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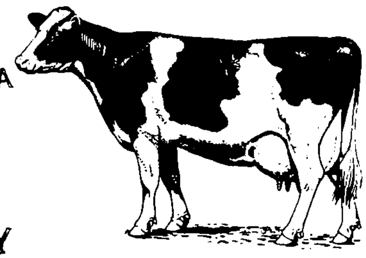

Dairy Update

TMR STRATEGIES TO OPTIMIZE RUMEN FERMENTATION: BALANCING RATIONS FOR CARBOHYDRATES AND PROTEIN

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The ruminant animal has a two component digestive system. The first component is a large fermentation vat inhabited by millions of bacteria and protozoa. The rumen and reticulum are the largest part of the first component and account for about 85% of the total stomach capacity in the adult ruminant. The second component is the postruminal digestive tract. Key parts of the postrumen tract are the abomasum (gastric stomach with function comparable to nonruminants) and the lower digestive tract (small and large intestines). The goal in feeding dairy cows is to optimize the fermentation of nutrients in the rumen/reticulum into microbial protein and endproducts metabolizable by the dairy cow. Nutrients escaping rumen fermentation should be used to balance or enhance the products of fermentation.

The rumen and reticulum are an ideal environment for anaerobic organisms to grow. Temperature, pH and ionic strength are relatively controlled and consistent. Nutrients are usually furnished in a plentiful and consistent supply and the endproducts of fermentation are continually removed through absorption or passage into the lower digestive tract. Optimum pH in the rumen-reticulum for fermentation of cellulosic fiber material is 6.2 to 6.8. If optimum production and profit are to be realized from dairy cows, fiber digestion in the rumen must be maximized while digestion of starches and sugars controlled. A generalized overview of the characteristics of microorganisms inhabiting the rumen is in Table 1.

The normal endproducts of rumen fermentation are volatile fatty acids (VFA), ammonia, methane, carbon dioxide and microbial protein. Methane and carbon dioxide are terminal products and of no further use to the animal. Some ammonia can be utilized by the bacteria to synthesize protein. Microbial protein, per se, is of extreme importance as 60 to 70% of the total protein required by a lactating dairy cow can be supplied from microbial protein (17). The normal pattern of VFA production in the rumen is 60 to 70% acetate, 15 to 20% propionate, 5 to 15% butyrate and 5% others. Acetate and butyrate are important precursors for milk and body fat synthesis whereas propionate is the primary source of glucose for the ruminant animal. Thus,

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the feeding of the rumen bacteria has to be the first and foremost consideration in balancing rations for dairy cows.

Table 1. General characteristics of rumen microorganisms.[1]

Class of organism	Substrate preference	Major need	Major product of importance	pH tolerance	Time to double, hr
Fiber bacteria	Cellulose Hemicellulose	NH_3 Iso-acids	Volatile fatty acids	Neutral	8-10
General purpose bacteria	Cellulose Starch	NH_3 Amino acids	Volatile fatty acids NH_3	Acid	6-8
Starch & sugar bacteria	Starch Sugar	Amino acids NH_3	Volatile fatty acids Lactic acid NH_3	Acid	¼-2
Secondary bacteria	Bacterial fermentation products	Amino acids	Iso-acids	Neutral	6-8
Protozoa	Starch Sugar Bacteria	Amino acids	Volatile fatty acids	Neutral	15-24

[1] Adapted from Chase and Sniffen (5).

CARBOHYDRATES

Carbohydrates are the primary source of energy for ruminants and compose the largest fraction of the dry matter (DM) fed at over 65% (5). Carbohydrates can be divided into two main fractions: structural and nonstructural. The structural carbohydrates are collectively termed fiber, with further distinction into neutral detergent fiber (NDF), or cell walls, and acid detergent fiber (ADF) based on composition. The constituents of fiber are cellulose, hemicellulose, pectin and lignin although lignin is chemically not a carbohydrate but a polyphenolic substance that is indigestible by rumen microbes and provides no nutritive value. Nonstructural carbohydrates are primarily starches and sugars with starches accounting for the largest segment in most feeds. Figure 1 is a schematic representation of the carbohydrate fractions in feeds.

