

## Nutritional Approaches to Minimize Subacute Ruminal Acidosis and Laminitis in Dairy Cattle\*

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### ABSTRACT

Lameness and subacute ruminal acidosis (SARA) both appear to be very prevalent throughout the US dairy industry. Reduced ruminal efficiency, liver and lung abscesses, and laminitis are all thought to be related to SARA. Both the nutritionist and dairy managers are responsible for the delivery and consumption of a ration that is likely to produce a ruminally healthy pH. Nutritionists should consider the expected amount of physically effective neutral detergent fiber provided by ration ingredients, along with their expected ruminal fermentabilities and resultant microbial acid production. Environmental conditions, such as heat stress, overcrowding, and uncomfortable stalls, which may alter feed intake patterns and animal behavior, should also be considered in ration formulation. Additional amounts of physically effective neutral detergent fiber, and/or a reduction in ruminal nonstructural carbohydrate availability, may be warranted during times of increased animal stress. Higher levels of intake may also predispose the rumen to SARA, since salivary buffer secretion may not adequately compensate for additional acid production. Forage dry matter should be determined twice weekly, or more frequently if results vary by more than 5 percent of the dry matter value. Ration variability can be further reduced by premixing individual forages, or at least attempting to make each loader bucket of feed a uniform mix obtained from the entire height or face of the bunker silo. Ingredient sequencing and mixing time should be standardized on a given dairy. Techniques to minimize sorting, including frequent feed pushups, the addition of water or a low dry matter by-product, and appropriate forage processing, should be adopted by managers.

**(Key words:** dairy cow, laminitis, subacute rumen acidosis, physically effective NDF)

**Abbreviation key:** NSC = nonstructural carbohydrate, **pef** = physical effectiveness factor, **peNDF** = physically effective NDF, **PSPS** = Penn State Particle Separator, **SARA** = subacute rumen acidosis.

### INTRODUCTION

Lameness is very prevalent throughout the dairy industry. Clarkson et al. (1996) assessed the incidence and prevalence of lameness in 37 dairy herds in the United Kingdom. The mean annual incidence of lameness was 54.6%, while the prevalence was 20.6%. Prevalence rates were higher in the winter (25%) than in the summer (18.6%). Lameness prevalence averaged 15.2% in 17 Minnesota and Wisconsin dairy herds, 2.5 times higher than the rate estimated by herd managers (Wells et al., 1993). Warnick et al. (2001) found the incidence of lameness in 2 New York herds to be 52 and 40% over a one and a half year period. Cook (2002) reported that lameness prevalence averaged 24.8% during the winter and 21.8% during the summer in 30 Wisconsin dairy herds.

Laminitis-related hoof problems (sole ulcer, white line abscess, and solar hemorrhage) are typically one of the leading causes of lameness (Clarkson et al., 1996; Smilie et al., 1996; Warnick et al., 2001). For example, in a study involving 13 Ohio dairy herds, all of the herds and at least 62% of the evaluated cattle had hoof lesions associated with laminitis (Smilie et al., 1996).

Laminitis has been associated with nutrition, specifically with acute and subacute ruminal acidosis (**SARA**) (Nocek, 1997; Vermunt, 2000). Although the exact relationship between SARA and laminitis is not known, one of the theories relates SARA-induced damage to the ruminal epithelium, allowing for the absorption of histamine and endotoxins. These and possibly other compounds disrupt normal circulation and cause inflammation within the hoof, leading to the condition commonly referred to as laminitis (Vermunt, 1992).

Because published data pertaining to the prevalence of SARA, lameness in general, and specific causes of lameness, along with losses caused by each of these disorders, are scant, it is difficult to estimate the cost of these disorders to the US dairy industry. Warnick et al. (2001) explained that studies investigating the

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cost of lameness have yielded inconsistent results, probably due to variations among trials in culling bias, lameness measurements, herd management, methods used to estimate milk loss, and statistical methods. Oetzel et al. (1999) had little difficulty finding herds with SARA; 20% of animals evaluated in 14 Wisconsin dairy herds were diagnosed by rumenocentesis as having SARA.

The importance of reducing SARA was demonstrated in a 500-cow dairy diagnosed with SARA by Stone (1999), who replaced high-moisture corn with corn meal. In an apparent response to increased ruminal pH, milk production increased by 2.7 kg/d, and milk fat and protein increased by 0.3 and 0.1 percentage points, respectively. The production and component increases resulted in an increased monthly income of \$20,000 for the dairy, presumably in large part from a reduction in the prevalence of SARA and an increase in rumen microbial growth.

The objective of this paper is to discuss the primary nutritional factors that should be considered to minimize the occurrence of SARA and laminitis.

### ACUTE ACIDOSIS VS. SARA

Acute acidosis is defined as a condition in which the ruminal pH is less than approximately 5 to 5.2, while SARA is defined as a ruminal pH of approximately 5.2 to 5.6 (Owens et al., 1996, 1998). Acute acidosis classically occurs when an animal consumes a large excess of grain. Rumen pH plummets to 5.2 or less as *Streptococcus bovis*, then the lactic acid-producing bacteria produce large quantities of lactic acid (Nocek, 1997; Owens et al., 1998). Lactate levels have been low in studies involving dairy cattle with SARA (Mishra et al., 1970; Oetzel et al., 1999; Oba and Allen, 2000a). It appears that ruminal pH in dairy cattle with SARA is usually closer to a pH range of 5.5 to 5.6 than 5.2 (Mishra et al., 1970; Oetzel et al., 1999; Keunen et al., 2002). *Streptococcus bovis* is generally regarded as the primary lactate producer when ruminal pH is above 5.0. The fermentation products of *Streptococcus bovis* depend on both pH and growth rate. Acetate and ethanol are produced above a pH of 5.7, while lactate levels do not increase markedly until the pH drops below 5.2 (Russell and Allen, 1984). Subacute ruminal acidosis appears to be caused more by an elevation in total VFA as compared with lactate (Burrin and Britton, 1986; Britton and Stock, 1989; Oetzel et al., 1999). Lactate accumulation may occur in animals postfreshening if the shift in fermentable carbohydrates between the pre- and postfreshening diets is too dramatic, as has been observed in beef steers abruptly switched from a diet

containing 100% hay to one containing 65% hay and 35% concentrate (Fulton et al., 1979).

