Ruminal Acidosis in Dairy Cows: Balancing Physically Effective Fiber with Starch Availability

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Introduction

The high energy diets that are typically fed to dairy cows can put the cow at risk of experiencing ruminal acidosis. High energy diets are low in neutral detergent fiber (NDF) and high in starch. The starch sources are often processed in a manner to optimize starch availability in the rumen and the fiber sources are often highly digestible and short in particle length. As a result, these types of diets are highly fermentable in the rumen and often lack the structural characteristics needed to maximize rumination time and the flow of salivary buffers into the rumen. The result is reduced pH in the rumen and increased risk of acidosis. While it is critical to meet the energy requirements of high producing cows, acidosis must be avoided to ensure high milk production and efficient use of feed.

Subacute Ruminal Acidosis

Diets that are rapidly fermented in the rumen lead to rapid production of volatile fatty acids (VFA). When VFA production exceeds the ability of the rumen environment to neutralize or absorb the acids, subacute ruminal acidosis occurs (Fig. 1).

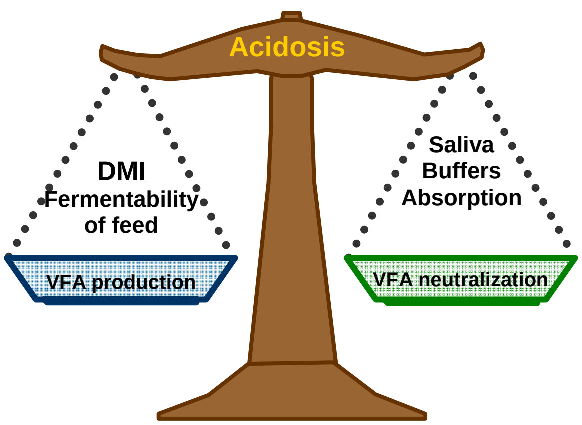

Fig. 1. Prevention of ruminal acidosis depends on balancing the production of VFA and the neutralization/removal of VFA. High feed intake and rapidly fermentable

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carbohydrates, such as starch, increase acid production. Neutralization occurs through buffering (mainly salivary buffers), absorption through the rumen wall, and passage from the rumen.

An episode of ruminal acidosis occurs when the pH in the rumen drops below a threshold value. We use a threshold value of 5.8 to define subacute ruminal acidosis because cellulolytic ruminal bacteria do not grow below pH 6.0 (Russell and Wilson 1996), which causes a decrease in fiber digestion and feed efficiency. Subacute ruminal acidosis is not to be confused with acute acidosis, which is more common in feedlot cattle. Lactic acid rarely accumulates in the rumen fluid of dairy cows experiencing subacute ruminal acidosis.

Systems that continuously monitor rumen pH allow researchers to characterize the changes in pH throughout the day as a function of diet and management (Dado and Allen 1993; Penner et al. 2006). Rumen pH changes throughout the day in relation to feeding with a variation of ±1.5 pH units over the course of the day. A typical pH profile for a dairy cow is shown in Fig. 2.

