# New Physically Effective Fiber Recommendations for High Producing Dairy Cows

**Karen A. Beauchemin**

**Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, 5403 1st Avenue South, Lethbridge, Alberta, Canada T1J 4B1 (Email: karen.beauchemin@canada.ca)**

## Introduction

Keeping the rumen environment "healthy" helps high producing dairy cows to meet their genetic potential for milk production. Cows with a healthy rumen ruminate extensively throughout the daytime and nighttime, the pH of their rumen contents is maintained above 5.8, and their rumen contractions are strong. These conditions help maximize fiber digestion by the rumen microorganisms and passage of undigested feed residues from the rumen, thereby promoting high dry matter intake (**DMI**) to meet the energy requirements of the cow.

Heathy rumen function is often attributed to the chemical and physical characteristics of forage fiber consumed by cows, but new information indicates that other factors such as diet fermentability and feeding management of the cow are also important. Chemical fiber, measured as neutral detergent fiber (**NDF**), supplies energy substrates for the rumen microbes, while the physical attributes of fiber stimulate eating, ruminating, and rumen motility that contribute to feed digestion and passage from the rumen. Maintaining healthy rumen function in high producing dairy cows is challenging because rations are comprised of grains and forages that are extensively processed (with small particle size) and highly fermentable in the rumen. Lack of physical fiber combined with highly fermentable carbohydrates increases the risk of sub-acute ruminal acidosis (**SARA**), which is characterized by repeated drops in pH <5.8. The objective of this paper is to discuss the factors that promote healthy rumen function in dairy cows, and provide new information for diet formulation and feeding management.

## Healthy Rumen Function

### The Importance of Chewing

Eating and ruminating play a vital role in maintaining high levels of feed intake and efficient digestive function in high-producing dairy cows (Figure 1). Ruminants chew their feed initially during eating, with swallowed feed later regurgitated and remasticated during rumination. As feed is chewed, particles are reduced in size and saliva is secreted. Saliva is an important buffer for the rumen, and thus chewing plays a key role in maintaining optimum rumen pH for microbial digestion of feed. Furthermore, physical breakdown of feed during chewing facilitates microbial colonization of ingested feed and passage of small particles from the rumen to the lower gastrointestinal tract. Thus, promoting chewing helps minimize the risk of SARA, enhances fiber digestion, and promotes high DMI.

Eating. On average, dairy cows spend about 4.7 h/d eating, ranging from 2.3 to 8.5 h/d (Table 1; Beauchemin, 2018). Time spent eating is highly variable because it is affected by feeding management, DMI, diet composition, and inherent variability among animals, but the main factors affecting eating time are particle size of the ration and feeding management. Long particles, defined as particles retained on the 19-mm sieve of the Penn State Particle Separator (**PSPS)**, slow the eating rate and increase eating time (Table 2). Starch and crude protein content decrease eating time because they are mainly contributed by concentrates, which are consumed more rapidly than forages. Greatest feeding activity typically occurs after feed is delivered or pushed-up in front of the cows. Thus, frequent delivery of feed tends to promote feeding activity and a more even distribution of feeding time throughout the day, which helps stabilize rumen pH.

**Table 1.** Summary of treatment means for chewing activity (min/day) of dairy cows from peer reviewed publications (from Beauchemin, 2018)

| | N | Mean | Min | Max |
|---|---|---|---|---|
| White et al., 2017a | | | | |
| Eating | 182 | 284 | 141 | 507 |
| Ruminating | 179 | 436 | 236 | 610 |
| Total chewing | 175 | 717 | 396 | 973 |
| Zebeli et al., 2006 | | | | |
| Eating | NR | NR | NR | NR |
| Ruminating | 99 | 434 | 151 | 632 |
| Total chewing | 99 | 691 | 425 | 969 |

NR, not reported.

Rumination. Rumination time is also highly variable with an average of 7.2 h/d, but ranging from 3.9 to 10.2 h/d (Table 1; Beauchemin, 2018). Rumination time is mainly influenced by DMI, forage-NDF intake (i.e., the intake of NDF from forage sources) and particle size of the diet (particles retained on 8- and 19 mm sieves), and to a lesser extent fragility (hardness) of the feed that imparts resistance to chewing and the digestibility of the fiber. There are complex interactions among these factors; thus, the correlations between rumination time and individual dietary factors are only low to moderate (Table 2).

