

Managing Rumen Fermentation in Barley-Based Diets: Balance Between High Production and Acidosis

Karen A. Beauchemin

Research Center, Agriculture and Agri-Food Canada, Box 3000, Lethbridge, AB T1J 4B1, Canada

E-mail: beauchemin@em.agr.ca

■ Take Home Message

- Feeding for maximum productivity increases the incidence of sub-clinical acidosis which occurs when ruminal pH ≤ 5.8 (pH ≤ 5.5 by ruminocentesis), but remains higher than during clinical acidosis.
- In addition to the financial losses attributed to health problems caused by subclinical ruminal acidosis, feed costs increase due to poor fiber digestion and lower feed efficiency.
- Ruminal acidosis occurs when the production of fermentation acids exceeds the ability of the animal to remove or neutralize the acids produced. Strategies to minimize ruminal acidosis should be based on reducing acid production in the rumen as well as neutralizing or removing acids from the rumen.

■ Clinical and Subclinical Acidosis

Clinical acidosis occurs when blood pH falls below 7.35, due to a decrease in the alkali (base) of body fluids relative to acid content (Owens et al. 1998). Other clinical signs are ruminal pH below 5.0, cows off feed, rumen stasis, diarrhea, dehydration and lethargy (Elam 1976). Lactic acid concentrations in the rumen exceeding 40 mM are indicative of severe acidosis, although acidosis can occur without build-up of lactic acid (Owens et al. 1998).

Although clinical acidosis is a major problem of economic significance for the Alberta feedlot industry, the incidence of subclinical ruminal acidosis is of greater concern for the dairy industry. Subclinical acidosis occurs when ruminal pH declines below optimum for fiber digestion by the rumen bacteria, but remains higher than for clinical acidosis (pH > 5.0). Nordlund et al. (1995)

suggested that subclinical acidosis occurs when rumen pH ≤ 5.5 using samples obtained by ruminocentesis. This corresponds to an actual pH of 5.8, since samples taken by ruminocentesis are about 0.3 pH units lower than those taken directly from the rumen (Garrett et al. 1999). Lactic acid concentrations do not usually increase during subclinical acidosis, and concentrations rarely exceed 5 mM (Oetzel et al. 1999).

Subclinical acidosis is estimated to cost the U.S. dairy industry between \$500 million to \$1 billion a year (Donovan 1999). A case study of a 500-cow dairy in New York State estimated the financial impact of subclinical acidosis due to lost income at \$400 to \$475 U.S. per cow per year (Stone 1999). While no figures are available on the cost of subclinical ruminal acidosis for the Canadian dairy industry, there is no reason to believe that the losses per cow are any less than experienced in the U.S.

■ Diurnal Fluctuations in Rumen pH

Typical profiles of ruminal pH in dairy cows fed total mixed rations containing rolled barley are shown in Figure 1. Ruminal pH is high before the morning feeding because extensive rumination, and limited feed intake, occur at night. After feeding, the pH drops and the extent of this decline depends upon the size and fermentability of the meal. Thus, subclinical acidosis usually does not persist the entire day.