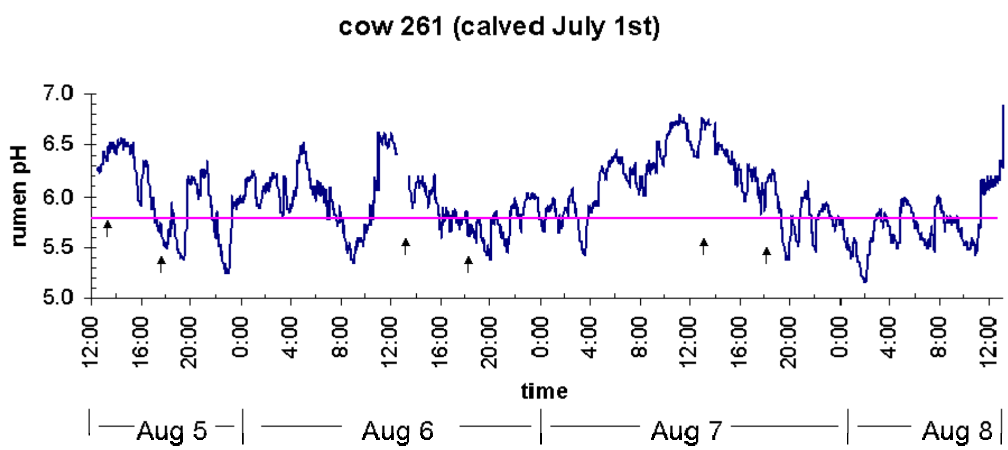

Fig. 2. Ruminal pH measured in a dairy cow over a 72-h period. Subacute ruminal acidosis (pH < 5.8) occurred for 6.4, 6.5 and 11.8 h/d and dry matter intake was 16.0, 15.6 and 14.1 kg/d on Aug 5/6, 6/7 and 7/8, respectively. Arrows show feeding times at 1330 and 1600 h; the solid line indicates the ruminal acidosis threshold of pH 5.8.

Variability in Acidosis among Cows

The risk of acidosis is not equal for all cows or all herds. In one US study, one-third of the herds tested had an incidence rate of ruminal acidosis greater than 40% (Garrett et al. 1999). In a recent study, we observed tremendous variability among fresh cows in terms of acidosis. Fig. 3 shows the rumen pH profile of two fresh cows fed the same lactation diet; rumen pH in the cow with the “best” profile remained very high throughout the day, whereas the cow with the “worst” profile experienced acidosis throughout the entire day. Factors accounting for the variation among cows are many, including dry matter intake (DMI), eating rate, sorting of feed, salivation rate, rate of passage of feed from the rumen, and other aspects of cow physiology and behavior. The goal is to minimize the number of cows that experience ruminal acidosis, and the duration and intensity of each episode of acidosis for individual cows.

Variability in Acidosis with Stage of Lactation

Absorption of VFA from the rumen occurs passively through papillae, which are finger-like projections located on the rumen wall. The papillae increase gradually in length when cows are fed a close-up diet or a lactation diet that contains more grain than the dry cow diet. Increased surface area and absorptive capacity of the rumen protects the cow from accumulation of VFA in the rumen which is the main driver of rumen pH depression. Because the papillae may not have attained their full potential size by calving, fresh cows are susceptible to ruminal acidosis.

We studied the occurrence of acidosis pre- and post-calving by monitoring ruminal pH using a stand-alone ruminal pH measurement system placed within each cow's rumen (Penner et al., 2006). Mean ruminal pH dropped abruptly from an average of 6.32 before calving, to an average of 5.98 after calving. Each day, pH was < 5.8 for 6 to 9 h, with severest acidosis occurring 3 wk after calving (Fig. 4, Penner et al., 2007).

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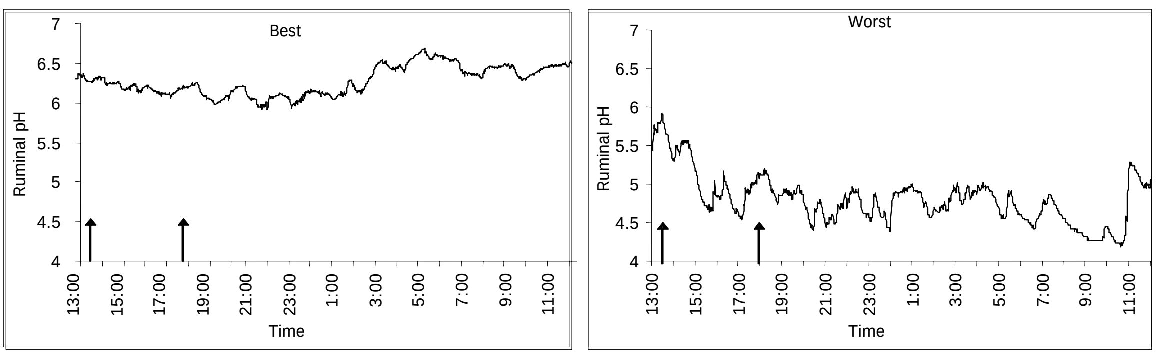

Fig. 3. Ruminal pH measured 5 days after calving in two cows (best and worst-case acidosis cows) fed the same lactation diet (Penner, Beauchemin and Mutsvangwa, unpublished data).