**Table 2**. Correlations between diet variables and eating and ruminating (from White et al., 2017a)

| | Eating time, min/d | Ruminating time, min/d |
|---|---|---|
| DMI | -0.06 | 0.19* |
| Starch, % DM | -0.22* | 0.09 |
| NDF, % DM | 0.12 | -0.15* |
| Crude protein, % DM | -0.22* | 0.14 † |
| Forage-NDF, % DM | 0.10 | 0.19* |
| Forage, % DM | 0.12 | 0.15* |
| TMR particles retained on sieve | | |
| 19-mm, % DM | 0.45* | 0.17 |
| 8-mm, % DM | 0.03 | 0.38* |
| Silage, % DM | -0.13† | 0.21* |

*$P \leq 0.05$; †$P \leq 0.10$. DM, dry matter; DMI, dry matter intake; NDF, neutral detergent fiber; TMR = total mixed ration.

**Saliva Secretion, Rumen Buffering, and Rumen pH**

For healthy rumen function, rumen pH needs to be maintained in the range of 5.8 to 7.0, with a mean rumen pH above 6.0. SARA occurs when rumen pH drops below 5.6 for more than 3 h/d (Plaizier et al., 2008) or below 5.8 for more than 5 to 6 h/d (Zebeli et al., 2012). Saliva plays an important role in buffering the pH of the rumen (Figure 1), accounting for 35 to 50% of the bicarbonate flow into the rumen of dairy cattle. The most important source of rumen buffering is absorption of short chain fatty acids (**SCFA**) from the rumen. Absorption of SCFA from the rumen stabilizes ruminal pH by removing protons during passive diffusion of undissociated SCFA and by secretion of bicarbonate during absorption of dissociated SCFA (Aschenbach et al., 2011).

Increased bicarbonate flow into the rumen can be achieved through increased chewing time to promote saliva secretion. Additionally, the need for rumen buffering can be lowered by decreasing or slowing the production of SCFA by reducing diet fermentability (primarily by lowering starch content). Although promoting chewing time helps increase the flow of bicarbonate into the rumen, keeping the rumen healthy needs to consider both increasing total buffering of the rumen as well as managing SCFA production in the rumen.

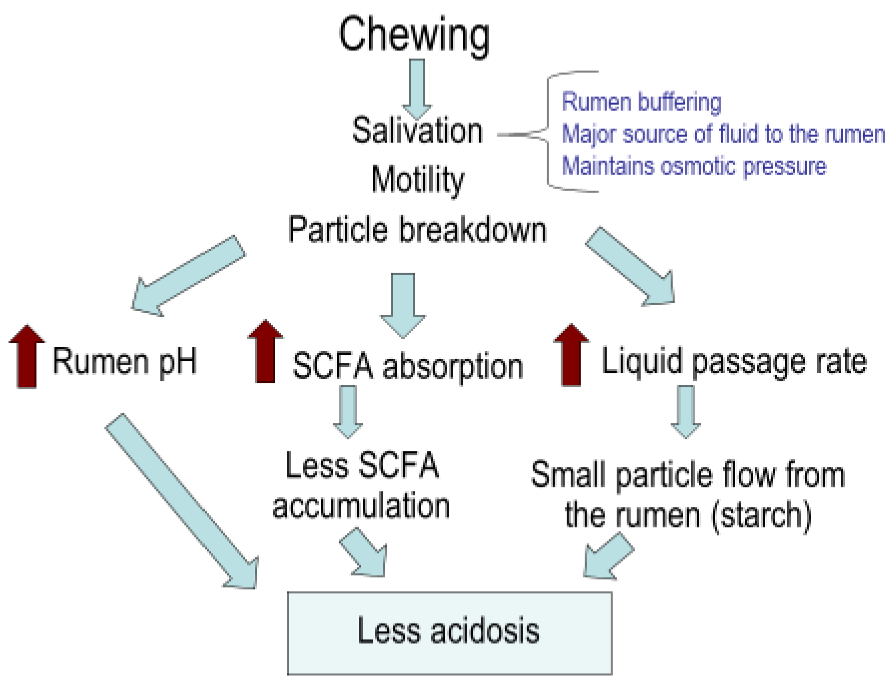


**Figure 1. Overview of the role of eating and ruminating in preventing ruminal acidosis.**

### Raft Formation, Motility, and Particulate Passage from the Rumen

The ruminal contents are stratified into a liquid phase, a floating mat (raft), and a pool of small particles dispersed within the fluid phase ventrally to the floating mat. Ruminal mat formation enhances the microenvironment needed by the fiber-digesting microorganisms. It also acts as a filter bed, which helps retain forage particles in the rumen increasing the time allowed for fiber digestion. Mat formation strongly depends on intake of forage-NDF and long particles.