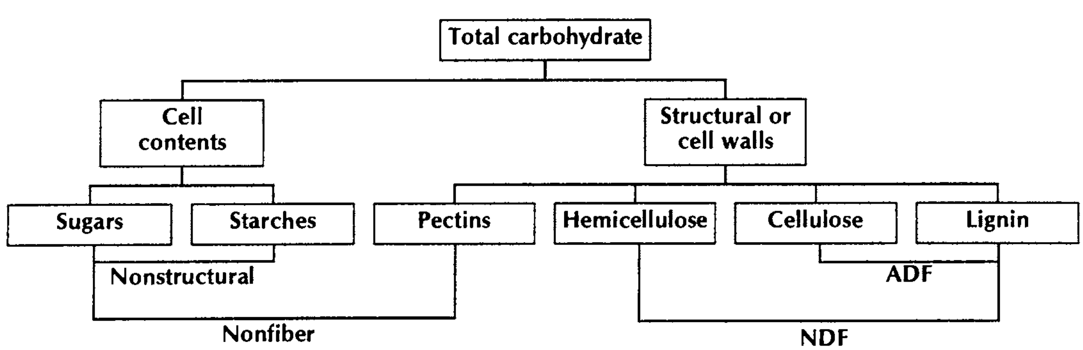

Figure 1. Schematic representation of carbohydrate fractions in feeds.

Structural carbohydrate (NDF and ADF) analysis of feeds is routinely performed. The NDF fraction is composed of cellulose, hemicellulose and lignin. The ADF fraction is composed of cellulose and lignin. Nonstructural carbohydrates can be determined enzymatically; however, this is a difficult and time consuming technique (20). Nonstructural carbohydrates that have actually been determined are usually indicated by the abbreviation NSC. A quicker, more practical way is to estimate nonstructural carbohydrates by a calculated difference method known as nonfiber carbohydrates (NFC) (14).

$$\% \text{ NFC} = 100 - (\% \text{ CP} + \% \text{ NDF} + \% \text{ Fat} + \% \text{ Ash})$$

All analyses are on a DM basis
CP = crude protein
NDF = neutral detergent fiber

The NSC and NFC content of feedstuffs can vary considerably. Table 2 shows some of these differences for several common feeds. Most of the difference between NFC and NSC can be attributed to pectin.

Table 2. Neutral detergent fiber (NDF) and nonstructural carbohydrate (NSC) or nonfiber carbohydrate (NFC) content of various feeds.[1]

Feed	n	NDF, %	NSC Analyzed[a]	NFC Difference[b]
		--------------------% of DM--------------------		
Alfalfa hay	1	40.0	22.0	27.8
Alfalfa silage	6	45.9	8.5	19.6
Grass hay	1	63.9	8.7	17.2
Corn silage	9	43.3	33.7	42.5
Beet pulp	1	48.1	12.8	36.1
Soyhulls	1	66.6	5.3	14.1
Wheat bran	1	32.8	46.8	45.0
Wheat midds	1	42.3	31.5	31.2
Hominy	2	24.8	49.6	53.8
Shelled corn, dry	1	13.4	73.3	71.4
HM ear corn	4	16.9	71.6	69.2
Barley	1	22.0	56.1	61.8
Soybean meal	1	9.6	17.2	34.4
Canola meal	1	20.7	14.7	25.8
Gluten feed	1	49.2	18.5	24.7
Gluten meal	1	7.0	12.0	17.3

[a] Method of Smith (20).
[b] 100 - (% NDF + % CP + % Fat + % Ash)
[1] Source: Hoover and Miller (11).

Nonfiber Carbohydrates (NFC)

Clark et al. (6) determined the greatest microbial growth, measured as microbial protein produced, occurred at about 11 kg of organic matter digested in the rumen. Other research (8,12) has shown similar findings and suggested the best way to increase digestion in the rumen is to increase NFC content of the ration. However, the amount of NFC in the ration is limited by the amount of starch in the NFC and by the rate and extent of the starch and non-starch component digestion in the rumen. Some factors that influence NFC digestion in the cow are listed below.

- Grain type. Grains vary in rate and extent of starch digestion in the rumen. In general, the rate of starch breakdown in the rumen from fastest to slowest by grain type is: oats, wheat, barley, corn and sorghum (10). The form of starch, amylose vs amylopectin, also influences starch digestibility (rumen and postrumen). Amylopectin is generally more digestible than amylose, but other reasons why waxy cultivars may be slightly more digestible are: less peripheral endosperm, larger starch granules in the endosperm and more water soluble endosperm proteins (1).

