybean hulls	Fine grind	3		20	2	30
Soybean meal 44%CP		23	23	20	23	40
Soybean meal 48%CP				20	23	40
Soybean seeds, roasted	Whole		100	50	100	
Sunflower meal w/o hulls		9		30	23	40
Sunflower meal with hulls				30		40
Wheat bran		33	33	45		40
Wheat middlings		2	2	50	2	40

[a] Proportion of particles retained on sieves with apertures > 1.18 mm (Mertens, 1985a, 1986).
[b] Effectiveness factors in Net Carbohydrate and Protein System (Fox et al., 1990; Sniffen et al., 1992).
[c] Roughage value adjustment factor proposed by Mertens (1992).
[d] Effectiveness factor in Nutrient Requirements of Beef Cattle (1996).
[e] Physical effectiveness factors proposed by Mertens (1997).

There is surprising agreement among the values when it is considered that some are based on particle size, others on summarization of independently derived values, and the remainder on chewing activity (table 9). Most discrepancies are associated with grains and other concentrates that can be processed in a variety of ways that might affect the effectiveness of fiber in these feeds. Although grains contain little NDF, it appears that the NDF they contain is effective if the particle size is large enough (whole, crimped or flaked) to stimulate chewing. Beauchemin et al. (1994) used mature Hereford cows fed at maintenance to determine the chewing activity of whole barley, corn, and wheat. They observed approximately 175, 190 and 195 min chewing per kilogram of NDF from barley, corn and wheat, respectively. Comparing these chewing times to dairy cows at maintenance intake eating the long grass hay standard (230 min/kg of NDF) indicates pef of .75 to .85 for whole grains, which agrees with the value of .80 reported by Mertens (1997) for high moisture corn.

Beauchemin et al. (2001) reported that the proportion retained on a 1.18 mm sieve was 97, 95, 91, and 86% for barley flaked without steam with thicknesses of 2.30, 2.17, 1.87 and 1.55 mm, respectively. Their data suggests that the pef of thin flakes would be about 90% of whole barley. Hironaka et al. (1992) observed that thin (1.61 mm) and medium (1.74 mm) steam flaked barley resulted in 75 to 85% of the rumination time of thick (2.00 mm) flaked or whole barley.

This suggests that thin flakes may disintegrate quickly in the rumen resulting in less chewing. The rumination data of Hironaka et al. (1992) suggest that the pef for thin flake barley would be about 0.60. Hinman and Johnson (1974) reported that the proportion retained on a 1.00 mm sieve was 90, 74 and 22% for sorghum grain that was steam-flaked (335 g/L), rolled (kernels cracked) or ground (4.76 mm screen), respectively. Their particle size data suggests that flaked sorghum would have a larger pef than ground sorghum. Uchida et al. (2001) reported that dairy cows chewed significantly more when flaked corn (3.18-mm thick) was fed compared to when ground corn (3.8-mm screen) was fed, which suggests that the pef for flaked corn should be greater that the 0.40 pef of ground corn.

Van Soest (1994) observed that when pelleted forages are fed the particle size of feces is larger than when long forages are fed. He concluded that large fiber particles may trap smaller ones in the ruminal mat and result is more extensive chewing of smaller particles. This logic suggests that the effectiveness of grains and other concentrates with small particle size may depend on the inclusion of some large particles in the ration. I observed when relating peNDF to average daily gain (**ADG**), that the effectiveness of cottonseed hulls were quite different when they were fed as the only roughage or when they were fed with a long or chopped forage.

DETERMINING MINIMUM peNDF REQUIREMENTS FOR RUMINANTS

Mertens (1997) observed asymptotic relationships between peNDF concentration in the ration and both milk fat percentage and ruminal pH of lactating dairy cows. He recommended a minimum peNDF concentration of 19-21% of ration DM for dairy cows. These recommendations are designed to maintain their long-term health and productivity. Feedlot production is a terminal process that rarely lasts beyond 180 days. Given the short-term nature of feedlot production and the need to maximize animal performance, the minimum fiber requirements for feedlot cattle may be substantially lower than that for dairy cows. Because fiber has lower productive energy density than concentrates and is poorly digested in high concentrate diets, lower fiber concentration in feedlot rations may improve animal performance and reduce manure excretion (Bierman et al., 1999).