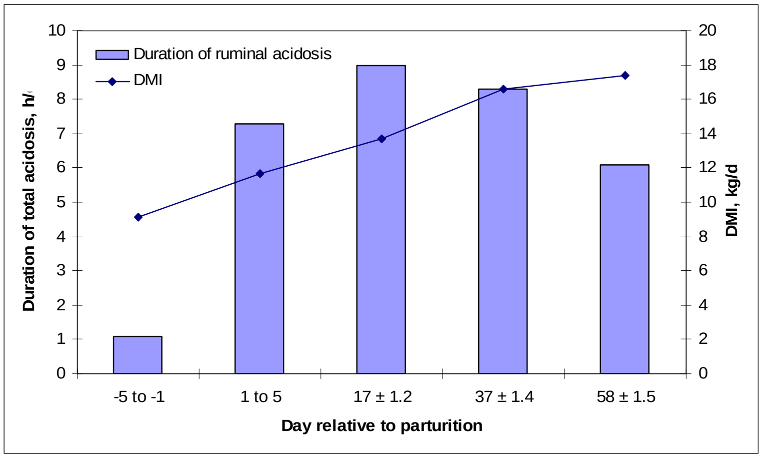

Fig. 4. The effect of day relative to parturition on ruminal acidosis (measured as h/d pH < 5.8) and dry mater intake in primiparous Holstein cows (Penner et al., 2007).

Impact of Ruminal Acidosis

It can be difficult to identify animals suffering from subacute acidosis because the clinical signs are not unique to acidosis. Cows with acidosis can experience diarrhea, weight loss, reduced milk production, and increased susceptibility to other metabolic disorders. Ruminal acidosis is a major problem for the North American dairy industry (Krause and Oetzel, 2006) costing between $500 million to $1 billion a year (Donovan, 1997). Financial losses occur due to treatment of sick animals, reduced productivity, and increased feed costs due to poor fiber digestion and lower feed efficiency.

Poor Health and Increased Lameness

Repeated bouts of subacute acidosis can damage the surface of the rumen wall (Krause and Oetzel, 2006). Once the rumen wall is damaged, bacteria and the toxins produced by bacteria can enter the portal circulation, causing liver abscesses and an inflammatory response (Gohzo et al., 2005). In addition, there is increasing evidence that these toxins are implicated in laminitis. In the hoof, the horn (or exterior surface) is joined to the major bone in the hoof (pedal bone) by highly vascularized connective tissue (corium), which acts as a shock absorber when the hoof comes into contact with the ground. During laminitis, the mechanical strength of the connective tissue within the hoof is disrupted which allows the bone to rotate laterally or sink into the corium of the hoof. The corium can then shift laterally, expanding the white line, or upwards, causing swelling around the coronary band (Blowey, 1993). Solar compression can lead to sole ulceration. The impact of acidosis on laminitis is thought to be mediated by proteinases within the connective tissue that are activated by the bacterial toxins. Once activated, these proteinases degrade the connective tissue within the hoof (Mungall et al., 2001).

Poor Feed Conversion Efficiency

Ruminal acidosis decreases the digestibility of fiber in the rumen, which decreases feed conversion efficiency and increases feed costs. In a study with ruminally and duodenally cannulated cows, we observed that NDF digestion in the rumen declined from 52% for cows with a mean ruminal pH of 6.4 to 44% for cows experiencing repeated episodes of acidosis with a mean ruminal pH of 5.8. This reduction in potential fiber digestion is equivalent to a loss of 2.5 kg/d of milk.