- Grain processing. Most grain processing methods increase both rate and total starch digestibility in the rumen. Reducing particle size increases surface area making more area available for bacterial attachment (13). Processing methods that gelatinize starch, such as steam flaking, change the form of starch and increase ruminal availability of starch. Other processing methods, such as extrusion and popping, also increase starch availability in the rumen (13).

- Ensiling of grains and corn forages. Ensiling of grains and corn forages tends to increase ruminal starch digestibility. The softer, wetter corn kernels in these feeds are likely to be broken from harvesting and/or removal from storage thereby increasing surface area. Corn kernels that are intact, especially in low moisture silages, are very poorly digested in the rumen or postruminally and usually appear in the manure.

- Site of starch digestion. The major portion of starch digestion should occur in the rumen. Postruminal digestion and absorption of starch decrease with increasing quantities of starch passed into the small intestine. The goal is to have a total tract starch digestibility of 85% or greater with a rumen degradability of 50 to 75% (18). The yield or outflow of microbial protein from the rumen has been directly related to the total carbohydrate digested (6). Increasing ruminal starch digestion to increase total tract digestion and microbial protein yield must be balanced against the negative effects of excess starch digestion in rumen (acidosis, off-feeds, low milk fat percentages, laminitis, etc.).

Feeding recommendations for nonstructural carbohydrates will vary depending on the method used to estimate them (NSC or NFC). A recent experiment with rations containing 42%, 36%, 30% or 24% NFC (calculated) suggested NFC levels below 30% depressed dry matter intake, but no advantage in production was observed by having greater than 40% NFC in rations (4). In this experiment, wheat midds, dried brewers grains and soyhulls were used in the ration to replace corn and soybean meal. Feng et al. (9) fed rations with either 39% or 29% NSC (enzyme determined) that were nearly identical in NFC (calculated) content at 38%. Milk production of cows fed the 29% NSC ration was greater (22.5 vs 21.3 kg/day) and fat percentage of the milk was higher (3.7 vs 3.2%) than cows fed the 39% NSC ration. Based on this research and other studies (1, 11), it can be concluded that both the rate and extent of NDF degradability are important factors to consider in optimizing rumen fermentation.

Structural Carbohydrates (Fiber)

Forage species. The fermentation of forages in the rumen depends on the composition of the NDF. Hemicellulose and cellulose each have different rates of fermentation, but lignin is not fermented at all. Lignin is negatively correlated to the amount of NDF that can be fermented while hemicellulose is negatively related to the rate of NDF fermentation (11). Table 3 shows legumes are high in lignin and low in hemicellulose compared to grasses and corn silage. Thus, the NDF in legumes is rapidly fermented, but limited in total or extent of fermentation. In contrast, grasses and corn silage are lower in lignin, but higher in hemicellulose which indicates they will be fermented to a greater extent than legumes but at a slower rate. For high producing dairy cows, legumes as the major forage source in the ration are advantageous as they ferment faster than corn silage or grasses in the 18 to 24 hours feeds typically spend in the rumen. The slower fermentation of grasses and corn silage causes a fill effect decreasing dry matter intake.

Table 3. Examples of fiber partition in various forage species.[1]

Forage	NDF	ADF	Hemi-cellulose	Cellulose	Lignin
	% DM	-----------------------% of NDF-----------------------			
Legumes	50	79	22	64	15
Grasses	59	68	32	57	11
Corn silage	45	58	42	51	6

[1] Adapted from Hoover and Miller (11).

NDF digestibility. Ruminal digestibility of NDF in various feeds is shown in Table 4. As forages mature, both the rate and extent of NDF fermented in the rumen decreases. Environment and growing conditions can greatly affect fiber digestibility in forages as well. At the present time, fiber digestibility is not considered in evaluating forages.