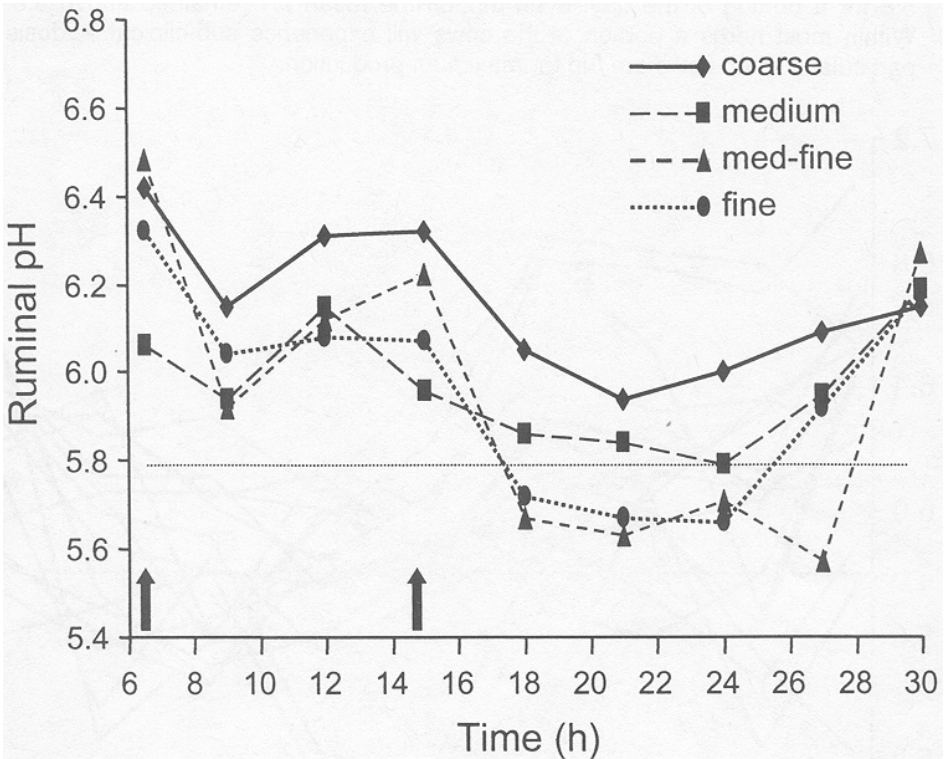


Figure 1. Rumen pH profiles in dairy cows fed total mixed ratios containing barley rolled to varying thicknesses. Each profile is the mean of four cows (arrows indicate feeding times).

Feeding a total mixed ration rather than individual components separately helps minimize pH fluctuations because blending the concentrate with the forage spreads the intake of concentrate over the day. However, cows fed a total mixed ration still experience fairly large fluctuations in ruminal pH. Even though the total mixed diet is offered free choice, cows tend to consume several large main meals, as well as frequent small meals, throughout the day.

Many research trials report mean ruminal pH for a group of cows fed a particular diet. It is important to realize that mean pH does not reflect the extent of the diurnal fluctuations. Furthermore, there is considerable variation in ruminal pH among animals fed the same diet (Figure 2). Some animals experience prolonged periods of low pH while for other cows, pH remains consistently high. For example, in Figure 2, 13 of the 16 cows experienced pH

5.8 for a portion of the day, even though the mean pH remained above 5.8. Within most herds a portion of the cows will experience sub-clinical acidosis particularly when cows are fed for maximum production.

