APPLYING NUTRITIONAL MANAGEMENT TO RUMEN HEALTH

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Take Home Message

The rumen environment must be kept in a "healthy" state. Keeping the rumen healthy means that fiber will be digested at a maximal rate and feed intake will be maximized.

Subclinical ruminal acidosis occurs when the production of fermentation acids exceeds the ability of the animal to absorb the acids through the ruminal wall or neutralize the acids through salivary buffers.

Increasing the intake of physically effective fiber reduces the risk of acidosis. The optimal level of physically effective fiber in the diet depends on the other risk factors, including diet fermentability and feeding management.

Introduction

In order for cows to achieve their genetic potential for milk production and remain healthy, it is critical that the rumen environment be kept in a "healthy" state. When the rumen becomes dysfunctional, feed digestion is impaired and cows become susceptible to a range of metabolic diseases.

The rumen microbial population has the first opportunity to digest any feed consumed by the cow and anything that affects the rumen ecosystem will ultimately affect what and how nutrients are available to the cow for productive purposes. Nutritionists need to take a step back and examine the diet as a whole and understand its impact on the rumen environment.

The Rumen Environment

The rumen is essentially a fermentation chamber in which the resident microbial population helps to digest the diet. The partially fermented food and the micro-organisms then pass out of the rumen, into the small intestine. Digestion of food in the rumen occurs by a combination of microbial fermentation and physical breakdown during regurgitation of the food by rumination. Microbial attack is carried out by a mixed population of bacteria, ciliate protozoa and a small number of anaerobic fungi. The products of microbial fermentation, mainly volatile fatty acids (VFA) and microbial protein, are available for absorption by the host cow. Volatile fatty acids can supply up to 80% of the animal's energy requirement, while microbial protein leaving the rumen can account for between 50 and 90% of the protein entering the small intestine. In view of the importance of the rumen in the nutrition of the host, it is perhaps not surprising that a great deal of effort has been devoted to investigating methods for manipulating this complex ecosystem.

The rumen microbial population is very dense, containing 10^{10} bacteria/ml, 10^{6} protozoa/ml, and 10^{3} fungi/ml. Because protozoa are so much larger than bacteria, the protozoa can make up close to half of the total microbial biomass. These microbes are very specialized to survive and thrive within the rumen. Conditions are strictly anaerobic. In fact, the presence of oxygen is highly toxic to most rumen microbes. The rumen is buffered over a range of pH 5.7 to 7.3 by phosphate and bicarbonate from saliva and bicarbonate from rumen fermentation. Temperature is tightly controlled in a range of 36 to 41°C. Rumen microbes are well adapted to these conditions and their specific growth requirements reflect the availability and types of nutrients present in the feed.

The rumen microbial population exists in a highly dynamic state. The total population can change dramatically with any number of dietary factors. From the perspective of the cow and the nutritionist, it would be best if rumen bacteria digested feed as fast as possible, reproduced and never died until they passed out of the rumen into the small intestine. This would maximize the digestion of plant fiber and production of microbial protein. Under perfect continuous culture conditions, bacterial growth rate is equal to the rate that nutrients are made available and the rate that older, mature bacteria are washed out of the system. This means that carbohydrates, nitrogen, and all other growth factors are constantly present at the optimal amounts. Unfortunately, perfect conditions seldom, if ever, exist in the rumen. In fact, while we often think of the rumen as a continuous culture system, we know that cows do not eat continuously, even when offered a total mixed ration (TMR) several times per day. What actually occurs in the rumen is more kin to a "fed-batch system", where feed sporadically enters the system, with a fluctuating rate with which undigested feed and bacteria leave the rumen for the small intestine.

pH - The Central Issue

Keeping the rumen healthy and in balance means that fiber will be digested at a maximal rate and feed intake will be maximized as well. Forages are seldom the sole source of feed for dairy cows and because concentrates are fermented faster in the rumen, more fermentation means more VFA production and a lower pH. When ruminal pH falls below 6, fiber digestion declines dramatically. There are two reasons for this. Firstly, the enzymes necessary for fiber breakdown do not function effectively at pH < 6.0 and secondly, the growth rate of fibrolytic bacteria declines markedly at low pH. Not only are these bacteria not able to obtain the sugars necessary for growth, the low pH impedes growth itself. Fibrolytic bacteria are unable to maintain the pH inside their cells when ruminal pH is low. This incapacitates the cell machinery making growth impossible (Russell and Wilson, 1996).