### MEASUREMENT OF RUMINAL pH

The method of measuring the pH of ruminal fluid influences the pH measurement. The pH reading of ruminal fluid varies between in vivo and in vitro measurement locations. In vitro results were 0.10 (McArthur and Miltmore, 1968), 0.11 (Dado and Allen, 1993), and 0.28 units (Smith, 1941) higher than in vivo recordings. Measurements for pH were conducted immediately following ruminal fluid collection from the rumen in each of the studies with the exception of Smith (1941), where the measurement was taken within 30 min of collection. Smith speculated that the difference between in vivo and in vitro measurements was due to loss of CO<sub>2</sub> by the in vitro samples prior to recording the pH. The pH of ruminal fluid collected via rumenocentesis was 0.15 (Nocek, 1997) and 0.28 (Garrett et al., 1999) units higher than that collected through a rumen fistula from the same region of the rumen. These results, taken together with the in vivo/in vitro results previously discussed (McArthur and Miltmore, 1968; Dado and Allen, 1993), indicate that the pH obtained via rumenocentesis is approximately 0.3 units higher than the in vivo pH at the same location in the rumen.

The relationship between the ruminal pH of samples collected via rumenocentesis and samples collected from the same area in the rumen with a jar was significant, but not as strong as ideal ( $R^2 = 0.52$ ). Additionally, the lowest pH in the data set used to derive the relationship was 5.9, a value greater than the pH of SARA (Garrett et al., 1999). Ruminal pH varies considerably throughout the day (Keunen et al., 2002; Oba and Allen, 2000a), with decreases occurring following eating and increases occurring following rumination. Despite these problems with the rumenocentesis technique, measurement of ruminal pH on commercial dairies is routinely performed utilizing rumenocentesis since few dairies have multiple cows with rumen fistulas. Nordlund and Garrett (1994) proposed that rumenocentesis be performed approximately 2 to 5 h postfeeding in component fed herds, and 4 to 8 h postfeeding in TMR-fed herds, to sample near the pH nadir. Garrett et al. (1999) proposed that a group of cows would be characterized (presence or absence of SARA) correctly 90% of the time if 3 or more out of 12 tested cows had readings  $\leq 5.5$ .

### OCCURRENCE OF SARA

There are probably 4 types of cattle at high risk of developing SARA: transition animals, high DMI animals, and those subject to either a high degree of vari-

ability in their ration and meal patterns, or to poorly formulated diets.

Transition animals have been considered to be more prone to developing SARA if their rumen bacterial populations and papillae have not been gradually acclimated to a higher starch ration prior to freshening. Rumen papillae significantly increased in size and ability to absorb VFA when animals were switched from a diet mainly of hay and straw (~70% NDF, converted from crude fiber according to Mertens, 1992) to a higher-energy diet containing a mixture of grass hay and grain 2 wk prior to freshening (Dirksen et al., 1985; Dirksen, 1989). Starch was gradually increased and fiber reduced during the postcalving period. Rumen papillae appeared to reach their maximum length 4 to 5 wk postcalving. In vivo VFA absorption rates performed 14 wk postcalving were substantially greater at this time compared with when cows were fed the hay-straw diet. Andersen et al. (1999) changed the diet fed to dry cows from a grass-silage based diet (approximately 64% NDF, converted from crude fiber according to Mertens, 1992) to one supplemented with a small (ration approximating 55% NDF, 11% nonstructural carbohydrates; NSC) or large (ration approximating 38% NDF, 38% NSC) amount of barley grain and concentrate at 4 wk precalving. Allowable intakes were relatively low, ranging from 6.5 to 9.4 kg DM during this period. Postcalving, cows in both treatments were offered grass silage *ad libitum* and 8.8 kg of grain. In contrast to the results seen by Dirksen (1989), increased carbohydrate levels did not result in any macroscopic or histologic differences in rumen papillae between treatments. Eight days postcalving, cows fed the additional grain during the prefresh period had lower DMI and a more rapid decline in ruminal pH following the morning feeding than control cows. The authors concluded that the lack of rumen papillae response may have been because grain levels were not increased enough during the pre-freshening period. Another possibility is that the grass silage was more digestible than the hay and straw mixture fed in the Dirksen studies (1985 and 1989), resulting in a more functional ruminal papillae in both treatments. Additionally, the low intakes in the pre-fresh period (9.4 and 8.2 kg maximum in the control and treatment groups, respectively), coupled with a substantial amount of concentrate (8.8 kg) offered on d 1 postfreshening, may have resulted in rumen acidosis, which could have negatively affected papillae development.

Stone et al. (2003) evaluated papillae size and their ability to absorb valerate in 4 Holstein heifers during the prefresh period and for the first 5 wk of lactation. Substantial variability occurred in papillae size and in ruminal absorption of valerate within individual heifers

between consecutive weeks during the first 5 wk postcalving. Much of this variation appeared to be related to postfreshening health disorders.

A common recommendation based largely on the papillae results from the Dirksen studies (1985, 1989) is to gradually increase NSC levels over a 5-wk period during the pre- and postcalving time periods. However, cows started these studies with poorly developed papillae, having been fed a 70% NDF diet composed of grass hay and straw. Less time is probably needed to develop papillae when animals are fed rations that contain higher levels of rumen-fermentable carbohydrates during the early part of the dry period. At freshening, slightly more (~1 to 3 percentage units) forage NDF and physically effective NDF (**peNDF**) (~1 percentage unit) than what is contained in the lactating cow TMR is commonly fed to fresh cows in an attempt to minimize ruminal health disorders (SARA and displaced abomasum). More research is needed to better define the relationships between DMI, carbohydrate amount and ruminal fermentability, ruminal mat formation, and rumen papillae development in transition cows.

Fresh animals are also at an increased risk of developing SARA if component-fed compared with being fed a TMR. Due to the increased rate of consumption, less saliva is produced per unit of feed consumed when grain is fed separately from forages. Additionally, animals fed ingredients separately may consume all of the allotted grain and leave some of the forage (Maekawa et al., 2002). The net result is the consumption of a diet containing less forage than intended, increasing the risk of SARA.

Cows rarely ruminate for more than 9 h, with 10 h proposed as the physiologic limit (Welch, 1982). Salivary flow rates are highest during rumination (1.8 times resting rate), followed by eating (0.18 to 0.22 L/min; Cassida and Stokes, 1986; Maekawa et al., 2002), and then resting (0.10 to 0.15 L/min; Cassida and Stokes, 1986; Maekawa et al., 2002).

Although the total flow of salivary buffers reaches an apparent maximum, the intake of rumen fermentable carbohydrates, and hence ruminal acid production, increases with increasing DMI (Beauchemin, 1991; Allen, 1997; Oetzel, 2000). Firkins (2002) used regression equations evaluating relationships between DMI, carbohydrate digestibility, and chewing time (Firkins et al., 2001) to predict that an increase in DMI would still result in an increase in ruminal degradable starch, despite a reduction in the percentage of ruminally degraded starch caused by the increase in passage rate. Thus, high-producing cows may be at an increased risk of SARA due simply to higher DMI.