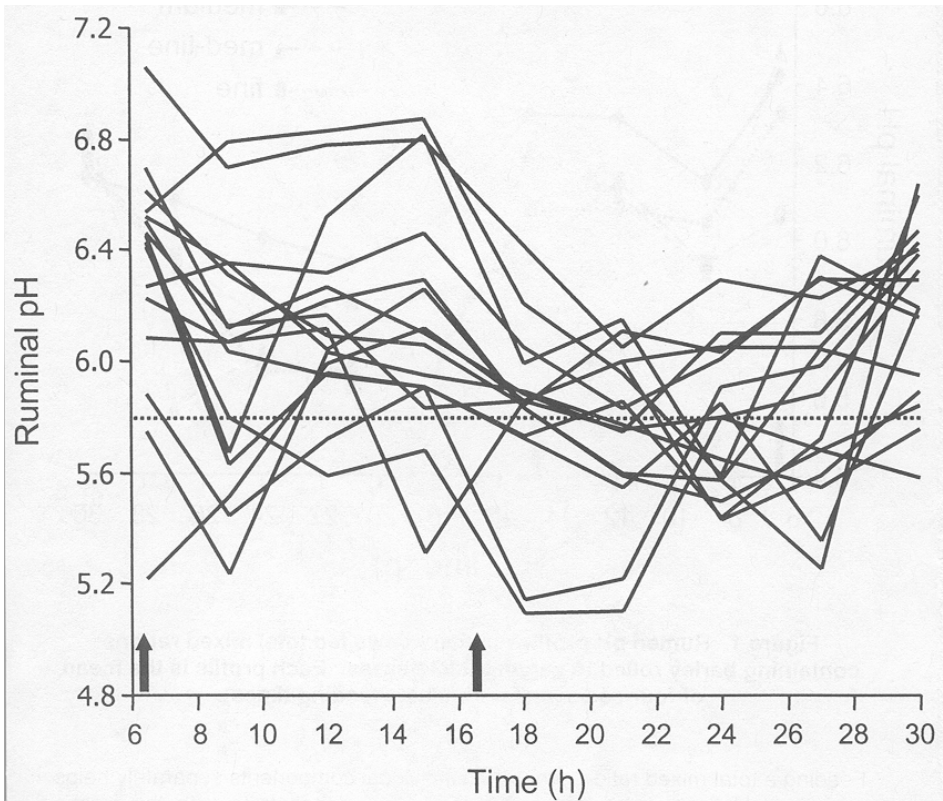


Figure 2. Rumen pH profiles of individual dairy cows fed total mixed rations containing barley rolled to different thicknesses (arrows indicate feeding times; dotted line indicates subclinical acidosis).

■ Assessing Ruminal Acidosis On-farm

Subclinical ruminal acidosis is difficult to judge in the field. Signs of acidosis are subtle because the cow remains alert, mobile, and consumes feed. An increase in the number of lame cows is thought to be a good indication of subclinical ruminal acidosis. However, lameness does not always indicate acidosis, because environmental and management factors can also contribute

to hoof lesions and laminitis (Greenough and Vermunt 1991). Additionally, it can take some time between the causative insult and the observation of lameness. Decreased milk production and milk fat also commonly occur. However, numerous factors affect milk yield and milk fat content is not always lowered by acidosis.

University of Wisconsin researchers recommend measuring rumen pH of cows on commercial dairy farms to assess the incidence of ruminal acidosis (Garrett et al. 1999). Samples of ruminal fluid are obtained by rumenocentesis or percutaneous needle (1.6 mm o.d.) aspiration of fluid from the caudal ventral rumen. Twelve cows per herd or per diet are sampled with samples taken 2 h after concentrate feeding in herds where forages and concentrates are fed separately, and 4 to 7 h after feeding in herds fed total mixed rations. Cows with a ruminal pH ≤ 5.5 are considered to have subclinical ruminal acidosis. If three of the twelve cows (25%) have a ruminal pH ≤ 5.5 , then the herd is considered to have an acidosis problem. They reported that a third of the herds tested, and 26% of the cows near peak intake, had subclinical ruminal acidosis (Donovan 1997).

■ Barley Versus Corn Diets

There are no data available on the incidence of subclinical acidosis in western Canada. However, the incidence of subclinical acidosis may be higher in western Canada than in other areas where corn is the major feed grain. Barley must be processed to maximize its digestibility, but processed barley grain is rapidly and extensively digested in the rumen. In contrast, ruminal digestion of corn grain is slower, thus a larger extent of corn starch escapes ruminal digestion and is available for digestion post-ruminally. Because starch digestion within the rumen is greater for barley than corn, cows fed diets containing barley tend to have a ruminal pH that is about 0.2 units lower than for cows fed corn, when diets are formulated to contain the same amount of forage fiber (Yang et al. 1997).

■ Rumen pH and Fiber Digestion

In addition to the financial losses attributed to health problems caused by subclinical ruminal acidosis, feed costs increase due to poor fiber digestion and lower feed efficiency. Numerous in vitro studies have shown that the major cellulolytic bacteria (*Ruminococcus albus*, *R. flavefaciens*, and *Fibrobacter succinogenes*) cannot tolerate pH below 6.0 (Russell and Wilson 1996). In addition to the effects of low pH, the importance of daily pH fluctuations in the rumen is uncertain. A continuous culture in vitro system was used to study the effects of pH fluctuations on digestion (Calsamiglia et al. 1999). The treatments

were: a) pH constant at 6.4 (High), b) pH constant at pH 5.7 (Low), c) repeated 4-h cycles at pH 6.4 and pH 5.7 (H-L), and d) pH constant at 6.4 except for two 30-min drops to pH 5.7 twice daily (H-2L). Digestion of NDF was significantly higher for High (53.8%) and H-2L (53.3%), intermediate for H-L (46.1%) and significantly lower for Low (37.4%). As predicted, continuously low pH decreased fiber digestion. However, when pH was high, short infrequent drops in pH had no effect on decreasing fiber digestion. However, constant fluctuation of pH from high to low resulted in fiber digestion similar to the mean of the High and Low treatments. These data suggest that for dairy cows, even though pH tends to remain high during the night time, low pH during the day following meals depresses fiber digestion.