Sub-clinical ruminal acidosis

Subclinical ruminal acidosis occurs when the production of VFA in the rumen exceeds the ability of the system to remove or neutralize the acids produced. In that case, ruminal pH declines below optimum for fiber digestion by the rumen bacteria, but remains higher than for clinical acidosis. A pH below 5.8, but above 5.0, is often used to indicate subclinical ruminal acidosis in ruminally cannulated dairy cows. Sub-clinical acidosis is not to be confused with lactic acidosis -- lactic acid concentration in the rumen does not usually exceed 5 m*M* during subclinical acidosis (Oetzel et al., 1999).

Many research trials report mean ruminal pH for a group of cows fed a particular diet, as shown in Fig. 1. Typically, 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. However, it is important to realize that mean pH does not reflect the extent of variation in pH among cows, or the extent of diurnal fluctuations in rumen pH for individual cows. There is considerable variation in ruminal pH among animals fed the same diet, as shown in Fig 2. Some animals experience prolonged periods of low pH while for other cows, pH remains consistently high. Within most herds a portion of the cows will experience sub-clinical acidosis particularly when cows are fed for maximum production. The goal is to minimize the number of cows affected, and to minimize the time each day that pH drops below 5.8.

Fig.1 Average rumen pH profile for a group of dairy cows fed a TMR consisting of 21% NDF from forage sources. Mean pH was 5.95. Cows were fed twice daily at 600 and 1430 h (Yang et al. 2000).

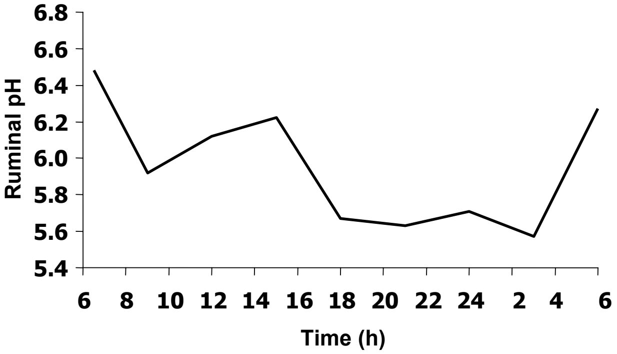
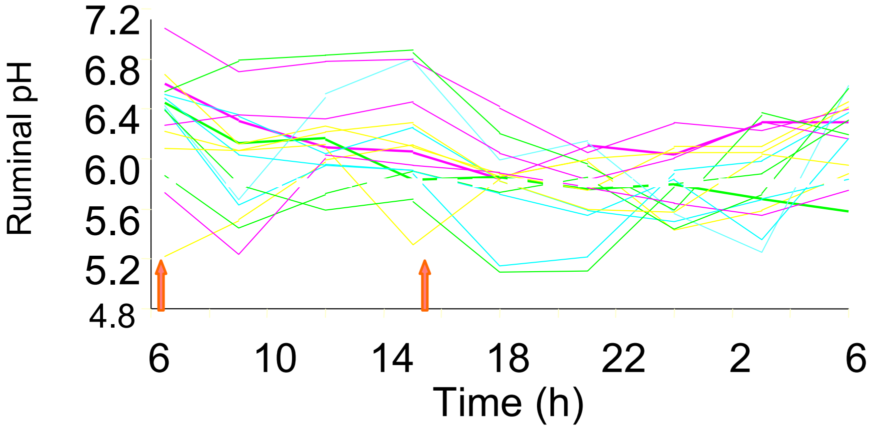


Fig. 2. Variation in rumen pH among individual cows. Each line on the graph represents the pH curve for an individual cow. Mean pH for the group is shown in Fig. 1. Thirteen of the 16 cows experienced a pH drop below 5.8 for some portion of the day.