## THE RUMEN BALANCING ACT

The design of a ration, and the manner in which it performs in the rumen, is a balance between physically effective fiber (**pef**) and its associated salivary flow, and rumen fermentable carbohydrates and the resultant microbial VFA (Allen, 1997). This relationship was emphasized in a study by Krause et al. (2002a, 2000b), where forage particle size and the level of ruminally fermentable carbohydrate were varied by feeding lactating cows the same amount of fine or coarse alfalfa haylage with the same amount of either dry or high-moisture corn. As expected, rumination and total chewing times were greater in the diets containing long haylage (Krause et al., 2002b), while effective ruminal digestibility of diet DM tended to be higher ( $P = 0.08$ ) in the diets containing high-moisture corn (Krause et al., 2002a). Diets containing finer haylage particles and high-moisture corn reduced mean ruminal pH, the minimum daily pH, and both the time and area (time\*amount) below pH 5.8 compared with diets containing coarser haylage and dry ground corn (Krause et al., 2002b). The results from this study indicate that ruminal pH is influenced both by dietary components affecting chewing and salivary buffer secretion, and by those affecting ruminal carbohydrate fermentation, as emphasized by Allen (1997).

Figure 1 provides guidelines and variables that should be considered when formulating rations to minimize SARA. The figure relates guidelines for ration structural and NSC levels (percentage of ration DM) to their relative effect on ruminal pH, and the type of forage or concentrate changes that should be made when feeding at low structural or high nonstructural levels (increased risk of SARA). Environmental conditions, such as overcrowding, stall comfort, heat stress, and feed availability can alter cow behavior, resulting in a shift in this balance and a decrease in rumen pH. The manner that these management and environmental variables could influence ration formulation for fiber and carbohydrate levels is indicated. Ruminal pH separates ration components that are more likely to increase ruminal pH (structural carbohydrates) from those that are more likely to decrease pH (NSC). The figure indicates that the desired rumen pH, as determined by rumenocentesis 2 to 5 or 4 to 8 h postfeeding in component-fed or TMR-fed herds, respectively, should be at least 5.8 to 6.1.

The 2001 Dairy NRC provides ration guidelines for forage NDF, dietary NDF and nonfiber carbohydrates (**NFC**), and contains an excellent discussion pertaining to formulating healthy rations while using minimal levels of forage. The objective of the following discussion is to expand on these guidelines and to provide a frame-

work that can be used to formulate diets that minimize the risk of SARA.

## Structural Carbohydrates

Fiber of adequate particle size promotes chewing and rumination (Welch, 1982); each of these behaviors can act to elevate rumen pH. Dietary NDF level is an important component of ration formulation, both because it is generally associated with forages, and the positive effects they tend to have on rumen pH, and because its level is inversely related to the more fermentable NFC component of the diet. Dietary NDF alone, however, did not have a significant relationship with ruminal pH (Allen, 1997), probably due to variability in ruminal fermentability and particle size across forages and fibrous by-product feeds. Although the data set was limited, Allen (1997) found a highly significant relationship between forage NDF percentage and ruminal pH. Because of this, and because it is easily obtainable, the 2001 NRC committee chose to adjust NDF recommendations based on the dietary forage NDF percentage. The committee recommended a minimum of 19% forage NDF, but cautioned that these guidelines were developed primarily from alfalfa-based rations of adequate particle size, fed as a TMR, with dry ground corn as the main energy source. Additionally, research conditions are more controlled and stable than most commercial settings. Hence, the NDF recommendations of the NRC should be viewed as absolute minimums when formulating rations for field conditions.

A variety of systems have been proposed to estimate the minimum amount of fiber necessary in rations for lactating dairy cattle. These systems have generally attempted to guide ration formulation by predicting the amount of chewing that various feedstuffs would generate, or their relative effectiveness at maintaining milk fat percentage (Mertens, 2002). A new system, **peNDF**, attempts to relate the ability of a feedstuff to promote chewing relative to a hypothetical long grass hay containing 100% NDF (Mertens, 1997). The **peNDF** system is of particular interest in this discussion since it more closely relates to ruminal pH than other proposed fiber systems. Indeed, the **peNDF** approach explained 71% of the variation in ruminal pH in published trials used to evaluate the system (Mertens, 1997).

The **peNDF** of a feed is the product of its **pef** and NDF concentration. It was proposed (Mertens, 1997) that the **pef** of a given feedstuff could be either estimated from tabular values or determined by measuring the proportion of dried sample retained on vertically oscillating screens >1.18 mm. Ideally, the NDF concentration of this retained proportion would also be determined. The **peNDF** of a feed would then be determined

| Risk of SARA <sup>1</sup>                                                         | Increased | Marginal | Low   |
|-----------------------------------------------------------------------------------|-----------|----------|-------|
| NDF <sup>2</sup>                                                                  | 25        | 28 – 32  | 35    |
| Forage NDF                                                                        | 16        | 20 – 25  | 27    |
| peNDF <sup>3</sup>                                                                | 18        | 21 – 23  | 25    |
| Ruminal pH <sup>4</sup>                                                           | < 5.6     | 5.8 – 32 | > 6.4 |
|  |           |          |       |
| NFC <sup>5</sup>                                                                  | 45        | 42 – 35  | 30    |
| NSC <sup>6</sup>                                                                  | 35        | 32 – 28  | 25    |

| Forage considerations |   |                         |   |         |
|-----------------------|---|-------------------------|---|---------|
| longer                | ← | Forage particle size    | → | shorter |
| slower                | ← | Rate of fiber digestion | → | faster  |

| Concentrate considerations |   |                                    |   |        |
|----------------------------|---|------------------------------------|---|--------|
| slower                     | ← | Ruminal starch digestibility       | → | faster |
| more                       | ← | High fiber byproducts <sup>7</sup> | → | less   |
| more                       | ← | Buffers                            | → | less   |

| Management and environmental considerations |   |                             |   |                   |
|---------------------------------------------|---|-----------------------------|---|-------------------|
| minimal                                     | ← | Heat stress, stall and bunk | → | severe            |
|                                             |   | over-crowding               |   |                   |
| excellent                                   | ← | stall comfort               | → | poor              |
| TMR fed                                     | ← | feeding system              | → | grain fed         |
|                                             |   |                             |   | infrequently      |
| consistently accurate                       | ← | forage DM                   | → | variable accuracy |
| entire height or                            | ← | silage obtained for         | → | regions within    |
| face of silo                                |   | a load of feed              |   | the silo          |

**Figure 1.** The rumen balancing act<sup>1</sup>. Nutritional relationships that should be considered when formulating rations to minimize subacute rumen acidosis (SARA).