Low Feed Intake

Ruminal acidosis can cause erratic fluctuations in feed intake (Fig. 5). Low ruminal pH causes the cow to go “off-feed,” which reduces the production of VFA, allowing the pH to recover. The cow then resumes a high feed intake that causes excessive production of acids, and the cycle is repeated.

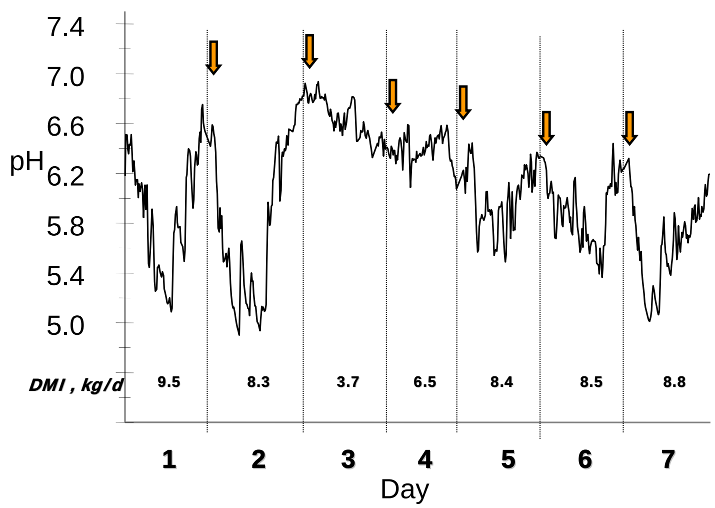

Fig. 5. Ruminal pH and dry matter intake (DMI) of a feedlot steer fed once daily (feeding indicated by arrows) measured for 7 days.

Reduced Microbial Protein Synthesis

Ruminal acidosis lowers the efficiency of microbial protein production in the rumen (i.e., the amount of microbial protein produced per unit of carbohydrate digested in the rumen). A decrease in microbial efficiency will decrease the yield of microbial protein (g/d), unless more fermentable carbohydrate is supplied, which further increases the risk of acidosis. Decreased microbial protein synthesis increases the need for supplemental feed protein in the diet, which in most cases increases feed costs.

Physically Effective Fiber (peNDF)

The Benefits of peNDF

Long forage particles in the diet promote chewing and salivary secretion, which helps buffer the acids resulting from feed digestion. Thus, particle length of forages and the amount of fiber in the diet can have a significant impact on ruminal pH through the provision of salivary buffers. Long particle forage causes the cow to spend more time eating and ruminating, which increases the flow of salivary buffers into the rumen. In addition, long forage fiber creates a floating mat in the rumen, which stimulates contractions of the rumen. Without these mixing motions the rumen can become a stagnant pool, and removal of VFA via absorption and fluid passage from the rumen declines, thereby increasing the risk of acidosis. Fiber is more slowly digested than starch and sugar, so including fiber in the diet slows the rate of feed digestion in the rumen. More VFA are produced right after a meal in the case of grain compared with forage which explains the large depressions in ruminal pH following concentrate meals. So, adding forage to the diet not only increases chewing time and saliva secretion, but it evens out VFA production throughout the entire day. Feeding long particle fiber can also shift the site of starch digestion from the rumen to the intestine, which reduces the potential for ruminal acidosis (Yang and Beauchemin, 2006b).

Measuring peNDF

There are several ways of characterizing physical fiber. Physically effective fiber relates to the physical characteristics of a feed and is an indication of the potential of a feed to stimulate chewing (Mertens, 1997). A limitation to using chewing time to indicate the physical effectiveness of feeds is the need to rely on book values to adjust the values for individual feed samples. Thus, laboratory approaches to measuring physical effectiveness (pef) of feeds that are based on particle length have been developed. The pef values determined by sieving are based on the concept that long particles (>1.18 mm) retained on sieves represent particles that require chewing. One limitation to this system is the many ways of measuring particle length of feeds.