Carbohydrate digestion is complex; however, when integrated with rate of passage, it becomes even more dynamic. As feed intake increases, the time available for digestion of feed particles decreases. Starch digesting bacteria grow rapidly and are generally not affected by fast passage rates through the rumen. Fiber digesters are slow growing microbes and may require 12 hours before beginning to optimally digest fiber. Thus, as feed passage rate increases, starch digesters proliferate and rumen pH tends to decrease. A pH below 6.2 negatively affects fiber digesters as fewer microbes become attached to feed particles further reducing cellulose, hemicellulose and pectin digestion. If particle size of forages is reduced at the same time, the net effect can be acidosis and its encompassing problems. Thus, a balance between fiber and starch is needed in the ration. The degree to which starch can replace fiber in diets is dependent on many factors including rate of passage and digestibility of NDF.

Table 4. Ruminal neutral detergent fiber (NDF) digestibility of various forages and high fiber byproducts.[1]

Feed	Ruminal NDF digestibility, % of NDF
Forages	
Alfalfa hay	33-63
Alfalfa silage	31-41
Corn silage	32-68
Orchardgrass hay	53-63
Orchardgrass silage	41-48
Red clover hay	31-59
Timothy hay	66-77
Timothy silage	49-52
High fiber by-products	
Beet pulp	69
Brewers grains	50
Corn cobs	28-56
Corn gluten feed	42-49
Distillers grains	64-79
Soybean hulls	86-95

[1] Source: Allen (1).

Replacement of forage fiber

The requirement of fiber by dairy cows is both chemical and physical. Discussions above on NFC and NDF have largely focused on the chemical aspects and resulting metabolic effects. However, to maintain good rumen function and healthy cows a certain amount of physically effective fiber is needed in rations. Determination of physically effective fiber is based on chewing responses in cows which is confounded by both quantity of fiber and particle size of the feed (2,3). As NDF increases, the time spent chewing the feed increases. Conversely, less chewing is required as particle size of the feed becomes smaller.

Physically effective fiber is needed in the rumen to form a mat. This fibrous mat traps feeds affecting their rate of passage and digestion in the rumen. The fiber mat is responsible for the stimulation of cud chewing, salivation and rumen motility. The predominate source of physically effective fiber is long or coarsely chopped forages. Ration recommendations of 21% NDF from forage are based on 15 to 20% of the coarse particles in the forage being greater than 4 cm in length (19). Several byproduct feeds high in NDF have the potential to replace some forage or NDF from forage in rations. A combination of 55% soyhulls:45% coarsely chopped hay has been found to successfully replace up to 66% of the forage dry matter from alfalfa and corn silages in lactation rations (23). In addition, this combination of soyhulls:coarse chopped hay maintained an effective rumen mat and stimulated rumination (22). However, very few physically effective replacement values for byproduct feeds have been determined based on chewing responses. Mertens (15) calculated some potential physically effective NDF values for feeds based on their particle size and retention on a 1.18 mm sieve (Table 5). Considerably more research is needed in this area as Mooney and Allen (16) showed whole linted cottonseed was 50% as effective at stimulating chewing as .95 cm chopped alfalfa silage but 75% as effective as .1 cm chopped alfalfa silage. Thus, the physically effective NDF value of a feed will vary depending on the feed it replaces in the ration.

Some research has evaluated the effectiveness of various NDF sources to support milk fat percentage in replacement of forage NDF (3). Hence, the term effective NDF refers to the effectiveness of NDF based on metabolic effects (fermentation endproducts) rather than the actual stimulation of rumination from physical effectiveness. The effective NDF value for some feeds is shown in Table 5.

Table 5. Physically effective and effective NDF values of various fibrous byproduct feeds.

Feed	Physically effective[1]	Effective[2]
	---------------% of NDF---------------	
Corn cobs - fine	40	51
Oat hulls	60	64
Beet pulp	40	51
Distillers grain	30	84
Cottonseed - whole	85	108
Wheat midds	50	38
Malt sprouts	45	48
Brewers grains	35	27
Corn gluten feed	50	44

[1] Physically effective refers to forage replacement for rumen stimulation. Source: Mertens (15).

[2] Effective refers to ability to support milk fat percentage. Source: Armentano (3).

To calculate either the physically effective or effective NDF value for a feed, multiply the NDF content of the feed by the coefficient listed in Table 5. (Example: wheat midds are 36% NDF; physically effective NDF is $36 \times 50\% = 18\%$; effective NDF is $36 \times 38\% = 14.4\%$.)