<sup>1</sup>Adapted from Allen (1995). The figure relates guidelines for ration dietary components (percent of ration DM) to their relative effect on ruminal pH, and the type of forage or concentrate changes that should be made when feeding a low structural or high NSC levels (increased risk of SARA). It also relates the manner that management and environmental variables could influence ration formulation for structural and NSC levels. Ruminal pH separates dietary components that are more likely to increase ruminal pH (structural carbohydrates) from those that are more likely to decrease pH (NFC/NSC).

<sup>2</sup>NDF determined with amylase and sodium sulfite.

<sup>3</sup>Physically effective NDF is obtained by multiplying a feed's NDF level by its physical effectiveness factor (Mertens, 1997).

<sup>4</sup>Expected minimum ruminal pH range when ruminal sample is obtained by rumenocentesis approximately 4 to 8 or 2 to 5 h post-feeding of a TMR or component feeding, respectively.

<sup>5</sup>Nonfiber carbohydrate (NFC) levels are obtained by difference (100-(%NDF+%CP+%ash+%fat)).

<sup>6</sup>Nonstructural carbohydrate levels are obtained by enzymatic measurement.

<sup>7</sup>Levels of high fiber byproducts should be increased when lower amounts of forage NDF and peNDF are fed. This will result in increased dietary NDF levels, and decreased dietary NFC and NSC levels.

by either multiplying its tabular pef by the measured NDF level, or by multiplying the percent retained on screens greater than 1.18 mm by the NDF concentration of the sample or of this retained portion.

Few trials have evaluated the peNDF concept. Beauchemin et al. (2003) fed lactating dairy cows a ration containing 40% alfalfa forage and 60% concentrate (barley based) where the forage was comprised of a mixture of either 50:50 or 25:75 alfalfa silage:alfalfa hay. The alfalfa hay was either chopped or ground. Particle size was determined using both the original,

2-sieve Penn State Particle Separator (**PSPS**) (Lammers et al., 1996) and a vertical oscillating, wet sieving technique. Wet sieving results were corrected for solubilized DM to be better correlated with the dry sieving recommendations of Mertens (1997). The predictions for peNDF values obtained from wet sieving, the PSPS, and tabular values (Mertens, 1997) were evaluated. The ration peNDF predictions derived from the 2-screen PSPS were about 40 to 60% as large as those obtained from wet sieving and tabular values, while the tabular predictions were approximately 94% as large as the pef

predictions derived from wet sieving measurements. The dietary percents of peNDF calculated by the wet sieving and tabular approaches varied from 18.3 to 26.7%, within the minimum recommended ranges (Mertens, 2002). Although peNDF was not correlated with mean ruminal pH, it was negatively correlated with the area (time\*amount) below pH 5.8, implying that there was an increase in ruminal pH and a decrease in ruminal pH fluctuations in the higher peNDF diets. The amount of peNDF was positively correlated with rumination time. The authors concluded that the diet should contain about 22% peNDF to maintain an average ruminal pH of 6.0 when using the wet sieving technique to determine pef values (Beauchemin et al., 2003). The tabular guidelines for pef for various feedstuffs were derived from studies that did not always include particle size measurements but may have provided either a general description of forage particle size (e.g., long or short), or a theoretical length of cut (Mertens, 1997). Considering this, the tabular results are very close to the wet sieving measurements derived by Beauchemin et al. (2003) and may err on the side of rumen and ration safety.

The PSPS (Lammers et al., 1996) has been used to quickly assess particle size distribution of forages and TMR. The original system consisted of 3 interlocking shaker boxes, the top two with apertures of 19 and 8 mm, respectively, followed by a collecting pan. Recently a third, wire-mesh screen with 1.18-mm openings was added to the system (Kononoff et al., 2003a). There are several complications with using the PSPS for obtaining pef values. First, a uniform, appropriate volume of feed must be used with the system to obtain consistent results, particularly with the top 2 screens. Too large of a sample size will result in a much greater proportion of the sample on the upper screen, while too little of a sample will result in a much lower proportion retained on the top screen. Lammers et al. (1996) recommend a sample size of  $1.4 \pm 0.5$  L. The sample volume should be more precise (1.4 L), particularly when the PSPS is used in research. The speed at which one shakes the boxes and the stroke length can also influence the results. A speed of 1.1 Hz (66 cycles/min) and a stroke length of 17 cm has been recommended (Kononoff et al., 2003a). Decreasing this speed by only 18% (0.9 Hz or 54 cycles/min) caused significant and usually large changes in results obtained. Large changes in DM content also significantly change results (Kononoff et al., 2003a). Thus, results would differ from samples of hay and haylage of identical particle size. Finally, errors can result from determining the peNDF of a TMR by simply multiplying the percent retained on the 1.18 mm and preceding screens by the TMR NDF percent because NDF levels can differ substantially between

material retained by the screens and that passing through to the pan (Kononoff and Heinrichs, 2003; Kononoff et al., 2003b). Variation in NDF levels between the sample, material retained on the screens, and that passing through to the pan could also easily occur with forage crops, particularly corn silage with large kernels. This point may be rather inconsequential with the modified PSPS; however, since it appears that very little sample makes it through to the pan. Approximately 98 to 99% of the sample from both haylage and corn silage samples was retained on the 1.18 mm and larger screens of the PSPS (Kononoff and Heinrichs, 2003; Kononoff et al., 2003a, 2003b), while only approximately 70% of the haylage sample was retained on the 1.18 mm and larger screens when using a wet sieving system (Kononoff and Heinrichs, 2003) without correction for solubilized DM (Beauchemin et al., 2003). It appears that the PSPS may significantly overestimate the amount of material retained on the 1.18 mm and larger screens as compared with wet sieving. Ruminal pH was not accurately predicted by peNDF when pef values were determined on alfalfa haylage-based TMR with the modified PSPS (Kononoff and Heinrichs, 2003). When using the PSPS in a research setting, particular attention should be paid to sample volume (1.5 L), shaking speed (66 cycles/min), and stroke length (17 cm) (Kononoff et al., 2003a).