The effects of diurnal shifts in rumen pH *in vivo* are uncertain. It appears that the extent to which fiber digestion is decreased *in vivo* due to low ruminal pH is less than predicted from *in vitro* studies. For example, we measured ruminal pH and fiber digestion in dairy cows fed diets that ranged in the extent to which barley grain was flattened during steam-rolling (Yang et al. 1999). The diets consisted of 53% concentrate and supplied 32% starch, 37% neutral detergent fiber (NDF) and 22% NDF from forage sources (dry matter (DM) basis). The diets exceeded minimum fiber requirements of the cows. Ruminal pH averaged 6.16 for cows receiving coarse barley and 5.96 for the other cows (Table 1). While differences in mean pH due to grain processing were not large, considerable differences in the duration that pH remained below the threshold for subclinical acidosis were observed. Ruminal pH of cows fed the coarse grain was 5.8 for 3.7 h/d, whereas the rumen pH of cows fed the medium, medium-flat and flat grains was pH 5.8 for 6.1, 9.0, and 10.6 h/d, respectively. Despite differences in duration of low pH, ruminal and total tract fiber digestion was unaffected by grain processing.

Table 1. Effects of barley rolled to various thicknesses on intake, production and digestive parameters.

Item PI ^y (%)	Diet ^z			
	Coarse	Medium	Medium -flat	Flat
	81	72.5	64	55.5
DM intake, kg/d	18.7 ^b	21.4 ^a	21.7 ^a	20.1 ^{ab}
Milk production, kg/d	25.6 ^c	28.1 ^b	30.8 ^a	29.0 ^b
Fat content, %	3.93	3.89	3.78	3.90
Protein content, %	3.15 ^b	3.30 ^a	3.29 ^a	3.34 ^a
Mean rumen pH	6.16 ^a	5.97 ^b	5.95 ^b	5.96 ^b
pH < 5.80, h	3.7 ^b	6.1 ^{ab}	9.0 ^a	10.6 ^a
Lowest pH	5.74 ^a	5.46 ^{ab}	5.31 ^b	5.43 ^{ab}
Ruminally fermented OM, kg/d	9.7 ^b	12.0 ^a	12.2 ^a	11.1 ^{ab}
Ruminal NDF digestion, %	47.7	48.0	53.2	47.1
Total tract NDF digestion, %	56.6	53.2	58.4	56.3
Total tract DM digestibility, %	62.4 ^b	63.9 ^{ab}	70.3 ^a	69.8 ^a

^z Diets consisted of 53% concentrate and supplied 32% starch, 36.5% neutral detergent (NDF) and 22% NDF from forage sources (DM basis).

^y PI = processing index measured as the volume weight of the barley after processing, expressed as a percentage of its volume weight before processing.

DM = dry matter; OM = organic matter; NDF = neutral detergent fiber

These data indicate that other fibrolytic organisms must contribute significantly to ruminal fiber digestion. Forster et al. (11) found that over 60% of rumen bacterial species have not been fully characterized and some of these species may be fibrolytic. The role of what has been considered to be minor populations of rumen bacteria on fiber digestion needs to be revisited.