Muscular contractions of the rumen promote mixing of the digesta and SCFA absorption, while pushing the indigestible material out of the rumen. The number and strength of the contractions are increased significantly during eating and ruminating. Contractions tend to be smaller when cows are fed finely processed feeds and during SARA.

### Saliva, Liquid Passage and Site of Starch Digestion

Increasing forage-NDF content and particle size of the diet increases fractional passage rate of liquid from the rumen due to increased salivation and motility associated with chewing. Faster liquid passage increases the flow of grain particles from the rumen, decreasing ruminal digestion of starch and the production of SCFA. Thus, increasing forage-NDF content of the diet, and to a lesser extent increasing particle size of diets, shifts the site of starch digestion such that less starch is digested in the rumen and a greater proportion of starch is digested in the intestine. The shift in site of starch digestion is a major contributing factor that reduces the risk of SARA with increased intake of physically effective fiber. In addition to shifting the site of digestion of starch, increasing forage-NDF content of the diet typically decreases the starch content of the diet by dilution. As a result, SCFA production in the rumen is also decreased, which helps minimize the postprandial drop in pH.

## Capturing the Characteristics of Fiber in Ration Formulation

Long fiber particles are important in dairy cow rations to promote healthy rumen function, yet it is very difficult to capture the characteristics of physical fiber in ration formulation. Mertens (1997) proposed the term physically effective fiber (**peNDF**) to reflect the effects of NDF content and particle length and indicate the overall potential of the feed to stimulate chewing. The particle size of the feed can be assessed using the PSPS. A physical effectiveness factor (**pef**, ranging from 0 to 1) is then calculated as the proportion of feed or TMR (on an as-fed or dry matter [**DM**] basis) that is retained on sieves ≥ 1.18 mm ($pef_{1.18}$) or sieves ≥ 8 mm ($pef_{8}$). The pef is then multiplied by NDF content to determine peNDF content ($peNDF_{\geq 1.18mm}$ and $peNDF_{\geq 8mm}$). Thus, peNDF relates to chewing, but does not account for rumen fermentability of the feeds.

Recently, White et al. (2017a) evaluated the literature on chewing, rumen pH and fiber, and concluded there was no advantage of peNDF compared with using particle size and NDF individually in ration formulation. Thus, they proposed using particle size and NDF content separately along with other dietary components to predict chewing time and rumen pH. The concept is referred to as physically adjusted fiber (**paNDF**). Equations were developed to predict eating time, ruminating time, and mean rumen pH using individual factors as inputs (including DMI, dietary forage content, NDF content, forage-NDF content, particles retained on various sieves of the PSPS, starch content, and so forth). Outputs from these models were used to develop recommendations for NDF content, forage-NDF content and particle size for diets that differ in fermentability (White et al., 2017b).

## Recommendations

**Forage-NDF, Particle Size and Starch Levels**

NRC (2001) recommends a minimum of 25% total dietary NDF, with 75% of this fiber from forages, which equates to 19% forage-NDF. It was stated that the amount of forage-NDF could be decreased to as low at 15% if total dietary NDF is increased and the non-fiber carbohydrate level (mainly starch) is lowered from 44% to 36%. These recommendations for minimum fiber levels are based on diets that contain alfalfa or corn silage as the predominant forage, with the silages being coarsely chopped. Thus, particle size of the forage is not accounted for.

Over the past couple of decades, there has been a lot of research to better understand the dietary factors affecting rumen pH and rumen function. Based on a meta-analysis of the literature, Zebeli et al. (2012) suggested that 31.2% $peNDF_{>1.18}$ or 18.5% $peNDF_{>8}$ in the diet (DM basis) is needed to prevent SARA. They stated that feeding < 14.9% $peNDF_{>8}$ results in an imminent risk of SARA, while feeding ≥ 14.9% $peNDF_{>8}$ in the diet DM may lower DMI and consequently the production of high-producing dairy cows.

Based on the meta-analysis of White et al. (2017a), response surfaces for variables affecting mean rumen pH were developed (While et al., 2017b). The response surfaces examine the interactions between particle size (measured as particles retained on the 8- and 19-mm sieves of the PSPS) of the total mixed ration (**TMR**), starch content, and forage-NDF content of the diet. Note that the particle size measurements are expressed on a DM basis, but in practice most on-farm measurements with the PSPS are on an as-fed basis. From a practical standpoint, the difference between the two methods is relatively small.