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. A continuous culture in vitro system was used to study the effects of reduced rumen pH on feed digestion (Calsamiglia et al., 2000). When pH was maintained constant at 5.7 rather than 6.4, neutral detergent fiber (NDF) digestion decreased from 53.8% to 34.3%, or by 36%. However, because rumen pH fluctuates in dairy cows, the extent to which fiber digestion is decreased in vivo due to acidosis is usually less than what is predicted in the laboratory.

The effects of pH fluctuations in the rumen is uncertain. However, there is increasing evidence that fibrolytic bacteria can survive transitory low pH without affecting overall microbial fermentation. In the in vitro study by Calsamiglia et al. (2002) short infrequent drops in pH had no effect on fiber digestion. However, prolonged fluctuation of pH (>3 h) from high to low resulted in a 14% depression in fiber digestion. 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, and consequently the metabolizable energy content of the diet is reduced. Low fiber digestion represents a considerable increase in feed costs for the dairy producer.

Sub-clinical ruminal acidosis can also reduce feed intake due to both short-term and long-term effects. The long-term effects on intake are mediated through a decrease in fiber digestion. Because sub-clinical ruminal acidosis decreases the rate of fiber digestion, the “fill effect” of the forage is increased, and intake is subsequently decreased. Low ruminal pH can also have short-term effects on dry matter intake that cause erratic intake patterns. Brown et al. (2000) observed for feedlot cattle a high correlation coefficient (r = 0.84) between lowest daily ruminal pH and feed intake on the subsequent day. Thus, when ruminal pH is low, the cow decreases her intake in an attempt to limit the production of fermentation acids and restore pH conditions to a “comfortable” level. Once the pH is restored, the cow then resumes a high level of feed intake which leads once again to excessive production of acids, causing the cycle to repeat. Variation in day-to-day intake is undesirable in terms of stabilizing the rumen ecosystem.

Nutritional Factors Affecting Rumen pH

Effective strategies that minimize ruminal acidosis are based on an understanding of the factors that promote acid production and the factors neutralize or remove acids from the rumen.

Chewing activity

Saliva secretion increases when ruminants chew during eating and ruminating, thus feeding strategies that increase chewing time increase the buffering capacity within the rumen. Because of its effects on salivary secretion, chewing time has been measured as a indirect indication of the potential of the diet to maintain high rumen pH. The dairy cow typically spends 3 to 8 h/d eating and 6 to 9 h/d ruminating. Dietary factors that affect time spent chewing of dairy cows are primarily the fiber content of the diet and the particle size of the diet.

Fiber content and/or particle size of the diet can be manipulated to increase chewing time and, consequently, salivary secretion. Increasing the proportion of long forage particles in the diet increases the time required for chewing, as shown in Table 1. In the study by Yang et al. (2001), increasing the proportion of forage in the diet increased total NDF intake by 0.8 kg/d and forage NDF intake by 1.45 kg/d and, consequently, chewing time increased by about 2 h/d. Similarly, in the study by Beauchemin (1991) increasing the proportion of forage in the diet from low to high increased NDF intake by 0.7 kg/d and forage NDF intake by 3.2 kg/d, and chewing time increased by about 2 h/d. Averaged over these studies, chewing time increased about 2.7 h/d for every 1 kg/d increase in NDF intake or 0.6 to 1.3 h/d for every 1 kg/d increase in NDF from forage.

Table 1. Chewing activity of dairy cows as affected by proportion of forage (%) in the diet.

Item	Study 1 (Yang et al. 2001)		Study 2 (Beauchemin 1991)		
	35	65	42	58	74
NDF intake, kg/d	6.69^b	7.47^a	7.0	7.5	7.7
NDF-forage intake, kg/d	3.19	4.64	3.07	4.73	6.25
Eating, h/d	4.0^b	4.6^a	6.1	6.4	7.5
Ruminating, h/d	6.8^b	8.0^a	6.7	7.0	7.4
Total chewing, h/d	10.7^b	12.6^a	12.8	13.4	14.8
Salivary secretion (est), L/d	218	232	233	237	247
Mean ruminal pH	6.04	6.06	5.63	5.78	6.08
pH < 5.8*, h/d	5.9	6.1	6.7	4.5	0.77
Mean lowest pH	5.43	5.50	NA	NA	NA

* values for Study 2 are pH < 6.0; NA = not available.