The Penn State Particle Separator (PSPS) is one method of measuring particle length of feeds that is gaining in popularity (Lammers et al., 1996). The pef of a forage or TMR can be determined using the PSPS, which consists of two sieves (19- and 8-mm openings), and a collection pan. The pef_{2s} (the 2s denotes two sieves were used) of a feed is the total proportion of the feed (DM) retained on both sieves. Using the long corn silage in Table 1 as an example, 10.2% of corn silage DM was retained on the 19-mm screen and 61.3% of the DM was retained on the 8-mm screen, so pef_{2s} is 0.72 (ie., 0.102 + 0.613 = 0.72). That corn silage contained 49.3% NDF, so its $peNDF_{2s}$ is 35.5% (49.3% × 0.72).

Table 1. Example of physically effective NDF (peNDF) values determined for some feeds using the Penn State Particle Separator with two (2s) or three sieves (3s) (Yang and Beauchemin, 2006a).

Feed	Proportion of DM retained on each sieve				Physically effectiveness factor[1]		peNDF[2] (% of DM)	
	Top (19-mm)	Middle (8-mm)	Bottom (1.18 mm)	Pan	pef_{2s}	pef_{3s}	$peND_{2s}$	$peNDF_{3s}$
Corn silage								
Coarse	10.2	61.3	24.0	4.5	.72	.96	35.5	47.3
Medium	8.3	59.8	27.6	4.3	.68	.96	31.5	44.5
Fine	2.7	38.7	51.5	7.2	.41	.93	19.6	44.5
TMR containing corn silage								
Coarse	7.6	47.9	33.8	10.7	.56	.89	17.7	28.1
Medium	4.8	43.7	38.6	12.9	.49	.87	15.0	26.6
Fine	2.3	29.9	52.8	15.0	.32	.85	10.0	26.5

[1]Determined using the Penn State Particle Separator. pef_{2s} = determined using two sieves (19-, 8-mm); pef_{-3s} = determined using three sieves (19-, 8-, 1.18-mm).
[2]peNDF = % NDF × pef

The pef should be determined on fresh samples, with the pef expressed as a proportion of the total DM sieved. This requires performing a DM analysis for the original sample and the material retained on each sieve. The correction for DM is important because moisture content of the sample affects the pef value. Physical effectiveness factors will be overestimated by up to 30% if not corrected for DM (Kononoff et al., 2003).

The PSPS now includes an additional third screen with 1.18-mm openings (Kononoff et al., 2003). Using three sieves results in higher pef_{3s} (3s denotes three sieves were used) values than when two sieves are used (Table 1). The advantage of using three sieves is the pef values are more closely in line with the values used in the CNCPS and CPM models because the peNDF values. The disadvantage of using three sieves is that the pef_{3s} values for forages with differing chop lengths are not very different, as shown in Table 1 for corn silage of various chop lengths. With two sieves, the pef_{2s} ranged from 0.41 to 0.72, but with three sieves the pef_{3s} ranged from 0.93 to 0.96, with no difference between long and medium chopped silages. In addition, a lot of the grain in a TMR is trapped on the 1.18-mm sieve, thereby inflating the pef_{3s} values of TMR. In contrast, when two sieves are used, there is only a small difference between using the TMR itself or the component forages to measure $peNDF_{2s}$, except when the TMR contains very coarse grains or large pellets. Although each system of measuring peNDF has its disadvantages, the PSPS with two sieves is the most useful of the systems available for measuring peNDF because it differentiates feeds based on particle length and it is correlated with chewing and ruminal pH.

peNDF and Chewing Activity

The average dairy cow spends 2 to 6 h/d eating, 3 to 9 h/d ruminating, and a maximum of about 14 h/d chewing (eating + ruminating) depending upon the diet (Fig. 6). Increasing the peNDF content of the diet either by: 1) increasing the NDF content (i.e., including more forage or byproduct feeds), or 2) increasing the chop length of forages, increases chewing, with greatest increases in chewing for low fiber diets.