Additional research on the peNDF system is needed to evaluate, validate, and refine the concept. The system was based on the vertical sieving of dry feedstuffs. Studies attempting to evaluate the peNDF system should try to use this approach when performing particle size analysis. Additionally, dry sieving removes the DM solubilization correction needed following wet sieving (Beauchemin et al., 2003). One of the assumptions of the peNDF system is that all particles retained on the 1.18-mm screen are equally effective at promoting chewing activity. However, since large feed particles probably require more chewing prior to ruminal passage than smaller particles, Mertens (1997) suggested that perhaps the use of 2 screens (1.18 and 3.35 mm) would more appropriately estimate the relationship between particle size and chewing activity than the 1.18-mm screen alone. Particle sizes of forage samples should be determined with dry, vertically oscillating screens to obtain pef of feedstuffs. The tabular values of Mertens (1997) should be acceptable for concentrates and can be used as an alternative for forages if screening results are not available. Until more controlled experiments have been completed, nutritionists should follow the recommendations of Mertens (1997) when using the peNDF system, and formulate diets to provide approximately 22% of ration DM as peNDF to maintain ruminal pH in a healthy range.

The rate and extent of forage NDF digestibility may influence ration formulation. Oba and Allen (2000a, 2003b) fed lactating cows diets based on corn silage that contained either a brown midrib hybrid or an isogenic control at 2 NDF levels (29 and 38%). The 30 h in vitro NDF digestibility of the brown midrib variety was greater (55.9 vs. 46.5%) than the isogenic control. Despite this, there were no differences in rumination or total chewing time, either per day or per unit of NDF, between the 2 types of corn silage. The authors concluded that enhanced degradability of the corn silage NDF did not reduce its physical effectiveness in promoting chewing. However, the BMR corn silage resulted in a significant increase in the time that ruminal pH was <5.5, although the area below 5.5 did not differ between the 2 types of corn silage ( $P = 0.10$ ) (Oba and Allen, 2000a). Rations should be adjusted to increase peNDF and/or reduce rumen fermentable carbohydrate when feeding a forage of increased NDF digestibility to decrease the risk of SARA.

### Nonstructural Carbohydrates

Nonfiber carbohydrate levels are calculated by difference  $[100 - (\%NDF + \%CP + \%fat + \%ash)]$ , while NSC levels are determined enzymatically. The NFC component of a feed contains the starch and sugar of NSC, along with primarily VFA, pectin, and galactans. Nonstructural carbohydrates are usually more digestible than forages. Increasing the NSC proportion of the ration results in higher yields of VFA and microbial protein, and increased milk yields, until decreasing rumen pH offsets these gains due to reduced ruminal microbial efficiency. Allen (1997) and Kolver and de Veth (2002) demonstrated significant relationships between ruminal VFA concentrations and ruminal pH, emphasizing the effect that the more fermentable NSC component can have on ruminal pH. These studies further indicate that the amount of buffer required in the rumen is not a constant, but instead is related to the amount of acid being produced, along with its absorption and passage rates (Allen, 1997).

Ranges for appropriate NFC and NSC levels are quite large (Figure 1), reflecting variability in both the composition and ruminal fermentability of each fraction. Wheat, barley, and oats all ferment more quickly than corn, which is quicker than sorghum (Herrera-Saldana et al., 1990). Reducing grain particle size generally increases ruminal fermentability (Galyean et al., 1981), although passage rate can also increase (Ewing et al., 1986), offsetting some or all of this gain. Ensiling of grain (Nocek, 1987) and steam flaking (Galyean et al., 1976) act to disrupt the crystalline structure of starch and increase its ruminal digestibility. Diets should be

**Table 1.** Effect of hay particle size on intake, production, ruminal pH, chewing activity, and predicted salivary and bicarbonate secretion<sup>1</sup>.

| Particle size                                 | Fine             | Medium             | Coarse            |
|-----------------------------------------------|------------------|--------------------|-------------------|
| Intake, kg/d                                  | 22.6             | 22.8               | 22.6              |
| Milk, kg/d                                    | 24.4             | 26.4               | 24.7              |
| Milk fat, %                                   | 3.2 <sup>d</sup> | 3.5 <sup>e</sup>   | 3.8 <sup>f</sup>  |
| Rumen pH                                      | 5.4 <sup>a</sup> | 5.8 <sup>b</sup>   | 6.25 <sup>c</sup> |
| Activity, min/24 h                            |                  |                    |                   |
| Eating <sup>1</sup>                           | 322 <sup>a</sup> | 346 <sup>b,c</sup> | 350 <sup>c</sup>  |
| Ruminating <sup>1</sup>                       | 381 <sup>a</sup> | 484 <sup>b,c</sup> | 496 <sup>c</sup>  |
| Resting <sup>1</sup> (difference)             | 736              | 610                | 594               |
| Additional HCO <sub>3</sub> -equivalents, g/d | —                | 161                | 181               |

<sup>a,b,c</sup>Different superscripts within a row indicate significant differences:  $P < 0.05$ .

<sup>d,e,f</sup>Different superscripts within a row indicate significant differences:  $P < 0.10$ .

<sup>1</sup>Intake, production, ruminal pH, and chewing activity are from Grant and Colenbrander (1990). Salivary secretion rates during eating, ruminating, and resting (Cassida and Stokes, 1986) were used to estimate total salivary secretion. The additional amount of bicarbonate equivalents produced by feeding the medium and coarse hay as compared to the fine hay was calculated according to Erdman (1988).

balanced toward the higher end of the NFC/NSC range when ruminal starch digestibility is expected to be lower (e.g., coarsely ground corn or sorghum), and toward the lower end when it is expected to be higher [e.g., wet (>30% moisture), fine high-moisture shelled corn, finely ground barley or oats]. By-product feeds such as soyhulls and beet pulp are high in digestible fiber and low in starch and provide an additional option in diluting the level of feeding of high-starch grains.

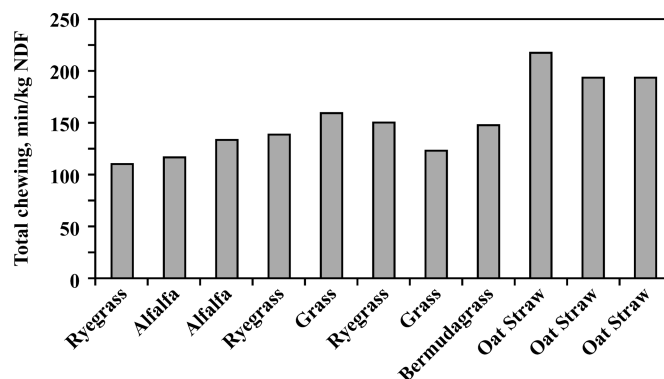
### Additional Nutritional Considerations Influencing Ruminal pH

**NFC dilutional effects of forage.** Increasing the amount of forage in a ration may increase rumination, yet not result in the flow of additional saliva. Maekawa et al. (2002) fed a TMR with 40, 50, or 60% barley silage and resultant NDF levels of 28.3, 31.0, and 32.2%, respectively. Rumination time increased with increasing forage levels, which by difference decreased resting time. Interestingly, total salivary flow across diets did not differ when the measured resting and eating, and estimated rumination salivary flow rates were multiplied by the time spent in each activity. Even if additional forage does not result in additional salivary flow, it can still act to increase ruminal pH by diluting the amount of more ruminally fermentable NSC in the ration.