Data from eight publications (White and Reynolds, 1969; Xiong et al., 1991; Bartle et al., 1994; Hussein and Berger, 1995; Zinn and Plascencia, 1996; Calderon-Cortes and Zinn, 1996; Bierman et al., 1999; Rossi and Loerch, 2001) were used to derive relationships between peNDF concentration in the ration and performance of feedlot cattle. The pef in tables 6 and 9 and NDF values from table 4 were used to calculate peNDF concentrations in rations. The database provided 27 comparisons in which differences in peNDF were evaluated. Differences in performance among citations were adjusted statistically and data were expressed as deviations from the average daily gain of all experiments (figure 2).

Figure 2. Relationship of average daily gain in feedlot cattle to physically effective neutral detergent fiber in the ration.

It appears that there are positive relationships between ADG and peNDF within trials when peNDF is less than 10% of ration DM and negative relationships within trials when peNDF is greater than 15%. Although Owens et al. (1997) indicated poor relationship between eNDF and feedlot cattle performance, there was a good relationship between peNDF and ADG in this database:

$ADG = 1.19 + 0.0269*peNDF - 0.000883\ peNDF^2$; $R^2 = .95$ and reg. SE = ±0.06 kg/d.

By taking the first derivative of this equation, the peNDF that maximizes ADG was determined as 15.3%. However, there is little difference in ADG when peNDF in the ration is between 12 and 18%. The optimum peNDF in the ration to minimize liver abscesses was about 22%, and the
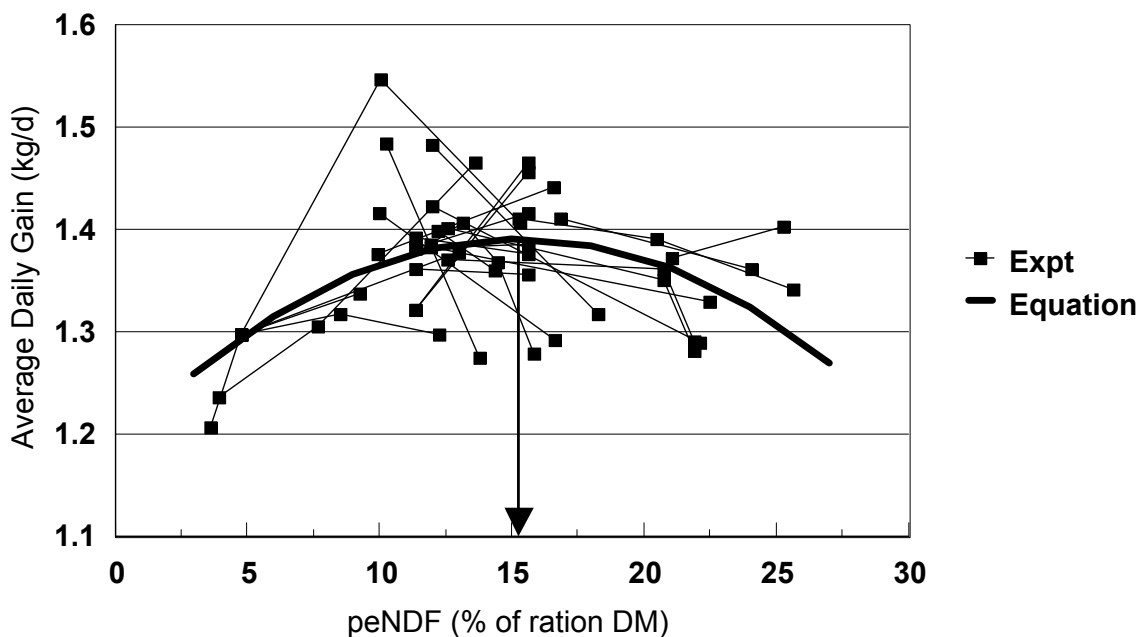
peNDF that maximized intake was about 25%. The regression coefficients for the relationship of ADG with peNDF were highly significant whereas the regression coefficients with NDF were not significant. Based on this database of feedlot performance it appears that the peNDF values generated from chewing activity of lactating cows can be used to formulate feedlot rations.