My interpretation of the results from White et al. (2017b) is shown in Table 3. The minimum forage-NDF required in the diet varies from 12 to 27% DM, depending upon starch content and particle size of the TMR. As starch content of the diet increases, the need for forage-NDF increases to offset the increased rate of production of SCFA. As the proportion of 8-mm particles in the TMR increases, the minimum amount of forage-NDF decreases. Similarly, as the proportion of 19-mm particles in the TMR increases, the minimum amount of forage-NDF decreases. For high starch diets (> 25% DM) that are low in forage proportion and therefore have ≤30% particles on the 8-mm screen, attaining the minimum level of forage-NDF required (26 to 27% of DM) may not be feasible when using good quality forages. This example illustrates the potential risk of SARA when feeding high starch diets that are finely chopped, as it can be difficult to supply the required minimum level of forage-NDF. In that case it is critical to implement feeding and management strategies that help prevent SARA (see **Other Considerations that Help Prevent SARA** below).

**Table 3. Minimum forage-NDF required in a total mixed ration (dry matter [DM] basis) to maintain average rumen pH of 6.1 (adapted from White et al., 2017b).**

| Starch, % DM | Particles retained on 8 mm sieve (% of TMR DM) | Particles retained on 19 mm sieve (% of TMR DM) | | | Range in forage-NDF required |
|---|---|---|---|---|---|
| | | 6 | 12 | 16 | |
| 15 | >50 | 14 | 13 | 12 | 12-21 |
| | 50 | 16 | 16 | 14 | |
| | 40 | 19 | 18 | 17 | |
| | ≤30 | 21 | 20 | 19 | |
| 20 | >50 | 19 | 18 | 17 | 17-24 |
| | 50 | 21 | 20 | 19 | |
| | 40 | 24 | 22 | 21 | |
| | ≤30 | 24 | 24 | 23 | |
| 25 | >50 | 21 | 20 | 19 | 19-26 |
| | 50 | 23 | 23 | 21 | |
| | 40 | 25 | 24 | 23 | |
| | ≤30 | 26 | 26 | 24 | |
| 30 | >50 | 22 | 21 | 20 | 20-27 |
| | 50 | 24 | 24 | 22 | |
| | 40 | 26 | 25 | 25 | |
| | ≤30 | 27 | 27 | 26 | |

Several important concepts are apparent from Table 3:

a) At a particular dietary starch content, the minimum level of forage-NDF required increases as proportion of 8- and 19-mm particles decrease.
b) Increasing the starch content of the diet increases the minimum concentration of forage-NDF required.
c) Increasing the proportion of material captured on the 8-mm sieve has a greater impact on reducing the minimum level of forage-NDF required, than does increasing the

proportion of material on the 19-mm sieve. Furthermore, rations with greater proportion of particles retained on the 19-mm sieve are prone to sorting by cows at the feed bunk, thus increasing the long particles in the diet is not a very effective way of promoting healthy rumen function.

d) As the proportion of particles retained on the 8-mm sieve increases, less long particles on the 19-mm screen are needed to maintain rumen pH.

## Evaluation of Fiber Recommendations

The data from Yang and Beauchemin (2007) can be used to compare the different recommendations for fiber (Table 4). The diets in that study varied in forage:concentrate ratio (**F:C**; 35:60, 60:40) and particle size was altered by using short and long-chopped alfalfa silage. The diets provided a large range in contents of starch, NDF, forage-NDF, and peNDF. Continuous measurement of rumen pH indicated that the cows fed the 35:65 F:C diets, regardless of silage chop length, experienced SARA. Although the mean pH of the coarsely chopped 35:65 F:C diet was 6.17, the pH dropped undesirably below 5.8 for 10.1 h/day. In contrast, the cows fed the 60:40 F:C diets did not experience SARA. The 35:65 F:C diets were below the recommendations for fiber for all models (NRC, 2001; Zebeli et al., 2012; White et al., 2017b). In contrast, the 60:40 F:C diets exceeded the recommendations of NRC (2001) and White et al. (2017b), but the diet contained less $peNDF_8$ than required according to Zebeli et al. (2012; 18.5% required versus 13.9% actual). Based on this single study, the recommendations for $peNDF_8$ by Zebeli et al. (2012) may be too high.