**Ruminal contractions.** Grant and Colenbrander (1990) fed lactating cows alfalfa hay that was chopped fine, coarse, or medium (a mix of fine and coarse), and measured production, chewing, and ruminal parameters (Table 1). Milk fat content, rumination, and rumi-

nal pH all increased with increasing forage length. Salivary flow rates (Cassida and Stokes, 1986) were multiplied by the time spent eating, ruminating, and resting for each forage type. The salivary bicarbonate equivalent concentration (Erdman, 1988) was multiplied by the total salivary flow, yielding the additional bicarbonate available to animals fed the medium (161 g of bicarbonate) and coarse (182 g of bicarbonate) rations. Bicarbonate is typically supplemented at 0.8 to 1% of ration DMI (Erdman, 1988), which would amount to approximately 180 g of bicarbonate, essentially the same additional amount as produced by the coarse ration. Milk fat increased from 3.2 to 3.8, and rumen pH increased from 5.4 to 6.25 when cows were fed the coarse as compared with the fine hay (Table 1). One would not expect this degree of response in milk fat and rumen pH when feeding supplemental bicarbonate at this level, particularly with alfalfa-based rations (Erdman, 1988). Nørgaard (1989) investigated the effect of physical form of the diet on rumen motility and chewing activity. A diet consisting of 80% concentrate and 20% forage was fed to 3 lactating cows in a 3 × 3 Latin square design. The forage was all barley straw, but the physical form was varied across treatments as follows: 4% long straw (LS), 16% pelleted straw (PS); 10% LS, 10% PS; and 20% LS, 0% PS. Increasing the LS from 4 to 20% of the diet resulted in linear increases in the time spent eating, ruminating, total chewing time, and the number and length of rumination periods. The frequency of primary contraction cycles of the reticulorumen at rest and during eating also increased linearly as the percentage of LS in the diet was increased from 4 to 20%. There was a significant, positive linear correlation between the time spent ruminating and the frequency of primary contraction cycles at rest (Nørgaard, 1989).

Volatile fatty acids are eliminated from the rumen primarily by absorption, while only a small quantity flow into the omasum (Bergman, 1990). Reticulorumen contractions mix the ruminal contents, enhancing the absorption of VFA by the ruminal epithelium, increasing the flow rate of digesta to the omasum, and dispersing saliva throughout the rumen (Hungate, 1966). Increasing the frequency of reticulorumen contractions should increase the rates of VFA absorption and passage, and ruminal saliva dispersement. Each of these processes should result in an increase in ruminal pH, either through a reduction in ruminal VFA concentrations, or the buffering of acid. The change in reticulorumen contractions caused by the increased amount of long fiber in the Nørgaard study (1989) may be the reason that the increased amount of coarse fiber used by Grant and Colbrander (1990) resulted in an unexpectedly large increase in ruminal pH. It should be



**Figure 2.** Total chewing (eating and ruminating) times per kg of NDF of different forages (Mertens, 1997).

noted, however, that the significant differences in ruminal contraction cycles observed by Nørgaard (1989) were between a ration mostly void of physically effective fiber (4% long straw) and one containing 20% long straw. Smaller differences in reticulorumen contraction cycles would be expected to occur if additional long fiber was added to a ration already containing an adequate or nearly adequate amount of fiber. Nonetheless, increased reticulo-ruminal contractions may be an additional benefit of long fiber that is not normally considered in ration formulation.

**Chewing and NDF.** The amount of rumination per unit of NDF for a specific forage is often the same at different feeding rates (Woodford et al., 1986; Beauchemin and Buchanan-Smith, 1989). For example, Woodford et al. (1986) increased the amount of alfalfa hay fed to cows so that rations contained 28, 36, 45, or 53% hay; rumination was essentially the same at 63.2, 60.6, 60.7, and 59 min/kg of NDF. However, total chewing (ruminating and eating) per unit of NDF across forages is not constant (Mertens, 1997). Mertens (1997) indicated that total chewing within and across forage types varied, with straw providing the greatest amount of total chewing per unit of NDF (Figure 2). A small amount (0.25 to 0.45 kg/d) of straw added to the TMR may be particularly useful when one wants to increase total chewing without displacing much of the other ration ingredients.

**Number of ration ingredients.** The composition of feed ingredients is inherently variable. Feedstuff variability in DM or carbohydrate composition increases the risk of SARA as animals consume an inconsistent diet. St-Pierre (2001) indicated that the portion of the total variance of the TMR in a nutritional component (e.g., NDF) contributed by a given feedstuff increases by the square of the amount of the feedstuff. Thus, a diet formulated to contain multiple ingredients will

likely be much more consistent than one designed around only a few ingredients. The variance can be further reduced by formulating with accurate ingredient analyses, and by selecting feedstuffs that are relatively consistent.

**Dietary buffers.** Sodium bicarbonate should be supplemented to corn silage-based diets at the rate of approximately 0.8 to 1% of ration DMI. It is less likely to be beneficial in alfalfa-based rations (Erdman, 1988). Added buffer may be more likely to be beneficial in scenarios similar to those in the “increased risk of SARA” column (Figure 1).

### Seasonality of Lameness and Heat Stress

Lameness often follows a seasonal trend (Clarkson et al., 1996; Cook, 2002), with an increase in lesions associated with laminitis appearing several weeks after some environmental hardship such as heat stress. Heat stress alters meal patterns, resulting in “slug-feeding” (Mallonée et al., 1985), and reduces rumination (Collier et al., 1982), rumen contractions (Collier et al., 1981), and rumen pH (Niles et al., 1980). Mishra et al. (1970) demonstrated that diet can influence ruminal pH in heat-stressed animals. Holstein cows were housed in climatic chambers and subjected to varying levels of heat and humidity. Cows were fed high roughage or high grain diets and exposed to hot or cool conditions. There was a significant effect on ruminal pH caused by temperature (lower when hot), ration (lower with high grain), and their interaction (more of a pH drop when animals fed the high grain ration were exposed to hot temperatures). Ration peNDF levels should be increased, and NSC levels decreased, when animals are undergoing heat stress to decrease the risk of SARA.