The relatively broad range in acceptable peNDF (12 to 18% of ration DM) suggests that recommendations can be modified to match multiple objectives and account for other factors that may influence minimum peNDF requirements for feedlot cattle. For example, if minimizing liver abscesses is a concern, then increasing the peNDF from the optimum of 15% to 18% will reduce the incidence of liver abscesses and still maintain ADG. Alternatively, if reducing feed per gain is desirable, then decreasing the peNDF concentration in the ration from 15 to 12% would be recommended.

In addition to multiple objectives, there are nutritional considerations that influence peNDF recommendations.

1. Decreased ease of particle size reduction of forages. Chewing per kilogram of NDF increases as the NDF concentration of the feed increases (Mertens, 1986). Thus, a kilogram of NDF from a very mature, high fiber forage or roughage will stimulate more chewing than the same amount of NDF from a low fiber forage. For every 10%-units increase in NDF above 40% for alfalfa and 55% for grasses, the peNDF requirement can be reduced by about 0.5%-units. Thus, if a low peNDF ration is desired, a low quality source of NDF such as straw or mature hay will be a better source of fiber than a high quality forage.

2. Decreased rate and extent of ruminal fermentation of forages. Mature or low quality forages result in less fermentation acids being produced because their rate and extent of digestion is less. When these sources of fiber are used the peNDF requirement can be reduced.

3. Increased use of byproduct feeds. In general, the peNDF of byproduct feeds or nonforage fiber sources is 40% of their NDF concentration (Table 6). Thus, the NDF concentration of the ration will be higher and NFC will be lower when an equivalent amount of peNDF is supplied by byproduct feeds compared to forages. Because the fiber in byproduct feeds typically produces less fermentation acids than the NFC it replaces, increased use of byproduct feeds in the ration should allow the peNDF requirement to be reduced 1-2%-units depending on the proportion and fermentability of the byproduct feed.

4. Decreased readily fermentable carbohydrates. In many situations, decreasing readily fermentable carbohydrates is the inverse of increasing the use of byproduct feeds and high quality forages. However, there are differences in the source, composition, and digestion kinetics of the readily fermentable carbohydrates that can also have significant impact on fermentation acid production and peNDF requirements. Sugars are very rapidly fermented and when there are significant amounts of sugars (molasses, beets, bakery and candy byproducts) in the diet the minimum peNDF requirement should be increased. Medium ground, dry grains vary in fermentability with corn and sorghum starch being the slowest fermenting followed by rice, potato, barley, wheat, and oats starches. Harvesting and ensiling grains increases the rate of fermentation as does steam flaking and fine grinding. Decreasing the proportions of processed (steam flaked or finely ground) or high moisture grains, or reducing the amounts of starch from oats and wheat can allow the minimum peNDF requirement to be less than 15% of the ration DM and increasing these factors would indicate that peNDF should be above 15% of the ration.

5. Increased fat concentration in the ration. When fat is added to a ration it is often possible to reduce the starch content and increase the fiber content of the ration. Thus, the net result of feeding fat is often a reduction in ruminal fermentation, which suggests that the minimum peNDF requirement can be reduced when the fat content of the ration exceeds 5%.

6. Increased consistency in ration composition and feeding schedules. Both research and field experiences suggest that ruminants can cope with rations that result in low ruminal pH (<6.0) for short periods of time. The key is to adapt animals to the ration slowly and then ensure that any change in the ration or intake of the animal is minimized. A careful review of the research literature indicates that acute acidosis can be accomplished consistently only with a dietary change. Thus, all changes in the diet or intake of cattle must be minimized when attempting to

reduce the peNDF requirement to the minimum. One of the main culprits that creates variation in the ration is changes in the DM concentration of the forage (especially decreases in DM). For example, if a ration is being fed with minimum forage and it rains on silage in a bunker silo or hay in a stack or pile, the weight of forage that will be mixed in the ration would contain significant additional water resulting in less fiber in the ration. This change would cause the ration peNDF to be below the minimum threshold for fiber that the animals can tolerate and acidosis would probably occur. Similar problems occur when silage changes due to differences in fields, varieties or cuttings within the silo.