Increased chewing time increases salivary secretion, although the increase in saliva output is not as great as often assumed. This is because the increased flow of saliva during chewing is accompanied by a decrease in resting saliva secretion. The net increase in total salivary secretion due to 1 h/d more chewing is about 7 L (Maekawa et al., 2002). The buffering capacity supplied by the additional saliva would adequately buffer the digestion of about 0.5 kg of ground corn. Thus, the net effect of this incremental saliva production on mean ruminal pH is relatively small. However, an increase in saliva secretion, particularly if secreted during eating, can help reduce the extent to which pH drops following meals, even though mean ruminal pH is not greatly affected.

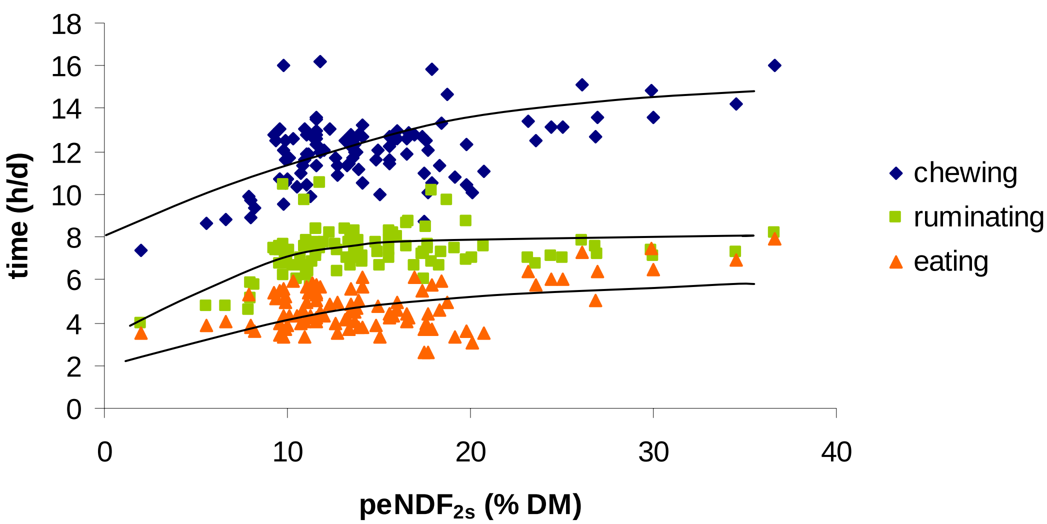

Fig. 6. Relationship between physically effective fiber ($peNDF_{2s}$) content of the diet and chewing time. Each point represents a treatment mean summarized from 24 published studies.

Starch Availability

Generally, the intent of grain processing is to optimize starch availability in the rumen while avoiding digestive disturbances. Firkins et al. (2001) summarized the published literature on the effects of processing corn for dairy cows. Ruminal digestibility was highest for high-moisture corn, followed by steam-flaking, dry grinding, and then coarse cracking or dry-rolling. While low ruminal digestion of starch is partially compensated for by post-ruminal digestion, the compensatory digestion is not always sufficient to avoid a reduction in total tract digestion. Thus, maximizing ruminal digestion of starch maximizes total tract digestion of starch (Fig. 7, left-hand side).