While fiber digestion in vivo is higher than expected based on in vitro results, it seldom approaches the maximum potential digestion of the diet. Consequently, feed efficiency is compromised. For example we fed dairy cows a diet containing 24% corn silage, 14% chopped alfalfa hay, and 62% concentrate (DM basis) and observed a DM and NDF total tract digestibility of 63.9% and 42.6%, respectively (Yang, Beauchemin and Rode; unpublished data). When the same diet was fed to lambs the digestibilities were 77.1% and 57.7%, respectively. Thus, the extent of fiber digestion by dairy cows is often lower than the potential digestion of the feed, as was achieved by sheep. Lower fiber digestion in dairy cows is due to the combined effects of low ruminal pH and reduced retention time in the rumen due to rapid throughput. Low fiber

digestion represents a considerable increase in feed costs for the dairy producer.

■ Nutritional Factors Affecting Rumen pH

It is often said that subclinical acidosis is caused by insufficient dietary effective fiber, which is fiber that stimulates chewing. In fact, the Cornell model predicts ruminal pH ($r^2 = 0.52$) directly from effective fiber (% of DM intake) using data from dairy, beef, and sheep (Pitt et al. 1996). However, our research does not support this finding when only lactating dairy cows are considered. We compiled data for dairy cows from numerous publications in which cows were fed a variety of diets including diets containing barley grain (99 diets, 755 cows). The relationship was poor ($R^2 < 0.13$) between ruminal pH and fiber, whether measured as NDF, NDF from forage, or effective NDF (Figure 3). Thus, simply increasing the fiber or effective fiber content of the diet does not guarantee an increase in ruminal pH. One must also consider the DM intake of the cows, the fermentability of the diet, and feeding management factors. That is not to say that fiber does not play a role in maintaining optimum pH in the rumen. It is simply that many additional factors also must be considered.

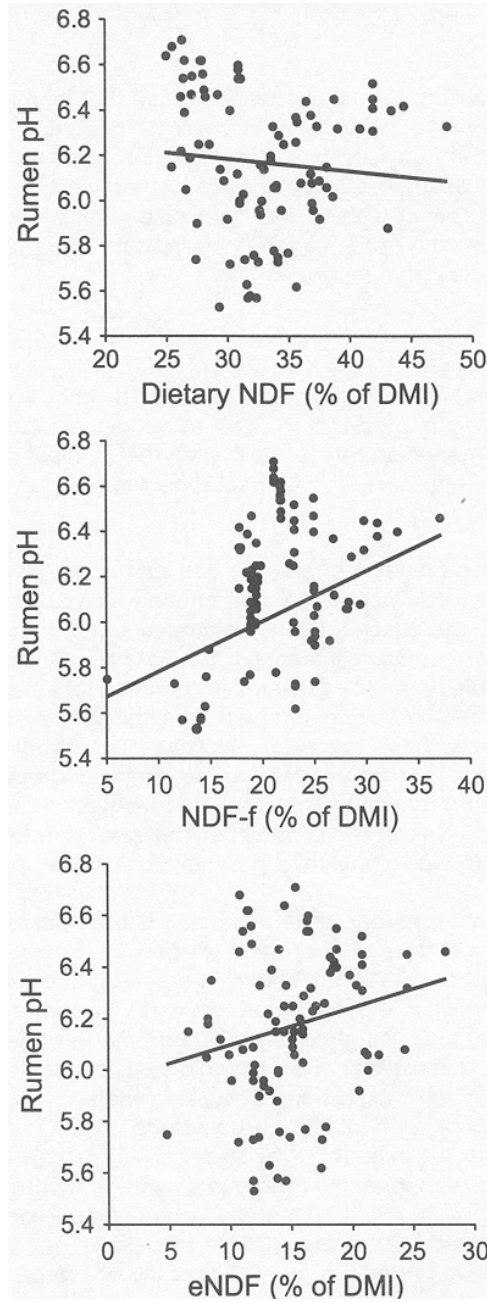


Figure 3. Relationship between rumen pH and proportion of dietary neutral detergent fiber (NDF), NDF from forage sources (NDF-f), or effective NDF (eNDF). The correlation coefficients were <0.12 .

Ruminal pH is the resulting balance between factors that lead to the production of fermentation acids and those that remove or neutralize acids. Ruminal acidosis occurs when the production of fermentation acids exceeds the ability of the animal to remove or neutralize the acids produced (Allen 1997). The development of effective strategies that minimize ruminal acidosis must be based on an understanding of the factors that promote acid production and the factors that remove acids from the rumen.