**Table 4. Evaluation of fiber recommendations using results from diets varying in forage:concentrate ratio (F:C) and chop length of alfalfa silage (from Yang and Beauchemin, 2007).**

| F:C: | 35:65 | 35:65 | 60:40 | 60:40 |
|---|---|---|---|---|
| Chop length: | short | long | short | long |
| TMR, % DM | | | | |
| 19-mm sieve | 3.6 | 7.1 | 7.1 | 13.1 |
| 8-mm sieve | 27.8 | 34.5 | 33.3 | 41.1 |
| 1.18-mm sieve | 63.0 | 52.8 | 52.9 | 39.1 |
| pan | 5.6 | 5.7 | 6.6 | 6.7 |
| DM content, % | 72.5 | 71.1 | 66 | 62 |

| | | | | | | |
|---|---|---|---|---|---|---|
| CP, % DM | 19.9 | 20.5 | 21.6 | 21.8 | | |
| NDF, % DM | 30.3 | 30.6 | 34.5 | 36.4 | | |
| Forage NDF, % DM | 16.0 | 16.5 | 26.6 | 27.5 | | |
| ADF, % DM | 20.4 | 21.6 | 26.9 | 27.4 | | |
| Starch, % DM | 30.6 | 30.6 | 17.8 | 17.8 | | |
| NEL, Mcal/kg | 1.65 | 1.65 | 1.65 | 1.65 | | |
| Eating time, min/d | 203 | 211 | 225 | 218 | | |
| Ruminating time, min/d | 441 | 444 | 446 | 522 | | |
| Mean rumen pH | **5.86*** | 6.17 | 6.46 | 6.55 | | |
| Time pH < 5.8, h | **11.5** | **10.1** | 1.1 | 1.3 | | |
| Assessment | | | | | Minimum required | |
| Actual forage-NDF, % TMR DM | **16.0** | **16.5** | 26.6 | 27.5 | 19.0 | NRC, 2001 |
| Actual $peNDF_{1.18}$, % TMR DM | **28.6** | **28.9** | 32.2 | 34.0 | 31.2 | Zebeli et al., 2012 |
| Actual $peNDF_{8}$, % TMR DM | **9.5** | **12.7** | **13.9** | 19.7 | 18.5 | Zebeli et al., 2012 |
| Forage-NDF required (White et al., 2017b) | **27** | **26** | 20 | 19 | | |

*Bold red indicates below requirement

## Other Considerations that Help Prevent SARA

### Straw and Supplemental Fat

As mentioned above, the recommendations for minimum forage-NDF levels in high starch diets are difficult to achieve when using high quality forages that are low in NDF concentration. In that case, supplementing diets with a limited amount of chopped straw can be very beneficial (Kahyani et al., 2019). However, it is important to compensate for the lower net energy content of straw by supplementing with rumen-protected fat. Additionally, supplemental fat can be used to lower the starch content (and fermentability) of the diet. The NRC (2001) recommends a maximum total concentration of 6 to 7% fat in the diet DM (basal diet + supplemental fat).

### Diet Adaptation/Transition Cows

Any major change in diet composition that affects carbohydrate fermentability requires an adaptation of both the rumen epithelium and the rumen microbiota. Such is the case in early lactation where the diet fermentability is increased due to the use of high quality forages and grain, while the particle size of the TMR decreases, compared with the close-up diet. The cow and its rumen must quickly adapt after parturition. The microbial community must transition from being primarily cellulose degraders to a more complex community of starch and cellulose degraders. This transition takes about 3 weeks to occur and during that time the rumen microbial community is highly unstable, and the risk of SARA is high (Humer et al., 2018). The rumen epithelium must also adapt to increase the functional capacity for absorption. This transition takes about 4 to 6 weeks (Humer et al., 2018). During dietary transition, there is a risk that the rate of SCFA production will exceed the rate of SCFA absorption and neutralization, thereby leading to SARA.

**Primiparous Cows**

Primiparous cows are at higher risk for SARA than multiparous cows because they: 1) are less well adapted to highly fermentable diets, 2) have lower chewing time, 3) eat more slowly and thus require more time for meals, and 3) are less dominant than mature cows and thus tend to eat larger meals because they have trouble getting access to the feed bunk (Beauchemin, 2018). When possible, it is advantageous to group primiparous cows separately from multiparous cows, or at the very least ensure pens are not overcrowded and that bunk space does not limit intake and meal frequency (minimum of 60 cm per primiparous cow; Rioja-Lang et al., 2012).