Increasing the particle size of forage also has a significant effect on increasing chewing time particularly if diets contain low levels of forage fiber, or if the TMR is very fine. For example, in the study by Krause et al. (2002) increasing the forage particle size of alfalfa silage increased chewing by 4.3 h/d (Table 2). In that study the basal alfalfa silage was chopped very fine. In contrast, the basal forage used by Yang et al. (2001) was a medium chop length, and increasing forage particle size only increased chewing time by 0.6 h/d. In another study, we used fine and coarsely chopped alfalfa silage in 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.

Table 2. Chewing activity of dairy cows as affected by particle length of forage.

Item	Forage particle size (Krause et al. 2002)		Forage particle size (Yang et al. 2001)	
	Short	Long	Medium	Long
Eating, h/d	4.0	5.0	4.0^b	4.5^a
Ruminating, h/d	4.8	7.8	7.3	7.5
Total chewing, h/d	8.7	13.0	11.4^d	12.0^c
Salivary secretion (est.), L/d	204	235	223	228
Mean ruminal pH	5.90	6.07	5.99	6.09
pH < 5.8, h/d	9.3	5.5	7.0	5.0
Mean lowest pH	5.59	5.73	5.46	5.47

Salivary secretion

The increase in saliva output due to increased chewing is not as great as often assumed (Table 1 and 2). This is because increasing eating and ruminating time decreases resting time, and the accompanying resting saliva secretion. Assuming a salivary secretion rate of 99 ml/min during resting and 217 ml/min during chewing (Maekawa et al. 2002), the increase in total salivary secretion due to 1 h/d more chewing is about would be 7 L. The buffering capacity supplied by the additional saliva is approximately equal to that required to buffer the products of fermentation resulting from the ruminal digestion of about 0.75 kg of cracked corn. Thus, the net effect of this incremental saliva production on mean ruminal pH is relatively small. However, an increase in saliva secretion, particularly if secreted during eating, can help reduce the extent to which pH drops below 5.8 following meals, even though mean rumen pH is not greatly affected. In addition, if the increase in chewing time is accompanied by a reduction in starch intake due to increased intake of fiber (as in Table 1), there can be a substantial effect on ruminal pH. In that case, the total amount of fermentation acids produced is lower, and 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.

Physically effective fiber

The term effective fiber was proposed as a method of describing the potential of individual feeds to maintain rumen pH (Mertens 1992). Effective NDF (eNDF) is a assessment of the ability of a feed to replace forage in a ration so that milk fat of the cows fed that particular feed is maintained (Mertens 1997). In some models of feed formulation, including the Cornell Net Carbohydrate and Protein Synthesis model (Pitt et al. 1996), the Cornell Penn Minor Dairy model, and the NRC beef cattle model, the effective eNDF content of the diet is used to predict ruminal pH. However, the relationship between eNDF and ruminal pH for dairy cows is poor. Recently, the term physically effective (pe) NDF (peNDF) which is an actual measure of feed particle size was introduced (Mertens 1997) to refine the concept of effectiveness of fiber. The pe factor can be measured as the sum of the proportion of material retained on the 2 sieves (19 and 8 mm) of the Penn State Particle Separator, and peNDF can be calculated by multiplying the NDF content by the pe factor.