Acid Production

Current practices that encourage high intakes of good quality feeds to maximize milk production predispose cows to rumen acidosis. When feed intake is high and fermentation rate is rapid such that ruminal digestion is high, production of volatile fatty acids (VFA) within the rumen is extensive, and pH tends to decrease.

The quantity of organic matter fermented in the rumen drives acid production. Furthermore, it is the rate of digestion that causes diurnal fluctuations in pH. Thus, it follows that decreasing intake, decreasing ruminal digestibility, or slowing the rate of fermentation increases ruminal pH. Obviously, restricting intake is not a desirable approach to increasing ruminal pH, because milk yield may also be lowered. Decreasing ruminal digestibility is also not desirable, except sometimes in the case of starch. However, with barley diets, ruminal starch digestion should not be reduced by minimizing grain processing as coarse processing also reduces postruminal starch digestion, thereby lowering total tract digestibility. In contrast, reducing the rate of fermentation in the rumen is an effective means of minimizing rumen acidosis.

One approach to slowing the rate of fermentation is to replace a portion of the grain with nonforage sources of fiber such as beet pulp, soy hulls, or alfalfa pellets (Beauchemin et al. 1991). Alternatively, a portion of the barley grain can be replaced by corn which is digested more slowly in the rumen. Of course, the most effective strategy to slowing fermentation rate in the rumen is to increase the proportion of forage in the diet. For example, 1 kg of alfalfa hay (40% NDF) supplies about 390 g of fermentable carbohydrate, whereas 1 kg of barley grain supplies about 430 g of fermentable carbohydrate. Thus, digestion of good quality forage only produces about 10% less total VFA than the digestion of barley grain. But, more importantly, forage is digested much more slowly than grain. After 2 h of digestion, 22% of the alfalfa hay compared with 36% of the barley would be digested. After 3h, 27% of the alfalfa hay and 46% of the barley would be digested. After 12h, only 45% of the alfalfa hay compared with 72% of the barley would be digested. Thus, more fermentation acids 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.

Adding forage to the diet not only increases chewing time and saliva secretion, but it evens out acid production throughout the entire day.

Acid Removal and Neutralization

Fermentation acids are removed from the rumen by absorption through the rumen wall, by neutralization due to salivary and other buffers, or by passage from the rumen.

Absorption. Absorption of VFA plays a significant role in the removal of fermentation acids from the rumen. About half of the acids produced are absorbed from the rumen through the rumen wall (Allen 1997). Extensive absorption of VFA can damage the rumen papillae and allow passage of bacteria from the rumen to the blood stream (Owens et al. 1998). Histamine production may also increase in response to bacterial invasion, causing blood vessels in peripheral tissues to dilate, thereby increasing the likelihood that laminitis may develop. Following a bout of acidosis, repaired tissues within the rumen thicken which reduces surface area for absorption. This situation slows the rate of removal of acids from the rumen and predisposes the cow to acidosis. A healthy rumen can be maintained by avoiding abrupt dietary changes, adapting the rumen environment prior to calving, providing a total mixed ration, and by encouraging small frequent meals.

Saliva. Saliva contains bicarbonate and phosphate buffers that play a major role in buffering acids within the rumen. It is estimated that salivary buffers account for about 30 to 40% of the neutralization of fermentation acids in the rumen (Allen 1997). It is generally accepted that salivary secretion increases during eating and ruminating, but there is some debate about how important chewing time actually is in terms of buffering the rumen.

It is usually assumed that increasing chewing time increases salivary secretion and this increases ruminal pH. Most of the information in the literature on saliva secretion is from animals with restricted feed intake and these values likely do not apply to dairy cows fed for ad libitum intake. The only published study for lactating dairy cows (Cassida and Stokes 1986) fed for maximum DM intake estimated salivary secretion during resting as 151 ml/min (Table 2). During eating, salivary secretion was 1.10 to 1.24 times higher than during resting for cows fed a total mixed diet consisting of 60 to 70% concentrate and either corn silage or alfalfa haylage (DM basis). The results of this study indicate that, for dairy cows, salivary secretion during eating is not as high relative to resting as often assumed. However, there are concerns that resting salivation may have been overestimated in this study due to the technique used, and that eating salivation was low due to the use of high grain diets.