### Management-Related Problems

Management-related problems, such as free stall overcrowding, inadequately bedded or otherwise uncomfortable stalls, and excessive parlor holding times may also alter feed intake patterns and animal behavior. Batchelder (2000) noted that cows kept in a pen with 30% more cows than free stalls ruminated less throughout a 24-h period than cows kept in a pen with one stall per cow. Of course, an attempt should be made to alleviate the environmental or management-related condition that is altering normal bovine behavior. If the problem is not corrected, dietary alterations can be made to increase ruminal pH. The degree of dietary adjustment depends on the severity of the environmental insult. An example of these changes would be to increase NDF and reduce NSC by approximately 2 to 3 percentage points, and to increase forage NDF and

peNDF by approximately 1 to 2 percentage points, in herds with management-related cow behavior problems. Substituting some fibrous by-product feeds for higher starch containing feeds would reduce the risk of an increase in ruminal lactic acid levels. Rumen VFA production could be further reduced by replacing a portion of carbohydrate with added fat.

**Microadditives.** Feeding supplemental biotin has resulted in a slight reduction in laminitis-associated lesions of the hoof (Midla et al., 1998; Potzsch et al., 2003). The mode of action of biotin in reducing white line disease, a consequence of laminitis, is thought to result from a strengthening of the extracellular cement of the white line tissues (Muelling, 2000).

Monensin and lasalocid have been used to prevent lactic acidosis (Nagaraja et al., 1981). The ionophores may be beneficial in dairy cattle if there is a poor transition to the lactating cow ration at freshening, or if there is slug-feeding occurring as during heat stress. They are not likely to alleviate SARA in dairy cattle where the reduced ruminal pH levels are from high ruminal VFA and not lactate (Mutsvangwa et al., 2002).

## FARM VARIABLES AFFECTING RUMEN PH

### Ration Preparation

Forages in general, and haylages in particular, have a large potential for variation. The degree of variation at a given dairy depends largely on the management of cropping and harvesting systems. One advantage that bunker silos have over upright silos and bags is that ensiled feed from a given load or field is spread over a larger area of the silo. Thus, changes in forage DM or chemical measurements occur more gradually than in other storage systems. However, variation can still occur across the height of a silo. To estimate this potential variation, 11 corn silage and 9 haylage bunker silos from 9 dairies located in central New York were evaluated. Samples were collected on 6 dairies with a backhoe, on 2 dairies with a loader bucket, and on one dairy with a face shaver. Sample collection was designed to reflect the feed that would be obtained if a feeder obtained a loader bucket of feed from a region (upper, middle, or lower) of the silo as compared with a bucket obtained from the entire height of the silo face. Silos above ( $n = 15$ ) approximately 4 m in height were split into thirds for sampling, while those less ( $n = 4$ ) than approximately 4 m were split into halves. The vertical trench was dug to a depth of about 0.2 to 0.3 m. Experimental feed within each section was thoroughly mixed with a silage fork and then subsampled to obtain a sample approximately 5 to 10% the size of the removed silage pile. This sample was then again thoroughly mixed with the silage fork and finally sampled for anal-



**Figure 3.** Method of sampling bunker silos to obtain consistent (DM) results. A trench 0.2 to 0.3 m deep was dug into a corn silage silo with a backhoe. The silage was segregated into three piles obtained from the upper, middle, and lower thirds of the silo. These piles were mixed with a silage fork and then sub-sampled twice to form two smaller, approximately 15 kg DM piles. These sub-piles were then further mixed and subsequently sampled twice for analysis. The two samples obtained from each region of the silo were tested in triplicate for DM. The results within and between samples for each region of the silo were very consistent, as the DM results indicate.

ysis of DM, ADF, NDF, CP, lactate, and VFA with wet chemical procedures (Dairy One, Ithaca, NY). The entire approximately 3-L sample was ground for analytical procedures.

Two test silos (one alfalfa and one corn silage) were used to evaluate the consistency of the sampling and the laboratory procedures. The sampling procedure described above was duplicated once for each silage pile obtained from the upper, middle, and lower sections of the silos. These samples were then examined in triplicate for DM and NDF, and singly for ADF, CP, lactate, and VFA to compare the consistency of sampling and laboratory procedures. Generally, the results were very consistent (Figure 3), indicating that the measured variation within silage regions was actually occurring.

Within each silo, deviations from the minimum analytical result for DM, ADF, NDF, CP, and VFA were determined. Maximum deviations within a given silo were determined by dividing the range within the silo by the minimum analyzed value. For example, a silo with measurements of 44.5, 41.2, and 36.6 would have a maximum deviation between regions of 21.6%  $[(44.5 - 36.6)/36.6]$ .

Haylage varied more than corn silage (Table 2), although there were examples of extreme variation, particularly in DM, in both crops. In some situations, a feeder could be delivering an entirely different ration from one load of feed to the next if the forage was not carefully removed from the silo. Techniques to minimize forage variation, such as obtaining each bucket of

**Table 2.** Deviations<sup>1</sup> between different regions (upper, middle, and lower) in 9 haylage and 11 corn silage bunker silos.

|                                    | DM   | CP   | ADF  | NDF  | NE <sub>L</sub> | Lactic | Acetic | Total VFA |
|------------------------------------|------|------|------|------|-----------------|--------|--------|-----------|
| <b>Haylage bunkers<sup>2</sup></b> |      |      |      |      |                 |        |        |           |
| Smallest deviation, %              | 5.2  | 3.3  | 1.1  | 5.4  | 1.6             | 5.2    | 25     | 7.0       |
| Largest deviation, %               | 44.7 | 52.1 | 20.0 | 24.8 | 20.0            | 646    | 163    | 287       |
| Average deviation, %               | 21.0 | 17.6 | 10.7 | 14.7 | 9.9             | 112    | 72     | 69        |
| Median deviation, %                | 19.4 | 9.5  | 9.9  | 14.4 | 9.3             | 57     | 50     | 38        |
| <b>Corn silage bunkers</b>         |      |      |      |      |                 |        |        |           |
| Smallest deviation, %              | 1.3  | 2.5  | 2.3  | 0.5  | 1.4             | 3.8    | 11.2   | 0.1       |
| Largest deviation, %               | 55.0 | 29.5 | 18.3 | 18.6 | 5.6             | 48.7   | 131    | 41.3      |
| Average deviation, %               | 12.3 | 11.0 | 8.4  | 8.6  | 3.1             | 25.6   | 53.7   | 20.5      |
| Median deviation, %                | 8.3  | 10.0 | 8.6  | 8.4  | 2.8             | 26.0   | 29.9   | 21.4      |

<sup>1</sup>The maximum deviation within a given silo was determined by dividing the range within the silo by the minimum analyzed value within the silo. For example, a silo with measurements of 44.5, 41.2, and 36.6 would have a maximum deviation of 21.6%  $[(44.5 - 36.6)/36.6]$ .