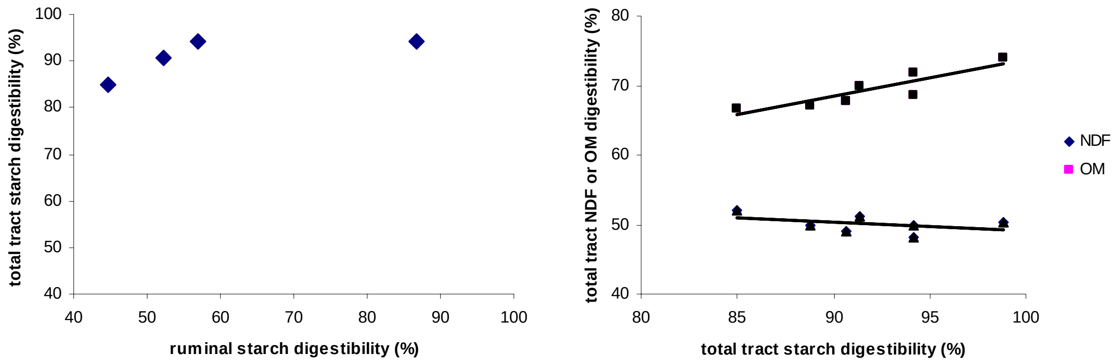

Fig. 7. Relationships between ruminal and total tract digestibility of starch (left-hand side) and between total tract digestibility of starch and total tract digestibility of NDF or organic matter. Data are from Firkins et al. (2001) and are means for processed corn grain.

As the amount of starch digested in the rumen increases, ruminal pH decreases and the risk of ruminal acidosis increases. Low ruminal pH due to increased ruminal digestion of starch decreases ruminal NDF digestibility (Fig. 7, right-hand side). The decrease in ruminal NDF digestibility negates some of the improvement in starch digestibility, but on average, the net benefit to digestion of organic matter in the total tract is positive. However, that is not always the case. The effect of increased ruminal starch digestion on total tract digestion of organic matter depends on the magnitude of the ruminal pH depression and the extent to which NDF digestion is depressed. Therefore, when formulating diets for increased ruminal starch digestion, it is essential to supply adequate physically effective fiber to minimize the incidence of ruminal acidosis.

Balancing peNDF and Starch Availability

NRC (2001) recommends a minimum of 25% NDF in the diet, with 75% of this fiber coming from forage sources (i.e., 19% NDF from forages). The amount of NDF from forage sources can be decreased to as low at 15% if total dietary NDF is increased and the non-fiber carbohydrate levels (usually about 85-90% starch) are lowered from 44% to 36%. These recommendations are based on diets containing alfalfa or corn silage and dry ground corn grain as the starch source. When more highly fermentable sources of grain are used (e.g., barley, high moisture and flaked corn), we recommend a minimum of 21 to 23% NDF from forages and a maximum of 38% non-fiber carbohydrates (or 33% starch).

Minimum fiber recommendations assume that the silages are coarsely chopped. When forage particle size is fine and diets are formulated to contain minimum levels of

NDF, then intake of physically effective fiber will be less than required. In that case, intake of physically effective fiber can be increased by increasing the NDF content of the diet and/or by increasing the physically effectiveness (pef) of the forage.

The relationship between $peNDF_{2s}$ content of the diet and ruminal pH is shown in Fig. 8. The high degree of variability in the prediction of ruminal pH from peNDF is caused by the many other uncontrolled variables that affect ruminal pH, particularly starch level and fermentability. From Fig. 8, about 14% $peNDF_{2s}$ is required in the diet to maintain a mean pH of 6.0. Thus, for a diet formulated to supply the minimum NRC requirement of 25% NDF, the pef_{2s} of the TMR would need to be 0.56 (i.e., 14%/25% = 56% of the TMR captured on the two sieves of the PSPS). If 75% percent of the NDF is from forages, the pef_{2s} of the forage would need to be > 0.70. If three sieves are used with the PSPS, then a minimum of 19% $peNDF_{3s}$ is required. However, the concept of physically effective fiber does not account for differences in fermentability of feeds, and does not predict differences in ruminal pH due to fermentability of the diet.