Another problem in ration consistency is related to particle size, mixing effectiveness and selection by animals. It is difficult, if not impossible, to uniformly mix and deliver rations containing concentrates and coarsely chopped roughage, especially if the ingredients are dry. In addition, animals will selectively eat roughage and grain when the forage is chopped coarsely even if a uniform ration is delivered. Thus, there is a tendency to reduce the particle size of the roughage to improve handling, mixing and delivery. When this occurs it is important that the peNDF value of the roughage be adjusted to reflect its effectiveness. Conversely, if coarse, dry mixed rations are delivered, the peNDF recommendation should be increased above 15% to accommodate the inconsistencies in feed uniformity and animal selection that will occur.

The difficulty in maintaining a consistent ration is increased when rations contain only 4 or 5 ingredients. A change in moisture or fiber content or in palatability of any one of the ingredients can greatly affect diet composition or feed intake. Rations with numerous ingredients tend to be more consistent because no single ingredient is a major portion of the ration and it is unlikely that several of the ingredients would have the same change in composition at the same time. In addition to consistency in the ration, there must also be consistency in feeding management when rations with the lowest peNDF are to be fed. Cattle should be fed at the same times, total mixed ration must be mixed thoroughly but without over mixing that can reduce particle size, bunks and waterers must be kept clean, and the time that animals are without feed must be minimized. The key to low fiber rations is consistency.

7. Improved bunk management and increased frequency of feeding. It is crucial that animals not be without access to feed for extended periods. When the bunk is clean for too long, cattle get hungry and gorge themselves when new feed is provided. This greatly increases the fermentation acid spike after eating, and results in ruminal acidosis. Similar things occur when concentrates are fed separately to dairy cows within a day. In effect, this results in an inconsistent ration within the day. If bunk management is poor and frequent feeding of concentrates is impractical, the minimum peNDF requirement should be raised above 15% of the ration.

8. Increased feeding of buffers or neutralizers (supplemental or intrinsic). Feeding supplemental buffers can be used to replace some of the salivary buffer that is not secreted when low fiber rations are fed. The peNDF concentration in the ration can be decreased about 1%-unit for each 1%-unit of buffer that is fed. Also recognize that some feeds have more intrinsic buffering capacity than others, e.g., alfalfa has greater buffering capacity than corn silage. In addition, the neutralizing effect of ammonia and buffering capacity of amino acids in the rumen suggests that rations that are higher in soluble crude protein may be beneficial when low fiber rations are fed.

CONCLUSIONS AND RECOMMENDATIONS

Both the chemical and physical characteristics of rations are important in determining animal performance. Physically effective NDF attempts to take into account both the chemical and physical nature of fiber that influences the chewing activity and ruminal function of ruminants. 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 for feedlot cattle is 15 % of ration DM with a range from 12 to 18%.

AREAS OF NEEDED INFORMATION

The quantitative description of fiber effectiveness is a relatively new phenomenon and more information is needed to help us to understand the biological principles involved and develop technologies that can be used to successfully feed rations with minimum fiber. Additionally, research is needed to quantify the relationships among the chewing activity and the NDF and physical form of feeds. We also need more measurements of chewing activity when fibrous byproduct feeds are fed to accurately determine their peNDF. Practical use of peNDF would be greatly enhanced if the relationship between feed particle size (using current sieving methods) and physical effectiveness factors would be established so that field or laboratory methods of assessing peNDF can be developed. Finally, more research is needed to determine if more accurate physical effectiveness factors could be derived using feedlot performance data and to define the minimum peNDF recommendations for both long term and short term feeding situations.

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