FAT

Fat is an energy source for the cow but provides no fermentative energy for microbial growth in the rumen. The general addition of fat to diets tends to deplete the protozoa population in the rumen and replace highly digestible carbohydrate in the diet lowering microbial fermentation. Wu et al. (24) found no differences between fat sources (tallow, calcium salts of long chain fatty acids or prilled fat) added at 2.5% of the ration dry matter in supporting milk production, milk composition or dry matter intake of mid lactation cows. Milk production increased by an average of 2.1 kg per day while milk protein percentage decreased about .1% with fat addition to the ration compared to the control or no fat added ration. Hence, when fat additions are limited to 3% of the ration dry matter or less, minimal or no affects on rumen fermentation should occur. The method of adding 5% fat to a TMR was found to have relatively small effects on dry matter intake, milk production or milk composition (7). Fat added either as part of the concentrate, added directly to the haylage or added as the last ingredient to the TMR had no affect on rumen fermentation characteristics.

PROTEIN

Two sources provide the protein needed for maximum milk production. The primary source should be microbial protein produced from fermentation in the rumen. Dietary protein escaping rumen fermentation should complement microbial protein making up for any deficiencies in amino acids occurring in the microbial protein profile. Thus, in the formulation of dairy rations, the total amount of CP (Nitrogen × 6.25), the amount of CP degraded in the rumen (DIP) and the amount of rumen undegradable protein (UIP) have to be considered.

The DIP fraction represents the dietary protein available to the rumen microbes. It includes nonprotein nitrogen (NPN), such as urea and ammonia, as well as true protein. Improved microbial production occurs when some amino acids and peptides as well as NPN are included as part of the CP supplied to the rumen. Research from West Virginia (12) has shown microbial protein yield is highly correlated with the percent DIP in the ration. Production of microbial protein increased linearly as DIP in the ration increased to 19%, DM basis. Although this level is above what can be practically attainable in rations, it does emphasize the importance of providing protein to the bacteria first and then fine tuning rations for UIP and amino acids. However, the most important factor affecting microbial protein production is intake of rumen fermentable organic matter (8). The pattern of energy and protein degradation in the rumen is of less importance than the continuous supply of energy, provided protein is not limited in the ration (21).

TMR FEEDING GUIDELINES FOR OPTIMIZING RUMEN FERMENTATION

Feeding a TMR offers the best opportunity to implement strategies for optimizing rumen fermentation. A balanced, blended source of both structural and nonstructural carbohydrates along with the protein and minerals needed for optimum microbial protein production can be fed through a TMR. Feeding a TMR is the best way to maximize energy intakes while minimizing fluctuations in rumen fermentation and pH. In addition, the blending of long coarse forage particles with high fiber byproducts supports good mat formation in the rumen for rumination. Based on the information presented, the following guidelines (Table 6) can be used to maximize rumen fermentation and microbial protein production in high producing dairy cows.

Table 6. Guidelines for optimizing rumen fermentation of high producing dairy cows fed a TMR.

Nutrients	% of total DM
General guidelines - long coarse forage in ration	
ADF	18-20
NDF - total	27-32
Rumen degradable NDF	> 15
NDF - forage sources	20-22 (75% of total)
Total carbohydrate (NDF + NFC)	70-75
NFC	35-42
NSC	< 35
Starch	< 35
Rumen degradable starch	< 25
Crude protein	18-19
Rumen degradable protein	> 12
Soluble protein	5-6
Limited forage feeding	
ADF	> 20
NDF - total	> 30
NDF - forage source	> 15
Effective NDF - total	> 23
NFC	< 35
NSC	< 30
Starch	< 30
Protein - same as for general guidelines	

Factors such as particle size of forages and grains can greatly alter the guidelines above. Coarse or long particle sizes will require higher levels of starch and less NDF in the ration to optimize rumen fermentation than when fine ground forages and grains are fed. In general, maximum energy intakes will be achieved when total NDF is at the lowest level allowable for good rumen function. At the present time, it is impossible to accurately quantify and balance rations for these guidelines because of the lack of analytical procedures and well-defined requirements for the fractions described above. As the term implies, the above are guidelines and may need to be altered by knowledgeable nutritionists to achieve optimum performance from dairy cattle.

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