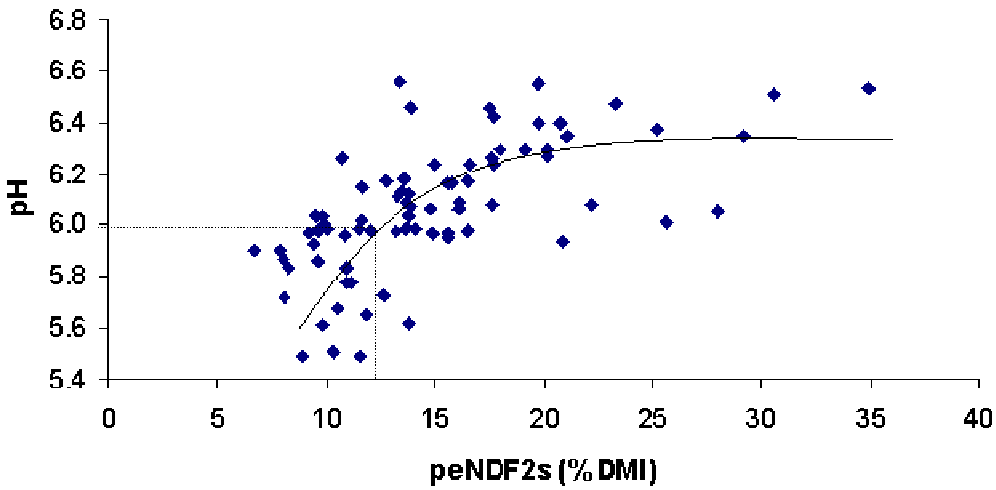

Fig. 8. Relationship between increasing the physically effective fiber ($peNDF_{2s}$) content of the diet and ruminal pH. Each point represents a treatment mean summarized from 23 studies published in the literature.

The values in Fig. 8 are means for groups of cows, and therefore don't reflect the variation in pH among cows, or the extent of diurnal fluctuations in ruminal pH for individual cows. Thus, these minimum recommendations do not include a margin of error to account for the variability among cows or the fermentability of the diet. As diets are formulated closer to the minimum level of physically effective fiber, a greater portion of the cows will experience ruminal acidosis. Formulating diets for the average cow is acceptable for cows in mid and late lactation, but diets for early lactation cows should be formulated above the minimum requirement because of their higher risk for acidosis. How far above the minimum depends on the other risk factors for acidosis, as well as the producer's tolerance for risk.

Preventing ruminal acidosis requires a balance between the production of VFA and the neutralization/removal of VFA. If the rumen availability of starch is high, then diets need to be formulated for higher levels of peNDF. Increased peNDF can be achieved by increasing the particle size (or pef) of forage or by formulating the diet for higher NDF content. In addition to providing adequate peNDF, good feedbunk management is critical. In particular, adequate bunk space is required to reduce competition, TMR rather than component feeding is required, abrupt changes in diet composition should be avoided, and consistent timing and quantity of feed delivery should be implemented.

Conclusion

The concept of physically effective fiber offers a means of balancing diets to promote healthy rumen function of dairy cows, which reduces the risk of acidosis and improves feed conversion efficiency. Other factors that affect ruminal pH, such as the fermentability of the diet (mainly starch content and grain processing) and feeding management practices need to be considered in addition to physically effective fiber to prevent ruminal acidosis. Use of high quality forages helps cushion against the risk of ruminal acidosis, because a greater proportion of forage can be included in the diet without lowering its digestible energy content.

Our recommendations for minimum levels of dietary physically effective fiber are based on the average cow, and do not include a margin of error to account for the variability among cows or the differences in the fermentability of the diet. As diets are formulated closer to the minimum level of physically effective fiber, a greater portion of the cows will experience ruminal acidosis. Formulating diets for the average cow may be acceptable for cows in mid and late lactation, but diets for cows in early lactation should be formulated above the minimum requirement because of their higher risk for acidosis.

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