<sup>2</sup>All results in percentage of DM.

feed from the height of the silo face or the premixing of forages obtained from across the entire face of the silo, should be part of feeding standard operating procedures on dairies. Mechanical face shavers can vastly improve bunker face management and reduce ration variation by mixing forages from across the height of the silo.

Variation within silos must be considered during the collection of a sample for DM or other analyses. Probably the ideal method to collect a forage sample from a bunker silo would be similar to that described above. A backhoe (or silage face shaver) would be used to dig a trench near the midsection of the silo, or the loader bucket could be used to uniformly scrape feed from across the entire face. The collected forage would then be mixed in the mixer wagon, discharged, subsampled, remixed by hand, visually divided into 4 quadrants, and finally sampled from each quadrant using a scooping motion with the hand. As a minimum, ensiled forages should be tested twice weekly for DM and monthly with a more complete laboratory analysis. More frequent analyses should be run if DM and fiber results vary by more than 5% (e.g., 30 to 31.5%).

Results obtained from both Koster testers and microwave ovens have been consistent with a laboratory standard (Oetzel et al., 1993). However, the microwave method required much more time since the operator must remain at the oven during drying. The microwave method also required additional training compared with the Koster tester. The Koster tester may be more reliable if it is used with a higher quality balance than the dial scale that typically accompanies the unit. The electronic moisture tester evaluated was comparable to the other on-farm methods for haylage DM determination but was not accurate for corn silage DM (Oetzel et al., 1993). The individual determining DM should know the relationship between DM measured on-farm and those generated by the laboratory by analysis of split samples of the same feedstuff. If a systematic bias is found, farm DM results can then be proportionally adjusted to correspond with laboratory derived values.

Feed mixers reduce ration particle size (Heinrichs et al., 1999), which could increase the risk of SARA. Feed mixers should be properly maintained, and operated only long enough to ensure the delivery of a consistent TMR.

**Bunk management issues.** Sorting of the ration by the cow can result in the consumption of a very inconsistent ration. Typically, long particles are selected against, resulting in some meals having a much greater grain content than intended (Martin, 2000; Leonardi et al., 2001; Leonardi and Armentano, 2003). It seems likely that sorting could result in SARA.

Cows with experimentally induced SARA preferentially consumed alfalfa hay over alfalfa pellets or the TMR, apparently in an attempt to modify SARA (Keunen et al., 2002). In a related experiment, consumption of free choice sodium bicarbonate did not differ between SARA and control time periods (Keunen et al., 2003). It seems unlikely that cows would preferentially sort long particles from the TMR to ameliorate SARA, since SARA has been routinely documented in herds via rumenocentesis (Oetzel et al., 1999), and sorting is a common occurrence in dairy herds. Free choice hay may be beneficial to cows with SARA, but cows have exhibited varying preferences when offered different forages (Coppock et al., 1974). Thus, the ad libitum availability of TMR and hay could be deleterious to production in high-producing cows.

Sorting can be minimized by avoiding excessive amounts of long material in the TMR. Added hay or straw should not be longer than 2.5 to 5 cm (Hall, 2002; Shaver, 2002). Wetter rations help the various feeds to stick together, thus making it more difficult to sort. Water, or wet feeds such as wet brewers grain, can be added to reduce ration DM to less than ~50%, or to a level that acts to reduce the sorting problem (Shaver, 2002). Palatable feeds are less likely to be sorted than unpalatable feeds (Leonardi and Armentano, 2003).

Feed should be available ad libitum to encourage maximum DMI. The amount of refusals is an economic concern, potentially increasing feed costs by 10% if one were to offer 110% of the normally consumed ration and then discard the Orts. Orts should not be fed to young heifers since they may be contaminated with manure and spread Johne's disease as well as other pathogens. Orts have been successfully fed to far-off dry cows when their approximate analysis is known and they are fed as a ration ingredient at a set amount per dry-far cow (W. C. Stone, unpublished observations). Another approach would be to limit Orts to 1 to 3% in an attempt to minimize feed costs and to ensure that, even if diets are being sorted, the prepared ration and essentially all long feed particles are consumed. A potential problem with this approach, however, is that animals would consume all available feed, and then exhibit slug-feeding when fed again. Slug-feeding can result in acidosis. In fact, it has been used as an experimental protocol to induce acidosis (Owens et al., 1998). An alternative approach would be to feed for a high refusal rate, but then refeed the Orts. In this system, cows are fed at approximately 106 to 108% of actual intake. A refusal of this level, along with steps taken to minimize sorting, ensures that the Orts are very similar to the original ration. It also allows cows to be fed on a consistent schedule without the concern of wasting leftover feed. Refusals are then incorporated into the

lactating cow TMR as an ingredient and refed to the lactating cows. Refusals from pens are then thrown away or fed to dry-far cows on a rotating basis by pen such that feed is never more than 3 d old in any pen. Mixing of orts and new TMR will not be successful if forages or any concentrates are prone to heating, as in the summer months. Refusals should not be refed to lactating cows if the feed has heated or the quality is noticeably different than the original TMR. The use of TMR preservatives (e.g., propionic acid) and *Lactobacillus buchneri* inoculation of forages at ensiling may also make this program more successful by improving aerobic stability of the TMR (Kung et al., 2003). Feed should be pushed up frequently, usually 8 to 10 times per day, to encourage intake and minimize sorting. Feed should be pushed up more frequently throughout the day the first several hours following feeding, when the majority of feed is generally consumed by cows (Robinson, 1989).

Recommendations for linear feed bunk space have ranged from 0.61 to 0.76 m/cow during the transition period (Shaver, 1993), to a "critical minimum" of approximately 0.2 m/cow for cows past their peak of lactation (Grant and Albright, 1995). Grant and Albright went on to conclude that the precise amount of bunk space needed by a cow is probably a "function of feed availability over 24 h, relative to when cows want to eat, and likely is not a constant." A more detailed discussion on bunk space is available in an accompanying paper by Cook et al. (2004).

## CONCLUSIONS

The nutrition program affects rumen health, which influences hoof health. Ration formulation involves a balance between acid and buffer production. The risk of SARA can be minimized by considering the feed ingredients used to formulate the ration, along with the environment and management specific to that dairy. The formulation balance should be shifted toward additional peNDF and less or slower fermenting NSC sources when the cow's environment (heat stress abatement, stall comfort, degree of over-crowding, etc.) or management (DM and ration accuracy, feed availability, etc.) is not as comfortable or reliable as desired. Farm management should strive to ensure that the consumed ration is extremely similar to the formulated ration.

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