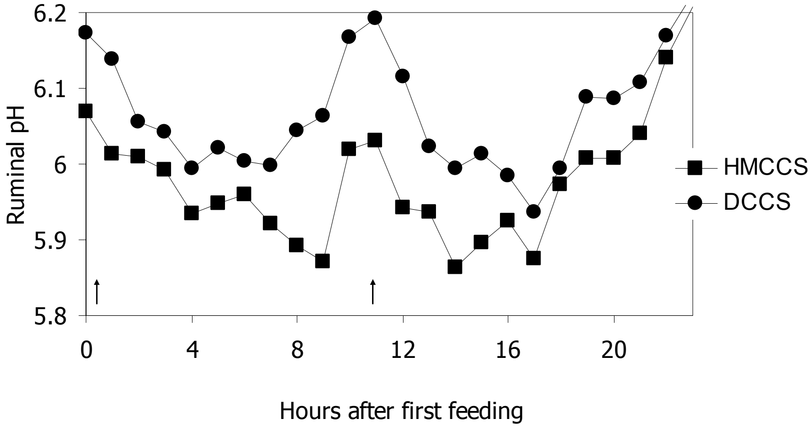
To evaluate the relationship between peNDF and ruminal pH we used data from two studies (Yang et al. 2001, 2002). The pe factors for the forages ranged from 49.5 to 90% and the pe factors for the TMRs ranged from 26 to 39%. The peNDF intake, ranged from 8.7 to 14.2% of dry matter intake. There was no relationship between peNDF and mean ruminal pH. Of the particle size variables examined, the proportion of TMR retained on the top sieve was the best predictor of mean rumen pH, but even then the correlation was low ($r = 0.25$; $P > 0.05$). However, there was a moderately strong inverse relationship ($r = -0.55$; $P < 0.05$) between peNDF intake and acidosis, measured as the depression (area) in pH below 5.8. This relationship indicates that that greater the peNDF intake of the cow, the lower the risk of acidosis.

The bottomline is that physically effective fiber plays a significant role in reducing the risk of acidosis, but the optimum level of peNDF in the diet will depend on the other risk factors. In particular, the fermentability of the diet and feeding management practices can significantly affect the relationship between fiber and ruminal pH. Thus, increasing the physically effective fiber content of the diet can increase chewing time, but this does not guarantee an increase in ruminal pH.

Fermentability of Feed

The quantity of organic matter fermented in the rumen drives VFA production. Furthermore, it is the rate of digestion that causes diurnal fluctuations in pH. For example, Krause et al. (2002) compared the effects of feeding high moisture shelled corn to feeding dry, cracked shelled corn to dairy cows (Fig. 3). Even though particle size of the forage was coarse, and considered adequate, rumen pH was lower for cows fed the high moisture grain because of its higher fermentability. Thus, it is critical to balance the rate of fermentability of carbohydrates with the ability of the diet to stimulate buffering through salivary secretion. Diets with higher fermentable carbohydrate sources require a higher proportion of peNDF to reduce the risk of acidosis.

Fig. 3. Ruminal pH of dairy cows fed high moisture corn (HMC) vs cracked shelled corn (DC). The forage was coarsely chopped (CS) alfalfa silage (from Krause et al. 2002).



Adaptation Strategies

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). Size and number of rumen papillae increase and decrease slowly as the need for surface area for absorption of acids increases or decreases. Thus, if the papillae have not sufficiently adapted to handle the acid load, pH in the rumen will drop. Furthermore, absorption of extensive VFA will 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 transition program that helps the rumen adapt to increased intake of fermentable carbohydrates is essential to reduce the risk of acidosis in fresh cows.

The rumen ecosystem is amazingly resilient to changes in diet, but the key is adaptation and stability. Rumen health is maintained by avoiding abrupt dietary changes, adapting the rumen environment prior to calving, providing a TMR rather than feeding concentrate and forages separately, and by encouraging small frequent meals throughout the day. Yeast and other direct-fed microbials can be very beneficial in terms of stabilizing the rumen ecosystem.

Conclusion

Maintaining a healthy rumen ecosystem while maximizing production is a balancing act. By maximizing fermentation, the cow obtains more volatile fatty acids for use as energy precursors and to synthesize microbial protein. However, more fermentation means more acid production and a lower rumen pH. Low rumen pH can depress fiber digestion and lead to metabolic disorders. Increasing the intake of physically effective fiber can help reduce the risk of acidosis, but the optimum level depends on the other risk factors. As we expect more production from our cows, they will have to eat more readily fermentable diets to meet their energy and protein requirements. This, in turn, may result in the cow getting less nutrients out of the diet than we expected. A better understanding of the workings of the rumen as a whole ecosystem will enable us to maintain the fine balance between productivity and acidosis.

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