Table 2. Salivary secretion during resting and eating in dairy cows.

Ref- erence ^z	Diet (DM basis)	Resting (ml/min)	Eating	
			ml/min	ml/g DM
Total mixed rations				
1	30% AH: 70% C	152.1	188	3.36
	40% CS: 60% C	150.7	166	3.11
2	40% BS: 60% C	104.5	121	1.71
	50% BS: 50% C	99.5	104	1.58
	60% BS: 40% C	91.3	121	1.73
3	20% AH, 20% CH: 60% C	...	199	3.71 <i>a</i>
	30% AH, 10% CH: 60% C	...	174	2.73 <i>b</i>
	20% AH, 20% GH: 60% C	...	187	2.65 <i>b</i>
	30% AH, 10% GH: 60% C	...	216	3.69 <i>a</i>
Component feeding				
2	C (50% of diet)	107.2	201	1.08 <i>b</i>
	BS (50% of diet)	107.2	94	1.58 <i>a</i>
4	BS	...	213	4.4 <i>b</i>
	AH	...	194	3.4 <i>b</i>
	Alfalfa hay	...	227	4.0 <i>b</i>
	Barley straw	...	199	5.6 <i>a</i>

a, b Means within an experiment with different letters differ ($P < 0.05$).

^z References: 1, Cassida and Stokes (1988); 2, Maekawa, Beauchemin, and Christensen, unpublished data; 3, Yang and Beauchemin, unpublished data; 4, Beauchemin and Erikson, unpublished data;

^y AH = alfalfa haylage, C = concentrate, CS = corn silage, BS = barley silage, CH = chopped hay, GH = ground hay.

We recently conducted several studies to quantify salivary secretion in dairy cows in an attempt to understand the role of diet in maintaining rumen pH. In the first study, dairy cows were fed total mixed diets ranging from 40 to 60% barley silage (DM basis) (Maekawa, Beauchemin and Christensen, unpublished data). Saliva secretion during resting was considerably lower (mean of 100 ml/min) than previous estimates. However, saliva secretion during eating was 1.15 times higher than during resting which was similar to previous estimates. The data also indicate that basal levels of saliva secretion during resting may vary according to the physiological status of cows. For example, resting saliva secretion was 25% lower for cows at 4 wk versus 8 wk of lactation (Cassida and Stokes 1988). This may explain why acidosis can be a problem particularly for cows in early lactation. Furthermore, salivary secretion per minute of eating is relatively constant over a range of diets within an experiment (Table 2).

Thus, feeds that are consumed more slowly, in longer meals, result in more total saliva output.

Saliva flow during rumination is usually assumed to be 1.8 times the resting saliva rate (Cassida and Stokes 1988). Although this estimate is based on numerous studies, it is not based on dairy cows consuming large quantities of feed. It is possible that saliva secretion during rumination is in fact similar to that during eating (Arglye and Balwin 1988). It is clear that better estimates of saliva production are needed for dairy cows in order to predict dietary effects on ruminal pH.

It is often assumed that fiber content of the diet can be manipulated to increase chewing time and, consequently, salivary secretion. Long fiber must be chewed to reduce its particle size, and this fiber is referred to as physically effective fiber (Mertens 1997). As intake of physically effective fiber increases, chewing time increases. Thus, as chewing time increases, total salivary output increases. However, the increase in saliva output is not as great as often assumed because increasing eating and ruminating time decreases resting time, and the accompanying resting saliva secretion.