**Feeding Management**

Greatest feeding activity typically occurs after feed is delivered or pushed-up throughout the day. Thus, frequent delivery of TMR tends to promote feeding activity and a more even distribution of feeding time throughout the day, which helps minimize the post-prandial drop in rumen pH. Once again it must be stated that it is important to provide sufficient space at the feed bunk, because increased competition increases eating rate and decreases chewing time (Crossley et al., 2017).

Even when a TMR is fed, cows will preferentially select the grain and leave the longer forage particles. Sorting of the ration can increase the risk of SARA. Increasing the frequency of feed delivery or feed push-up reduces feed sorting (Miller-Cushon and DeVries, 2017). Overfeeding such that there are excessive orts left in the feed bunk also increases sorting.

**Feed Additives**

*Buffers:* Incorporating sodium bicarbonate into the diet at 0.5 to 1% of DM increases the total bicarbonate flow to the rumen by 3 to 4%. The effects of adding sodium bicarbonate on rumen pH are highly variable, but on average pH is expected to increase by about 0.13 units (Hu and Murphy, 2005). Thus, dietary buffers will not eliminate SARA, but they do help stabilize the overall acid load in the rumen.

*Yeast:* There is overwhelming evidence that including active dry yeast and yeast cultures (from *Saccharomyces cerevisiae*) in the diet of dairy cows can improve milk production and feed conversion efficiency, partially due to beneficial effects on rumen pH (Chaucheyras-Durand et al., 2008). However, effects of yeast on rumen pH can depend on a number of conditions, such as whether the yeast is viable or non-viable, the strain of yeast, dose rate, and diet. Many *in vitro* and animal studies have examined the effects of yeast and provide evidence for changes in rumen fermentation, stabilization of rumen pH, stimulation of the growth and metabolism of lactate-utilizing bacteria, scavenging of oxygen present in the ingested feed particles (active dry yeast only), promotion of growth of protozoa, and improvement in fiber digestion (Chaucheyras-Durand et al., 2008; McAllister et al., 2011).

Mohammed et al. (2017) demonstrated that some cows benefit more from supplemental yeast than others. They fed cattle a diet with 50:50 forage:concentrate ratio that did not include ionophore. Based on continuous measurements of rumen pH, the cattle were characterized as being more or less susceptible to SARA. The more susceptible cattle benefited when fed active dry yeast especially when the yeast was viable (Table 5). However, when the cattle were subsequently subjected to grain overload to destabilize the rumen, yeast failed to attenuate severe acidosis (data not shown). The study demonstrates that yeast can help stabilize rumen pH of cattle that are prone to SARA, but yeast will not prevent acute acidosis.

**Table 5. Effectiveness of viable and non-viable yeast (ADY) for cattle grouped by susceptibility to SARA during a baseline period (Mohammed et al., 2017)**

| | Most susceptible cattle | | | Least susceptible cattle | | |
|---|---|---|---|---|---|---|
| | Control | Viable ADY | Non-viable ADY | Control | Viable ADY | Non-viable ADY |
| Lactate, m*M* | 0.53 | 0.09 | 0.19 | 0.03 | 0.02 | 0.01 |
| Minimum pH | 5.26 | 5.55 | 5.53 | 6.03 | 6.08 | 5.99 |
| Mean pH | 5.93 | 6.30 | 6.18 | 6.55 | 6.68 | 6.56 |
| pH<5.8, h/day | 12.9 | 2.0 | 5.8 | 2.5 | 0.03 | 0 |
| pH<5.5, h/day | 9.0[a] | 0.3[b] | 1.1[b] | 0.5[b] | 0[b] | 0[b] |

[a-b] Values within a row with different letters differ ($P < 0.05$).

## Conclusions

Cows with a healthy rumen ruminate extensively, have a mean rumen pH > 6 with very short infrequent dips below pH 5.8, have strong rumen mixing contractions, and their rumen microbiota are well adapted to a mixed diet of cellulose and starch. Maintaining healthy rumen function can be particularly challenging for cows in early lactation and primiparous cows because they are at a higher risk for developing SARA. New recommendations for the minimum amount of forage fiber needed to maintain healthy rumen function depend on particle size and fermentability of the ration, with starch content used as a proxy for fermentability. Diet formulation, feeding management, and feed additives can also help reduce the risk of acidosis.

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