Using the estimates of saliva secretion from Table 2, the effects of increasing chewing time on saliva secretion can be predicted (Table 3). We observed that increasing the forage content of the diet from 30% to 81% alfalfa hay (from 32% to 40% dietary NDF), increased eating time by 2.2 h/d and ruminating time by 1.2 h/d (Beauchemin et al. 1994). We estimate that increased chewing time increased saliva output by 8 to 12 L/d, which represents only a 4.4% increase in buffering capacity of the rumen. Although total saliva output was not substantially increased, the quantity of saliva secretion during eating was increased by 40%. Increased saliva output during eating would enable the cow to buffer the large quantity of fermentation acids produced soon after the feed is consumed. In addition, increasing forage intake while decreasing grain intake (11.8 kg/d) would reduce the total amount of fermentation acids produced by about 10%. But more importantly, the rate of fermentation acids produced would be considerably slower and more in tune with the constant output of salivary secretion during the day. Thus, the true benefit of increasing the effective fiber content of the diet is to synchronize the production of fermentation acids with the output of saliva, rather than strictly increasing total saliva secretion.

Table 3. Estimates of saliva secretion for cows fed low or high forage diets.

Diet	Chewing time ^z (min/d)	Based on Cassida and Stokes (1988)		Based on Maekawa, Beauchemin, Christensen (unpublished)	
		ml/min	L/d	ml/min	L/d
30% alfalfa hay (32% NDF)					
Eating	314	174	55	115	36
Ruminating	392	272	107	180	71
Resting	733	151	111	100	73
Total			272		180
81% alfalfa hay (40% NDF)					
Eating	444	174	77	115	51
Ruminating	463	272	126	180	83
Resting	533	151	80	100	53
Total			284		188

^z Chewing time based on alfalfa hay diets from Beauchemin et al. 1994.

Increasing forage particle size is another important strategy for preventing acidosis, particularly if diets contain low levels of forage fiber. For example, we used fine and coarsely chopped alfalfa silage in barley diets containing less than adequate or adequate NDF from forage (12 vs 22% of dietary DM) (Beauchemin et al. 1994). For the low fiber diet, feeding the coarsely chopped silage increased rumination time, such that rumination time was similar to that of cows fed the higher fiber diet containing fine silage. Milk fat also increased when coarse versus fine silage was fed, but the extent of the increase was greater when high forage diets were fed. This is because increasing particle length of forages results in a larger intake of long forage particles when forages comprise a larger portion of the diet. This study shows that increasing forage particle length in itself does not always overcome milk fat depression. This is because longer forage particle length only increases buffering within the rumen due to the additional saliva produced during chewing. Increased particle length does not, however, reduce fermentation rate. Thus, it is much easier to increase the buffering capacity within the rumen by increasing the proportion of forage in the diet rather than increasing forage particle length. However, increasing the forage content of the diet may lower the energy density of the diet and may decrease energy intake, resulting in lower milk yield unless good quality forages are used.

Other Buffers. Fiber, VFA, and ammonia produced as a result of protein degradation, contribute to the buffering capacity of the rumen. However, the net contribution of these factors is relatively minor as they provide relatively little buffering effect between pH 5.5 and 6.8 (Kohn and Dunlap 1998). Thus, selecting feeds based on their buffering capacity is not an effective means of preventing acidosis.

In contrast, adding buffers to the diet can be effective, as recently reviewed at this conference (West, 1998). Sodium bicarbonate and magnesium oxide are commonly used together at 0.75 to 1.0% (160 to 210 g/d) and 0.25 to 0.45% (50 to 85 g/d) of the diet, respectively. Adding this level of buffer is roughly equal to the net buffering effect of increasing chewing time by 1 h/d which could be accomplished by increasing the proportion of forage in the diet by about 10 to 15% units. This comparison accounts for the increase in saliva secretion and the decreased rate of VFA production resulting from the higher forage diet.

■ Conclusions

Although subclinical ruminal acidosis normally occurs in high producing, well-managed herds, it is a costly problem that must be managed. Ruminal acidosis occurs when the production of fermentation acids exceeds the ability of the animal to remove or neutralize the acids produced. Strategies to prevent ruminal acidosis should be based on reducing acid production in the rumen as well as neutralizing or removing acids from the rumen. Some strategies to consider are: avoid abrupt dietary changes, adapt the rumen environment prior to calving, provide a total mixed ration, encourage small frequent meals, and balance the intake of ruminally degradable starch with the proportion of forage in the diet, forage particle size, and dietary buffers.

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